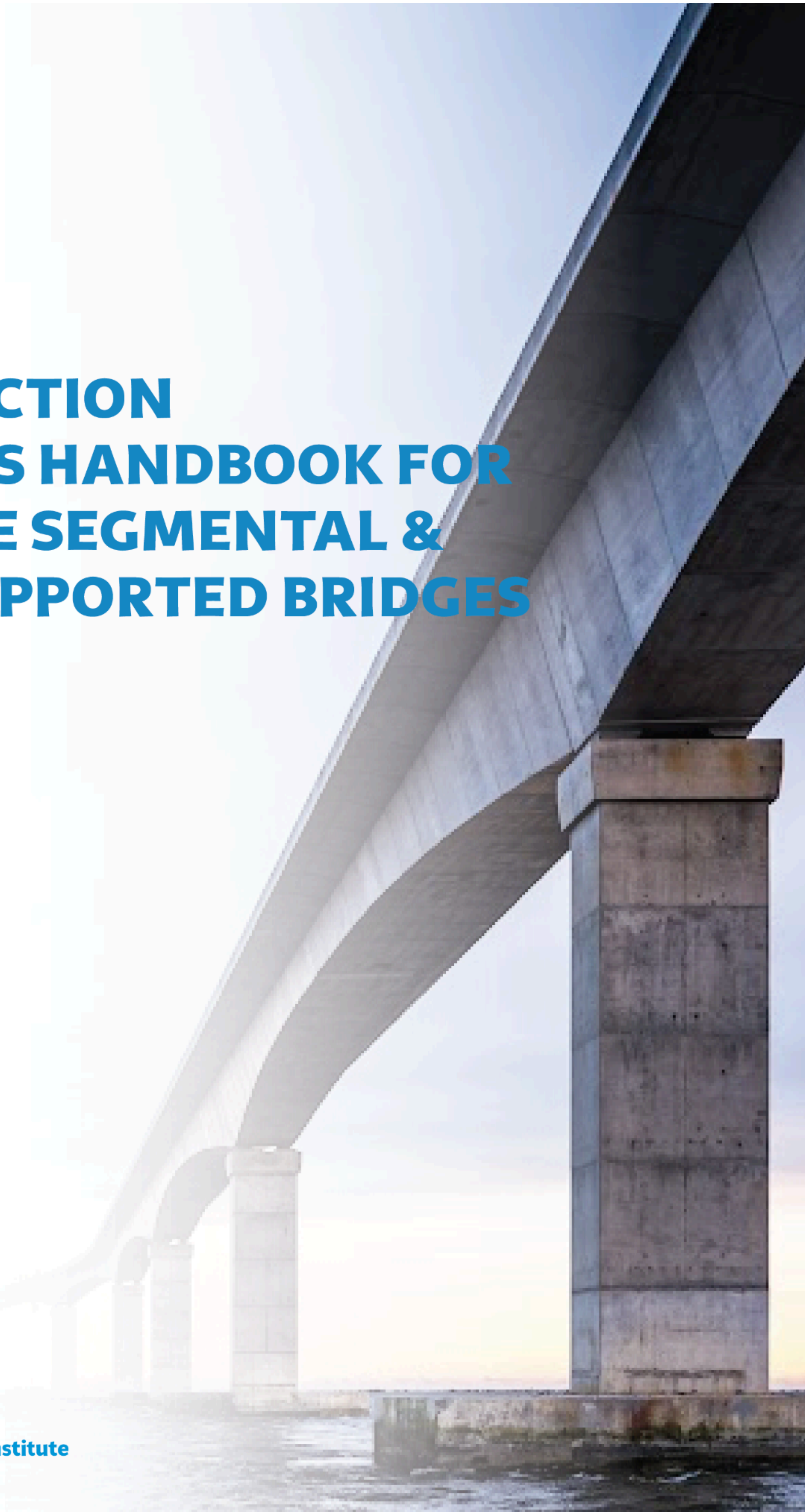
# CONSTRUCTION PRACTICES HANDBOOK FOR CONCRETE SEGMENTAL & CABLE-SUPPORTED BRIDGES

Published June 2026.



American Segmental Bridge Institute

# CONSTRUCTION PRACTICES HANDBOOK FOR CONCRETE SEGMENTAL AND CABLE-SUPPORTED BRIDGES

**Published June 2026**

**by**

ASBI
American Segmental Bridge Institute

9901 Brodie Lane, Suite 160 PMB 516, Austin, TX 78748
Telephone: (512) 523-8124
e-mail: info@asbi-assoc.org     web: www.asbi-assoc.org

# CONSTRUCTION PRACTICES HANDBOOK FOR CONCRETE SEGMENTAL AND CABLE-SUPPORTED BRIDGE

# MASTER TABLE OF FIGURES

# Acknowledgements

## (4th Edition)

In addition to the acknowledgements of individuals who were primary authors of chapters of the Third Edition, the following individuals were primarily responsible for writing or revising chapters of the Fourth Edition:

| | |
|---|---|
| *Chapter 1* | *Introduction and Overview of Segmental Construction*<br>***Wade Bonzon, GM2 Associates, Inc.*** |
| *Chapter 2* | *Terminology*<br>***Gregg A. Freeby, American Segmental Bridge Institute***<br>***All contributing others of other chapters*** |
| *Chapter 3* | *Construction of Precast Segmental Span-by-Span Bridges*<br>***Matthew Lengyel, GM2 Associates, Inc.***<br>***Darren Lueking, Traylor Bros., Inc.*** |
| *Chapter 4* | *Construction of Precast Segmental Balanced Cantilever Bridges*<br>***John Lynch, Modjeski & Masters***<br>***Chris Ursery, Arup*** |
| *Chapter 5* | *Construction of Cast-in-Place Balanced Cantilever Bridges*<br>***Jeff Mehle, McNary, Bergeron, and Johannesen***<br>***Eric Sommer, Structural Technologies, LLC*** |
| *Chapter 6* | *Incremental Launching Segmental Bridges*<br>***Erwan Allanic, SYSTRA International Bridge Technologies***<br>***Eric Sommer, Structural Technologies, LLC*** |
| *Chapter 7* | *Special Requirements for Construction of Concrete Segmental Cable-Stayed Bridges*<br>***Matthew Lengyel, GM2 Associates, Inc.***<br>***Eric Sommer, Structural Technologies, LLC*** |
| *Chapter 8* | *Segmental Substructures*<br>***Matthew Lengyel, GM2 Associates, Inc.***<br>***Jeff Mehle, McNary, Bergeron, and Johannesen*** |
| *Chapter 9* | *Casting Yard Planning and Set Up*<br>***Gowen Dishman, HNTB***<br>***Forrest Prillaman, FlatironDragados*** |
| *Chapter 10* | *Procedures for Handling, Transporting and Erecting Precast Segments*<br>***Darren Lueking, Traylor Bros., Inc.***<br>***Daniele Ortis, Parsons Corporation*** |
| *Chapter 11* | *Post-Tensioning Details and Procedures*<br>***Shahid Islam, DYWIDAG Systems International***<br>***Corey Rogers, RS&H*** |
| *Chapter 12* | *Epoxy Jointing, Duct Coupler Devices, and Prepackaged Grout*<br>***Timothy Barry, RS&H***<br>***Shahid Islam, DYWIDAG Systems International*** |
| *Chapter 13* | *Geometry Control*<br>***John Corven, Hardesty & Hanover***<br>***Ahmmad Eldieb, COWI***<br>***Kevin Yole, Traylor Bros., Inc.*** |
| *Chapter 14* | *Bearings and Expansion Joints*<br>***Jay Conklin, R.J. Watson, Inc.***<br>***Corey Rogers, RS&H***<br>***Ron Watson, R.J. Watson, Inc.*** |

| | |
|---|---|
| *Chapter 15* | *Lessons Learned*<br>***Rob Boyce, Louisiana Bridge Builders***<br>***Darren Lueking, Traylor Bros., Inc.***<br>***Forrest Prillaman, FlatironDragados***<br>***Benjamin Soule, SYSTRA International Bridge Technologies*** |
| *Chapter 16* | *Construction Engineering and Inspection (CEI) of Segmental Construction*<br>***Timothy Barry, RS&H***<br>***Robert Bennett, RS&H*** |
| *Chapter 17* | *Construction Inspection Guidelines for Concrete Segmental Bridges*<br>***Timothy Barry, RS&H***<br>***Kevin Yole, Traylor Bros., Inc.*** |

Graphics and diagrams in the Fourth Edition have been adapted and updated from a variety of sources that contributed to those in the Third Edition. Acknowledgement regarding this work is given to **Matthew Lengyel, GM2 Associates, Inc.**, with assistance from **John Corven, Hardesty & Hanover**.

# Acknowledgements

## (3rd Edition)

In addition to the acknowledgements of individuals who were primary authors of chapters of the Second Edition, the following individuals were primarily responsible for writing or revising chapters of the third edition:

| | |
|---|---|
| *Chapter 1* | *Introduction and Overview of Segmental Construction*<br>***Timothy Barry, RS&H, Inc.*** |
| *Chapter 2* | *Terminology*<br>***Brawn Lausen, Kiewit Infrastructure West Co.***<br>***Gregg A. Freeby, American Segmental Bridge Institute*** |
| *Chapter 3* | *Construction of Precast Span-by-Span Bridges*<br>***Wade Bonzon, FIGG*** |
| *Chapter 4* | *Construction of Precast Segmental Balanced Cantilever Bridges*<br>***Benjamin Soule, SYSTRA International Bridge Technologies*** |
| *Chapter 5* | *Construction of Cast-in-Place Balanced Cantilever Bridges*<br>***Eric Hiemke, Archer Western Construction*** |
| *Chapter 6* | *Incremental Launching Segmental Bridges*<br>***Wade Bonzon, FIGG***<br>***Benjamin Soule, SYSTRA International Bridge Technologies*** |
| *Chapter 7* | *Special Requirements for Construction of Concrete Segmental Cable-Stayed Bridges*<br>***Benjamin Soule, SYSTRA International Bridge Technologies*** |
| *Chapter 8* | *Segmental Substructures*<br>***Brenda Nichols, Cianbro Corporation*** |
| *Chapter 9* | *Production of Precast Segments*<br>***Bryant Helvey, Graham Construction*** |
| *Chapter 10* | *Procedures for Handling, Transporting and Erecting Precast Segments*<br>***Elie Homsi, Parsons*** |
| *Chapter 11* | *Post-Tensioning Details and Procedures*<br>***Shahid Islam, DYWIDAG-Systems International (DSI)*** |
| *Chapter 12* | *Epoxy Jointing, Duct Coupler Devices, and Prepackaged Grout*<br>***Chris Ursery, FIGG*** |
| *Chapter 13* | *Geometry Control*<br>***Matthew Lengyel, FIGG*** |
| *Chapter 14* | *Bearings and Expansion Joints*<br>***Stephen R. Pabst, Watson Bowman Acme*** |
| *Chapter 15* | *Construction of Precast Balanced Cantilever Bridges*<br>***Sean Bush, PCL Civil Constructors, Inc.*** |
| *Chapter 16* | *Construction Engineering and Inspection (CEI) of Segmental Construction*<br>***Gowen Dishman, HNTB Corporation*** |
| *Chapter 17* | *Construction Inspection Guidelines for Concrete Segmental Bridges*<br>***Benjamin Soule, SYSTRA International Bridge Technologies***<br>***Gowen Dishman, HNTB Corporation*** |

# Acknowledgements

## (2nd Edition)

In addition to the acknowledgements of individuals who were primary authors of chapters of the First Edition, the following individuals were primarily responsible for writing or revising chapters of the second edition:

| | |
|---|---|
| *Chapters 2 & 11* | *Post-Tensioning Terminology and Post-Tensioning Safety*<br>***Shahid Islam, Dywidag-Systems International USA, Inc.*** |
| *Chapter 3* | *Construction of Precast Segmental Span-by-Span Bridges*<br>***Jim Schneiderman, PCL Civil Constructors, Inc.*** |
| *Chapter 4* | *Construction of Precast Segmental Balanced Cantilever Bridges*<br>***Ben Soule, International Bridge Technologies, Inc.***<br>***David Goodyear, T.Y. Lin International, Inc.***<br>***Scott McNary, McNary Bergeron Associates, Inc.*** |
| *Chapter 5* | *Construction of Cast-in-Place Balanced Cantilever Bridges*<br>***Sean Bush, PCL Civil Constructors, Inc.*** |
| *Chapter 6* | *Construction of Cast-in-Place Incrementally Launched Bridges*<br>***Marco Rosignoli, HNTB Corporation***<br>***Takahiro Kakuta, PSM Construction, USA, Inc.*** |
| *Chapter 7* | *Special Requirements for Construction of Concrete Segmental Cable-Supported Bridges*<br>***Daniel Tassin, International Bridge Technologies, Inc.*** |
| *Chapter 9* | *Production of Precast Segments*<br>***Arthur Palmer, Consultant*** |
| *Chapter 10* | *Procedures for Handling Transporting and Erecting Precast Segments*<br>***Elie Homsi, Flatiron Constructors, Inc.***<br>***Riccardo Castracani, DEAL/Rizzani de Eccher USA*** |
| *Chapter 13* | *Geometry Control*<br>***Alan Moreton, Corven Engineering, Inc.*** |
| *Chapter 15* | *Lessons Learned*<br>***Cliff Freyermuth, ASBI***<br>***Ben Soule, International Bridge Technologies, Inc.***<br>***Ralph Salamie, Kiewit Pacific Company*** |
| *Chapter 16* | *Construction Engineering Inspection of Segmental Construction*<br>***Ian Hubbard, Parsons Brinckerhoff, Inc.***<br>***Thomas DeHaven, FIGG***<br>***John W. Jordan, Earth Tech, Inc.*** |

# Acknowledgements
## (1st Edition)

"A Guide to the Construction of Segmental Bridges" developed by and for the Florida Department of Transportation; October 1989, was used by the American Segmental Bridge Institute Construction Practices Committee as a source document in the development of the "Guidelines for Construction of Segmental Concrete Bridges" presented in this publication.

Contributions to the Handbook by individuals who were primary authors of chapters of this section of the manual are acknowledged as follows:

Chapter 3 Construction of Precast Segmental Span-by-Span Bridges
**– R. Kent Montgomery, FIGG**

Chapter 4 Construction of Precast Segmental Balanced Cantilever Bridges
**– David Jeakle, URS Corporation**

Chapter 5 Construction of Cast-in-Place Balanced Cantilever Bridges
**– Teddy Theryo, Parsons Brinckerhoff, Inc.**

Chapter 13 Segmental Substructures
**– R. Kent Montgomery, FIGG**

# CONSTRUCTION PRACTICES HANDBOOK FOR CONCRETE SEGMENTAL AND CABLE-SUPPORTED BRIDGE

## ASBI Construction Committee

May 2026

WADE BONZON, Chair
Project Development Manager
GM2 Associates, Inc.
(214) 304-1080
wbonzon@gm2inc.com

ERWAN ALLANIC
Senior Bridge Engineer
SYSTRA International Bridge Technologies
(858) 566-5008
eallanic@systra.com

TIMOTHY BARRY
Vice President and Area Manager
RS&H, Inc.
(904) 303-2507
timothy.barry@rsandh.com

ROBERT BENNETT
Project Engineer
RS&H, Inc.
(276) 591-8665
robert.bennett@rsandh.com

GUY CLOUTIER
Project Manager
Traylor Bros., Inc.
(808) 673-5252
gcloutier@traylor.com

JAY CONKLIN
Vice President of Project Development
R.J. Watson, Inc.
(716) 901-7020
jconklin@rjwatson.com

JOHN CORVEN
Director of Complex Bridges
Hardesty & Hanover
(850) 386-6800
jcorven@hardestyhanover.com

GOWEN DISHMAN
Senior Resident Engineer
HNTB Corporation
(662) 347-6506
gdishman@hntb.com

JOHN DUNHAM
Senior Vice President and COO
GM2 Associates, Inc.
(203) 410-9632
jdunham@gm2inc.com

AHMMAD ELDEIB
Senior Field Engineer
COWI
(850) 445-6313
ahel@cowi.com

ELIE H. HOMSI
Senior Vice President
Parsons Corporation
(303) 564-3426
elie.homsi@parsons.com

SHAHID ISLAM
Technical Director – Americas
DYWIDAG-Systems International
(630) 972-4028
shahid.islam@dywidag.com

MATTHEW LENGYEL
Senior Project Manager
GM2 Associates, Inc.
(214) 551-5051
mlengyel@gm2inc.com

HONGFEN LI
Structural Design Policy Engineer
South Carolina Department of Transportation
(803) 737-0217
lihongfen@scdot.org

**CONSTRUCTION PRACTICES HANDBOOK FOR**
**CONCRETE SEGMENTAL AND CABLE-SUPPORTED BRIDGE**

## ASBI Construction Committee
## May 2026

DARREN LUEKING
Pursuit Manager
Traylor Bros., Inc.
(409) 692-5733
dlueking@traylor.com

JOHN LYNCH
Senior Structural Engineer
Modjeksi & Masters, Inc.
(303) 933-9114
jvlynch@modjeski.com

JEFF MEHLE
Partner/Principal Engineer
McNary, Bergeron, and Johannesen
(720) 810-4572
jmehle@mcnarybergeron.com

DANIELE ORTIS
Construction Engineering Manager
Parsons Corporation
(778) 581-3530
daniele.ortis@parsons.com

FORREST PRILLAMAN
Project Manager
FlatironDragados
(540) 420-4225
fprillaman@fdcorp.com

COREY ROGERS
Nat'l Bridge Inspection & Preservation Leader
RS&H, Inc.
(214) 2087912
Corey.Rogers@rsandh.com

ERIC SOMMER
Vice President of Operations
Structural Technologies LLC
(817) 657-5653
esommer@structuraltec.com

BENJAMIN SOULE
Principal Engineer
SYSTRA International Bridge Technologies
(858) 229-8330
bsoule@systra.com

CHRIS URSERY
South Roads & Streets Deputy Business Lead
Arup
(225) 266-2028
chris.ursery@arup.com

RON WATSON
President
R.J. Watson, Inc.
(716) 901-7020
rwatson@rjwatson.com

KEVIN YOLE
Project Engineer
Traylor Bros., Inc.
(812) 477-1542
kyole@traylor.com

# Disclaimer

This publication is intended for the use of professionals competent in evaluating the significance and limitation of its contents and who will accept responsibility for the application of the materials it contains. *American Segmental Bridge Institute makes no warranty regarding the recommendations contained herein, including warranties of quality, workmanship or safety, express or implied, further including, but not limited to, implied warranties or merchantability and fitness for a particular purpose.* THE AMERICAN SEGMENTAL BRIDGE INSTITUTE SHALL NOT BE LIABLE FOR ANY DAMAGES, INCLUDING CONSEQUENTIAL DAMAGES, BEYOND REFUND OF THE PURCHASE PRICE OF THIS PUBLICATION. The incorporation by reference or quotation of material in this publication in any specifications, contract documents, purchase orders, drawings or job details shall be done at the risk of those making such reference or quotation and shall not subject the American Segmental Bridge Institute to any liability, direct or indirect, and those making such reference or quotation shall waive any claims against the American Segmental Bridge Institute.

**American Segmental Bridge Institute**

9901 Brodie Lane, Suite 160 PMB 516, Austin, Texas 78748
Telephone: (512) 523-8124
e-mail: info@asbi-assoc.org web: www.asbi-assoc.org

# TABLE OF CONTENTS

# Chapter 1:
# Introduction and Overview of Segmental Construction

## 1.1 Purpose

The purpose of this handbook is to provide guidance for construction of concrete segmental bridges. Although the segmental construction concept is generally very simple, the construction technology involved is, in numerous ways, more demanding than that required for other types of technology used in the industry. In spite of this, the advantages afforded by concrete segmental bridge construction have resulted in its continued growth throughout the United States and Canada. Increased use of this technology has led to a need to provide industry standard information for use by contractors, inspectors, quality control staff, and owners. In the interest of educating the industry, sharing best practices, and standardizing methods, this handbook is intended to provide a basic understanding of segmental construction technology. The overall goal is to facilitate the construction process, avoid common difficulties previously encountered, and reduce impacts to projects. This handbook is intended to be an industry guide aimed at focusing on specific aspects of the technology based on past experience.

## 1.2 Advantages of Segmental Construction

Concrete segmental bridge construction offers the advantages of industrialized, repetitive construction procedures. The methods used in the industry have been shown to contribute to reductions in traffic impacts, reduced cost, reduced construction time, as well as improved quality control and long-term durability. Segmental bridge construction offers maximum protection to the bridge environment and provides for maintenance of highway and railway traffic at the construction site. Segmental bridge technology is easily adaptable to tightly curved highway alignments. It provides many aesthetic advantages and is often chosen for signature bridges and other projects with high visual impact. The advantages of segmental bridges have led to their widespread use for urban viaducts, interchanges, rapid transit bridges, light rail, marine structures, and for very long span bridges. One of the major advantages segmental construction offers is that it provides options for longer span lengths that traditional concrete beam structures cannot achieve. Span lengths up to 550 ft. can be accomplished using precast segments, and up to over 800 ft. using cast-in-place segments. Studies have also shown that concrete segmental bridges perform very favorably in terms of long-term durability when compared to other bridge types.

## 1.3 Structure Types

The following is a summary of the most common types of concrete segmental bridge structures being used in the industry today. Each has unique features and unique advantages that contribute to their most appropriate use. The selection of which type to be used for a particular project depends on the location of the structure, access to the site, environmental considerations, desired span lengths, availability of pre-cast location, and ability to deliver materials to the site.

### 1.3.1 Precast Segmental Span-by-Span

In span-by-span construction, an entire span of precast segments is erected, post-tensioned, and becomes self-supporting before the next span is erected. A means to support the span is required, typically a temporary erection truss/gantry, during the erection and post-tensioning process. Precast segmental span-by-span bridges have normally been used for a span range of 80 to 160 ft. Some more recent applications have demonstrated feasible span lengths up to 180 ft.. Span-by-span bridges provide very high speed of construction and can be constructed over or parallel to existing highways with little or no impact on traffic. Span-by-span bridges are most often constructed using an erection truss, an erection gantry, or other temporary support or falsework **(Figure 1.1)**.

***Figure 1.1 –Precast Span-by-Span, Honolulu Light Rail, HI***
***(Photo Courtesy of Parsons)***

### 1.3.2 Precast Segmental Balanced Cantilever Bridges

Balanced cantilever construction uses a process where erection progresses outwards from a central pier, on alternating sides of the pier, until the cantilever is complete. Adjacent cantilevers are then constructed until a span is completed via a mid-span concrete closure. Precast segmental balanced cantilever bridges are commonly used in the U.S. for spans up to 400 ft. When circumstances permit the use of “heavy” segmental construction, such as those where segments can be transported by water, spans as long as 820 ft. have been built by the balanced cantilever method. For this method, individual segments are cast at an off-site location and then transported to site for erection. Segments can be erected by land-based cranes or barge-mounted cranes. Other methods involve deck-mounted lifting equipment **(Figure 1.2)**, or by an overhead gantry. Erection speed using cranes typically varies between 2 to 4 segments per day per crane.

*Figure 1.2 – Precast Balanced Cantilever, Bonner Bridge, NC*
*(Photo Courtesy of RS&H)*

### 1.3.3 Cast-in-Place Segmental Balanced Cantilever Bridges

Cast-in-place (CIP) balanced cantilevered construction refers to a process where segments are progressively cast at their final position in the structure, cantilevered on alternate sides of a central pier. Cast-in-place balanced cantilever bridges are used for spans ranging from 350 to 850 ft. Construction of cast-in-place cantilever bridges relies on the use of self-launching Form Travelers which provide the in-situ forming system for each segment cast (see **Figure 1.3**). The segment casting progresses outward from the central pier, sequentially on each side of the pier in a balanced manner with previous segment placements. Typically, segments are constructed in each form traveler on a 5-day cycle. However, 2-, 3- and 4-day cycles per segment have been achieved in some cases.

***Figure 1.3 – US 54 Canadian River Bridge, Logan, NM***
***(Photo Courtesy of Krew Heavy Civil)***

### 1.3.4 Precast Segmental Progressive Placement

Precast segmental progressive placement may be used for spans ranging from 100 to 300 ft. This method of construction has been applied or considered in environmentally sensitive locations where construction access is restricted to one or both ends of the bridge. Segments are erected sequentially from one end of the span toward the other and typically supported by some means of temporary falsework **(Figure 1.4)**.

*Figure 1.4 –Precast Segmental Progressive Placement, Linn Cove Viaduct, NC*
*(Photo Courtesy of FIGG)*

### 1.3.5 Cast-in-Place Segmental Incremental Launching

Cast-in-place segmental incremental launching involves construction of segments, one at a time, in a casting bed at one or both abutments. The entire completed span is then launched ahead across the piers by means of hydraulic jacks **(Figure 1.5)**. This process is repeated until the span is complete. Spans may range to about 350 ft., but longer spans could be achieved through the use of temporary mid-span supports. A steel launching nose is attached to the first segment to reduce moments and stresses during launching.

*Figure 1.5 – Incremental Launch, Bellaire Beach Bridge, FL*
*(Photo Courtesy of VSL)*

### 1.3.6 Precast and Cast-in-Place Segmental Cable-Stayed Bridges

Concrete segmental bridge construction can also be applied to cable-stayed bridges **(Figure 1.6)**. Both precast and cast-in-place segmental technology are applicable to construction of concrete cable-stayed bridges, as discussed in this Handbook. The major advantage of cable-stayed segmental bridges is the increased span lengths that can be achieved. Spans of up to 1,600 ft. have been accomplished using cable stay construction.

***Figure 1.6 – Penobscot Narrows Bridge and Observatory, Bucksport, ME***
***(Photo Courtesy of FIGG)***

## TABLE OF CONTENTS

# Chapter 2:
# Terminology

## 2.1 General Terminology

*Relevant figure and chapter references are provided in parentheses.*

*Anchorage Blister* – A build-out area in the web, flange, or flange-web junction for the incorporation of tendon anchorage fittings. **(Figure 2.2)**

*Balanced Cantilever Erection* – An erection method where segments are erected alternatively on either side of the pier in cantilever, up to the point where a cast-in-place closure is made with the previous cantilever or existing side span structure. **(Chapter 4)**

*Beam and Winch* – Custom-made segment hoisting equipment consisting of a longitudinal beam fitted with lifting pulleys, tackle, and winches, and attached to the end of a cantilever. After erecting one segment, the equipment is advanced to the next position in order to hoist the next segment. A beam and winch are used in balanced cantilever or progressive cantilever erection. **(Figure 4.26)**

*Box Girder or Box Pier* – A box-shaped structural member used for bridge superstructures and piers. **(Figure 2.2)**

*Cantilever Tendons* – Longitudinal post-tensioning installed in the top slab of a segmental bridge built with the balanced cantilever erection method.

*Cast-in-Place Segmental Bridge* – A bridge constructed with cast-in-place concrete segments.

*Casting Curve* – The geometric profile segments must be built to match in order to achieve the required theoretical bridge profile after all final structural and time-dependent (creep and shrinkage) deformations have taken place.

*Casting Manual* – A document that includes the procedures and engineering requirements for casting, handling, and storage of precast segments. Typically, this document is created by the Contractor and their Erection Engineer and submitted to the Owner for review and concurrence. **(Chapter 10)**

*Closure* – Cast-in-place concrete segment or segments that complete a span.

*Continuity Tendons* – Longitudinal post-tensioning installed in the bottom slab of a segmental bridge built in balanced cantilever.

*Diabolo* – Uniquely shaped voids designed and formed into concrete deviator segments in a shape that accommodates the tendon angle change through the deviator. **(Figure 2.3)**

*Deviation Saddle* – A concrete block build-out in a web, flange, or web-flange junction used to control the geometry of, or to provide a means for changing direction of, external tendons.

*Deviation Trumpet* – Detail for tendon connection of deviation saddles and diaphragms that provides tolerance for the angle of tendon connection. **(Figure 2.4)**

*External Tendon* – Tendon located outside the flanges or webs of a structural member, generally inside the box girder cell.

*Erection Manual* – A document that includes the procedures and engineering requirements for handling, erection, and post-tensioning of concrete segments. For a precast segmental bridge, this document often includes operating procedures and launch kinematics for erection equipment such as overhead gantries. For cast-in-place segmental bridges, this document often includes procedures for operating the self-launching form travelers. Typically, this document is created by the Contractor and their Erection Engineer and submitted to the Owner for review and concurrence. **(Chapter 11)**

*Erection Truss Span-by-Span* – A custom-built truss resting below or above a span on supports connected to the pier and/or previously erected superstructure, onto which a complete span of segments is placed by crane or another device. Such trusses may be self-launching to the next span or moved by cranes.

*Form Traveler* – Equipment used in construction of cast-in-place segmental bridges to advance the forms from segment to segment and support the leading edge of the forms throughout the “form-rebar-pour” cycle. Major components include the structural frames (horses), upper work platform, lower work platform, and trailing work platform.

*Launching Gantry* – Custom-built erection equipment used to take delivery of segments and lift, move, and place them in their final erected locations within the superstructure. After completion of a cantilever or span, the gantry is capable of launching itself forward into position to construct the next cantilever or span.

*Internal Tendon* – Tendon located within the flanges or webs (or both) of a structural member.

*Long-Line Casting* – A method of precasting segments on a long casting bed that incorporates the complete cantilever or span between field closures.

*Match-Casting* – A method of precasting segments whereby each segment is cast against an existing segment to produce a matching joint. When segments are separated and re-assembled in the structure, the mating surfaces fit together to reproduce the "as-cast geometry."

*Permanent Post-Tensioning* – Post-tensioning required as part of the completed structure.

*Pier Table* – The portion of a cast-in-place segmental bridge built atop the piers before assembly of the form travelers. A pier table may be designed to provide space for assembly of one form traveler or to accommodate concurrent fabrication of two form travelers.

*Precast Segments* – Box-shaped precast concrete elements which can be assembled to form a bridge superstructure or pier. **(Figure 2.1)**

*Precast Segmental Bridge* – A bridge constructed from precast concrete segments. (Common types of precast segmental bridges are described in **Chapter 1, Section 1.3.**)

*Progressive Erection in Cantilever* – Segments erected in cantilever in one direction only, from one pier to the next, using either temporary intermediate piers or cable stays (or both) to support the advancing cantilever.

*Segmental Construction* – Fabrication and erection of a structural element (superstructure or substructure) using individual elements, which may be either precast or cast-in-place. The completed structural element acts as a monolithic unit under some or all design loads. Post-tensioning is typically used to connect the individual elements. For superstructures, individual elements are typically short (with respect to the span length) box-shaped segments with monolithic flanges that comprise the full width of the structure.

*Short-Line Casting* – A method of precasting each segment in a special form called a casting cell that has a fixed bulkhead at one end and a previously cast segment at the other. The form is only one segment long, hence the term "short-line." **(Figures 6.10, 6.11, and 6.12)**

*Span-by-Span Erection* – A segment erection method where all the segments for one span are placed on a temporary support truss, aligned, jointed, and longitudinally post-tensioned together in one operation to make a complete span. **(Chapter 3)**

*Temporary Post-Tensioning* – Post-tensioning installed solely for erection purposes.

*Transverse Tendons* – Post-tensioning installed in the top deck and perpendicular to the centerline of the bridge, typically to strengthen the cantilevered wings of the segments.

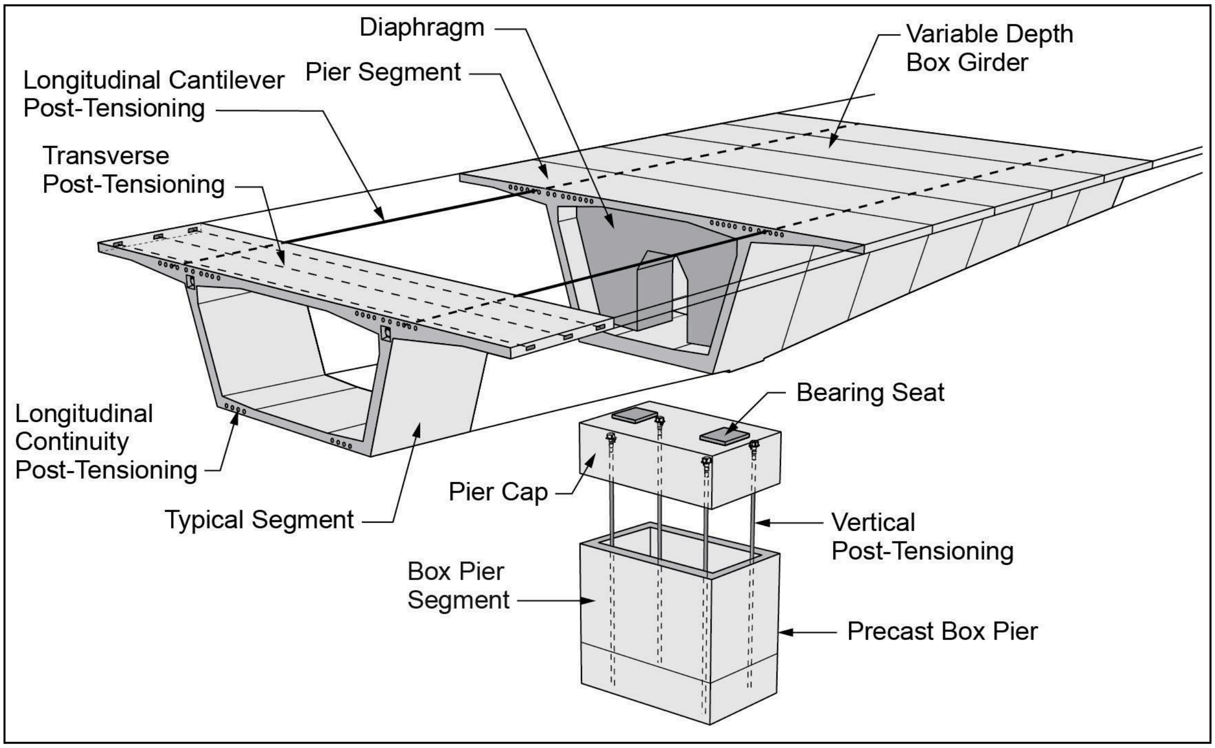


*Figure 2.1 – Segmental Bridge Components*

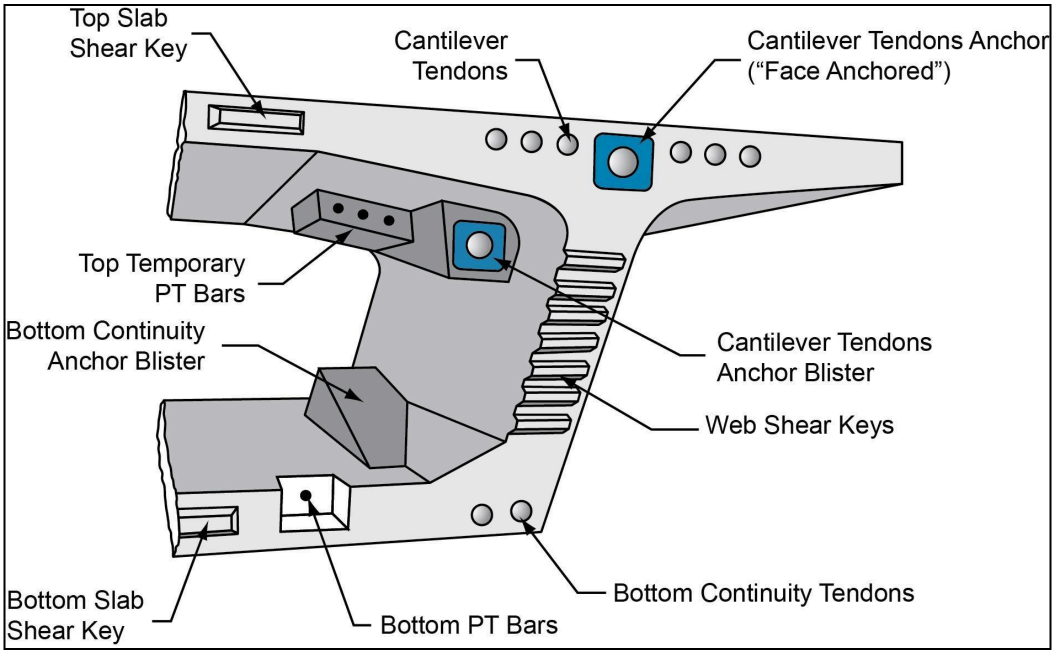


*Figure 2.2 – Individual Segment Features*

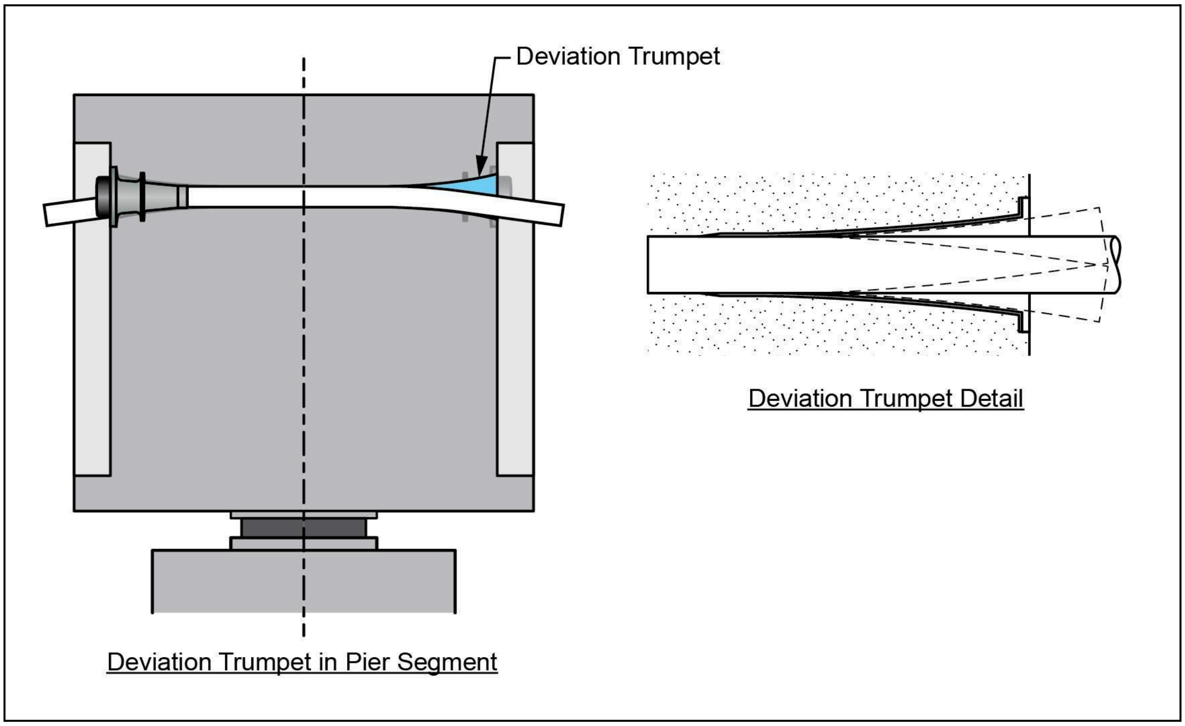


*Figure 2.3 – Detail of Deviation Trumpet*

## 2.2 Post-Tensioning and Grouting Terminology

*Anchorage Assembly* – Mechanical device comprising all components required to anchor the prestressing steel and permanently transfer the post-tensioning force from the prestressing steel to the concrete. **(Figure 2.5)**

*Anchor Set* – The expected movement of the wedge into the wedge plate or nut into the bearing plate during the transfer of the prestressing force to the anchorage assembly.

*Bar* – Bars used in post-tensioning tendons conform to the ASTM A722, Standard Specifications for Uncoated High-Strength Bars for Prestressing Concrete. Bars have a minimum ultimate tensile strength of 150,000 psi. A Type 1 bar has a plain surface and a Type 2 bar has surface deformations.

*Bearing Plate* – Hardware that transfers the tendon force into the structure.

*Bleed* – The autogenous flow of mixing water within, or its emergence from, the newly placed grout; caused by the settlement of the solid materials within the mass and filtering action of strands and bars.

*Bursting Force* – Tensile forces in concrete near the transfer or anchorage of prestressing forces.

*Coupler* – A device used to transfer the prestressing force from one partial-length tendon to another.

*Deviation Saddle* – A concrete block build-out in a web, flange, or web-flange junction used to control the geometry of external tendons.

*Duct* – A conduit to accommodate prestressing steel installation that provides an annular space for the tendon filler material that protects the prestressing steel.

*Effective Prestress* – Stress or force remaining in the prestressing steel after all losses (short- and long-term) have occurred.

*Fluidity* – A measure of time, expressed in seconds, needed for a stated quantity of grout to pass through the orifice of a flow cone.

*Grout* – A mixture of cementitious materials and water, with or without mineral additives or admixtures; proportioned to create a pumpable consistency without segregation of constituents when grout is injected into a duct to fill the space around the prestressing steel.

*Grout Cap* – A device that contains the grout and forms a protective cover, sealing the post-tensioning steel at an anchorage.

*Heat Shrink* – A heat welding technique used at the splice location between two pieces of plastic duct to add an additional layer of corrosion protection in accordance with manufacturer instructions. Heat shrink sleeves have unidirectional circumferential recovery manufactured specifically for the size of the duct being coupled. The sleeves consist of an irradiated and cross-linked high-density polyethylene backing for external applications and linear-density polyethylene for internal applications.

*Inlet (also Inlet Pipe or Grout Injection Port)* – Tubing or duct used for injecting grout into a duct.

*Jacking Force* – Force exerted by the device introducing tension into a tendon.

*Mandrel* – A cylindrical insert that is used to support and maintain the alignment and shape of a tendon duct (usually along the length of a wet-cast segment from bulkhead to match-cast segment) during concrete placement. For straight alignments, steel pipes are often used. Rubber tubes that can be inflated with pressurized air are often used for curved alignments.

*Outlet (also Ejection Pipe, Grout Outlet Vent, or simply, "Vent")* – Tubing or duct used to allow the escape of air, water, grout, and bleed water from a duct.

*Post-tensioning* – A method of prestressing in which the tendons are tensioned after the concrete has reached a predetermined strength.

*Prestressing Steel* – The steel element of a post-tensioning tendon, elongated and anchored as needed to provide the required permanent prestressing force.

*Post-Tensioning Scheme* or *Layout* – The pattern, size, and locations of post-tensioning tendons as provided by the designer on the contract plans.

*Prepackaged Grout* – Prepackaged proprietary mixes of cementitious material and admixtures that feature anti-bleed, low permeability, and thixotropic characteristics.

*Post-Tensioning System* – An assembly of hardware used to construct a tendon of particular size and type. Specific hardware may include, but is not limited to, an anchorage assembly, local zone reinforcement, wedge plate, wedges, inlet, outlet, couplers, duct, duct connections, and grout cap. The entire assembly must meet the system pressure testing requirement. Internal and external systems are considered independent of one another.

*Pressure Rating (also Working Pressure)* – The estimated maximum continuous pressure that a duct or duct component will tolerate without failing.

*Special Anchorage Device* – An anchorage device whose adequacy should be proven in a standard acceptance test; most multiple anchorages and all bond anchorages fall into this category.

*Strand* – An assembly of several high-strength steel wires wound together, usually six outer wires wound helically around a single straight wire of similar diameter.

*Stressing Jack and Gauge* – A jack equipped with an accurate reading gauge for determining the jacking pressure; gauge dial is at least 6 in. in diameter.

*Temporary Corrosion Protection* – Introduction of a substance into post-tensioning ducts after installing and stressing post-tensioned tendons, but prior to grouting, to prevent or mitigate corrosion of post-tensioned steel.

*Tendon* – A single or group of prestressing steel elements and anchorage assemblies that transfer prestress forces to a structural member or to the ground; a tendon includes ducts, grouting attachments, grout, and corrosion protection filler materials or coatings.

*Tendon Size* – Given as either the number of individual strands of a certain diameter or as the diameter of a bar.

*Tendon Type* – Description of tendon relative to location in the concrete element and/or functional use (that is, internal, external, cantilever, transverse, longitudinal, continuity, stem wall, sop slab, and so on).

*Thixotropic* – The property of a material that enables it to stiffen in a short time while at rest, but to acquire a lower viscosity when mechanically agitated, the process being reversible.

*Transfer* – The operation of imparting the force in a pre-tensioning anchoring device to the concrete.

*Vacuum Grouting* – Grout injection used to repair voids in ducts and anchorages; requires first generating a vacuum in the void space.

*Vacuum–Assisted Grouting* – Normal grout injection preceded by generating a vacuum in the duct containing the tendon.

*Wedge* A conically shaped device typically containing two or three pieces, which anchors the strand in the wedge plate.

*Wedge Plate (also Anchor Head)* – Hardware holding the wedges of a multi-strand tendon that transfers the tendon force to the anchorage assembly*.*

*Wire* – A single, small-diameter, high-strength steel member that is typically the basic component of a strand, although some proprietary post-tensioning systems are made up of individual wires or groups of single wires.

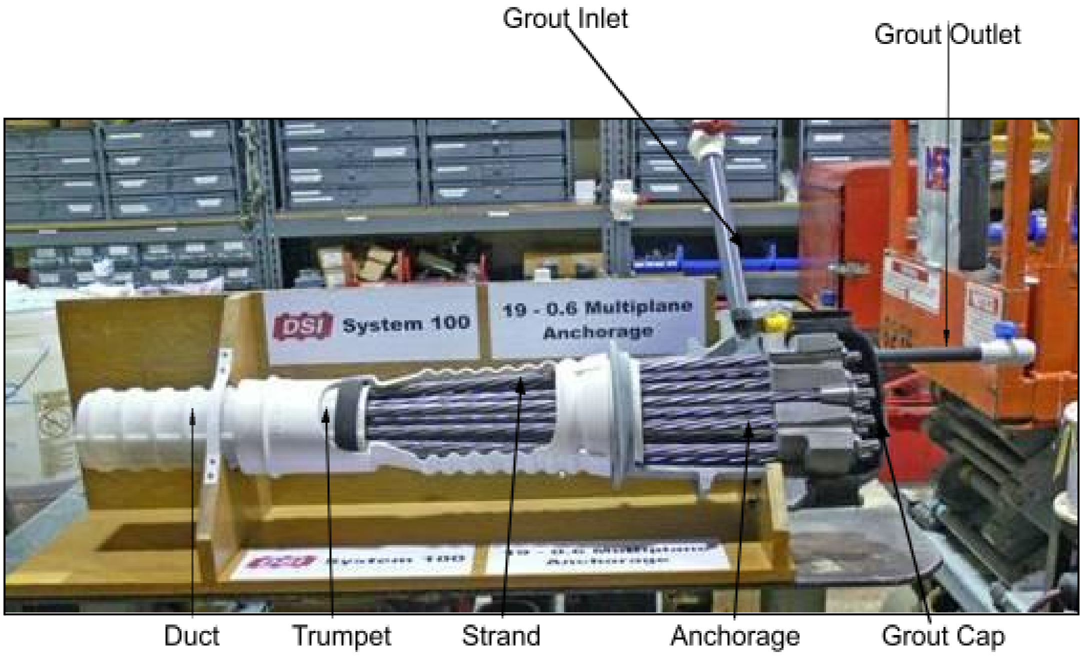
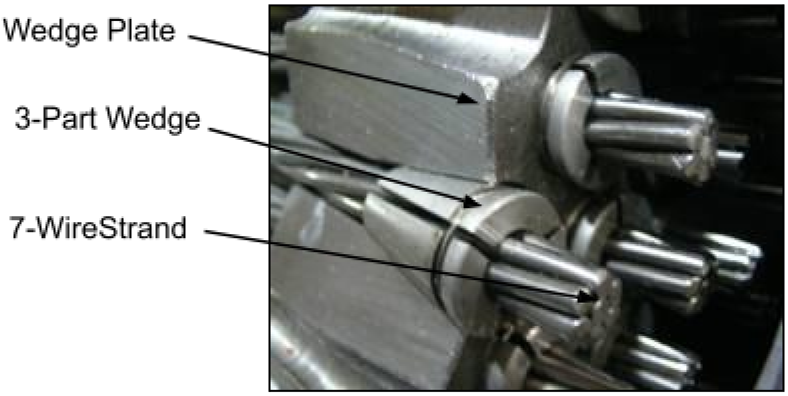


*Figure 2.4 – Tendon Details*



***2.5 Tendon Details***
***Figure 2.5 – Anchorage Details***

## TABLE OF CONTENTS

# Chapter 3:
# Construction of Precast Segmental Span-by-Span Bridges

## 3.1 Introduction

In span-by-span construction, an entire span of precast segments is erected and becomes self-supporting before the next span is erected. Typically, a temporary erection truss is used for support while the segments are epoxy-joined and the post-tensioning is stressed, at which point the span becomes self-supporting. The erection truss is then moved to the next span and the process is repeated. Erection trusses that support each segment under the wings or bottom soffit are referred to as Underslung Trusses. Erections trusses that are above the segments are referred to Overhead Truss or Gantries. Examples of both underslung and overhead erection trusses can be seen in **Figures 3.1** and **3.2** below. Erection trusses have many variations in layouts and configuration. There are conventional trusses that allow for minor grade changes and curves, and articulating trusses that allow for erection of segments in tight radius curves and more severe grade changes.

Of all segmental bridge types, span-by-span bridges are often the simplest and most cost-effective. The span-by-span construction method can be very effectively applied to moderate span lengths up to approximately 150 ft., although it has been extended to spans upwards of 180 ft. For spans longer than 160 ft., the erection truss often becomes much larger and the method then becomes less cost-effective.

***Figure 3.1 – Underslung Erection Truss, Honolulu Light Rail, HI***
***(Photo Courtesy of FIGG)***

There are several variations of span-by-span construction. Individual precast segments can be delivered to the site and lifted individually before being epoxied and post tensioned together. Alternatively, entire spans of precast segments may be constructed on the ground, or on barges, and then lifted into position. **Figure 3.3** below shows a span being lifted into its final position. It is also possible to use the previously completed spans to transport segments up the completed bridge deck and erect them "from the top down" **(Figure 3.4)**.

In all variations, an entire span is erected and made self-supporting before the next span successive span is erected.

***Figure 3.2 - Precast Segmental Erection with Overhead Articulating Gantry,***
***(Photo Courtesy of Traylor Bros. Inc.)***

***Figure 3.3 – Lifting an Entire Span, Jamestown-Verrazzano Bridge, RI***
***(Photo Courtesy of FIGG)***

***Figure 3.4 – Underslung Erection Truss Used in Top-Down Erection, Susquehanna River Bridge, PA (Photo Courtesy of FIGG)***

## 3.2 Typical Precast Segmental Span-by-Span Bridge Configuration

The elements that make up a precast segmental span-by-span bridge superstructure often differ from those of a typical girder bridge superstructure. The ends of each span in a span-by-span bridge have either a pier segment or an expansion joint segment at each end. These are special segments that are needed to fill multiple roles. First, they transfer all of the load from the span into the bearings and piers that support the span. This often requires a large concrete diaphragm within the segment to adequately transfer these large forces to the bearings. Second, the concrete diaphragm within the pier segment or expansion joint segment anchors all of the longitudinal post-tensioning strands needed to support the span. Finally, two spans that meet at an expansion joint in the bridge will each have an expansion joint segment at that pier, and two spans that are continuous over a pier will each have a pier segment at their ends that will be connected together to make the span continuous over that pier.

Deviator segments are also special segments and are typically located at the quarter or third points in precast segmental span-by-span bridge. These segments often contain partial concrete diaphragms within them that are necessary to resist the forces from deviating the longitudinal post-tensioning from a low point in the segment (within the middle part of the span) to a high point in the segment (at the pier or expansion joint segments). Deviating the tendons within the span is necessary to efficiently resist the positive and negative bending moments in the span created by the applied loads.

Between the expansion joint, pier and deviator segments are typical segments. These segments are typically hollow and are designed to support the loads from the deck and transfer them to the supporting pier or expansion joint segments.

The final segment that makes up a precast segmental span-by-span bridge superstructure is a cast-in-place (CIP) closure segment. Basically, these are narrow unreinforced typical segments (often just 6" long) that are cast on-site (using a high early strength concrete) and are necessary to accommodate final geometry adjustments that are often needed to properly position the precast segments in their final erected position. These segments are typically located between the pier segment or expansion joint segment and the first typical segments in the span.

Finally, all of the segments are compressed together with longitudinal post-tensioning strands that are installed to resist the positive and negative moment demands in the span. The post-tensioning strands are located in the lower part of the segment in the middle part of the span (to resist the positive moment demands on the span), and are located in the upper part of the segment in the ends of the span (to resist the negative moment demands on the span, particularly over support piers for continuous spans).

**Figure 3.5** below shows the basic layout described for an "End Span" (a span containing one pier segment and one expansion joint segment) and an "Interior Span" (a span containing two pier segments). **Figure 3.6** below shows the location of CIP closure segments in a precast segmental span-by-span bridge superstructure.

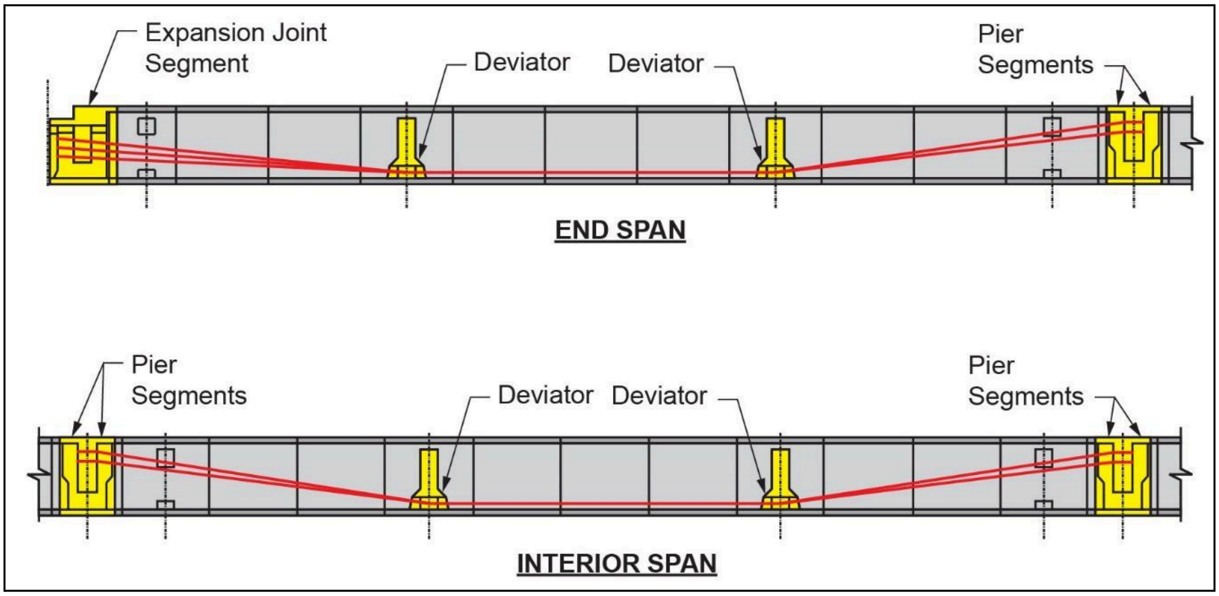


*Figure 3.5 – Different Elements within a Precast Segmental Span-by-Span Bridge*

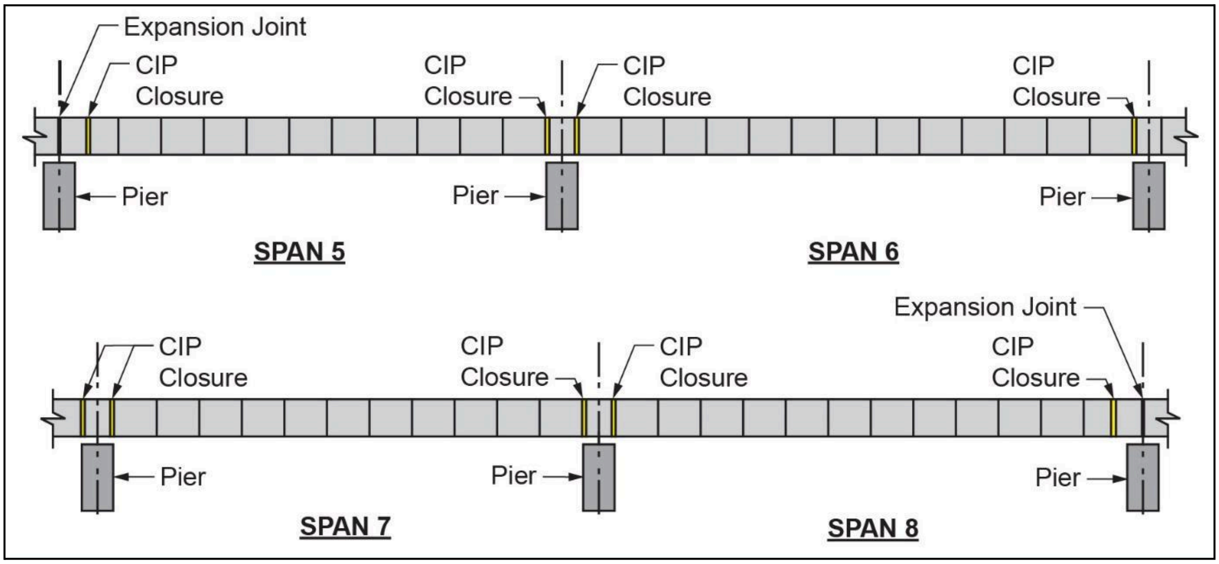


*Figure 3.6 – Location of CIP Closure Segments in a Precast Segmental Span-by-Span Bridge*

## 3.3 Advantages of Segmental Span-By-Span Bridges

There are many advantages to precast segmental span-by-span construction, including:

- Lower Construction Cost
- Faster Construction
- Easier Maintenance of Traffic
- Higher Long-Term Durability

Each of these is presented in more detail below.

As noted previously, span-by-span is generally the most cost-effective of all the segmental construction methods, competing successfully against cast-in-place concrete bridges, prestressed girder bridges, and steel girder bridges with similar span lengths in alternate bids.

Much of the work associated with span-by span bridges is done in the precasting operation, which occurs in a casting yard that typically has no impact on highway, waterway or railway traffic at the site of the new bridge. Once the segments are cast, span-by-span bridges can be erected quickly, often completing 2 to 3 spans per week per erection truss, minimizing the time that construction impacts the site.

Traffic can be maintained under the temporary erection trusses once they are in position for erection of a span. Traffic must be halted during placement of each segment, but this takes only 15 - 30 minutes in most cases. Note that care must be taken to protect vehicular traffic and/or pedestrian facilities from epoxy squeeze during segment erection. This is most commonly accomplished by using tarps that hang underneath the segments during the epoxy operation. These epoxy tarps are sometimes referred to as diapers and are shown in **Figures 3.7** and **3.8** below.

***Figures 3.7 and 3.8 – Tarps Underneath the Segments During Epoxy Operations***
***(Photos Courtesy of Traylor Bros. Inc. and FIGG)***

Examples of traffic being maintained under and around spans being erected are illustrated in **Figures 3.9**, **3.10**, and **3.11**.

***Figure 3.9 – Maintenance of Road Traffic, Ernest F. Lyons Bridge, FL***
***(Photo Courtesy of PCL Civil Constructors, Inc.)***

***Figure 3.10 – Maintenance of Railway Traffic, Susquehanna River Bridge, PA***
***(Photo Courtesy of FIGG)***

***Figure 3.11 – Maintenance of Road Traffic, Honolulu Light Rail, HI***
***(Photo Courtesy of Traylor Bros. Inc. )***

Construction of the precast segments in the precise quality-controlled environment of the casting yard greatly improves the quality of the precast segments when compared to on-site cast-in-place concrete construction. Additionally, the top deck of the span-by-span bridge is the top flange of the precast girder that uses the same high strength concrete mix as the rest of the girder. The top deck/flange is also post-tensioned both transversely and longitudinally, which significantly reduces in-service cracking and chloride penetration in the top deck of the bridge. When precast elements are combined with a high strength concrete and bi-directional post-tensioning bridge deck, it creates a structure that is much more durable than typical beam bridges with standard reinforced concrete bridge decks.

## 3.4 Typical Span-By-Span Erection Sequence

Erection of each span begins with moving the temporary erection trusses into position, as shown in **Figures 3.12** and **3.13** below. More often, though, the trusses feature a launching nose (and tail) that eliminates the need for crane support or intermediate temporary bents. Overhead gantries are typically self-launching and may require a series of launching steps where the gantry load is transferred among several supports before arriving in the final position for segment erection.

Depending on the erection truss design, pier mounted brackets or falsework may be required to be installed for the support of the front part of the truss.

Once truss is positioned over the next span, **Figures 3.14-3.17** details how segments are loaded on an underslung truss. **Figure 3.14** illustrates the process; the other figures show project examples.

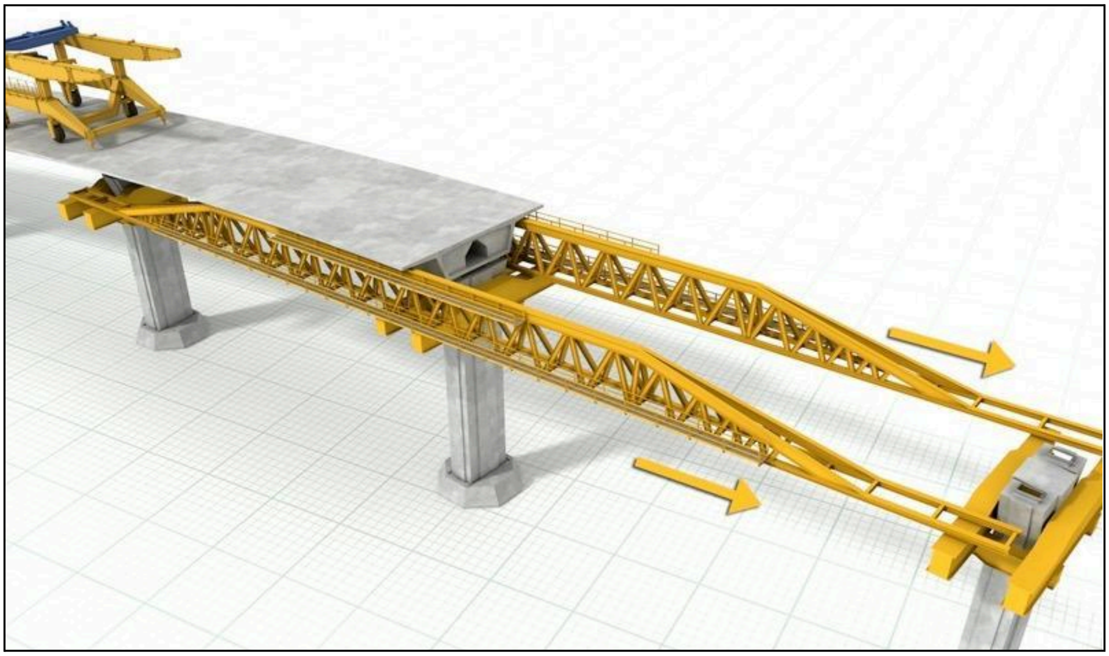


***Figure 3.12 – Advancing Trusses into Span to be Erected***
***(Graphic Courtesy of FIGG)***

*Figure 3.13 – Underslung Truss Advancing into Span to be Erected, Lee Roy Selmon Crosstown Expressway, FL*
*(Photo Courtesy of FIGG)*

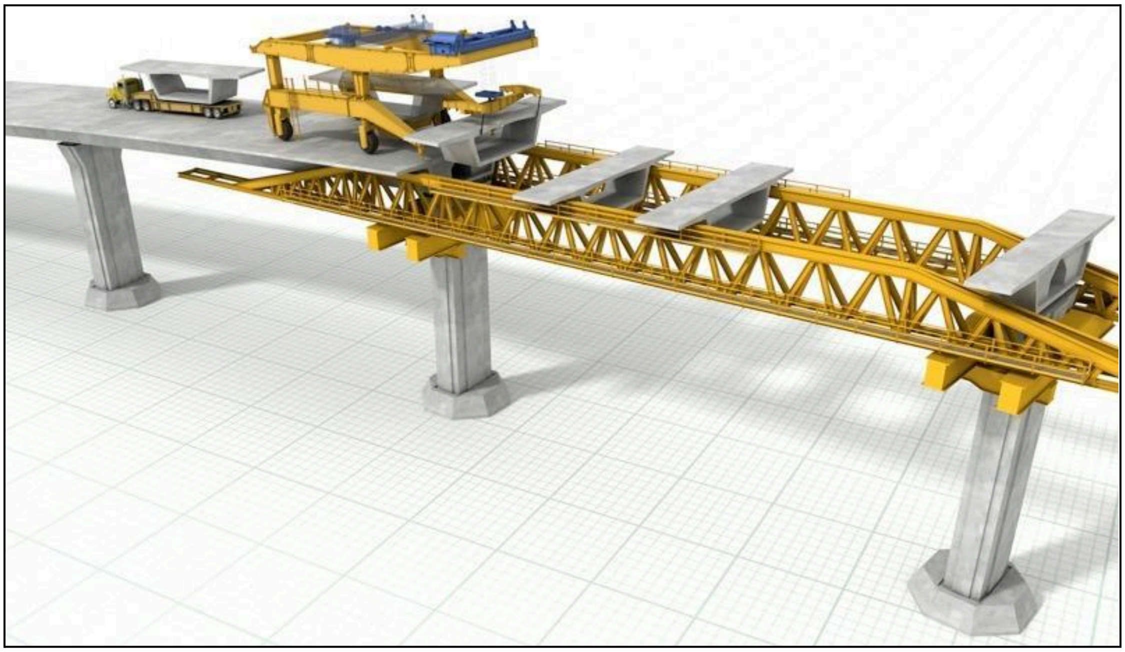


***Figure 3.14 – Erecting Segments onto Trusses***

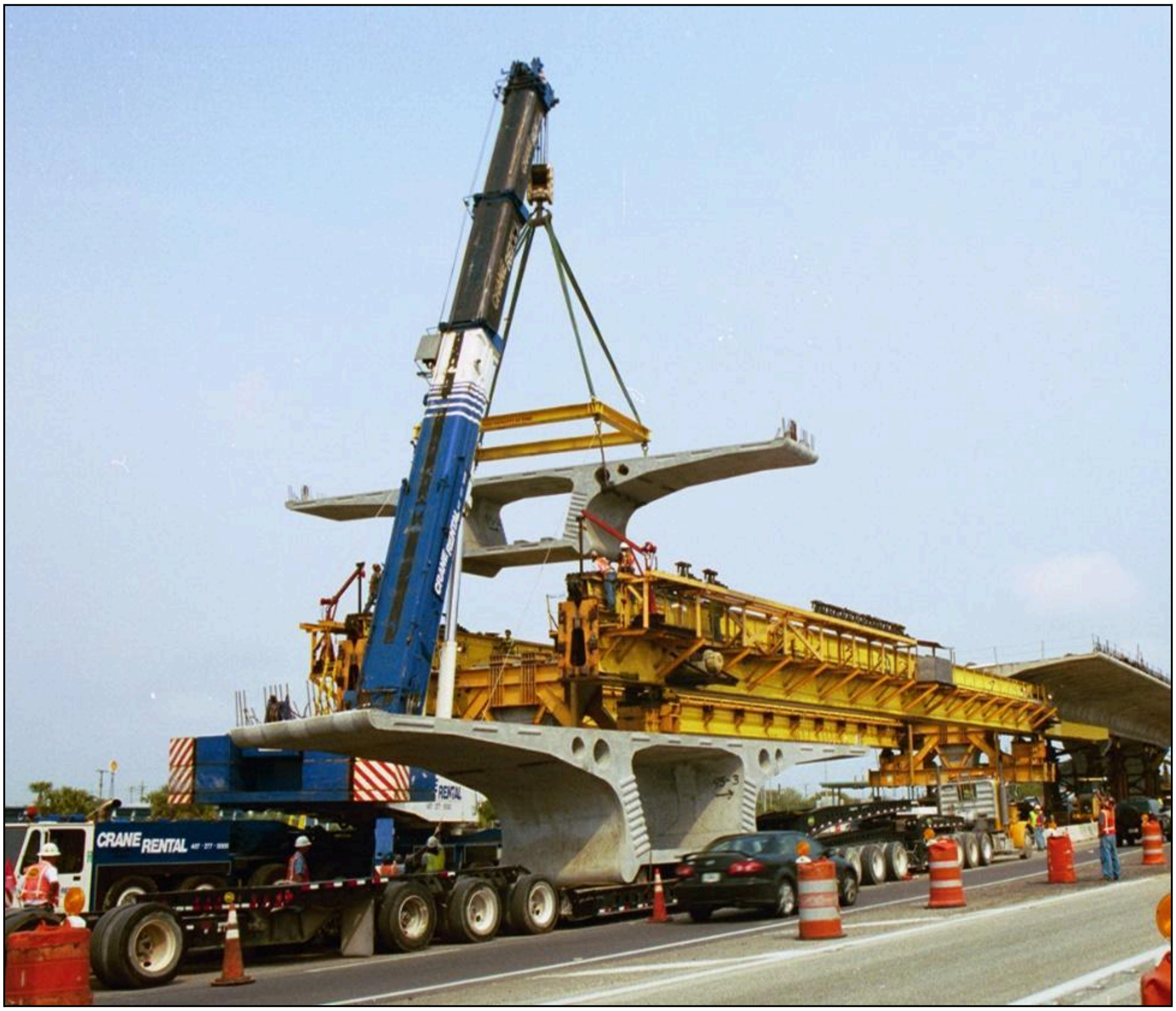


*Figure 3.15 – Erecting Segments onto Trusses, Lee Roy Selmon Crosstown Expressway, FL (Photo Courtesy of PCL Civil Constructors, Inc.)*

***Figure 3.16 – Erecting Segments onto Trusses, Evans Crary Sr. Bridge, FL***
***(Photo Courtesy of FIGG)***

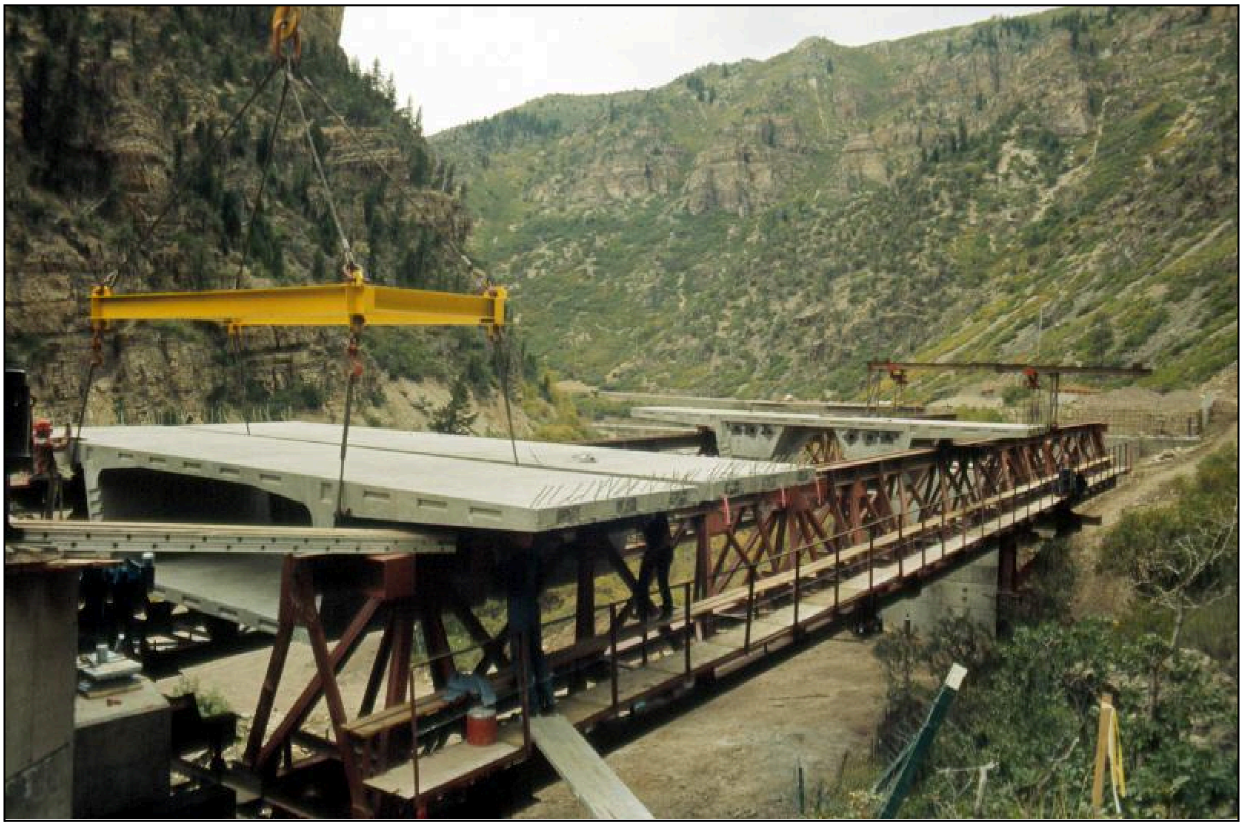


***Figure 3.17 – Erecting Segments on the Glenwood Canyon Bridge, CO***
***(Photo Courtesy of FIGG)***

Typically, all segments, but one, are loaded onto the trusses before epoxy joining begins. This allows truss deflections to occur before the segments are epoxy-joined; otherwise, the deflections can crack a previously epoxied joint. **Figure 3.18** below shows epoxy being applied to segments as part of the joining process. Temporary post-tensioning bars located in small anchor blocks inside the segments, shown in **Figure 3.19**, are often used to apply the necessary pressure across the epoxied segment joint for epoxy squeeze. The number and location of anchor blocks is determined by the designer to provide even contact pressure across the entire cross-section during epoxy curing. Typically, they are located so that two segments are stressed together before epoxy is applied to the next segment joint.

***Figure 3.18 – Applying Epoxy for Joining Segments***
***(Photo Courtesy of FIGG)***

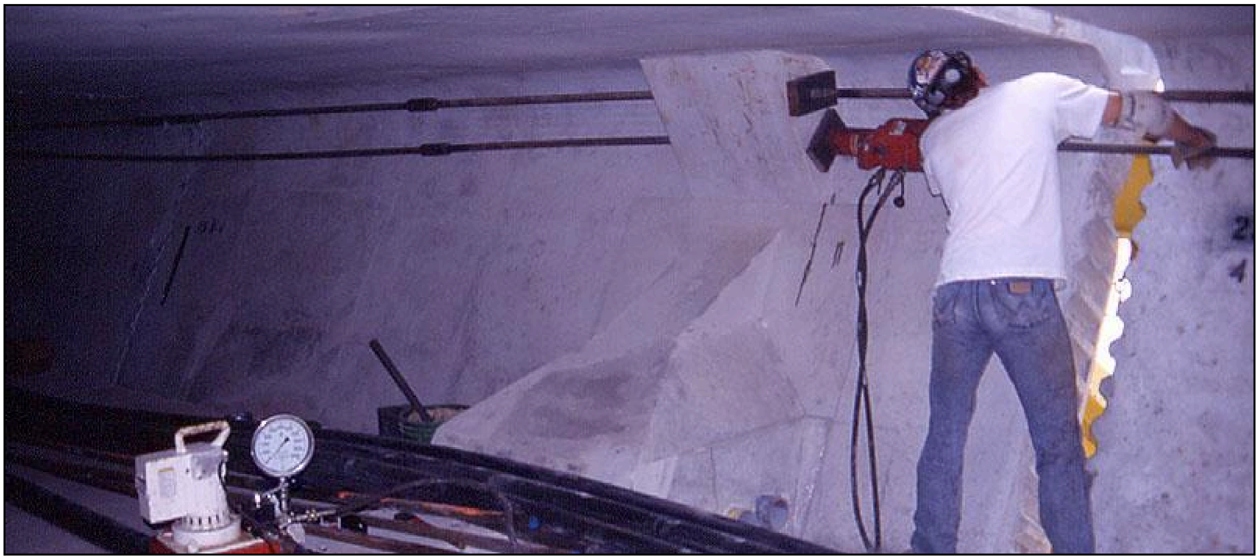


***Figure 3.19 – Applying Temporary Post-Tensioning for Epoxy Squeeze***
***(Photo Courtesy of FIGG)***

Epoxy is sometimes applied to groups of segments that are then stressed together using the temporary post-tensioning bars. However, even with slow-set epoxies, beyond a maximum of three to four segments at once there is a risk that the epoxy will set before the group is stressed together. If the epoxy sets prior to stressing the temporary bars, costly repairs are required. It is important to make sure you are using the right epoxy for the weather conditions and also that epoxy expiration dates on cans are checked prior to application.

When groups of segments are stressed together, a significant amount of epoxy squeezes from the joint(s) out of all sides, including the top deck. If the epoxy is not swabbed down flush with the deck before it hardens, problems may arise during the deck grinding operation (which is required by most specifications). Deck grinders often cut grooves into hardened epoxy, rather than removing it, causing the back wheels of the grinding machine to ride up onto the epoxy and the front of the machine to grind deeper into the deck. This results in a dip in the traveling surface of the structure, which is considered unacceptable by most standards.

Similarly, it is important to swab the inside of the permanent post-tensioning ducts of the pier segments after the epoxy operation. In some cases, epoxy continues to squeeze into the duct after the initial swabbing and a second swabbing is necessary. If epoxy is left in the post-tensioning ducts, crews may have difficulty installing the permanent post-tensioning cables. Swabbing prevents the epoxy from becoming a "hard point," at which strand breakage could occur during longitudinal tendon stressing.

Caution should be used in swabbing epoxy flush against the outside surfaces of the web walls and bottom slab. Doing so can result in a permanent "stripe" of epoxy several inches wide at each segment joint that finishing crews cannot "rub down" to match the surrounding web concrete. Also, any aesthetic coatings applied to the exterior superstructure surfaces may not adhere properly to the flattened epoxy. These issues can be avoided by applying a strip of duct tape (or similar adhesive material) to either side of the segment joint prior to epoxy joining. Excess epoxy squeezes onto the duct tape rather than the concrete surface and can easily be chipped off once hardened. The duct tape or similar adhesive material is then removed, leaving a clean concrete surface right up to both sides of the segment joint.

If your bridge span has cast in place closure joints after all the segments, but one, are in place and epoxied, the final segment is installed, epoxy- joined, and temporarily stressed. Small spacer blocks are placed in the closure joints between the typical segments and the pier segments, and approximately 5-8% of the permanent longitudinal post-tensioning is stressed. This locks the geometry of the span in place and prevents movement during the placement of the cast-in-place closure joint concreting operations. Spacer blocks can be made of either precast concrete or cast-in-place high-strength grout. (Some grout products can achieve the required strength in approximately two hours.)

Once the blocks are in place, high-strength concrete is placed in the closure joints, as illustrated in **Figures 3.20 and 3.21**. This is typically done at the end of a shift to allow the concrete to cure, as even high-early-strength concrete takes 10 to 12 hours (depending on the ambient temperature) to achieve the required strength. After the closure joints achieve a nominal strength (typically 2,500 to 3,000 psi, as specified by the designer), the longitudinal post-tensioning is stressed to the final force, as illustrated in **Figures 3.22 - 3.24**. Continuous span units may be created by using draped external tendons that run the length of one span and overlap the tendons from the previous span across a pier segment **(Figure 3.25)**.

Until closure joints have been cured to a specified strength and final stressing is complete, construction loads (i.e., fully loaded concrete trucks, etc.) may be prohibited on adjacent spans. This is because the vibration and movement can be transferred across the closure joint and, if the joint has not been properly cured then this activity may jeopardize the structural integrity of the joint.

*Figure 3.20 – Cast-in-Place Closure Joints*

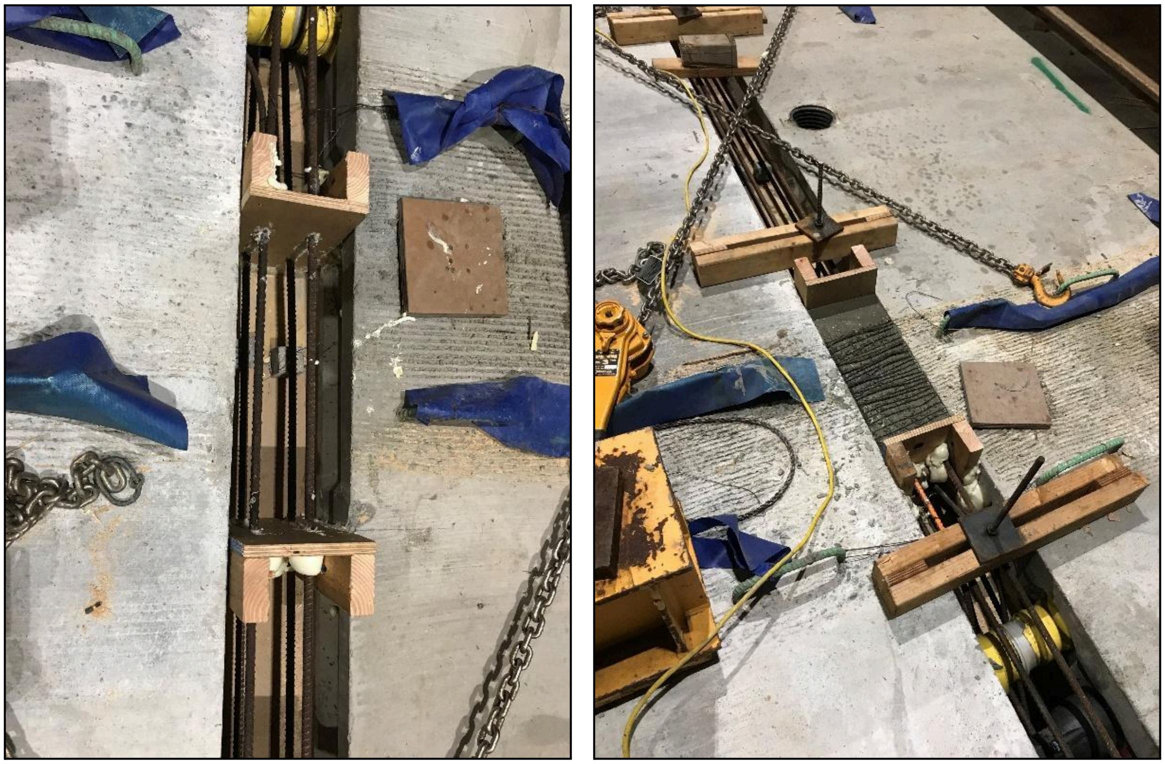


*Figure 3.21 – Casting Closure Joints*
*(Photos Courtesy of Traylor Bros. Inc.)*

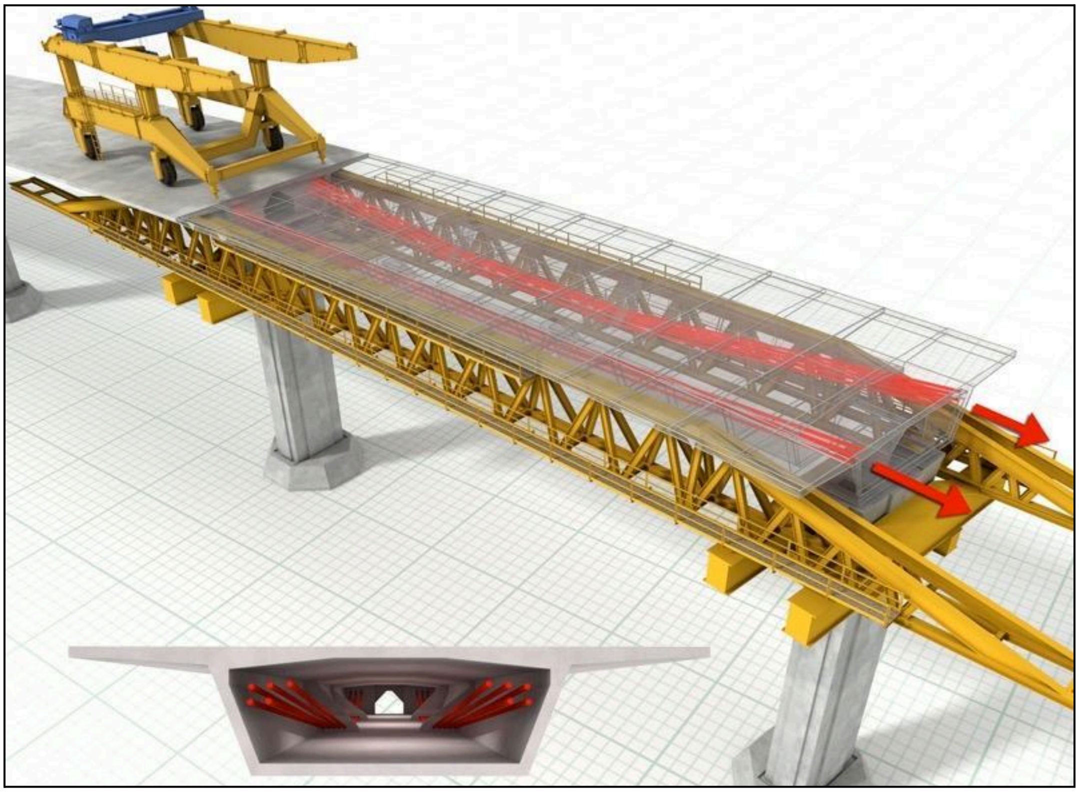


*Figure 3.22 – Permanent Longitudinal Post-Tensioning Layout*

Stressing of the permanent post-tensioning tendons is usually performed from a specially fabricated stressing platform attached to the pier segment or supported by the erection truss. The platform provides safe and convenient access for personnel to efficiently perform stressing operations. Most stressing platforms are equipped with chain-falls used to support the stressing jacks from above. **Figure 3.23** below shows a stressing jack being supported from above by a chain-fall during stressing operations.

***Figure 3.23 – Stressing Permanent Post-Tensioning***
***(Photo Courtesy of PCL Civil Constructors, Inc.)***

When designing a stressing platform, consideration must be given to the amount of working room required to thread the stressing jack over the strand tails extending from the anchor head. If the tails are not taken into account, crews will not have sufficient room to insert the strand tails into the jack without leaning over the edge of the platform, thus creating an unsafe condition. **Figure 3.24** below shows a crew safely working on a stressing platform.

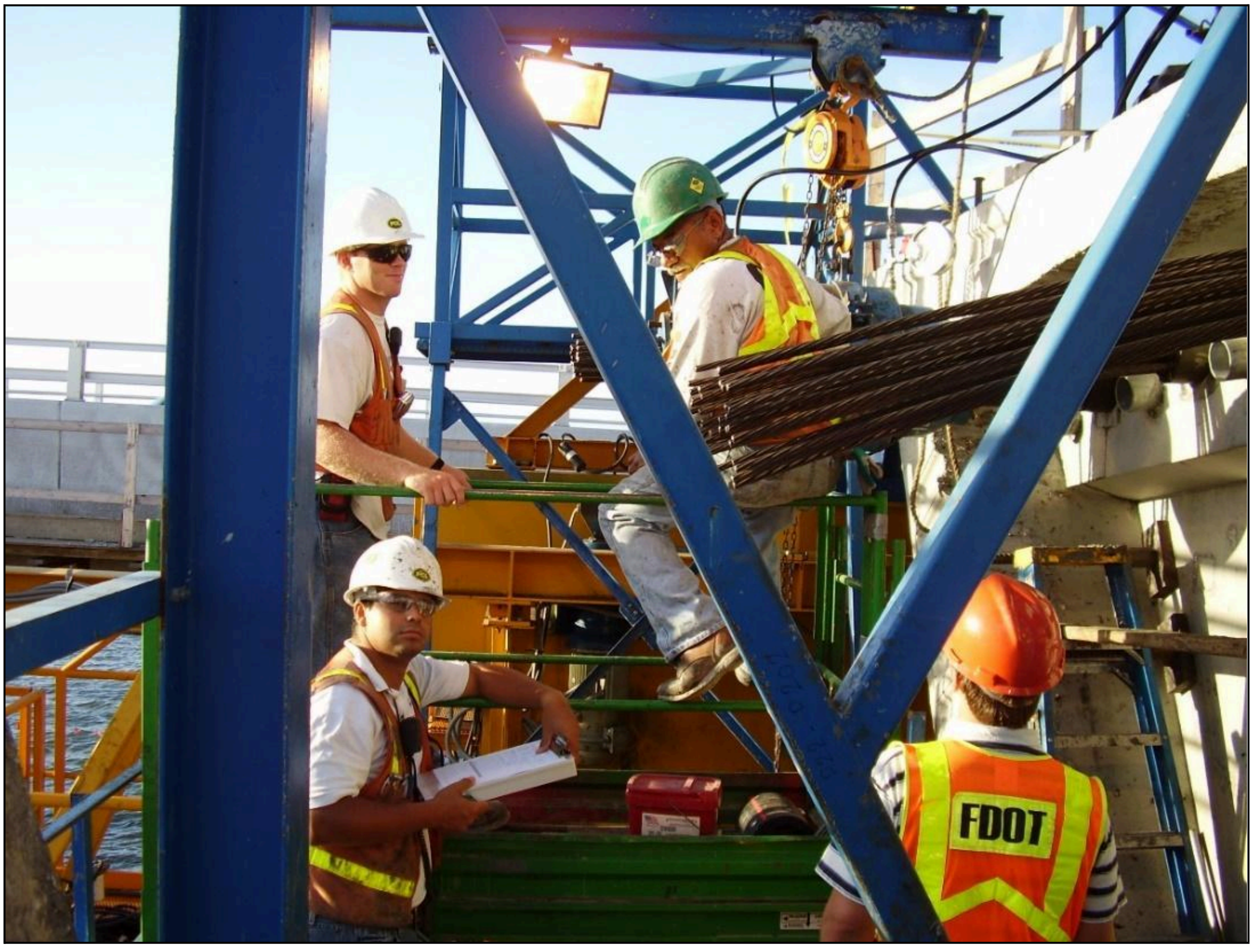


***Figure 3.24 – Stressing Crew Working on a Stressing Platform, Ernest F. Lyons Bridge, FL***
***(Photo Courtesy of PCL Civil Constructors, Inc.)***

*Figure 3.25 – Typical Span-by-Span External Post-Tensioning Tendons at Pier Segment (Photo Courtesy of FIGG)*

Some bridges, especially for light or heavy rail bridges, may be designed as simple spans rather than longer multiple-span continuous units. If the bride is designed as a simple span, it will not have closures joints at both ends of the span, full span of segments are erected, stressed together then lowered onto bearings or pads on top of the piers.

## 3.5 Special Considerations

An efficient construction plan and process using the span-by-span method requires special attention to certain aspects. For example, sufficient clearance must be allowed between temporary truss supports and the bottom of the completed structure for removal of the temporary supports. **Figure 3.26** shows a temporary support being lowered through the completed deck above using steel rods.

Sufficient temporary clearance must also be provided beneath the erection truss and traffic passing under the span being constructed during construction. Often, bridges are designed to just meet the permanent minimum vertical clearance requirements under span. This sometimes means that certain deep girder or soffit supporting underslung trusses could not be used because they cannot provide the necessary temporary minimum vertical clearance under the truss, and a shallow girder underslung truss or overhead gantry would need to be used to construct the span. Additionally, clearance above the bridge should also be evaluated, particularly when considering the use of an overhead gantry. Clearance requirements for overhead powerlines (particularly high voltage lines) may limit or preclude the use of certain overhead gantries and segment lifting equipment (i.e. often ground based cranes). If the project is close to an airport, there may be flight path clearance requirements that need to be evaluated when selecting the erection equipment. **Figure 3.27** shows shallow underslung girder and low-profile segment erector that was required to meet the railroad clearance requirements under and the high voltage powerlines clearance requirements over the new bridge.

It is also important to consider how and when construction materials and equipment will be placed inside the bridge structure. As in all segmental bridge construction, a significant portion of the work must take place inside the bridge structure. This requires tools, equipment, and materials to be transferred into and out of the bridge structure. Once a span has been completed and the trusses have been advanced, it can be extremely difficult to place bulky materials such as HDPE ducts, strand, temporary post-tensioning bars, electrical conduits and junction boxes, drainage pipes, etc. inside the bridge structure. Consideration should also be given to access needs for longitudinal tendon grouting operations, which typically lag several spans behind the erection front.

It is easiest to place construction materials inside the bridge through the open end of the structure (leading edge of construction) while crews have access from the trusses and stressing platforms. Likewise, it is best to dispose of waste materials as each span is completed rather than waiting until the end of the project, when access is not readily available.

Lighting of the trusses/gantries, segmental work area, and also inside of the segments is also something that should be considered especially when bridges are being built in urban areas and requires night work for erection and stressing. Good lighting is key to providing safe and efficient segmental operations. In cost evaluation of trusses and gantries include these costs.

Access into segments via bottom slab or top slab needs to be considered for follow on activities that have to occur after the span has been set. Inspection access points for a final configuration may not be as frequent as is needed for construction operations.

***Figure 3.26 – Temporary Supports Being Lowered After Span is Complete, Ernest F. Lyons Bridge, FL (Photo Courtesy of PCL Civil Constructors, Inc.)***

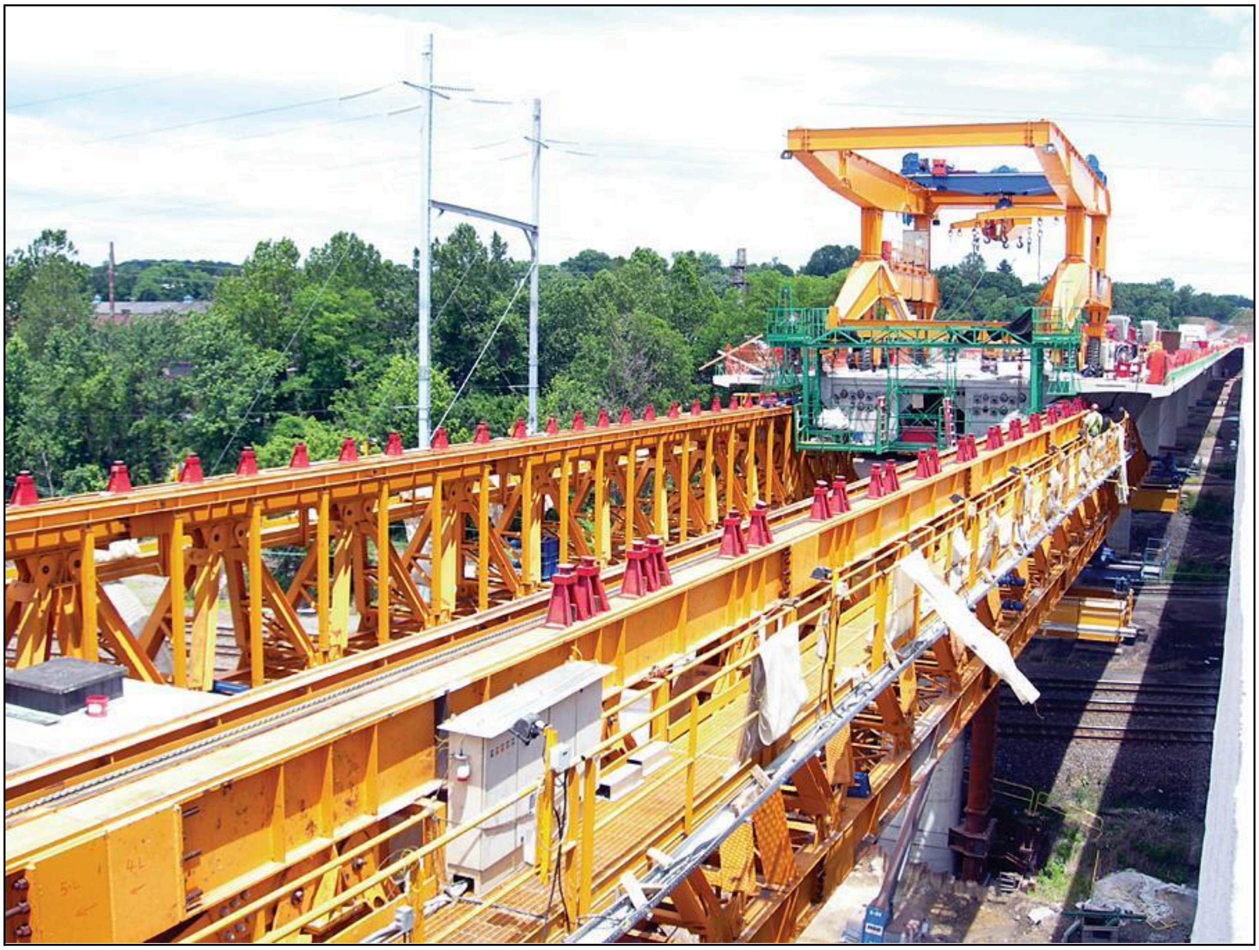


***Figure 3.27 – Erection Equipment Required to Pass over the Railroad and Under the Power Lines (Photo Courtesy of FIGG)***

Finally, a well thought out plan must be in place for removing the erection trusses after the final span is complete. Many structures require special erection sequences during the final span to allow removal of the trusses. If the final span is at an abutment, block-outs may be required in the back wall to allow permanent stressing or truss removal. **Figure 3.28** shows a typical situation, in which trusses must be removed from underneath a structure with very little vertical clearance.

***Figure 3.28 – Typical Conditions of Trusses After Erection of Final Span, Ernest F. Lyons Bridge, FL (Photo Courtesy of PCL Civil Constructors, Inc.)***

Another option is to construct the last one or two spans at the abutment on falsework towers. This then provides sufficient clearance to remove the erection truss while allowing other construction activities to continue parallel to superstructure construction. Additionally, constructing the last one or two spans at the abutment on falsework often removes the construction of those spans from the projects critical path and often provides flexibility in the construction schedule. **Figure 3.29** shows a span at the abutment being constructed on falsework.

***Figure 3.29 – Final Span being Constructed on Falsework, Veterans Glass City Skyway, OH (Photo Courtesy of FIGG)***

## 3.6 Summary

Span-by-span constructed bridges offer one of the simplest and most cost-effective forms of segmental construction. The method has successfully competed against cast-in-place concrete bridges, prestressed girder bridges, and steel bridges in alternate bids on design-build and other competitive contracting types. Because span-by-span bridges can be erected very rapidly while maintaining traffic under the erection trusses (except while segments are actively being placed on the truss), this construction method often results in significant savings in maintenance of traffic costs, as well as a reduction in user delays (that has been significant on some projects). Span-by-span bridges are also very durable, as they incorporate high-performance concrete and a bi-axially post-tensioned deck that is subject to high amounts of wear and harsh environmental exposures.

## TABLE OF CONTENTS

# Chapter 4:
# Construction of Precast Segmental Balanced Cantilever Bridges

## 4.1 Overview

### 4.1.1 Basics of the Technique

Precast segmental balanced cantilever construction is arguably considered the most used construction method in the segmental bridge industry. In balanced cantilever construction, erection progresses outwards from a central pier until adjacent cantilevers meet at mid-span. Segment erection generally progresses in symmetric pairs, with one segment of each pair secured to opposite ends of the previously completed structure with post-tensioning bars. Each pair is stressed against the structure with cantilever tendons located in the top flanges of the segments and run from one cantilever tip to the other. As segments are added, each new cantilever tendon becomes progressively longer than the previous cantilever tendon. A typical sequence for a three-span bridge is illustrated below in **Figures 4.2-1 – 4.2.-2**. Uni-directional cantilever construction is a variation of the balanced cantilever method in which the cantilever progresses outwards in only one direction from a previously erected span, typically utilized when additional span length is required to cross wide navigation channels, railroads, highways, etc. (see **Figure 4.1** below).

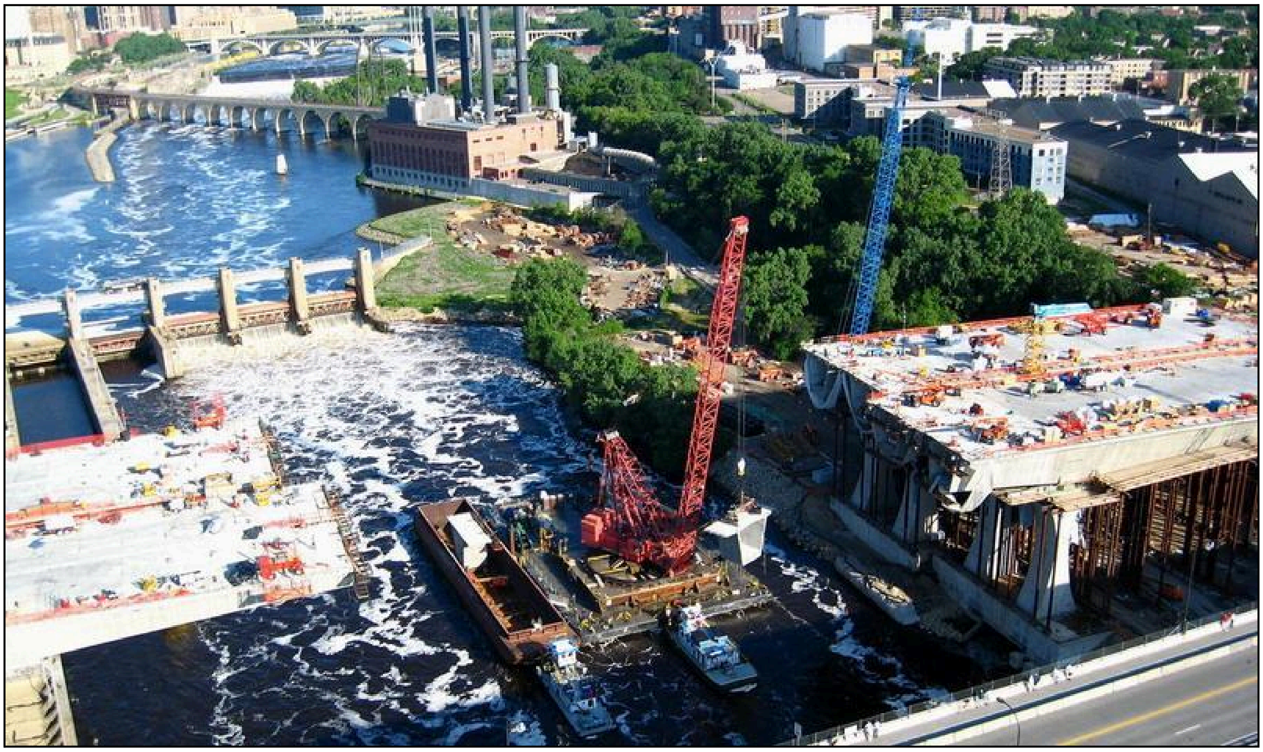


***Figure 4.1 – Uni-Directional Cantilever Erection***
***(Photo Courtesy of FIGG)***

Precast cantilever construction is used when longer spans are needed, often in response to obstacles like rivers or highways that have limited ground access. Precast balanced cantilever spans are an elegant approach that minimizes the impact on the site and can be companions of span-by-span erection on long viaducts.

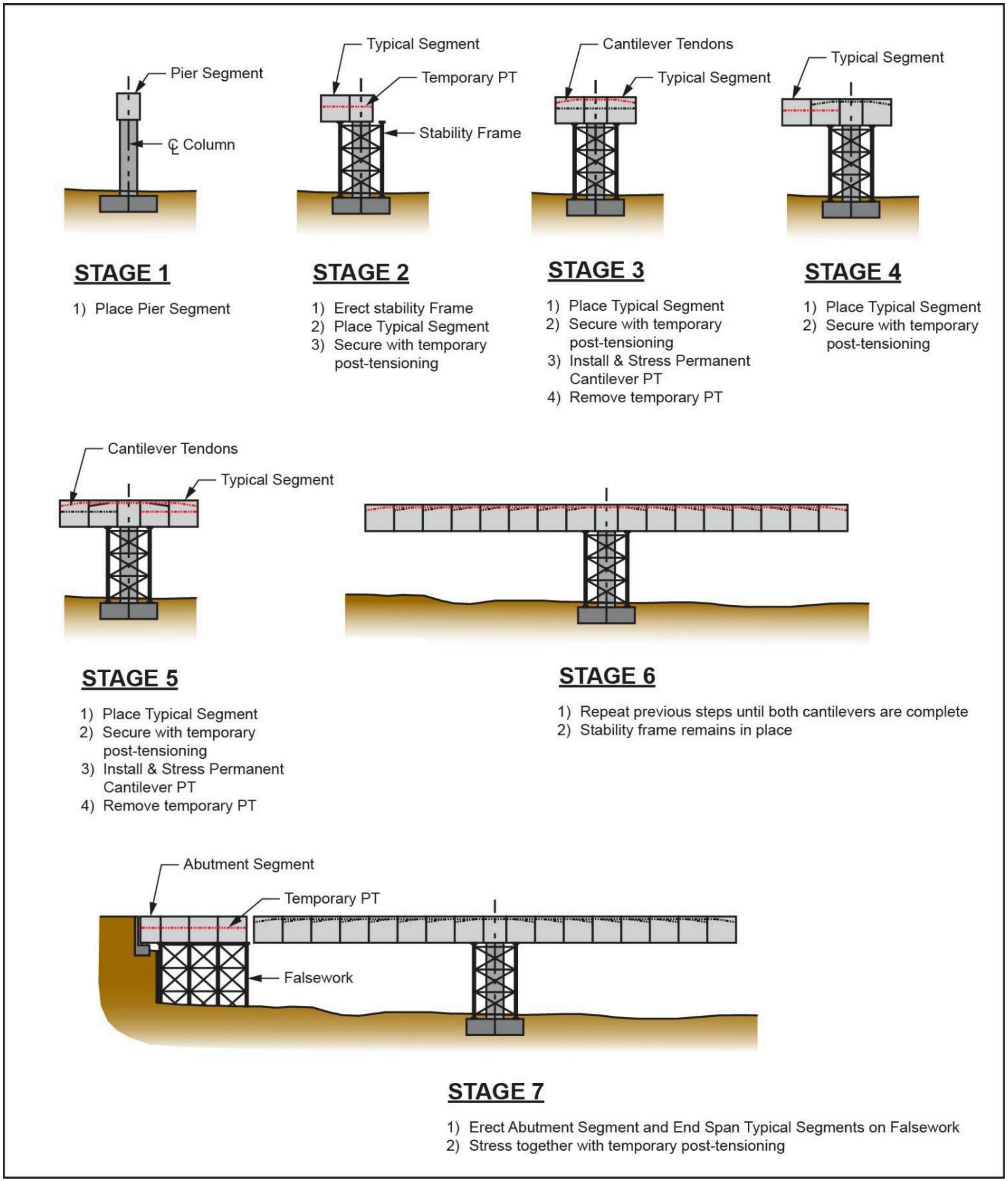


*Figure 4.2-1 – Typical Sequence for Three-Span Bridge (1 of 2)*

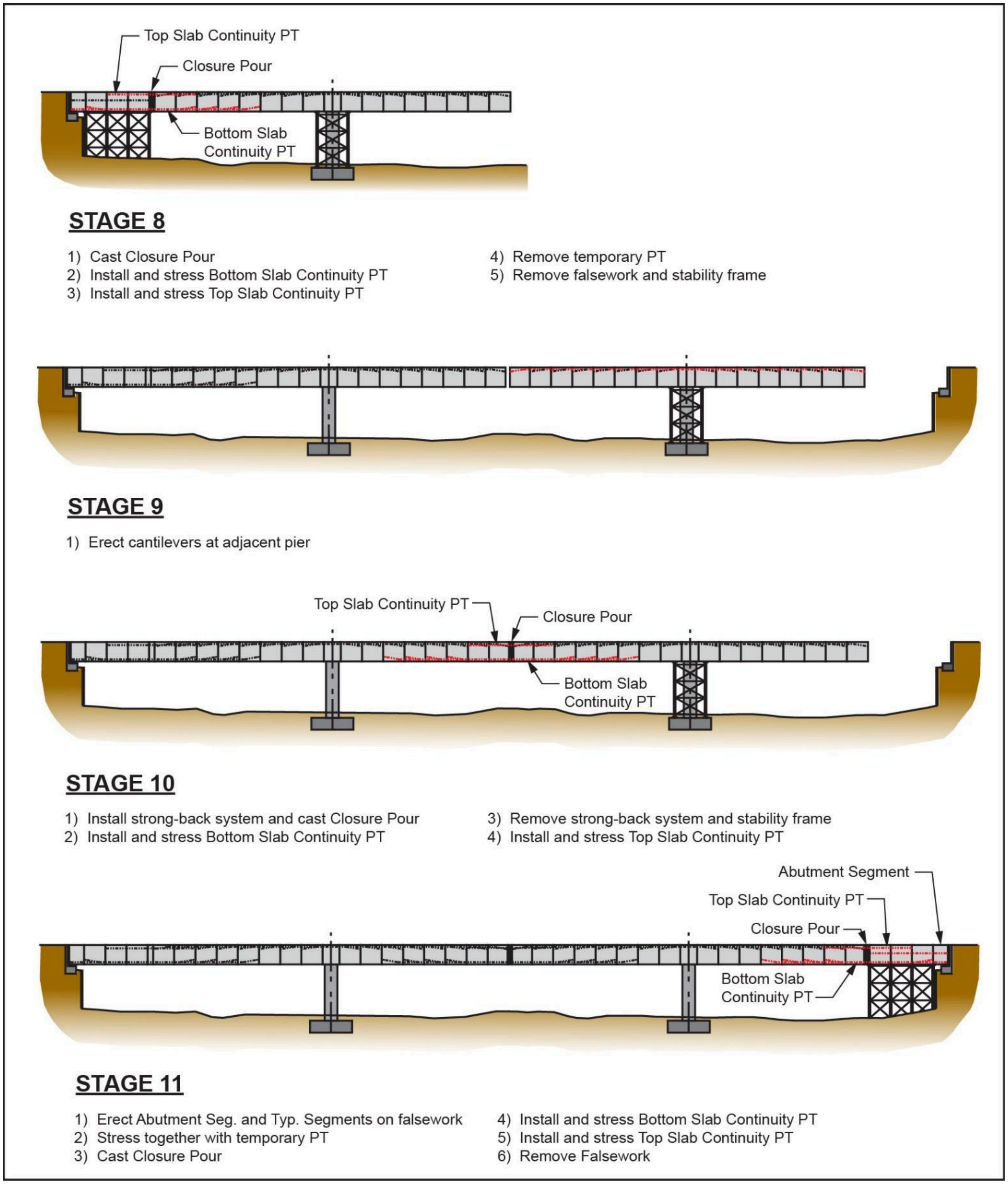


*Figure 4.2-2 – Typical Sequence for Three-Span Bridge (2 of 2)*

Balanced cantilever spans are generally considered when span-by-span erection is impractical. For example, while span lengths greater than 150 ft. are typically prohibitive for span-by-span construction, the precast balanced cantilever method can effectively be applied to lengths of up to 450 ft. With special considerations, even span lengths of more than 500 ft. have been accommodated by this technique. Similarly, balanced cantilever construction is well-suited to alignments with tight curvature. Typical span-by-span erection equipment cannot accommodate tight horizontal curvature, although some equipment can be designed for such alignment. With balanced cantilever erection, segments are placed individually and are typically unaffected by equipment limitations such as tight horizontal curvature.

Precast balanced cantilever erection does have a few drawbacks. One is that it requires access along the cantilever for delivery of segments and placement of erection equipment. Also, constraints related to crossing major roadways and railroads can make this method less efficient. The use of top-down erection and segment delivery methods, covered later in this chapter, can reduce these impacts.

### 4.1.2 Typical Segments Configurations

The majority of balanced cantilever construction is performed using a single-cell trapezoidal box girder. For the sake of simplicity, this section will focus on this configuration. However, since single-cell sections are limited to a width of about 60 ft., several methods have been successfully developed to achieve wider bridge decks, as shown in **Figure 4.3** below.

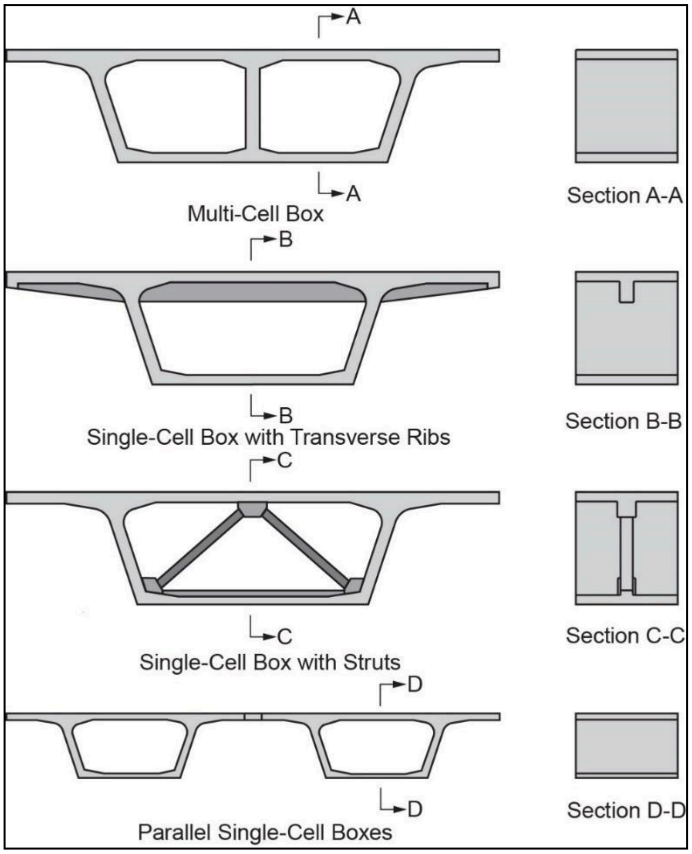


*Figure 4.3 – Wider Box Girder Cross-Sections*

### 4.1.3 Segment Details

As illustrated by the typical bulkhead drawing shown in **Figure 4.4**, some notable common features of precast balanced cantilever segments are outlined below.

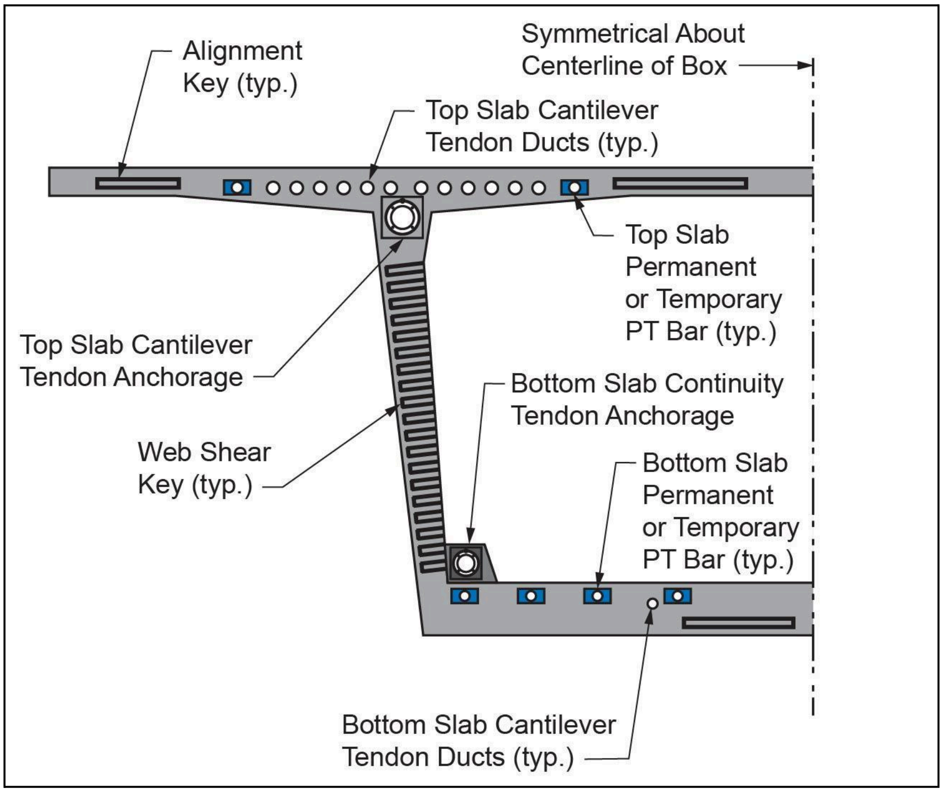


*Figure 4.4 – Details of a Typical Bulkhead*

### 4.1.3.1 Cantilever Tendon Anchorages

Cantilever tendon anchorages serve as the anchor points for each pair of cantilever tendons to the cantilever. They are typically located in the top flange, close to the web/flange junction, either at the segment face or on an internal blister to accommodate the anchorage. Considerations for anchorage placement include the maximum tendon size, thickness of the top flange, interference with web stirrups, and cost and complexity of the forms. **Figure 4.5** shows several possible configurations. It is important to detail anchorages to accommodate the project's grouting, inspection, and anchorage protection requirements.

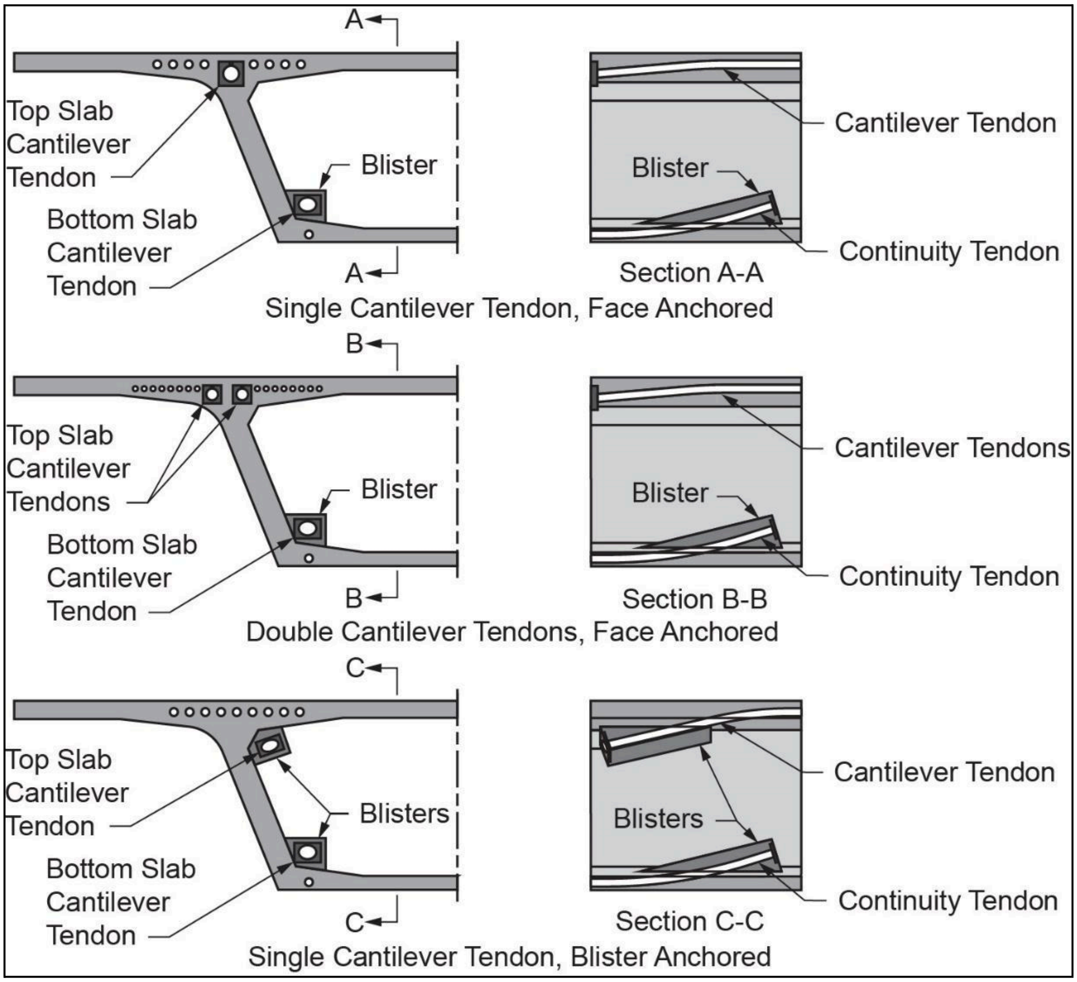


*Figure 4.5 – Possible Anchorage Configurations*

### 4.1.3.2 Continuity Anchors

When two cantilevers are joined, continuity tendons are stressed across the completed construction joint to create a single completed span. Continuity tendons are either internal or external. Internal continuity tendons are anchored in internal blisters concentrated in the bottom flange, at the web/flange interface. In some cases, there are a limited number of continuity tendons in the top flange as well. External continuity tendons are anchored in pier segment diaphragms and use an external post-tensioning duct located inside the segment box. Larger, more complex blisters called "deviators" develop the required tendon profile. Deviators typically contain multiple continuity tendons as depicted in **Figure 4.6**.

*Figure 4.6 – Typical Deviator Segment*
*(Photo Courtesy of FIGG)*

Continuity tendons can be used in a single-span configuration, as described above, or can be used to provide overall integration of the bridge structure by spanning multiple spans.

### 4.1.3.3 Temporary Post-Tensioning

During a typical erection cycle, segments are secured against the cantilever with post-tensioning bars until the permanent tendons have been stressed. The bars must be anticipated from the earliest stages of design and accommodated using one of the methods presented below.

### 4.1.3.4 Permanent Ducts

Precast segments for balanced cantilever construction are notable for the number of holes on the face of the segment. Because each cantilever tendon stretches from one end to the other of a cantilever, segments near the pier must accommodate nearly one set of tendons for each segment in the cantilever. **Figure 4.7** shows a typical longitudinal post-tensioning layout, with tendons concentrated in the top flange, near the pier, and in the bottom flange, near mid-span.

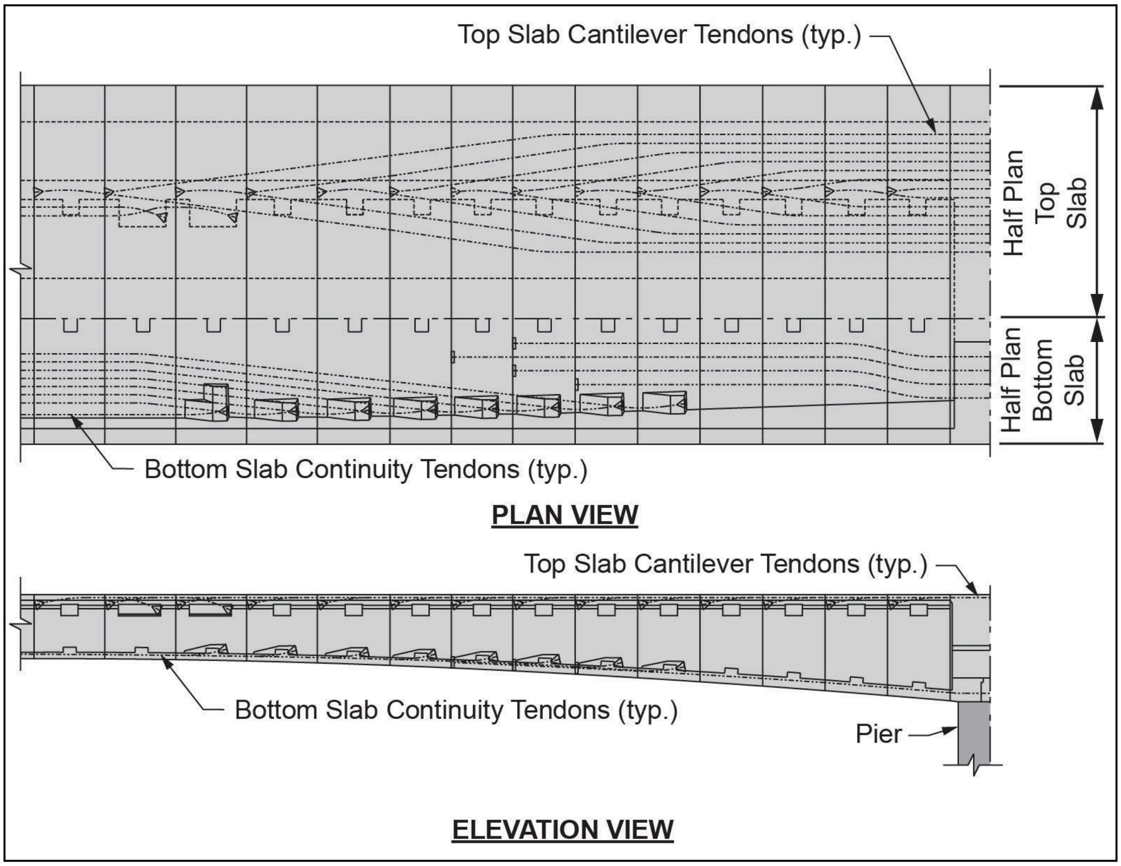


*Figure 4.7 - Typical Tendon Layout*

While span-by-span designs often employ external tendons, balanced cantilever construction relies primarily on internal tendons. Paying attention to the relevant details during planning is important and often results in a simpler and overall, more efficient design. In some cases, the contractor may be permitted to adjust tendon layout and local details as long as the post-tensioning force and eccentricity is maintained.

Some aspects of tendon layout and detailing include:

1. **Duct detailing** – The spacing of ducts is governed by the requirements of the AASHTO Bridge Design Specifications and deserves careful attention. Locating ducts too close together increases the risk of pull-through failure where transverse deviations occur. Ducts should be spaced at least one duct diameter apart, though this is generally increased due to practical considerations such as the size of post-tensioning hardware and bulkhead formwork fabrication. Tendon details should be adequately spaced to avoid conflicts with the spiral reinforcement at the anchorages.
Duct spacing also helps prevent grout communication between ducts match cast segment joints. Structurally, having sufficient concrete between ducts is necessary to ensure proper transverse bending behavior in the top flange before the ducts are grouted. Duct couplers may also be required, depending on the PTI protection level required in the project criteria.

2. **Duct alignment** -- Ducts should be straight across all joints. When segments are match-cast, ducts should be aligned across the segment joint. This is generally done by inserting a short, rigid mandrel into those ducts that cross the joint. If a duct is curved, a smooth transition is

difficult to achieve, which can lead to unwanted kinks at the joint. It is often necessary to include tendons that run at a slight angle to the bridge axis. This is easily accommodated – it is only a curve that is to be avoided.

3. **Standardized detailing** -- Tendon and anchorage details should be standardized to the greatest extent possible. Ducts may be placed in areas necessitating complicated and congested reinforcement, and standardized details help reduce conflicts and errors. Anchors generally require a small blockout behind the anchor plate to accommodate the geometry of the anchorage and allow clearance for the stressing ram. If anchor orientation can be standardized to one or two positions, production efficiency is increased and opportunities for confusion are reduced. Standardized duct layouts will also simplify the casting bed bulkheads. This again mitigates opportunities for casting errors and improves quality by reducing form seams that wear and increase spall risk during form removal.

4. **Relationship of transverse tendons to longitudinal ducts**—This should not be overlooked. The need for transverse tendons to avoid all longitudinal ducts may impact transverse deck design.

5. **Tendon Profiles and Reinforcement Detailing** – When designing internal tendon profiles, accommodations for the vertical and horizontal deviations must be considered when detailing the reinforcement in each segment. For instance, when internal tendons deviate horizontally across the web/top slab interface, often, atypical reinforcement shapes will have to be provided locally in the web to allow for the necessary deviation of the tendon duct as most web reinforcement form closed or open-end stirrups along the length of the segment. Additionally, when internal tendons are vertically deviating from a bottom slab anchorage blister into the bottom slab proper, accommodations must be made in the bottom slab reinforcement to allow for the curved tendon profile.

#### 4.1.3.5 Web Shear Keys

Shear keys are indentations along the mating faces of the webs. Their purpose is to ensure transfer of global shear across the segment joint. As such, they should cover as much of the web as possible. Project specifications typically provide a maximum allowable shear key area loss. Care must be taken in casting, transporting and erecting the segments to ensure integrity of the shear keys is maintained.

#### 4.1.3.6 Alignment Keys

Alignment keys are generally located in the top and bottom flanges of the segment. Their primary function is to ensure proper fit-up between segments erected in the field. Alignment or flange keys are also important in transferring local shear in the top flange at the joints. Balanced cantilever segments typically have large portions of the top and bottom flanges reserved for longitudinal ducts, so consideration should be given in design and construction to accommodate both ducts and alignment keys.

## 4.2 Casting Yard and Transportation

### 4.2.1 Forms

As in most precast segmental construction, the casting cell bulkhead is a critical part of set-up. The basics of the bulkhead are covered in **Chapter 9**, but there are a few features specific to balanced cantilever bridges that are worth noting here.

When span lengths are over 200 ft., it is frequently more cost-effective to use a variable depth superstructure. This helps provide peak shear and bending capacity where it is needed most – but it also adds a layer of complexity and inefficiency to casting operations. Forms created for variable depth segments need to accommodate changes in depth with minimal interruption to the casting schedule. One common solution involves two-piece bulkheads, where the bulkhead can be lengthened or shortened by bolting together different pieces, adjustable soffit tables, and adjustable core forms. While a single set of forms can accommodate a wide range of depths, it may be economical to have one set for the deepest segments, and another for the shallowest. If this is done, the workflow must be analyzed to ensure the forms work together without interruption (see **Figure 4.8** below).

While the fixed bulkhead is an important part of any casting cell, in a balanced cantilever bridge it takes on additional significance as the template for all longitudinal post-tensioning. All tendon ducts are secured to pre-existing holes in the bulkhead. This means the bulkhead must include a hole at every location where a tendon crosses the joint, not just for that joint, but for all joints. It is beneficial to standardize and re-use duct locations to avoid unnecessary or overlapping holes in the bulkhead.

***Figure 4.8 – Typical Form and Fixed Bulkhead***
***(Photo Courtesy of FIGG)***

Balanced cantilever designs make use of internal blisters and deviators for anchoring continuity tendons and temporary post-tensioning. While blister locations should be standardized whenever possible, it is likely that the location of internal blisters will vary. Core forms should be able to accommodate the addition or removal of an internal blister on a regular basis. Additional core form configurations are needed when continuity tendons are external and use deviation segments to accommodate tendon profiles.

### 4.2.2 Detailing and Workmanship

Proper attention to detail and good workmanship are always critical, but the stakes are raised in precast construction. Problems that may affect the structure during erection may not be discovered until much of the superstructure has been cast, making remedial action more expensive.

Many of the detailing issues for balanced cantilever segments are directly related to successfully integrating the internal tendons. When tendons deviate, they can exert significant force on the section, either by design or unintentionally.

The information below addresses a few areas that merit especially close attention.

Areas where ducts cross segment joints -- At this location, the two primary requirements are (1) to create a smooth transition across the joint and (2) to eliminate the natural tendency for the ducts to sag (see **Figure 4.9**). A smooth transition is generally achieved by inserting a mandrel into the ducts of the match-cast segment, which aligns and seals the ducts. Mandrels built with a semi-flexible material may be required to penetrate into the match-cast segment a sufficient distance when casting a cantilever in a tight radius. Sagging is prevented by ensuring the duct is firmly supported against the rebar cage at close intervals to maintain a tangent alignment to the joint. Post-tensioning duct suppliers may offer segmental duct couplers with more rigid connections across the match cast joint to build a more positive connection across the match cast joint during casting.

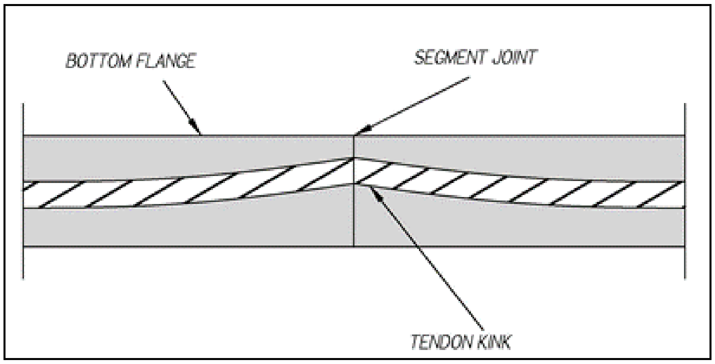


***Figure 4.9 – Duct Sagging at Segment Joint***

Adequate duct support is important in other areas as well, such as in the bottom flange, where continuity tendon ducts run the length of the segment. If concrete is placed in a manner that requires a transverse flow (from web to centerline), ducts that are not adequately secured tend to bow **(Figure 4.10)**. This can create small kinks at the bulkhead, where the duct is firmly attached. Proper duct support is the key to avoiding these unwanted kinks. The PTI/ASBI M50.3-19 specification on multi-strand post-tensioning provides guidance on proper support intervals of internal tendon ducts.

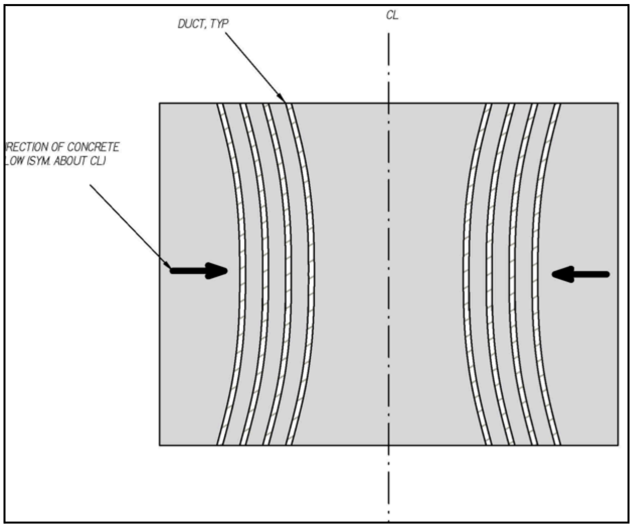


***Figure 4.10 – Bottom Flange: Ducts Bowing Due to Inadequate Support***

The toe of anchorage blisters -- This region typically includes a relatively tight curvature of the continuity tendon anchored in the blister **(Figure 4.11)**. As the tendon deviates, it exerts a radial force on the concrete as it effectively tries to straighten. This deviation must be fit to the proper radius (not kinked) and tied back into the segment flange to avoid cracking. While it is the responsibility of the designer to provide adequate steel for this force, care should also be taken in the casting yard to ensure the steel is well-distributed along the full length of the deviation, and the duct profile closely matches the radius shown in the plans.

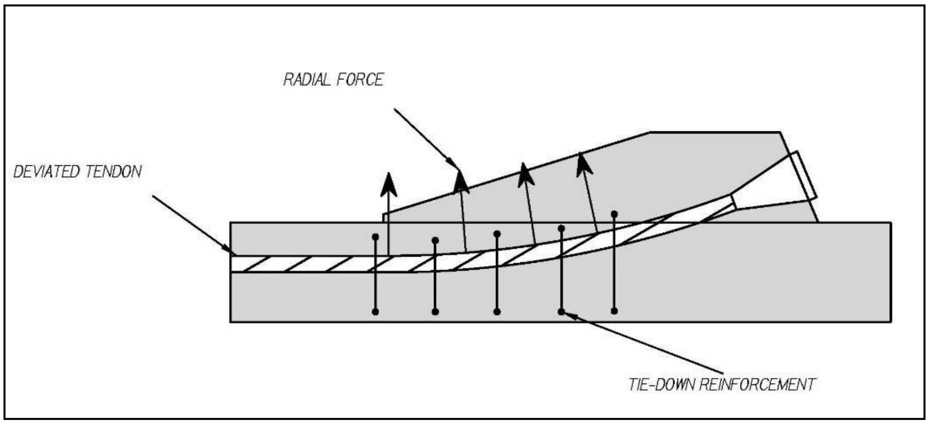


*Figure 4.11 – Radial Force in an Anchorage Blister*

It is good practice to ensure the curved portion of the duct is contained entirely within the toe of the blister. Duct placement in the yard should match this requirement.

When continuity tendons are external and use large deviator blisters housing multiple tendons, close attention to detail is needed. Some designs use steel pipes **(Figure 4.12)** to accommodate the tendon's change in profile through the deviator. Each pipe is bent to a specific geometry that can differ based on the pipe's location. It is critical that the pipes are bent properly and installed at the correct location, in the correct orientation. Steel pipes should be marked with a punch or other permanent identifying mark at zero degrees. The pipes are then rotated to a precise angle provided by the Engineer and tack welded in place to ensure no movement during concrete placement. The next morning, the punch marks on the steel pipes should again be recorded as part of the morning survey / as-built procedures. Errors can change the tendon profile, resulting in kinked or broken tendon strands that increase stresses in the superstructure.

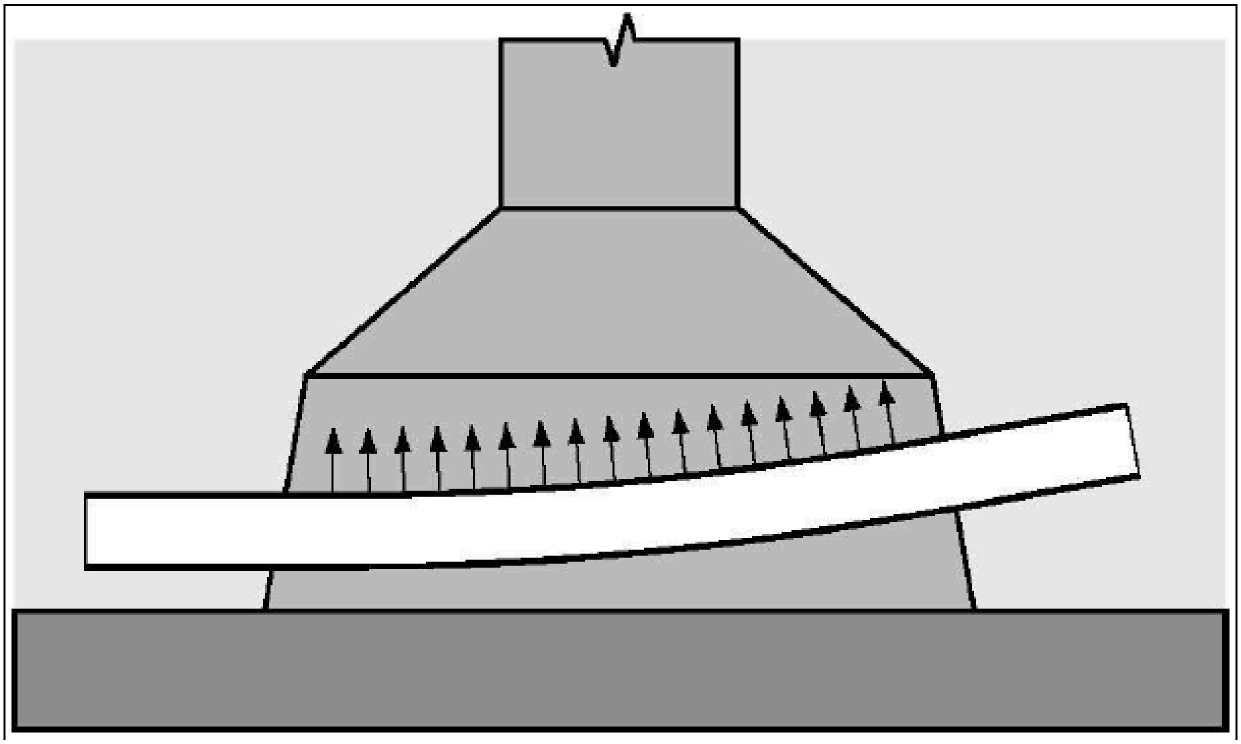


*Figure 4.12 – Deviator with Curved Pipe Pre-Bent to Radius*

One alternative that eliminates the potential for the errors related to steel pipes is using a diabolo **(Figure 4.13)**. A diabolo is a curved block-out which is flared on both ends and installed in the deviator. It allows the tendon duct to enter and exit the deviator in a range of geometric angles in plan and elevation, eliminating the need for duct fabricated to a specific geometry. Note that the reduced bearing area, as compared to embedded steel pipes, must be accounted for in the design of the concrete deviator diaphragm. A reduced bearing area results in higher concentrated stresses.

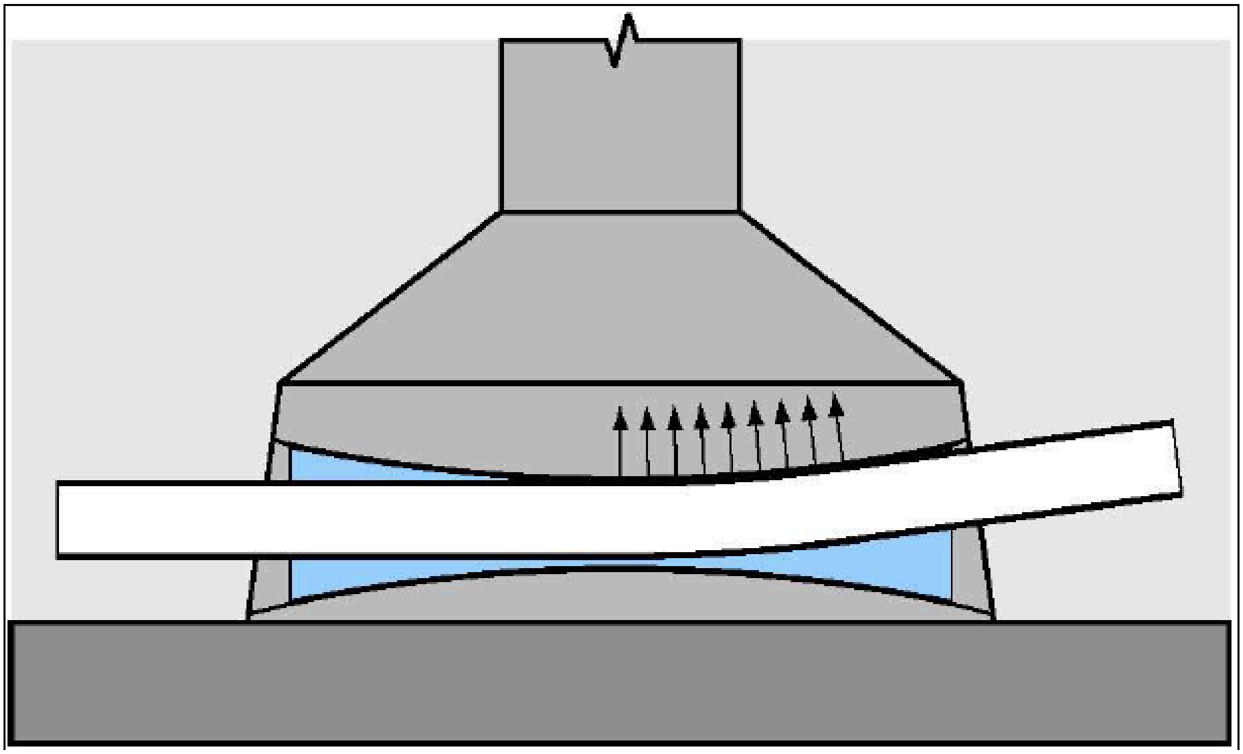


*Figure 4.13 – Diabolo Deviator*

Due to the large amount of force generated from multiple tendons changing profile over a relatively short distance, it is important to use sufficient reinforcing steel at deviator locations. Failure to do so will result in structural cracking and, potentially, a bursting failure after continuity tendons are fully stressed.

There are several locations where the presence of numerous internal tendons – and the resulting tendon force -- increases the potential for delamination (a portion of the flange peeling away from the segment). The first area of concern is in the upper and lower flanges, where segments near the pier segment or mid-span contain multiple closely spaced ducts. Since grouting generally is not performed until the cantilever is complete, a significant portion of the flange is effectively voided during erection. This is often mitigated by including "J" ties to secure the top and bottom mats of rebar **(Figure 4.14)**. Typically, the ties are distributed evenly along the length of the segment. Care should be taken to place and develop the ties as indicated on the plans.

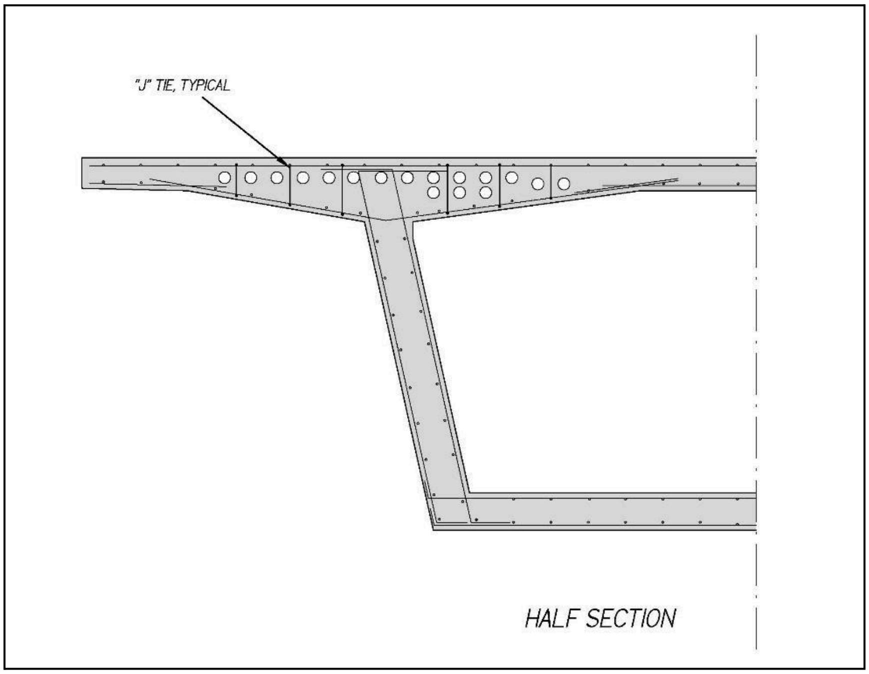


*Figure 4.14 – "J" Ties Used in Segment Erection*

Another area where delamination may occur is in the bottom flange of variable depth segments. The change in angle at the segment joint creates a natural deviation in the bottom flange tendons that has a tendency to pull out and delaminate the bottom flange. To prevent this, supplemental stirrups are required to restrain the deviating tendons. A common configuration is shown in **Figure 4.15**. Though seemingly minor, the stirrups play an important role and must be placed correctly.

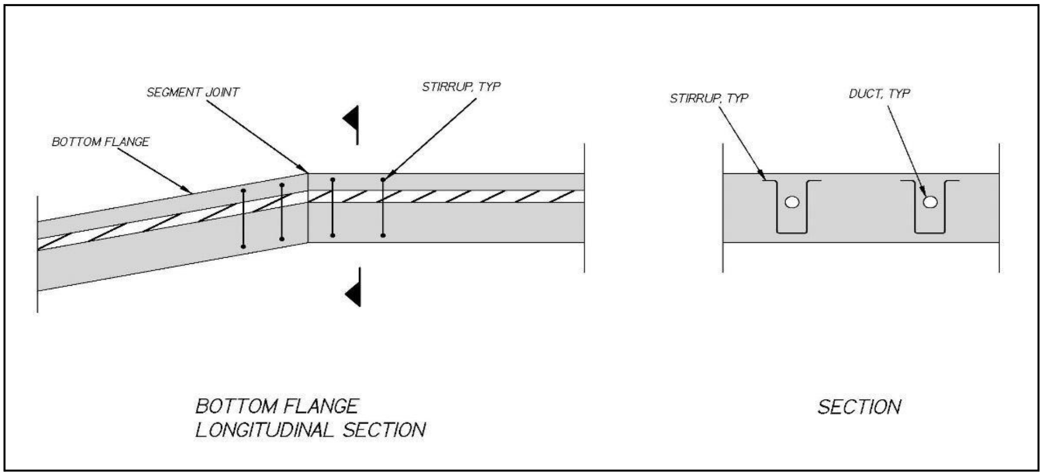


*Figure 4.15 – Typical Configuration of Supplemental Stirrups*

The examples of common critical details given in this chapter do not constitute an exhaustive list. Good engineering judgment must be used in developing segment details, so that critical aspects are clearly shown in the plans and accurately implemented in the casting yard. Specific requirements for many of these details are given in AASHTO Bridge Design Specifications; their successful implementation begins with careful detailing during design.

### 4.2.3 Geometry Control

In most respects, geometry control for short-line casting is no different for balanced cantilever spans than for any other precast span (see **Chapter 13**). The major differences are the casting sequence of segments in the cantilever and the calculated geometry at different stages of erection.

Regarding the casting sequence, casting of balanced cantilever spans progresses from the pier to the cantilever tip as shown below in **Figure 4.16**. This means that the casting direction reverses for up- versus down-station cantilevers. Though easily achievable, this requires extra care in determining casting coordinates, setting up the geometry control program, and determining the nomenclature for the casting coordinates. It is best to use a 3D CADD program to plot all casting coordinates for the entire bridge at once, and to check for any unintended kinks or misalignments.

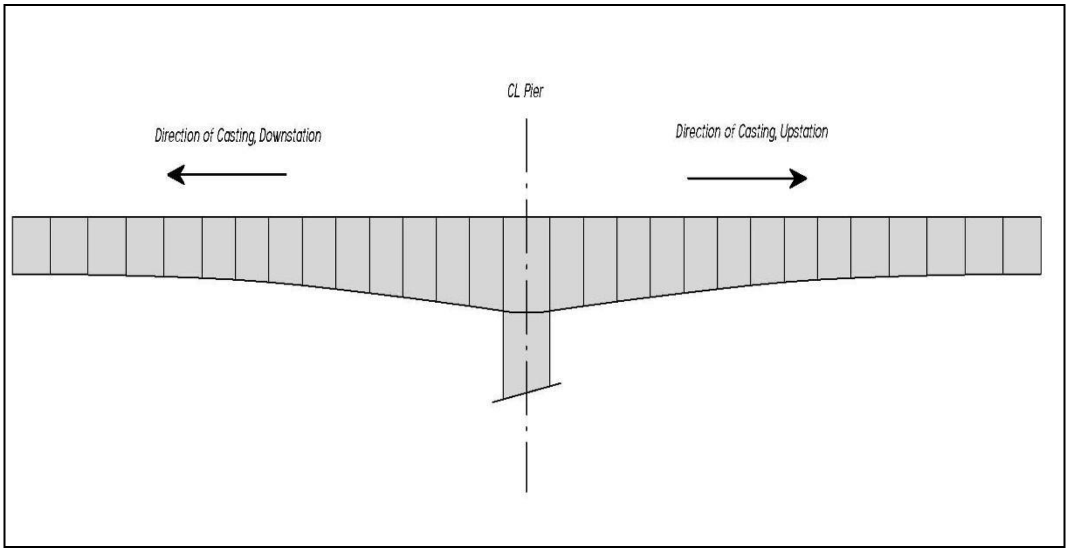


*Figure 4.16 – Casting Direction*

The most critical factor in geometry control during segment erection is accurately determining the geometry of the cantilever at different stages of construction. There are numerous variables, including segment age, concrete strength, creep and shrinkage, effects of post-tensioning forces, and small geometry deviations incurred during casting. The contractor and geometry control engineer must thoroughly coordinate the casting and erection schedules. Instances where project phasing demands cantilever tips to remain floating for extended periods of time may warrant the casting geometry to intentionally cast the cantilever tip high in anticipation of settlement prior to connecting to the adjacent cantilever. Deviations from the erection schedule after the segment has been cast can result in closure pour misalignment and project delay. Monitoring the cantilever geometry during the early stages of erection so alignment deviations are noted early is key to adequate correction. More on this later in this chapter, as well as in **Chapter 13**.

### 4.2.4 Lifting Details

Many schemes have been developed for lifting segments for transport, some of which are illustrated in **Figure 4.17**. A common feature is using holes in the top flange to secure the lifting devices. For balanced cantilever segments, it is often difficult to identify a single lifting-hole arrangement that reliably avoids the cantilever tendon ducts. Better to design the lifting equipment used at both the casting yard and the erection site to accommodate a reasonable variation in pick points. Any holes will need to be patched after erection, using materials and procedures approved by the Engineer.

Sling supports are generally not compatible with balanced cantilever erection since the segment must be supported by the lifting equipment when the joint is closed. Slings can be used in the casting yard for moving and loading segments for transport to the erection site. Also note that Lifting Methods 2 and 3 in **Figure 4.17** require access outside the box for removal during erection.

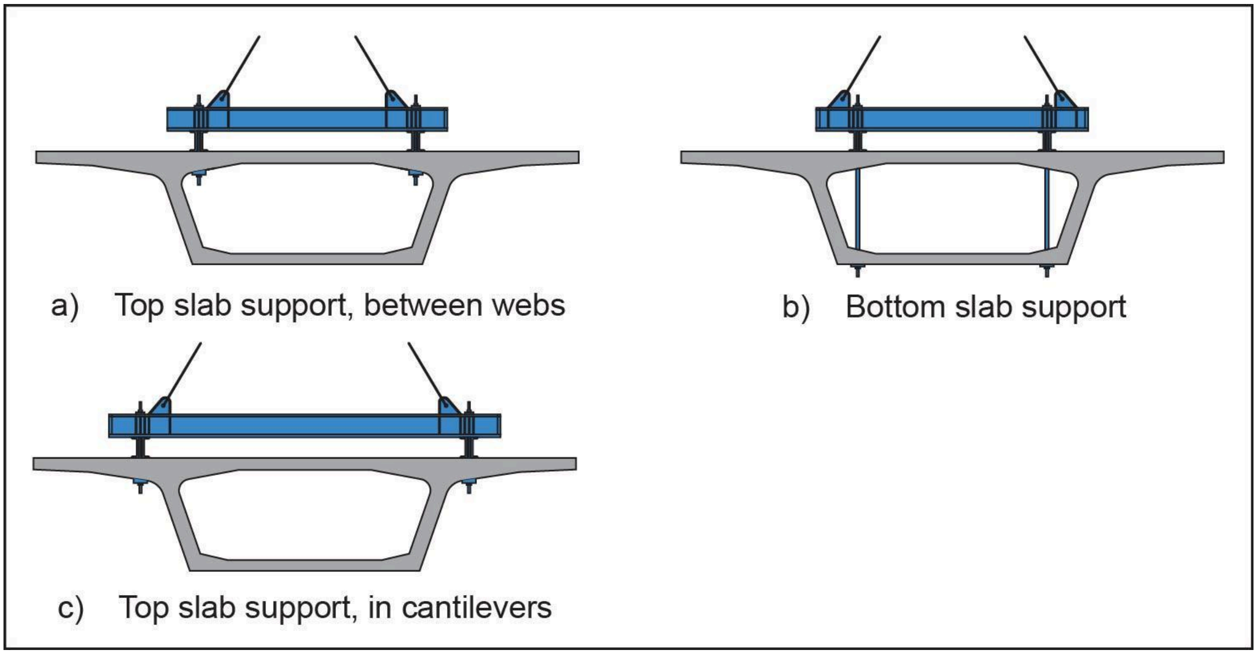


***Figure 4.17 – Typical Segment Lifting Methods***

Other lifting device designs, such as the C-Frame depicted in **Figure 4.18,** eliminate the need for tie-down holes in most of the segments. Reducing these top deck penetrations promotes a watertight deck and improves durability of the overall structure. (See **Chapter 10** for additional details.) Any lifting details must be compatible with the equipment used to align and adjust the segment to the bridge geometry – often referred to as the manipulator.

***Figure 4.18 – C-Frame Lifting I-49 Bridge Segment K, LA***
***(Photo Courtesy of PCL Civil Constructors, Inc.)***

### 4.2.5 Transportation

Several key decisions for the project will be influenced by segment transportation requirements. If transportation by road is anticipated, this will limit the practical limits of segment height, length and weight. Typical values are 15 ft tall, 10 ft long and 50 tons. These dimensions often require low-clearance trailers and attention to protruding details, such as parapet bars. If transportation is by water, or if the casting yard is adjacent to the site, then these limits may not apply. In any case, an understanding of the routes, methods, clearances and limitations are important to the planning process.

## 4.3 Typical Erection Cycle

### 4.3.1 Overview

Balanced cantilever erection is based on a standard two-segment cycle that begins when the first segment is lifted into position at the tip of the cantilever. Epoxy is applied to the segment face(s) immediately before they are joined together, then the new segment is stressed against the existing structure by post-tensioning bars. These steps are repeated on the opposite end of the cantilever with the second segment. Then, the cantilever tendons are stressed and anchored at the ends of the cantilever. At this point, the cycle begins again. **Figure 4.19** below illustrates this cycle.

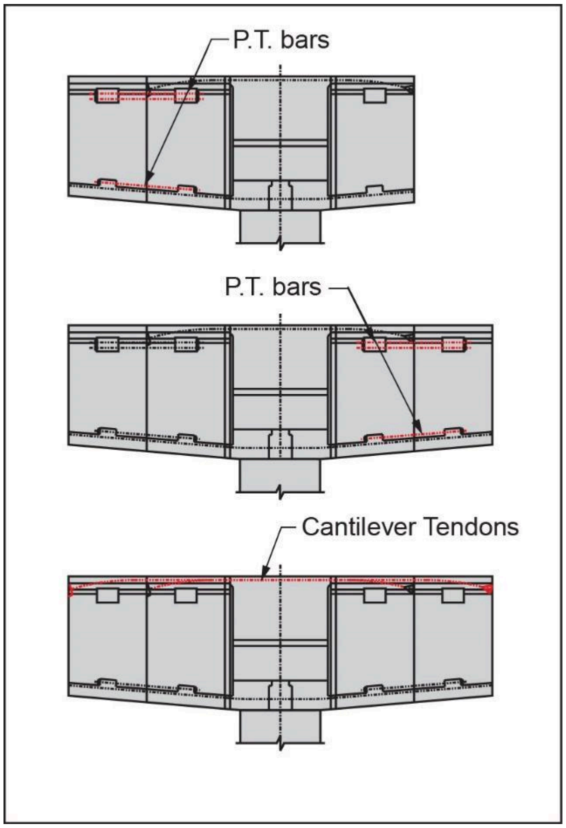


*Figure 4.19 – Standard Two-Segment Erection Cycle*

### 4.3.2 Epoxy

Epoxy has always been an AASHTO requirement for joints with internal tendons. Now epoxy is required by AASHTO for all segment joints, on both faces of the segments to be joined. It serves two main purposes: (1) to provide a strong, impermeable seal at the joint to prevent corrosion in the tendons, and (2) to lubricate the joint during installation. **Figures 4.20-1** and **4.20-2** show epoxy being applied.

If empty ducts are not adequately protected, epoxy may enter when the segments are stressed together. For the same reason, ducts must also be swabbed after each segment is erected; otherwise, epoxy can block the duct, hindering tendon installation on subsequent segments. Post-tensioning duct couplers are often required at the segment face, which reduces this risk. (See **Chapter 12** for more on this topic.)

***Figure 4.20-1 – Epoxy Application***
***(Photo Courtesy of SYSTRA IBT)***

Frequently, epoxy is squeezed out of a joint when segments are initially stressed together with bars. When this happens, uncured epoxy often drips from the bridge, both onto the ground and into the box interior. In some cases – e.g., over active roadways or in environmentally sensitive areas – precautions may be necessary to prevent epoxy from reaching the ground as shown in **Figure 4.20-2**.

***Figure 4.20-2 – Epoxy Application***
***(Photo Courtesy of SYSTRA IBT)***

### 4.3.3 Temporary Post-Tensioning

Temporary post-tensioning, or PT, is needed in most typical erection cycles, usually in the form of high-strength bars placed near the top and bottom flanges. The purpose of the temporary bars is two-fold. First, they provide a means of securing the new segment to the cantilever so it can be released from the lifting equipment. Second, post-tensioning bars help compress the wet epoxy to a required minimum of 40 psi during the cure time (which varies depending on product and temperature). They should provide the minimum compression stress both while the segment is supported solely by the bars, and after the cantilever tendons have been stressed.

There are three main methods of incorporating temporary PT into a segment, as described below.

The first method uses small blisters cast on the interior of the box girder. The blisters are typically located as shown in **Figure 4.21,** which allows easy access to both ends of the bars, so they can be removed and re-used for later cycles. To be re-used, the bars must be stressed to a low level, typically 50% of their ultimate strength. During construction, this method is very efficient and requires a limited number of bars. However, casting forms and efficiency are impacted by the inclusion of interior blisters.

***Figure 4.21 – Typical Location of Temporary Post-Tensioning Blisters (Photo Courtesy of SYSTRA IBT)***

The second method incorporates internal PT bars into the segment cross-section **(Figure 4.22)**. Subsequent bars are coupled onto the previous set and cannot be removed. Since these bars are permanent, they can be stressed to higher levels and included in design of the final structure. They also must be properly grouted and protected against corrosion. This method eliminates the need for internal blisters, which benefits the casting yard. However, more bars are needed -- and cannot be reused. Also, bar ducts may require specialized couplers at the bearing plate (segment joint face), which affects the casting operation.

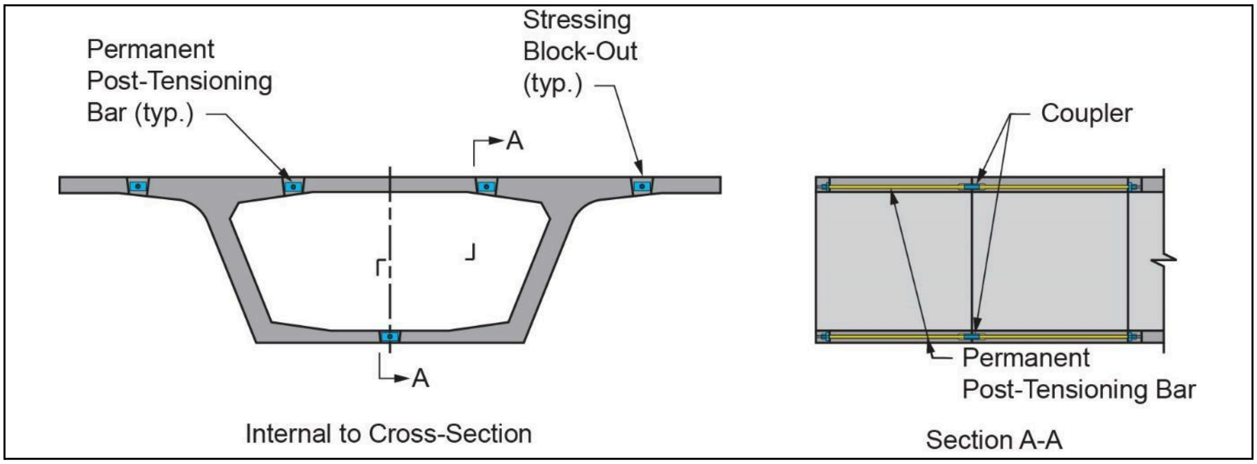


*Figure 4.22 – Internal Permanent Post-Tensioning*

The third method employs a bracket attached to the segment to anchor the bars. This works much like the first option but eliminates the blisters from the interior. This method, like the others, has pros and cons. Careful attention must be paid to bracket detailing to avoid local spalling and operations are added to the typical erection cycle to secure the brackets for each segment. On the plus side, brackets can be reused and a savings can be achieved in the casting yard.

### 4.3.4 Tendon Installation and Jacking

Though in many ways, tendon installation is the same on a balanced cantilever bridge as on any typical bridge, two features set it apart.

The first is the frequency of required tendon installation and stressing. With each cycle, at least two and, occasionally, four or six tendons must be installed and stressed. This is a critical path activity, as the next pair of segments cannot be placed until the previous tendons have been completed. In some cases, three or four cycles are completed in a day, a rate that requires efficient post-tensioning operations.

The second unique aspect is the location of the work. All post-tensioning installation and stressing is done from the end of the cantilever. To access the anchor heads, the post-tensioning platforms have to serve each end of the cantilever, meaning they must be removed and re-positioned with every cycle (see **Figure 4.23** below). Integrating the stressing platforms with segment placement equipment and operations early on can positively impact the speed of a typical cycle.

As discussed previously, continuity tendons are used to join two adjacent cantilevers, in some instances extending over multiple spans. Continuity tendons can be either internal or external tendons tensioned from inside the segmental box. In either case, considerations need to be given to stressing jack handling, as well as adequate clearance around the anchorage blockout.

*Figure 4.23 – Stressing Platforms on the Otay River Bridge, CA*
*(Photo Courtesy of SYSTRA IBT)*

### 4.3.5 Grouting

Proper grouting procedures and quality control testing are key in the long-term performance of segmental bridges including balanced cantilever bridges. **Chapter 12** covers grout in more detail. Also, refer to PTI M55.1-19 grouting specification for the most up-to-date guidance on the grouting of multi-strand post-tensioning.

Since tendons are installed and stressed daily during cantilever erection, it is ideal to wait until the entire cantilever is complete before grouting the cantilever tendons. This is more efficient and prevents grout from getting into the empty ducts that are often directly adjacent to each tendon when it is installed.

The allowable period for leaving a stressed tendon ungrouted can be extended by using a corrosion inhibitor. Check the compatibility of the corrosion inhibitor with the cable grout, as flushing the duct with water is typically prohibited.

In all cases, care should be taken that water is not allowed to enter the ducts during cantilever erection.

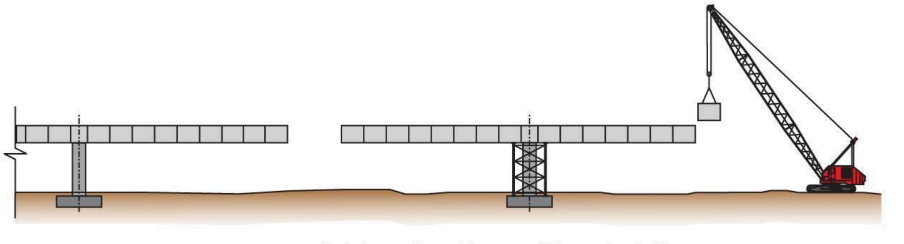
Because cantilever tendons are often very long and flat, with little variation in elevation other than roadway grade, there are few high or low points where grout vents are required. For longer tendons, it is worthwhile to install supplemental grout vents along the length of the tendons to improve grouting results.

Make sure that any grout vents that go through the top deck will not provide a pathway for water during the service life of the structure. In many cases, it's ideal to exit grout vents into the box-girder interior or underneath secondary concrete placements, such as a barrier wall.

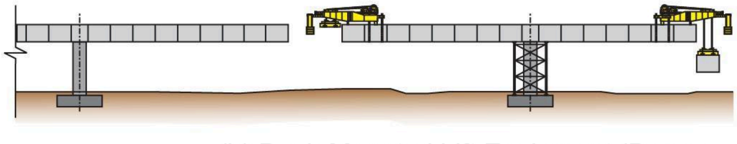
## 4.4 Erection Equipment and Methods

The defining operation of balanced cantilever erection is delivering segments to the cantilever tip, and the equipment selected can meaningfully impact project cost and schedule. Typically, as shown in **Figure 4.24**, one of three methods is employed: a crane, a beam and winch, or an erection gantry. Factors influencing equipment selection include:

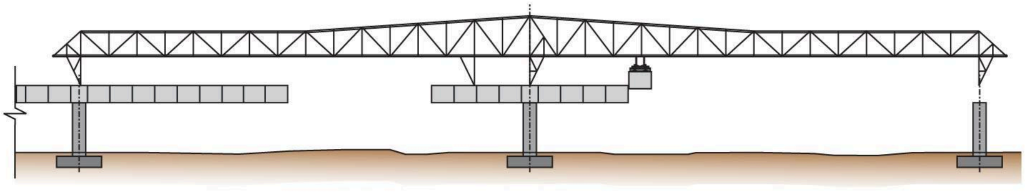
- Upfront Cost
- Operating Height
- Lifting Capacity
- Terrain / Access
- Required Safety Factors (e.g., Crossing a Railway)
- Erection Sequence
- Loads on the Structure
- Foundation, Substructure and Superstructure Capacities



(a) Land or Barge Mounted Cranes



(b) Deck-Mounted Lift Equipment (Beam and Winch)



(c) Overhead Gantry

*Figure 4.24 – Common Erection Methods*

### 4.4.1 Land- or Barge-Mounted Crane

Cranes are readily available, making this method of segment delivery and erection very cost-effective. It also makes it possible to save on schedule by erecting multiple cantilevers at once.

The main constraint on crane erection is access. Balanced cantilever bridges are often selected in response to inaccessible terrain, be it over a highway, railways, water, or an environmentally sensitive area. Since the crane will be used to place the segments in their final position, it must have access along the entire alignment (see **Figure 4.25** below).

*Figure 4.25 – Segment Erection by Crane on PR18*
*(Photo Courtesy of SYSTRA IBT)*

For relatively light sections, access issues may be addressed by using a light crane positioned on the bridge deck. First a land-based crane places the segments on the deck, typically at the pier; then the deck-mounted crane picks up the segments and carries them to the tip. This technique was used on the Sound Transit balanced cantilever spans shown in **Figure 4.26**.

***Figure 4.26 – Deck-Mounted Crane Erection, Sound Transit Tukwila Line, WA***
***(Photo Courtesy of SYSTRA IBT)***

### 4.4.2 Beam and Winch

In this method, a beam and winch system are placed on each end of the cantilever. The segment is delivered below the tip, and the beam and winch lifts it into position. This is often selected for construction over water, where a custom-built system can accommodate heavier segments. A notable example of this method is the San Francisco-Oakland Bay Bridge, pictured in **Figure 4.27**.

***Figure 4.27 – Beam and Winch System, San Francisco-Oakland Bay Bridge, CA***
***(Photo Courtesy of Flatiron Constructors, Inc.)***

Considerations for beam and winch systems include access and height. With a fixed system, access is required at every location along the alignment. Hoisting segments over significant heights can be time- consuming and have a negative impact on the erection cycle.

Specialized equipment can help overcome these difficulties. Mobile lifters, like the one shown in **Figure 4.28** below, move along the deck to hoist segments at an accessible location and deliver the segment to the cantilever tip for erection. These are generally custom-built for a specific project. This method may present some engineering challenges during erection. Since the lifter will occupy many different positions, foundation and substructure elements may have to be scaled up to accommodate the additional construction loads. Alternatively, demand on the substructure can be reduced by means such as tie-downs, counterweights, or support towers. Further reinforcing the superstructure with provisional cantilever post-tensioning tendons or temporary bar tendons may be necessary in this case.

***Figure 4.28 – Specialized Equipment: Mobile Lifter, Dallas High-5, TX***
***(Photo Courtesy of Zachry-Rizzani, JV)***

Another way to reduce the impact of the construction loads generated by a single lifter is to use a pair of lifters on either end of the cantilever. Using lifters in tandem reduces the out-of-balance moment and the demand on the substructure and foundational elements. An example of this technique is shown in **Figure 4.29** below.

*Figure 4.29 – Mobile Lifters Erecting Cantilevers on the I-4 Connector Project, FL*
*(Photo Courtesy of PCL/Archer-Western JV)*

### 4.4.3 Erection Gantry

Segmental construction is often chosen for sites with limited access from the ground, a factor which generally favors use of an erection gantry (see **Figure 4.30** below). One advantage of a gantry is the ability to work from the top down, delivering segments over completed spans. It also offers external stabilization for out-of-balance moments, which over the length of major structures can represent significant cost savings. Additionally, with an overhead gantry segments can be lifted directly from the ground (or water) depending on access.

Because gantries have evolved to a high level of sophistication and are generally customized for a project, they represent a major investment. This cost is felt less keenly on larger projects but should be considered and weighed against any potential savings. The cost of a gantry may be justified by the volume of segments erected, increased speed of erection, or overcoming access restrictions.

Schedule savings can be the deciding factor in procuring a gantry. When a structure is relatively long and there is a reasonable repetitiveness of spans, a gantry can be a fast and efficient means of erecting cantilevers. Note, however, that gantries limit construction to a linear erection sequence. It is not possible for a single gantry to erect on multiple piers, as can be done with crane erection.

Additional factors to take into account include the degree of horizontal curvature and the maximum grade the gantry will be required to accommodate. Also, many gantries are designed and/or fabricated overseas, introducing considerations such as lead time, import challenges, quality control, design criteria and standards, availability of replacement parts, and equipment training.

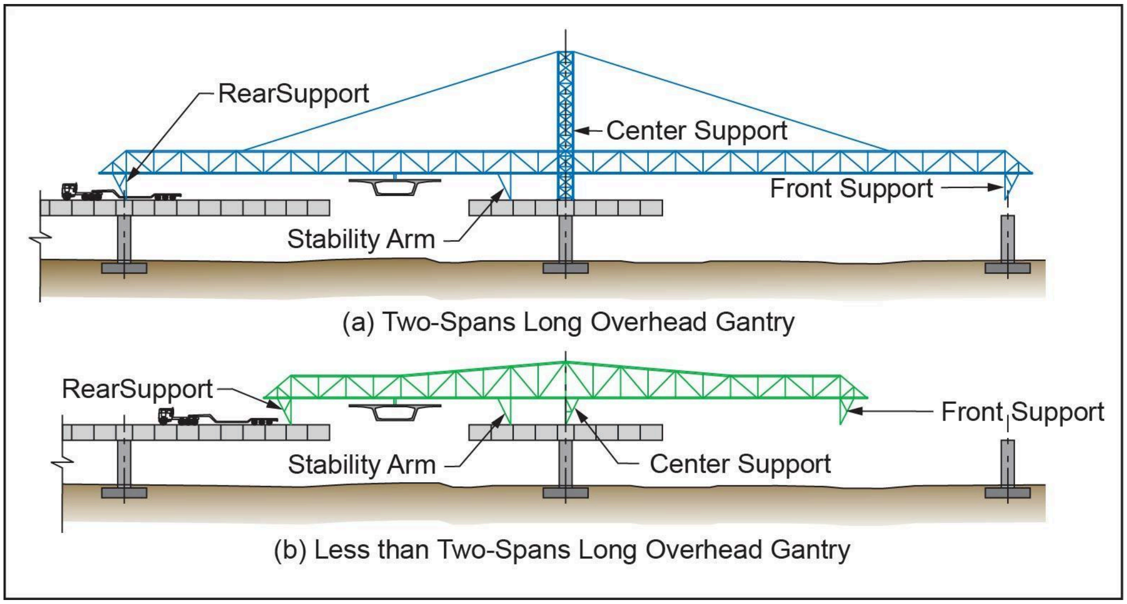


***Figure 4.30 – Erection Gantries in Position***

<u>Gantry Selection</u>

Once the decision has been made to use an overhead gantry, the specific type must be chosen. Availability, contract bid price, and the potential for re-use on future projects should all influence this decision.

The length of the gantry with respect to the typical span length is of particular importance. The earliest gantries were designed to be slightly longer than the span length of the bridge on which they were being used, as shown in **Figure 4.30b**. The length was sufficient to span the previous cantilever and the one presently being erected while supported at rear and center. Minimizing the distance between gantry support points resulted in a minimal-weight design. The disadvantages of this design, however, involve the position of the rear support on the previous cantilever during segment erection and the increased complexity of pier segment placement and girder launching operations. The proximity of the rear gantry support to the tip of the cantilever may require additional temporary post-tensioning above service level requirements for moment or shear consideration in the cantilever or bending reinforcement in the pier. Also, an intermediate step must be taken during launching operations to position the temporary nose support over the pier – or, alternately, a temporary pier bent must be used to support the nose when a span is exceptionally longer than the typical.

More recent launching gantries have evolved toward girders whose total lengths are equal to or slightly greater than twice the typical span length. There are two main reasons for this: the increasingly efficient use of materials and the recognition that additional bridge reinforcing and the associated labor is often more expensive over the course of a large project than additional gantry length. As demonstrated by **Figure 4.30a**, longer girders offer the advantage of ensuring that loads transmitted to the superstructure remain over the piers or very near. Pier segment placement and girder advancement operations are simplified by allowing simultaneous placement of the typical segments of a cantilever and the pier segment at the following cantilever pier location.

As a practical matter, a gantry is sized for twice the "typical" span length, which keeps the gantry to a reasonable length and facilitates erection and launching operations for the majority of spans. For span lengths in excess of the typical span, special, though not necessarily complex, procedures launch the gantry from one pier segment to the next.

### Gantry Operations

Once a pier segment is in place, either by setting it (precast) or by casting it in place, the overhead gantry is positioned as shown in **Figure 4.30** to begin erection. The gantry rests on two supports and is, therefore, statically determinate. The center support is anchored to the pier segment where the cantilever is being erected; the rear support is tied down on the previous cantilever. Depending on access at the site, segments are either transported from the rear of the gantry along the completed structure or lifted directly from below. In the first case, the gantry supports must be transversely spaced so that a segment, when rotated 90° to the bridge, can pass between them **(Figure 4.31)**. A trolley riding on the upper or secondary chords of the launching girder typically transports the segment and positions it for erection.

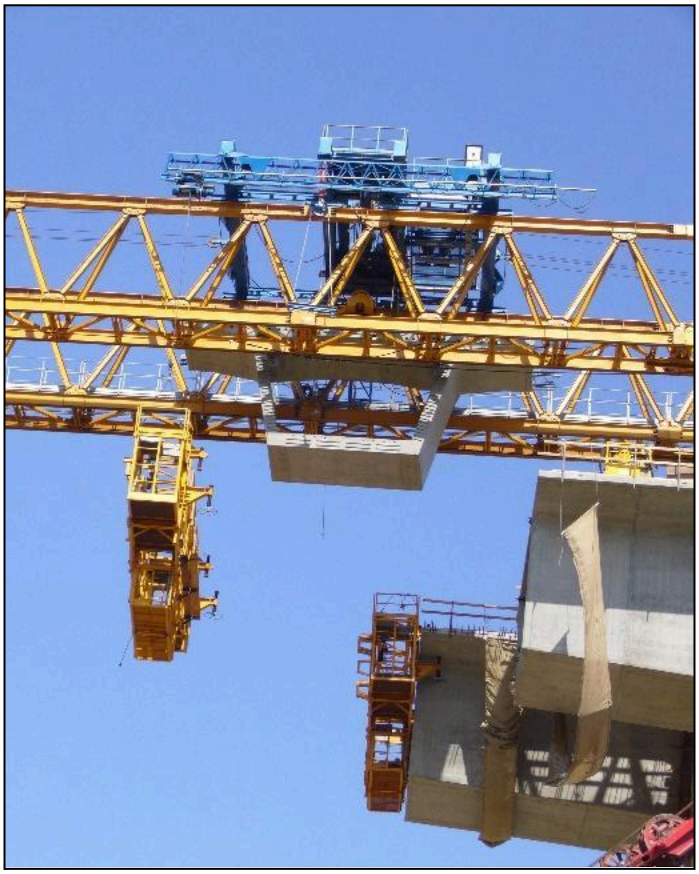


***Figure 4.31 – Segment Rotated 90˚ Between Truss Chords, Otay River Bridge, CA***
***(Photo Courtesy of SYSTRA IBT)***

After erection of a cantilever is complete and span closures are made, the gantry is launched to begin erection on the next pier. The exact sequence involved depends largely on the type of gantry being used and the span configuration of the bridge under construction. If the gantry is of sufficient size relative to the forward span length, as shown in **Figure 4.30a**, the pier segment for the next cantilever may be placed without changing the longitudinal position of the gantry. If the nose section of the gantry is shorter than the forward span length (**Figure 4.0b**), a two-stage launch, or temporary intermediate bent must be used.

Once a pier segment is in position, the gantry is advanced until the central support is located over it. The support is then anchored to the pier to begin the next cycle of segment erection on the new cantilever.

The method by which a launching gantry advances relative to the bridge depends on the design of the gantry and the construction application. In some designs, the gantry is supported on temporary front and rear supports. It is prepared for launch by freeing the primary (center) support, then rolling the gantry over the front (nose) support by means of a trolley fixed to the support. A similar trolley may be used on the rear support, which typically has already been advanced and reattached to the deck near the center support. Alternately, the rear support may be attached to the launching gantry itself, using rubber tires or a rail system to roll over the completed deck. Other designs feature two moveable primary supports. The gantry relies on temporary supports just long enough to advance the two primary supports along the completed deck. Once the primary supports are repositioned and reengaged, the gantry rolls over trolleys fixed to those supports. **Figures 4.32** through **4.34** show some examples of different types of gantries.

*Figure 4.32 – Erection Gantry Launched Forward, Otay River Bridge, CA*
*(Photo Courtesy of SYSTRA IBT)*

***Figure 4.33 – Self-Launching Dual Erection Gantry, H-3 Windward Viaduct, Oahu, HI***
***(Photo Courtesy of T.Y. Lin International)***

***Figure 4.34– Launching Gantry, Hanging Lake Viaduct, Glenwood Canyon, CO***
***(Photo Courtesy of Flatiron Constructors, Inc.)***

### 4.4.4 Hauler

In some cases, a specialized segment hauler may be used to transport segments at the erection site, including delivery of segments over a completed structure to the erection gantry. The width of the hauler should be matched to the webs of the box girder, as the loaded hauler places significant concentrated loads on the bridge, and local bending of the top flange should be minimized. Care should be taken to limit the path taken by the hauler to avoid overloading the structure.

## 4.5 Special Topics

### 4.5.1 Surveying and Deflections

Surveying and geometry control are just as important during segment erection as during casting. Because of the length, a small error in orientation at the beginning of a cantilever can have significant impact at the tip. Surveying personnel should be experienced in this type of construction and coordinate closely with site engineering staff to keep the bridge in proper alignment.

Controlling cantilever geometry during erection can be complex on a balanced cantilever bridge because the bridge will deflect many times during construction because of unbalanced segment weights, closure sequence, staged post-tensioning, or unbalanced erection equipment.

Surveys should be carried out daily and always before or near sunrise to avoid tip deflections associated with differential temperatures. The survey data is used to compare the projected position of the cantilever tip to the target position for that stage. Note that the target position may vary from day to day as the structure is loaded. It is important to monitor the actual position of the cantilever compared to its theoretical position for the stage of construction. The construction engineer plays an important role in this effort, calculating the deflected shape of the cantilever at multiple phases during erection – such as the completion of each cycle, before and after stressing post-tensioning, or before and after shifting major equipment (e.g., launching an erection gantry). These deflections can be combined by site personnel with the casting data and compared against the daily surveys.

Should the actual position of the cantilever depart from its theoretical position, the deviation should be corrected early with countermeasures such as shims. Shims are only effective early in cantilever erection as the angle break they create is small and has a negligible effect over short lengths. More extreme measures to correct cantilever geometry include implementing a small CIP closure between segments. The closures, or “wet joints,” are highly inefficient and reduce quality of the overall structure. Wet joints should be avoided by frequently monitoring cantilever alignment during all stages of erection.

### 4.5.2 Pier Segments

As the critical transition element from the super- to the substructure, pier elements can be relatively complex and congested – demanding special design and construction effort. They are often the heaviest segments on the project. There are three main types of pier segments in general use.

#### 4.5.2.1 Cast-in-Place

With cast-in-place pier elements, the entire segment is cast as part of the substructure (see **Figures 4.35** and **4.36** below). The great advantage of this method is weight. Since segments with a thickened diaphragm can be the heaviest, casting them in place reduces loads on transportation and erection equipment. This frees the designer to use a larger diaphragm, which is often advantageous in seismic regions where heavy column reinforcement must be continuous into the pier cap.

***Figure 4.35 – Cast-in-Place Pier Segment, Otay River Bridge, CA***
***(Photo Courtesy of SYSTRA IBT)***

***Figure 4.36 – Cast-in-Place Pier Segment, I-4 Connector Project, FL***
***(Photo Courtesy of PCL/Archer-Western JV)***

These advantages do not come without costs, however. Chief among them is schedule impact. If a pier segment is cast in place, there is no match-cast joint with the first precast segment, and a small CIP closure is required between the two (see **Figure 4.37**). This requires supporting the first segment in proper position while the closure pour is formed, poured, and cured. This can take several days, whereas a match-cast segment cycle takes only a few hours. If an erection gantry is not used, additional falsework is necessary to support the first segment.

*Figure 4.37 – First Precast Segment Supported Prior to Casting Closure Joint, Otay River Bridge, CA (Photo Courtesy of SYSTRA IBT)*

Furthermore, for a cast-in-place pier table, all rebar is tied, and the concrete poured, in place. The reinforcement is often tightly congested. All of this work is performed away from the controlled conditions of the casting yard, and often at significant height.

Geometry control is another important consideration for a CIP pier table. Care must be taken to ensure the pier segment is both in the correct position and matches the cross-section of the precast segments. Flexibility to adjust cantilever alignment for casting deviations can be lost with this method. Care must also be taken to ensure there is no movement after aligning the pre-cast segments, and prior to casting closure pour against the CIP pier segment. Minor deviations can project out to significant misalignment at the cantilever tip. This can be mitigated by aligning the typical segments to the target geometry, pouring grout blocks and stressing the CIP pier and first pre-cast segments together.

Also, tendon ducts must be in close alignment across the CIP joint. Additional space for coupling the ducts across the closure can be provided by including a small blockout on either side **(Figure 4.38)**. Alternatively, the CIP closure between the pier and first cantilever segment can be sized to accommodate the coupling of ducts.

***Figure 4.38 – Coupling of Ducts at Cast-in-Place Closure Joint***
***(Photo Courtesy of SYSTRA IBT)***

### 4.5.2.2 Precast Pier Segment

Precast pier segments are often not as long as typical segments, in order to reduce weight (see **Figure 4.39** below). This, plus a thicker internal diaphragm, often requires a unique mold. Often a pier segment is cast in two halves joined together onsite, either before or after erection on top of the column.

***Figure 4.39 – Placing Precast Pier Segments, PR181***
***(Photo Courtesy of SYSTRA IBT)***

There are two main advantages to precasting pier segments. First is that the exacting rebar placement and concrete operations take place in the casting yard, where the conditions are much more controlled. The second advantage relates to segment placement during erection with a match-cast joint. The need for a CIP joint between the pier and first typical segment is eliminated, greatly enhancing the erection speed of a typical cantilever. Also, adjustments to the alignment of the pier segment can be made to account for casting deviations.

Using precast pier segments for balanced cantilever construction often divides the cantilever erection sequence into two stages. The first stage is erection of the pier table, which consists of the pier segment and either one or two pairs of cantilever segments. Once the pier table is erected, final alignment of the cantilever geometry takes place before the remaining segments of the cantilever are erected.

In most cases, a precast pier segment is supported on the permanent bearings and jacks located on the pier cap, making structure stability an important consideration during construction. The large unbalanced loads encountered in balanced cantilever erection can be difficult to accommodate with a bearing connection in the absence of a gantry designed to provide stability. Supplemental towers, tie-downs, brackets, are some methods to provide global stability. Since the configuration of support towers is often dictated by site constraints, a combination of the supports shown in **Figure 4.40** may have to be used. The cost of stability structures can become substantial as unbalanced loads increase. One option to increase efficiency of the support towers and reduce their overall size is to grout the permanent bearings after alignment of the pier table. This allows the dead-load of the superstructure to be carried by the substructure through the bearings. The support towers then only have to accommodate the out-of-balance moment of the cantilever during erection.

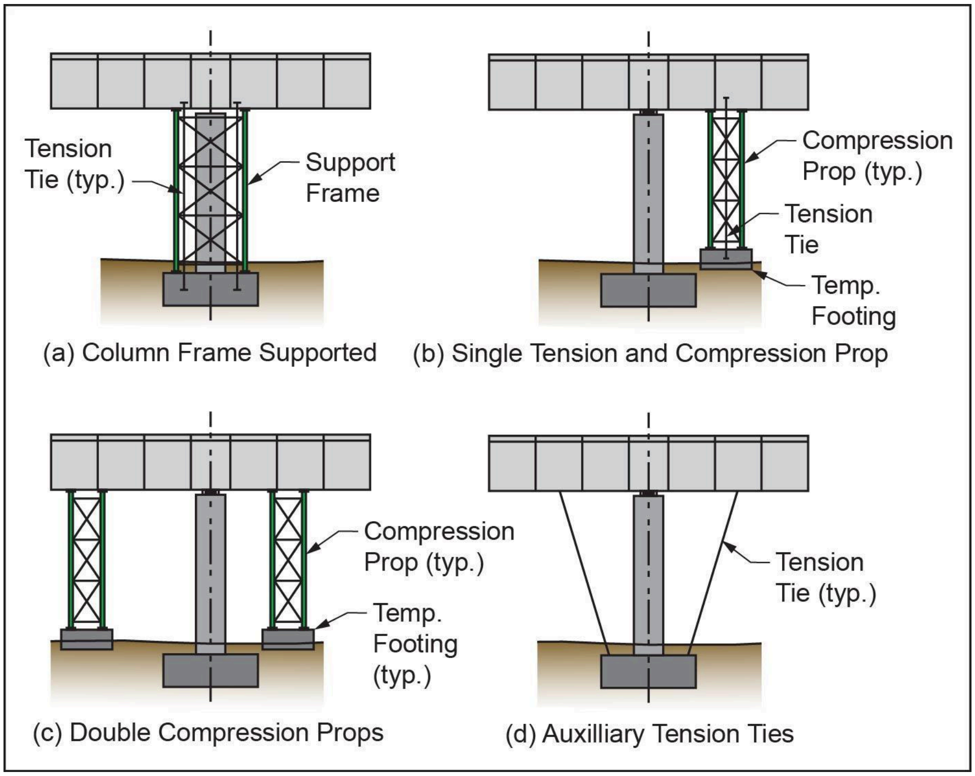


*Figure 4.40 – Methods for Additional Stability*

### 4.5.2.3 Precast Shell

A hybrid of CIP and precast pier segments, the exterior shell of the pier segment is precast in the casting yard and transported to the site, where it is positioned over the continuous rebar coming up from the column (see **Figure 4.41** below). Supplemental rebar is tied in place, and the internal diaphragm is cast using the concrete shell as a portion of the formwork.

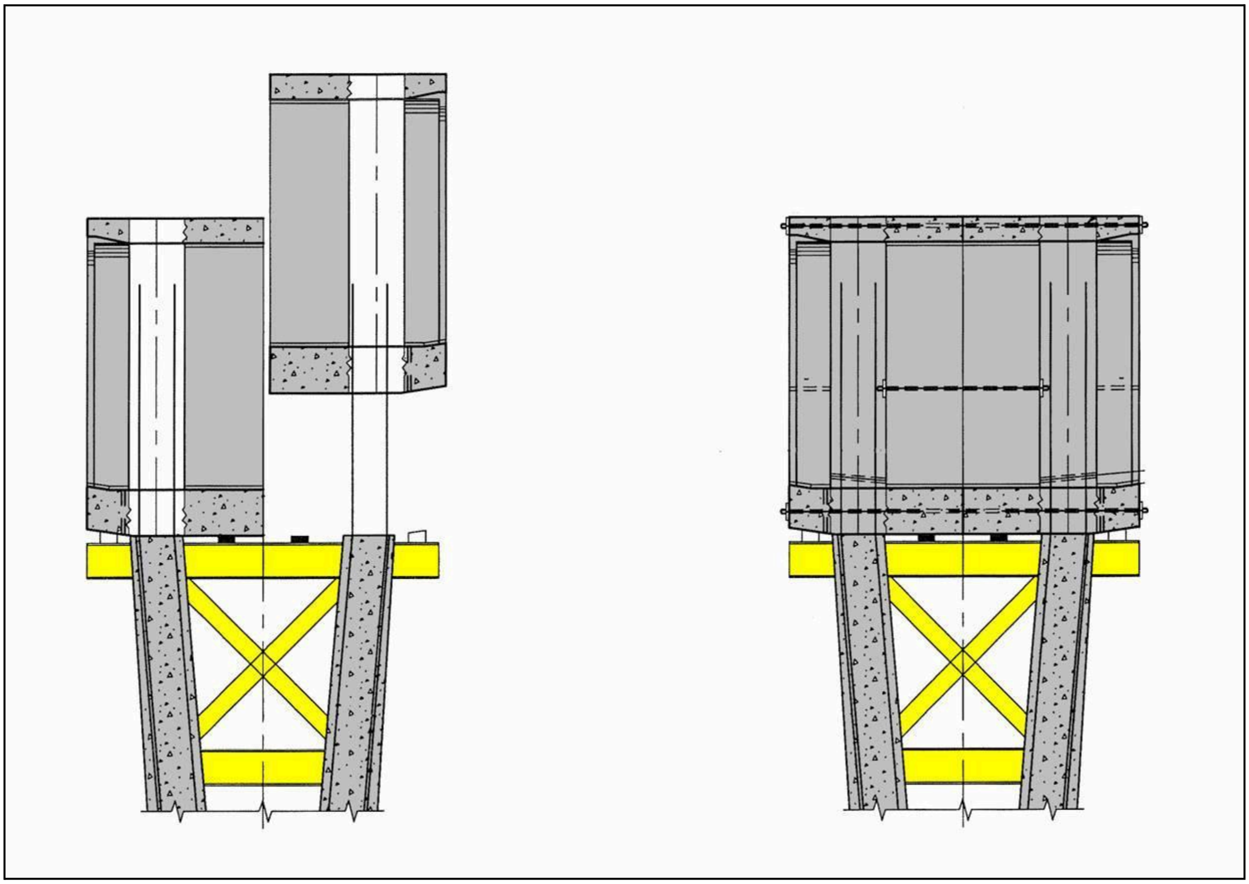


*Figure 4.41 – Precast Shell Installation*

This method brings both the advantages and drawbacks of conventional methods. Its chief advantage is the ability to create a monolithic connection with the pier, while still maintaining a match-cast joint at the pier segment (see **Figure 4.42** below). This provides the global stability of a CIP pier table, without sacrificing the speed of segment erection. However, many of the challenges of CIP work remain. Continuous rebar is needed between the precast shell and the CIP diaphragm, often leading to many rebar couplers on the shell's interior face (see **Figure 4.43** below). Complex rebar and higher-strength concrete must be placed onsite. An additional consideration with this method is the degree of grade and crossfall. Precast shells must be supported accurately to set the alignment for the entire cantilever. Placing the segment and tying the supplemental rebar can be a challenge when the segment is at a steep angle to the vertical column steel. If all these challenges can be met, the precast shell method may offer a further advantage in erection speed.

***Figure 4.42 – Installation of Precast Shell, Vancouver Millennium Line, BC***
***(Photo Courtesy of Rizzani de Eccher)***

***Figure 4.43 – Installation of Supplemental Rebar Inside Precast Shell,***
***Dallas High-5, TX***
***(Photo Courtesy of Zachry-Rizzani, JV)***

A variation on the precast shell method is using multiple precast pier segments tied together with CIP diaphragms to form a single pier unit (see **Figure 4.44** below). This is done when site constraints do not allow the pier to align with the curvature of the superstructure.

*Figure 4.44 – Precast Segments with CIP Diaphragms, I-4 Connector Project, FL*
*(Photo Courtesy of PCL/Archer-Western JV)*

### 4.5.3 Expansion Joints

Longer viaducts may need expansion joints to alleviate the effects of creep, shrinkage, and temperature. While span-by-span precast segmental construction typically places expansion joints at the piers, balanced cantilever construction offers three methods for locating the joint at a different location within the span.

First is the mid-span hinge method, which places an expansion joint in the middle of the completed span, between two adjacent cantilevers, as shown in **Figure 4.45**. Continuity is created by steel beams that cross the joint and are anchored on both sides. There are several possible configurations for support of these beams, but all are designed to transfer moment and shear, while allowing longitudinal movement. Transfer of moment is important, because without moment continuity the angle break under creep redistribution and live load would be unacceptable.

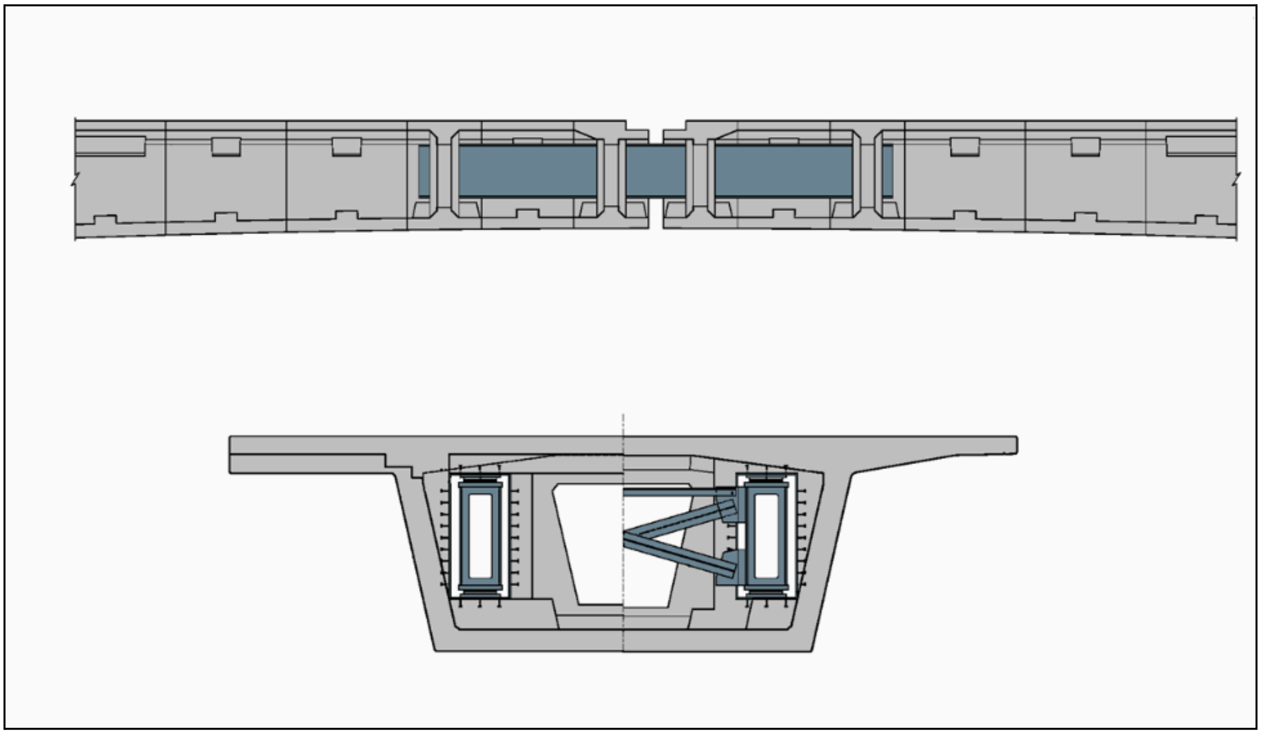


*Figure 4.45 – Mid-Span Hinge Schematic*

This method enjoys advantages from its compatibility with the balanced cantilever erection sequence. After an entire cantilever is erected, beams can be lifted into position and pushed back into the completed box girder. The adjacent cantilever is built, then the beam is pushed back across the expansion joint and secured in its final position. Special diaphragm segments are required to anchor the steel beams to the concrete box girder. As with any diaphragm segment, weight is an important consideration. Beam installation is performed inside the concrete box girder, which limits the space available for work. A generous allowance for construction tolerances for all components (beam, segment, bearing, geometry) helps avoid placement problems in the field. **Figure 4.46** shows a mid-span beam installation as performed on the Otay River Bridge.

The beams are important structural members, and their long-term performance should be considered during design, including issues such as access and bearing replacement. During construction, maintenance requirements and the long-term impact of proposed modifications should be weighed against any gains in constructability.

***Figure 4.46 – Mid-Span Hinge Beam Installation, Otay River Bridge, CA***
***(Photo Courtesy of SYSTRA IBT)***

The second method locates the expansion joint at the columns. One approach to this is building the spans adjacent to the expansion joint on falsework, as shown in **Figure 4.47**.

***Figure 4.47 – End-Span Falsework at Expansion Joints, I-4 Connector Project, FL***
***(Photo Courtesy of PCL/Archer-Western JV)***

Since balanced cantilever construction is often selected to avoid falsework, another approach is to use temporary post-tensioning. The pier segments at the expansion joints are blocked and secured together to create a monolithic pier segment, and the segments on either side are equipped with ducts for temporary cantilever tendons (see **Figure 4.48** below). These spans can be built out from the expansion joint pier in typical balanced cantilever fashion, held in place by the temporary tendons. Once continuity has been achieved on both sides, the temporary tendons are cut, and the blocking removed. This method is generally feasible only for shorter spans.

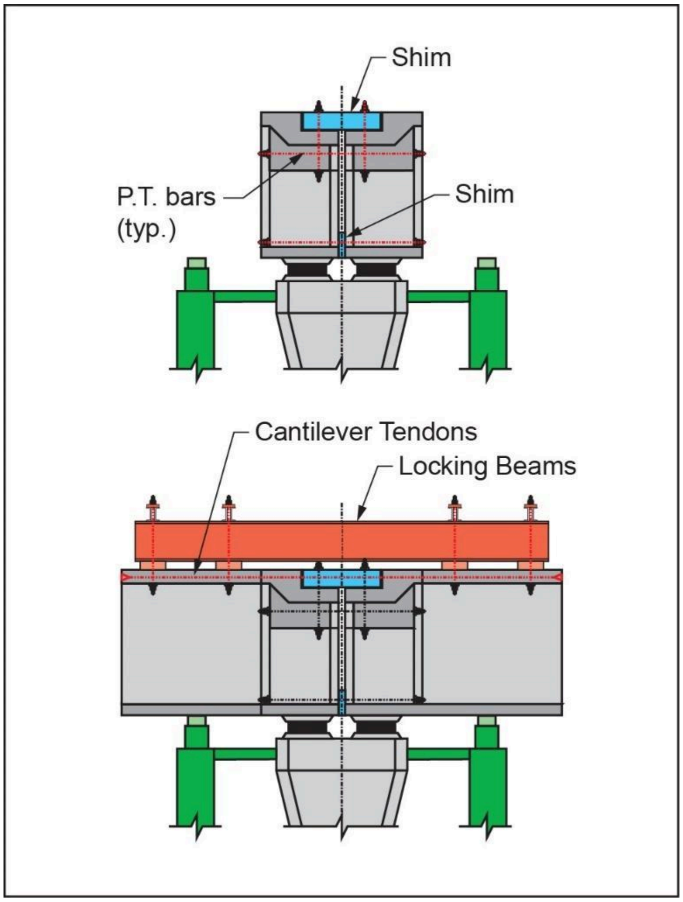


***Figure 4.48 – Column Expansion Joint Erection Schematic***

A third method, not commonly employed, is the quarter-span hinge, which locates a hinge at the quarter point of the completed span, or halfway out one of the cantilevers (**Figure 4.49**). The hinge has a concrete hinge seat, similar to what is done in cast in place on falsework construction. This method involves tightly congested post-tensioning and reinforcement in the hinge segments to accommodate large concentrated loads. The quarter-span hinge should be used only as a last resort because of long-term durability issues resulting in high maintenance costs. A quarter-span hinge installation is shown in **Figure 4.50**.

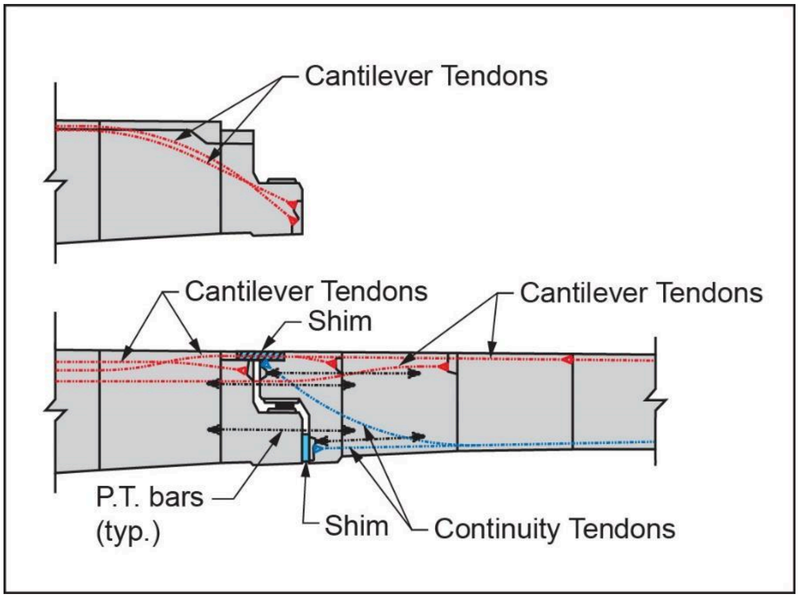


***Figure 4.49 – Quarter-Span Hinge Erection Sequence***

***Figure 4.50 – Quarter-Span Hinge Installation, H3 Viaduct, HI***
***(Photo Courtesy of T.Y. Lin, International)***

### 4.5.4 Mid-Span Closure

Typical balanced cantilever construction includes a small closure joint poured at mid-span, ranging from one to six feet in length. This closure is formed and cast in place, with the precast segments forming the respective bulkheads. For longer closure joints, one or two sets of typical segment rebar and the installation of transverse tendons may be required.

The most important consideration in performing mid-span closure is aligning and securing the opposite cantilever tips. It is likely that small adjustments in both vertical and horizontal alignment will be necessary. Regardless, the tips should be held firmly in position to avoid relative movement during curing of the closure joint. Generally, this is achieved via strongback beams placed across the joints (see **Figure 4.51** below). The beams are configured to transfer a moment to the box girder, so tension tie-downs are often necessary. The contractor should coordinate with the construction engineer to determine the necessary strength and rigidity of the tie-down beams and verify they will not damage the deck under anticipated loads. Provisions for securing the strongback beams to the deck should be developed early, so they can be easily integrated into the casting yard work.

***Figure 4.51 – Strongback Beams at Closure Joint Pour***
***(Photo Courtesy of SYSTRA IBT)***

### 4.5.5 Temporary Access Openings

As with all segmental construction, much of the work is performed on the interior of the box girder. However, moving people and equipment to the interior from the open end of a cantilever is impractical and can be unsafe. In addition, there is a need to take the equipment out after completion of the mid-span closure. For these reasons, it is advisable to include temporary access openings at regular intervals along the bridge deck. Access to the interior needs to be convenient for the first segment (e.g., for installing temporary post-tensioning bars), so some access locations should be located at or near the piers. Best practice for design of the access opening includes a keyway in the pour back to promote adherence to watertight deck requirements.

## 4.6 Construction Engineering

Construction engineering is an important aspect of balanced cantilever construction. Though construction schematics are typically included in design, wide variations in schedule, methods, and equipment make it unlikely that the chosen approach will line up exactly with assumed conditions. Below are some of the construction engineering tasks associated with a precast balanced cantilever bridge.

### 4.6.1 Built-In Loads

Compared to other bridge types, balanced cantilever bridges are more sensitive to built-in loads. Generally associated with the closure pour sequence, built-in loads are present when the closure pour is cast and therefore "locked in" to the completed structure. In designs with precast pier segments, the timing of grouting the permanent bearings during the cantilever erection sequence affects built-in loads by increasing built-in forces in the substructure elements. The closure pours themselves should be timed to minimize thermal effects, including thermal gradients.

The plans should indicate the sequence and related factors considered in calculating the assumed built-in loads assumed for design. These might include the sequence of closure pours, the stage when permanent bearings are grouted, the sequence of stressing continuity tendons, pre-loading or ballasting, or equipment loads. The construction engineer needs a good understanding of what is required in the design sequence in order to identify and resolve any discrepancies in the contractor's proposed sequence. In many cases, this information is included in an Erection Manual provided by either the specialty construction engineer or even the engineer of record.

### 4.6.2 Erection Loads

Construction of a balanced cantilever bridge entails numerous loading conditions, applied to a structure that is different after every stage. These may include the loads due to an unbalanced segment, reactions from an erection gantry, counterweights, post-tensioning, wind and miscellaneous equipment. It is important that the full structure be checked at all critical phases and loading conditions. In some jurisdictions, it is also necessary to check the structure for a low-level seismic event for the governing temporary conditions.

Erection using a gantry or mobile lifters is generally the most complex in this regard. Typical segment erection, travel of lifter pairs, and gantry-launching sequences comprise numerous steps, with reactions at multiple locations. All critical loads must be identified, necessitating close coordination among the truss or lifter supplier, contractor, and construction engineer. Transverse eccentricity should always be considered, as induced torsion can be significant when the gantry negotiates tight curves.

The structure may also need to be checked for segment delivery loads, as large local loads can develop when the completed portion of the deck is used to transport and stage segments.

AASHTO Bridge Design specifications provide guidelines for construction loads and load combinations, including some specific to balanced cantilever construction. These additional loads specific to the project, such as seismic or collision loads, are added if applicable. The specifications do specifically define the accidental release load, applying a dynamic impact factor of 2.0 (twice the segment weight) to approximate catching a lost segment load using lifting equipment. This is an ultimate load case and frequently a governing one among the construction loads.

### 4.6.3 Cambers and Deflections

Related to the calculations of the critical erection loads are the development of camber and deflection data. Before segment casting can begin, the construction engineer develops a Casting Manual which defines the camber to include in the casting coordinates based on the construction sequence, the loads and equipment used, the concrete age at erection, and the properties of the concrete. Again, close coordination between contractor and construction engineer is necessary for an accurate estimate of these parameters. On some projects, testing concrete behavior is required for developing accurate creep and shrinkage characteristics. This testing should begin early, as the full process can take six months or more.

### 4.6.4 Temporary Post-Tensioning

Calculations are needed to verify the segment joints are evenly stressed during installation, when segment self-weight and construction equipment are factors. For variable depth cantilevers, variations in temporary post-tensioning forces along the length can occur as segments become lighter toward the end of the cantilever. It is important to maintain compression on the epoxy joint throughout its cure time, since stress reversal during this period can destroy the bonding capacity of the epoxy. After the cantilever tendons have been stressed, compression must likewise be maintained on the bottom flange, as the weight of the segment is often insufficient to keep the joints near the tip closed. This can lead to cracks in the cured epoxy, or to gaps and geometry errors in uncured epoxy.

Other applications of temporary post-tensioning include temporarily strengthening the superstructure to accommodate construction loads generated by erection equipment.

# TABLE OF CONTENTS

# Chapter 5:
# Construction of Cast-in-Place Balanced Cantilever Bridges

## 5.1 Introduction

**Cantilever:** A rigid structural member projecting from a vertical support, especially one in which the projection is great in relation to the depth, so that the upper part is in tension and the lower part is in compression. (Webster's Dictionary)

Another meaning of "cantilever" is "bracket."

**Free cantilevering** is a method of construction that builds outward from a fixed point, using staged construction to form a cantilever structure without temporary support (**Figure 5.1**, below).

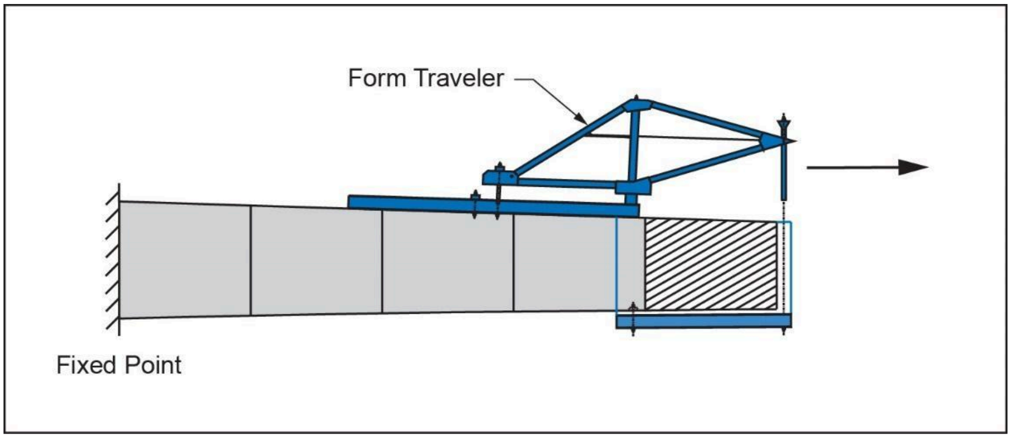


*Figure 5.1 – Cantilever Construction Method*

The **balanced cantilever construction method** attaches two opposing free cantilever structures to a single structure, erected at the same step (**Figure 5.2**).

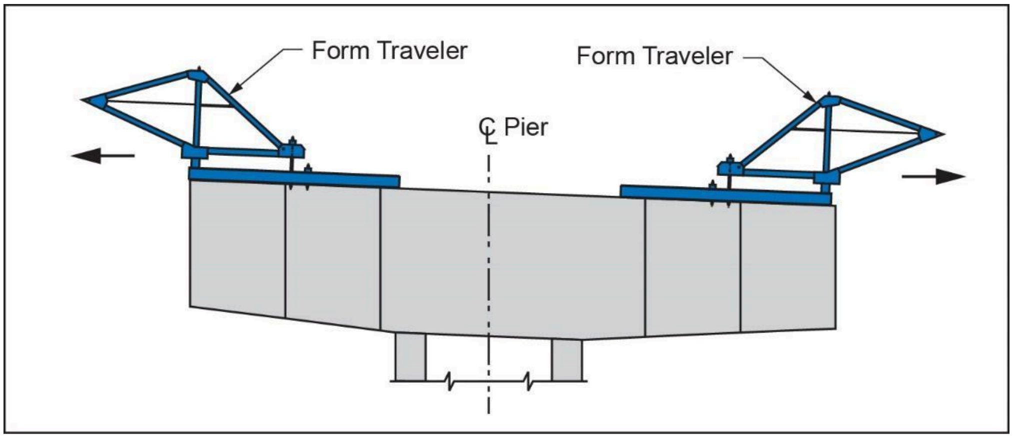


*Figure 5.2 – Balanced Cantilever Construction Method*

In basic terms, **cast-in-place (CIP) balanced cantilevered construction** refers to a construction process where segments are progressively cast on site, at their final position in the structure. This differs from precast construction, where segments are prefabricated at a casting plant, either on site or at a remote facility, then transported to the project site and erected as a completed unit in the final position.

With CIP construction, the bridge segments are built in place, in progressive increments, one segment at a time. This removes manufacturing from the casting yard to the superstructure itself. As segments are cast, the segment formwork cantilevers from the previously cast segment and remain in place until the new segment has achieved sufficient strength to be post-tensioned and permanently held in place to the previously cast segments behind it.

The cast-in-place reinforced concrete method was first applied to a bridge in 1930, on a 223 ft span across the Rio de Peixe in Brazil. However, the cantilevering method for reinforced concrete never gained popularity due to excessive deflection and the heavy reinforcing required.

In 1950-1951, Dr. Ulrich Finsterwalder of Dyckerhoff & Widmann AG (now DYWIDAG Systems International [DSI]) successfully applied post-tensioning to a cast-in-place concrete bridge, using the balanced cantilever method to construct the Lahn Bridge in Germany (**Figure 5.3**). Fixed at both ends and with a span length of 203.7 ft, it is considered the pioneering application of modern long-span segmental concrete bridge construction.

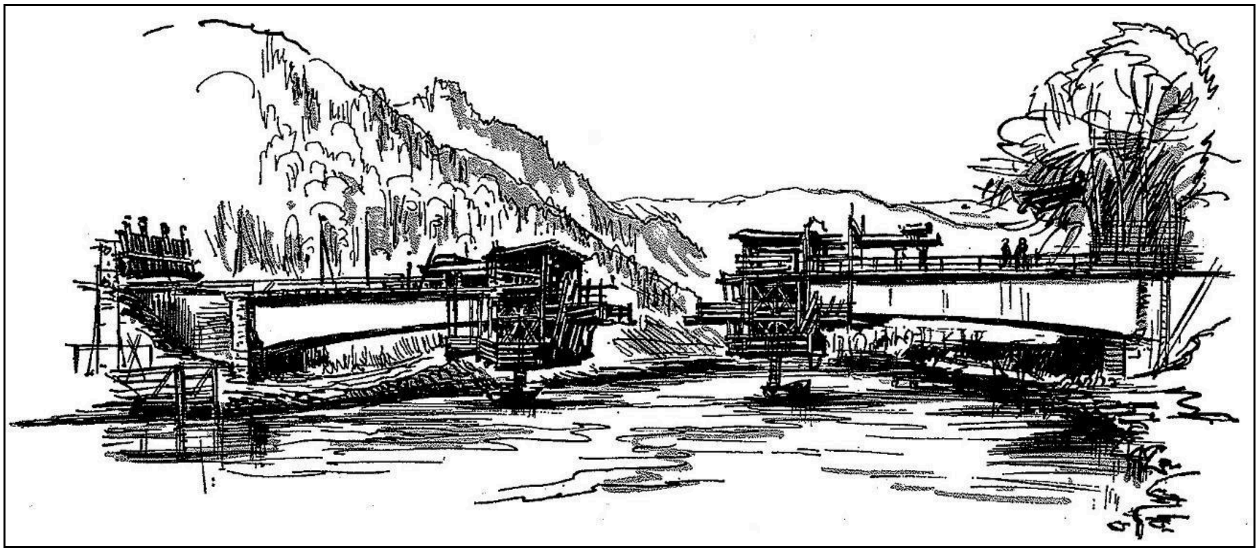


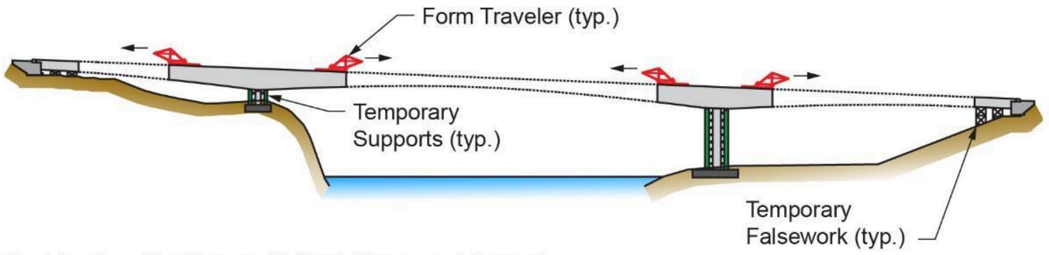
***Figure 5.3 – Lahn Bridge, Balduinstein, Germany***
***(Courtesy of DYWIDAG Systems International, Inc.)***

After the Lahn Bridge, the cast-in-place balanced cantilever method continued to improve and gain popularity around the world. The technique is especially suitable for long span bridges in locations where placing temporary supports is either not possible or cost-prohibitive. Examples include deep valleys, rivers, and railroad yards or highway crossings with insufficient space for support structures. The only drawback is the time required for superstructure construction. While more time is required for a typical cast-in-place segment as compared to precast, this should be considered in the context of the longer span lengths for which cast-in-place balanced cantilever construction is used.

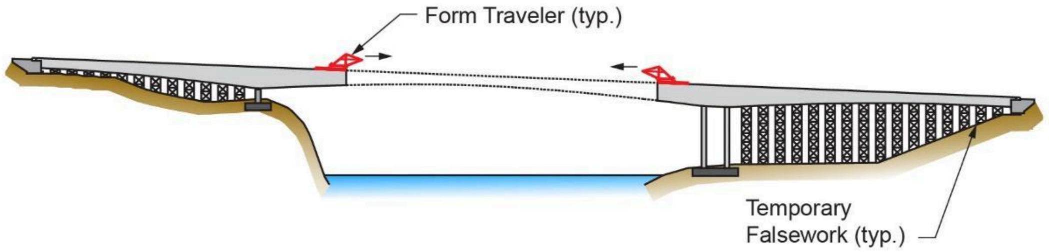
Span length of a cast-in-place segmental bridge is a function of several factors, with the most economical length ranging from approximately 230 ft to 820 ft. Major cost factors include the large pier tables and specialized equipment required to construct longer segments.

**Figure 5.4** illustrates a few of the different types of cast-in-place cantilevered construction used for bridges. **Figures 5.5 through 5.7** are construction photos of three types of cast-in-place cantilevered construction.

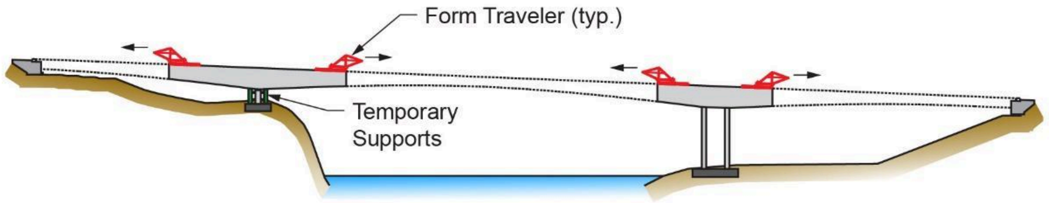
a) Cast-in-place Balanced Cantilever with End Spans on falsework.



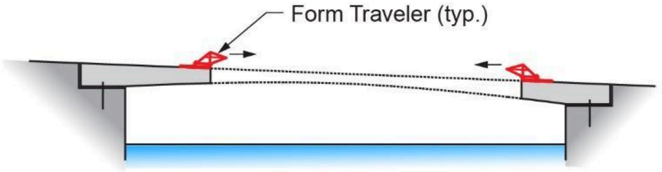
b) Cast-in-place Cantilever with Back Spans on falsework.



c) Cast-in-place Balanced Cantilever.



d) Cast-in-place Cantilever (no Back Spans).



e) Cast-in-place Cantilevered Arch.

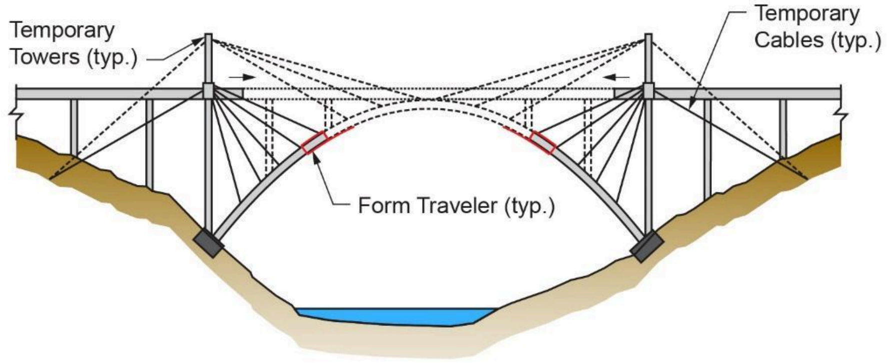


*Figure 5.4 – Cast-in-Place Balanced Cantilever Bridge Design and Construction: Typical Cast-in-Place Balanced Cantilever Bridges*

*Figure 5.5 – Balanced Cantilever with End Spans on Falsework: US 54 Canadian River Bridge, NM*
*(Photo Courtesy of Krew Heavy Civil)*

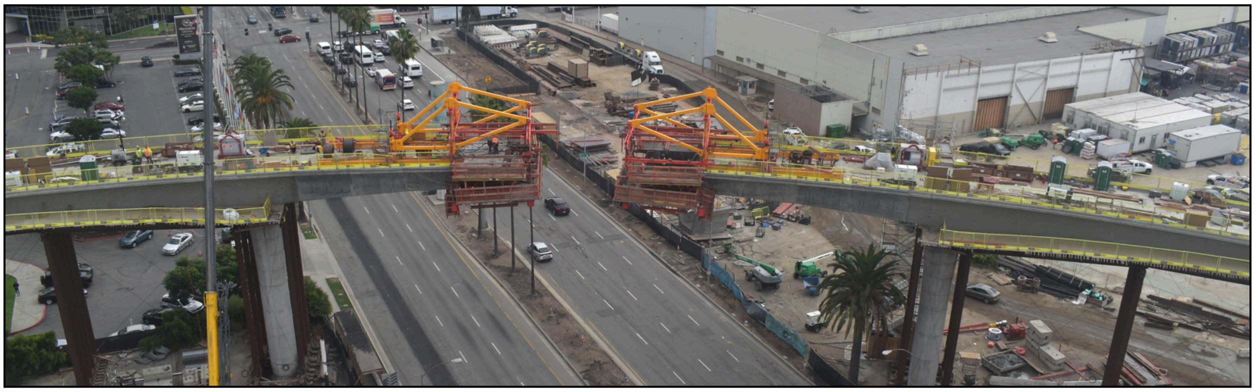


*Figure 5.6 – Cantilever with Back Spans on Falsework: LAX Automated People Mover, CA*
*(Photo Courtesy of Flatiron Construction)*

*Figure 5.7 – Cast-in-Place Cantilever Arch: Hoover Dam Bypass Bridge, AZ-NV*
*(Photo Courtesy of McNary Bergeron & Johannesen)*

## 5.2 Construction Methods

Cast-in-place balanced cantilever construction begins with an initial construction over the pier column called a Pier Table. Multiple methods are used for construction of the Pier Table on conventional CIP balanced cantilever bridges. The following sequence applies whether the substructure uses a single pier stem or multiple pier stems. Design considerations and methods for construction of the Pier table begins with the foundation & substructure in case they need to accommodate additional loads, reinforcing, sleeves, and/or other inserts. Previous methods have used suspended or hanging supports, and shoring founded on the top of footings. The typical sequence builds the pier table in 3 concrete placements with construction joints between each section:

1) installation of the pier table support system,
2) Construction of the bottom slab,
3) Construction of the web walls and diaphragm,
4) Construction of the bridge deck,
5) Post tensioning of the pier table deck and
6) Removal of the support system.

Typically, a large level support platform is installed (dance floor) to accommodate not only the bottom slab dimensions, but it must be wide (and long) enough to accommodate the bridge deck overhang and walkway areas around the perimeter. The bottom slab is then formed to the plan line & grades which may include a false bottom form on top of the dance floor for the bottom slab parabolic curve. Projecting web wall reinforcing must also be accommodated at this stage, which may require exterior web wall forms to be in place, prior to bottom slab concrete placement. This is shown in **Figure 5.8.**

***Figure 5.8 – Pier Table Dance Floor and Bottom Slab: Trinity River Bridge, TX***
***(Photo Courtesy of Williams Brothers Construction)***

After curing the bottle slab, diaphragm reinforcing and forms are installed and web wall concrete is placed next. Ensure to review diaphragm reinforcing alignment & projection in the bridge deck for clearance for the cantilever tendon post tensioning ducts. These bars are extremely difficult or impossible to move after concrete placement. Web wall and diaphragm construction is shown in **Figure 5.9**.

***Figure 5.9 – Pier Table Web and Diaphragm Construction: Trinity River Bridge, TX***
***(Photo Courtesy of Williams Brothers Construction)***

Web wall forms are then removed, and the top slab soffit is formed. Pier table heights are usually high, and conventional shoring can be utilized to from the dance floor to the deck soffit. Perimeter walkways are also accommodated with the top slab form area. During the reinforcing installation the longitudinal and transverse PT ducts are placed and all sleeves for traveler tie-downs and forms. Top slab concrete is cured to proper strength prior to stressing transverse & longitudinal tendons. All forms are then removed, prior to erection of the travelers. Top slab construction is shown in **Figure 5.10**.

***Figure 5.10 – Pier Table Top Slab Construction: Trinity River Bridge, TX***
***(Photo Courtesy of Williams Brothers Construction)***

From the pier table, construction moves toward the mid-span. At mid-span, the two adjacent cantilever tips are connected with a closure pour segment to make a continuous structure. At this point, minor corrections to horizontal misalignment and elevation can be made to both cantilever tips. A bridge can be built from either a single pier or multiple piers simultaneously, depending on the project schedule and the amount of equipment needed to achieve on-time completion.

After completion of the pier table, installation of the form traveler begins. Supported off the leading cantilever tip, a form traveler is a self-launching structural system that bears the segment formwork and weight of the newly cast segment. It remains in place until the new segment has gained sufficient strength to be post-tensioned to the previous cantilever segments. The form traveler is moved forward, one segment length at a time, as the cantilever is constructed. **Figures 5.11** illustrates cantilever construction. Segments are placed symmetrically from the pier table, with typical segment lengths ranging from 10 ft to 16 ft. Additionally, form travelers for segment lengths of up to 16 ft are widely available, and can often be reused, making them more economical. A more detailed discussion of form travelers is provided in **Section 5.3** of this chapter.

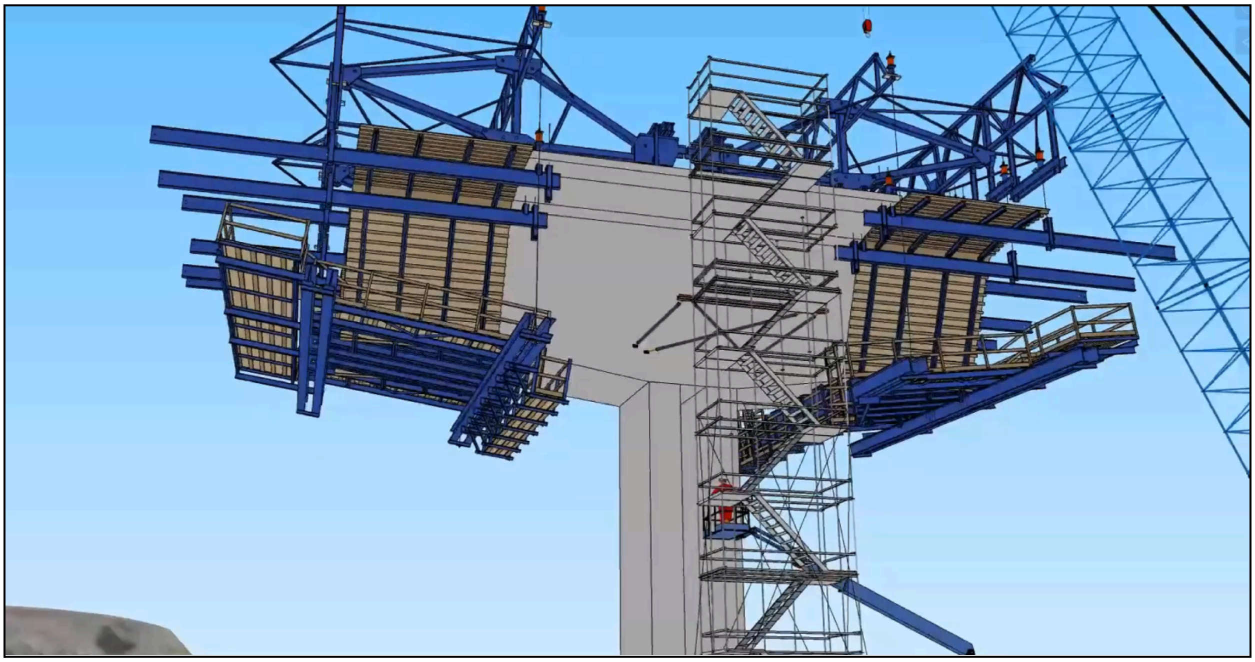


*Figure 5.11 – Pier Table with Form Travelers*
*(Graphic Courtesy of Krew Heavy Civil)*

The balanced cantilever method of construction is the most common technique for cast-in-place segmental bridges. Several advantages have contributed to its success, one of the most important being the repetitive cycle used to construct each segment, which allows efficient and rapid construction of the superstructure. This method is well suited to long span bridges located high above ground because it eliminates the need for extensive falsework, as access from the ground is necessary only for construction of the abutments and piers.

Long-span balanced cantilever bridges require post-tensioning for support during construction and service loading of the completed structure. During construction, the cantilever arm increases in length as each additional segment is cast. This applies large tension stresses to the top deck of the segment. The stresses are smallest at the cantilever tip, increasing to a maximum adjacent to the pier. A series of post-tensioning tendons, called cantilever tendons, are located in the top deck to resist the tension and keep the cantilever tip from sagging. **Figures 5.12** illustrates cantilever tendons in the top deck. The tendons tie a newly cast segment back to the existing structure, and they must be stressed from the leading cantilever tip each time a new segment is cast. The majority of the tendons are located at the point of maximum stress; they decrease in number toward the end of the completed cantilever arm. Each cantilever tendon passes through a thin conduit, referred to as a duct, which stretches from one end of the cantilever tip to the other. As new segments are added, the cantilever tendons increase in length, reaching their maximum with the completed cantilever.

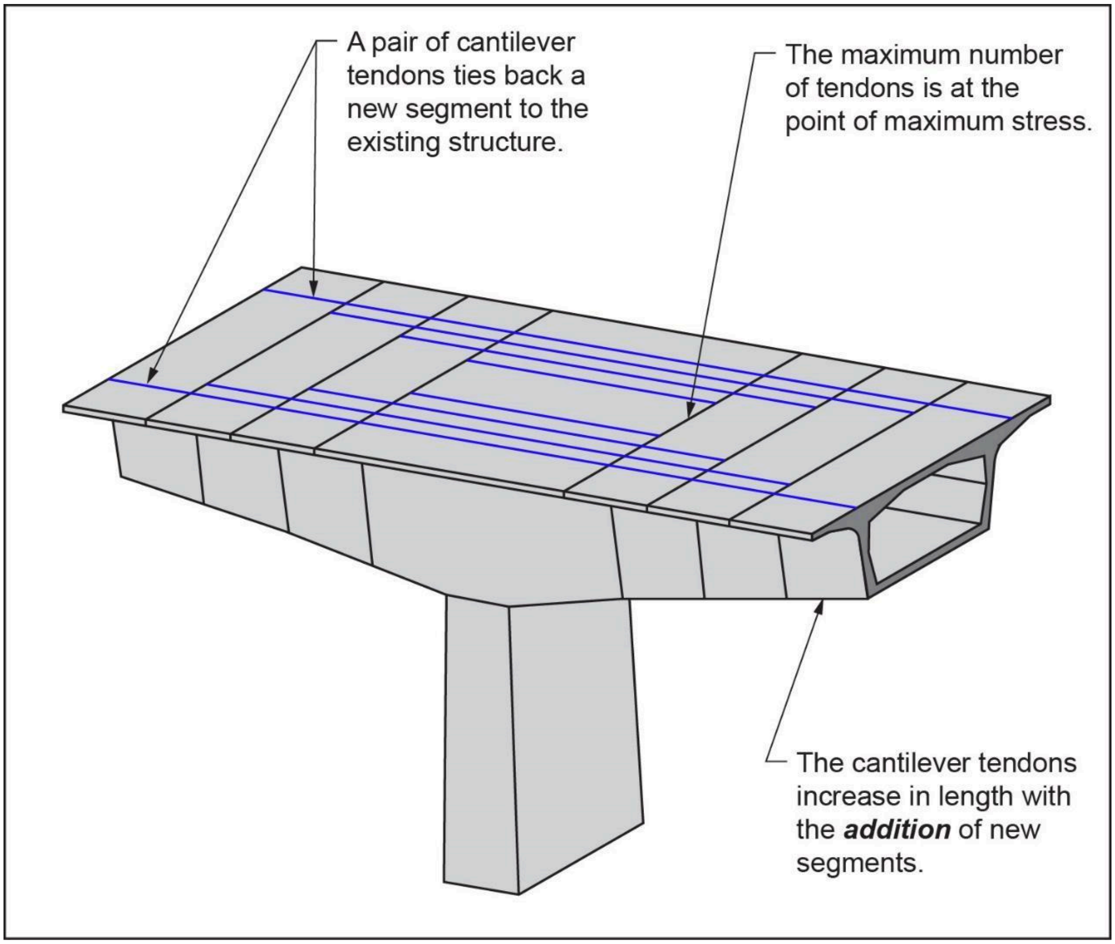


***Figure 5.12 – Cantilever Post-Tensioning in Cast-in-Place Segmental Construction***

Once two adjacent cantilever arms are connected with a closure segment, a span is complete and continuous from pier to pier. After continuity is achieved, a redistribution of stresses takes place, reducing the values applied during construction. The span must now withstand the self-weight of the structure combined with design load conditions including vehicles, temperature, future overlays, and snow. Large tension stresses are now applied to the bottom deck of the cross-section. The stresses are smallest adjacent to the pier and increase to a maximum at mid-span, exactly the opposite of the stresses in cantilever tendons. To balance these tension stresses, continuity tendons are located in the bottom deck. Again, higher concentrations of tendons are required at the location of maximum tensile stress; they decrease in number towards the piers. Continuity tendons are stressed at concrete anchor blocks inside the box segment after the closure pour is made. **Figures 5.13** illustrate span continuity tendons.

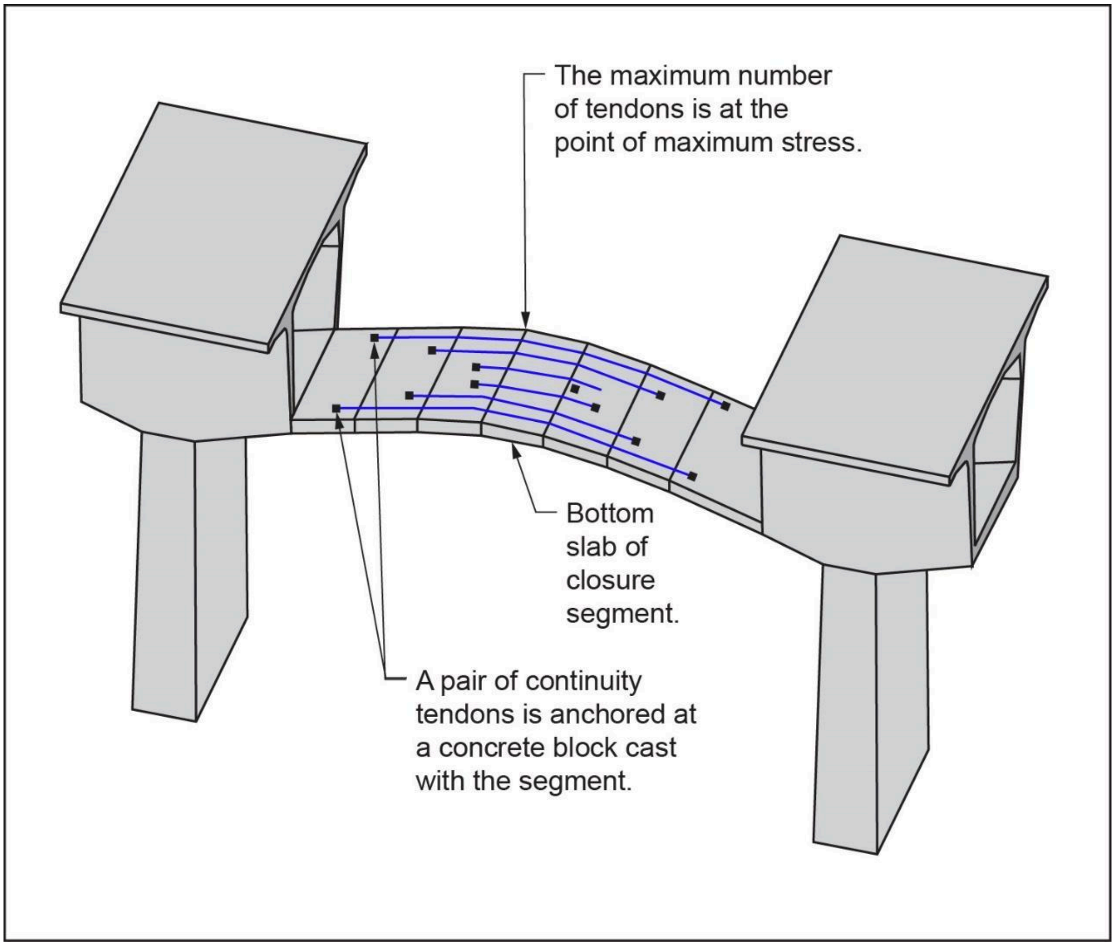


*Figure 5.13 – Continuity Post-Tensioning in Cast-in-Place Segmental Construction*

During casting, the cantilever is subjected to out-of-balance loading, alternating casting on one side and then on the opposite side. As listed below and shown in **Figure 5.14**, there are several major out-of-balance loads to consider in cantilever construction.

- Segment Dead Loads, Including Fresh Concrete and Formwork
- Form Travelers
- Construction Equipment
- Construction Materials
- Construction Live Loads
- Wind Loads
- Seismic Loads
- Accidental Loads, Such as the Loss of a Form Traveler

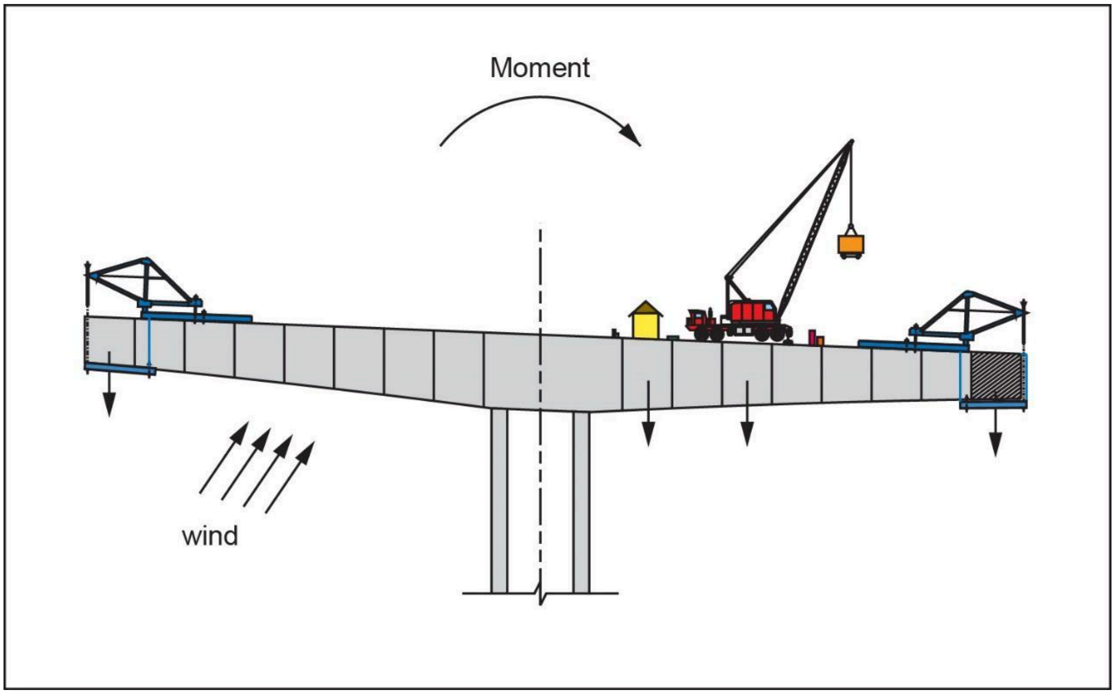


***Figure 5.14 – Cast-in-Place Balanced Cantilever Bridge Design and Construction: Out-of-Balance Loads During Construction***

For horizontally curved superstructures, out-of-balance loads also occur in the transverse direction. For this reason, a three-dimensional structural model is required. It is critical to check and design columns, footings, and foundations for construction loads. In addition to serviceability and strength, stability of the overall structure must be checked. Due to large out-of-balance loads during construction, it is common to provide temporary supports to provide structural stability and resist out-of-balance forces. (See **Figure 5.15 and 5.16**.) Stability may also be provided by double-walled piers (**Figure 5.17**), or by a monolithic connection between the pier and superstructure (**Figure 5.18**).

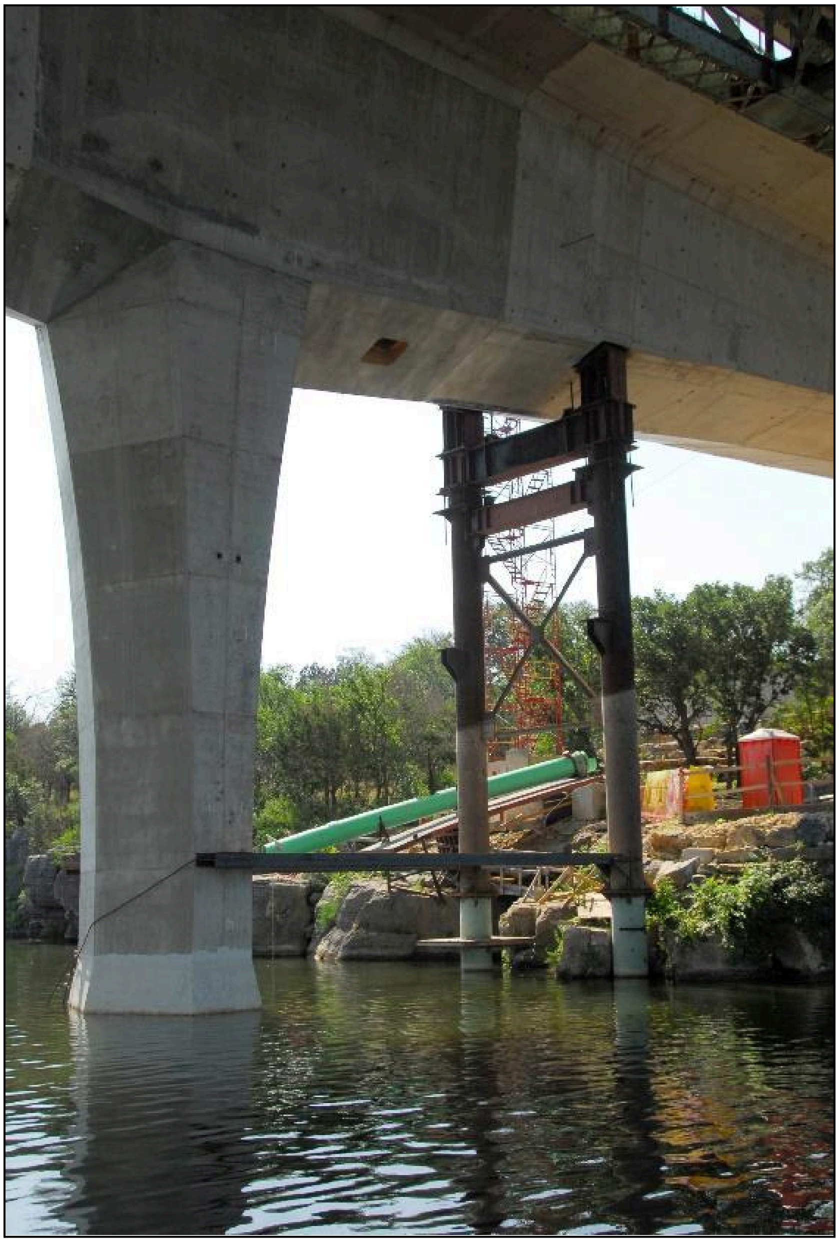


***Figure 5.15 - Temporary support during construction for the US-281 Colorado River Bridge, Marble Falls, TX (Photo Courtesy of Archer Western)***

***Figure 5.16 Temporary supports during construction, Folsom Dam Bridge, CA (Photo Courtesy of Kiewit)***

***Figure 5.17 – Double-Walled Pier Superstructure Connection, Allegheny River Bridge, PA***
***(Photo Courtesy of FIGG)***

***Figure 5.18 – Monolithic Column Superstructure Connection, US-281 Colorado River Bridge, TX (Photo Courtesy of Archer Western)***

## 5.3 Construction Sequence

During construction of the substructure, segment dead load is a large source of out-of-balance moment. These loads can be reduced using an asymmetrical pier-table (**Figure 5.19**). Alternatively, the same result may be obtained with a symmetrical pier table by constructing one half-segment on one side of the pier table, as shown in **Figure 5.17** below. The difference in cantilever length is approximately half of one typical segment length. At each stage, full segment lengths constructed on each side of the pier table produce out-of-balance loads of about half the segment. At the same time, the shorter cantilever arm reduces the out-of-balance load due to the form-traveler.

***Figure 5.19 - Cast-in-Place Balanced Cantilever Bridge Design and Construction: Asymmetrical Pier Table, US 54 Canadian River Bridge, NM***
***(Photo Courtesy of Krew Heavy Civil)***

Pier tables are normally constructed in three to four months. Once the pier table has been placed, cured and the formwork is removed, assembly of the first form traveler can take place on the pier table. It is very important that this work be well planned and sequenced since the assembly takes place at height, and special considerations must be made to protect the workers against fall hazards. Additionally, a well thought out plan allows installation of the form traveler and the formwork to be integrated into a single operation.

It typically takes approximately two weeks to assemble the first traveler for one end of the cantilever and another two weeks to assemble and attach the associated soffit, side, and ceiling forms, along with hardware to the traveler prior to beginning the initial casting cycle. Casting the initial segment typically takes another one to two weeks (depending on the amount of reinforcing steel and post-tensioning to be installed), totaling five to seven weeks from completion of the pier table to the first completed casting. Once the first segment has been cast and the traveler is advanced out on the cantilever, the top of the pier table will again have sufficient space for assembling the second traveler for the opposite end of the cantilever. Similar time frames for assembly, attachment, etc. apply. It must be noted though that the duration of the installation of the form traveler and the construction of the first segment can vary depending on the depth and width of the segmental box.

After a learning curve, one working cycle typically can be accomplished in one week, though this can vary. One advantage to this repetition of activities is that over the course of multiple cycles, the contractor can correct and improve procedures.

Typically, a minimum pier table length is approximately 32 ft, though as shown in **Figures 5.20 and 5.21**, special form-travelers have been designed to accommodate a pier-table as small as 10 ft. With collaboration between the form traveler designer and the installer, it is sometimes possible to fit two form travelers back-to-back on a single 32-35 ft long pier table. Typically, a minimum length of 40 ft pier table will allow the erection of the two travelers and formwork to be erected concurrently.

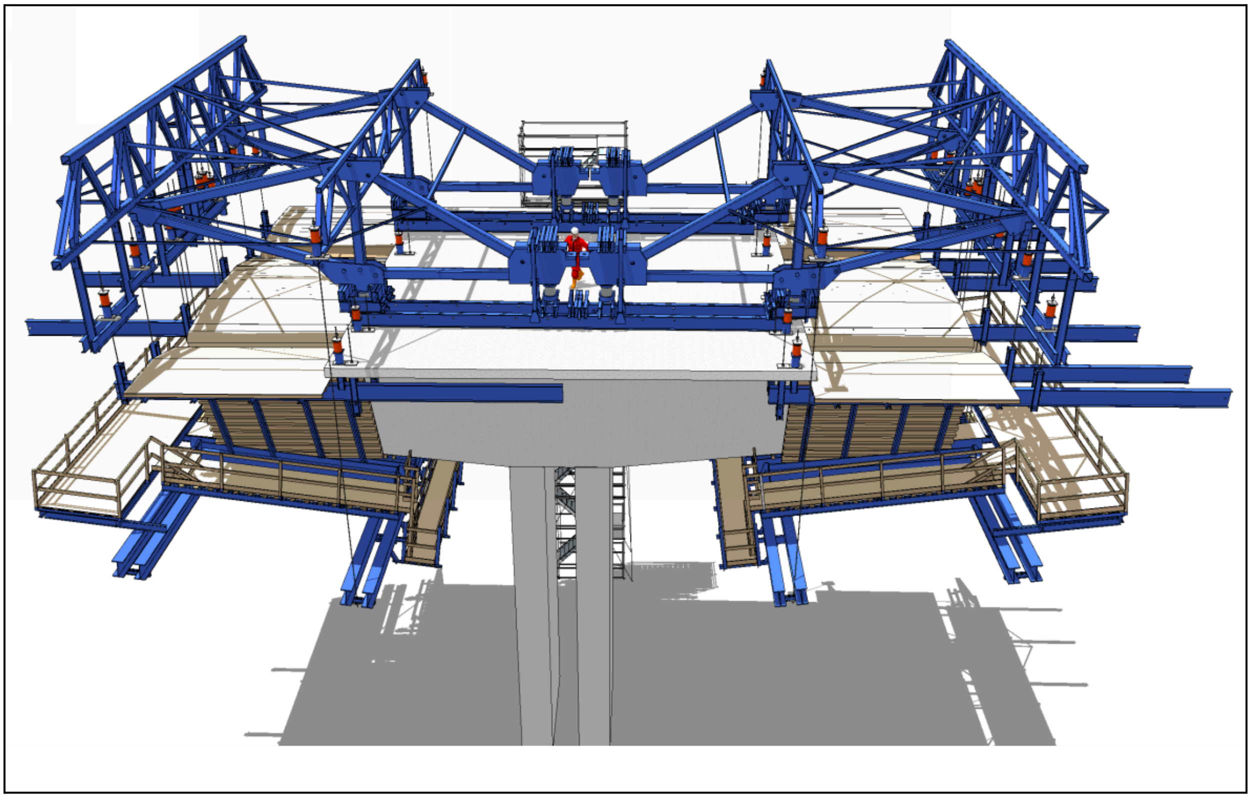


***Figure 5.20 – Form Traveler placement on the pier table***
***(Graphic Courtesy of Krew Heavy Civil)***

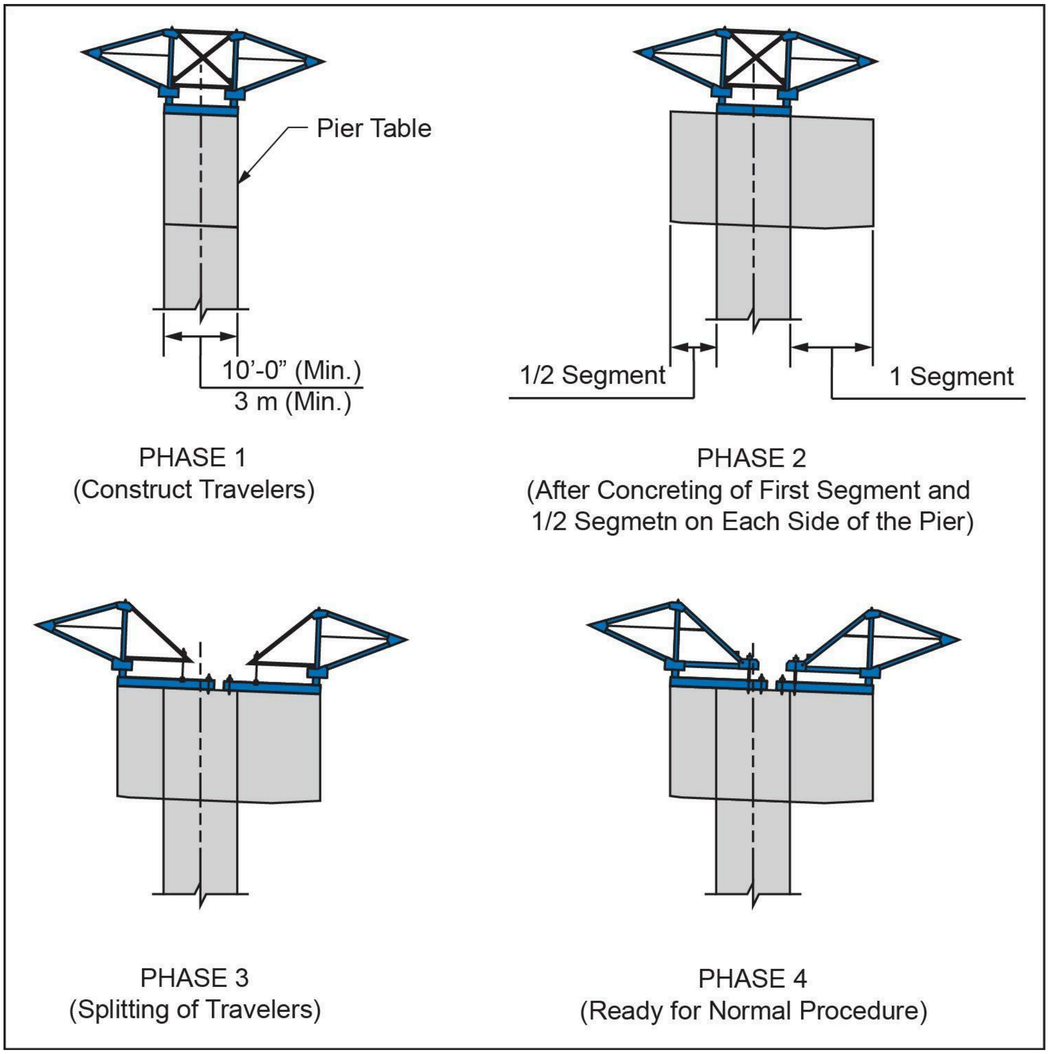


*Figure 5.21 – Special Form Traveler for Smaller Pier Tables*

### Form Traveler Operation

Form travelers are a specialized pieces of construction equipment that are specifically designed for balanced cantilever bridge construction. They consist of two main structural frames, often referred to as "horses." The front and rear trusses connect the two main frames and provide overall stability. The weight of a typical form traveler, including formwork, typically weighs around 50% of the maximum segment weight. However, the actual weights will vary based on several criteria (type of formwork, height of the segment, width of the segment, etc.) and can require heavier structural members in the form traveler thus increasing the weight. A single cell box consists of two main traveler frames (**Figure 5.22**), while a two-cell box has three main traveler frames (**Figure 5.23**). Essentially, each web in s segmental bridge will have a main traveler frame (**Figure 5.24**).

***Figure 5.22 – Single cell box with two traveler frames, Maroon Creek Bridge, CO***
***(Photo Courtesy of McNary, Bergeron, and Johannesen)***

***Figure 5.23 – Two cell box with three traveler frames, Folsom Dam Bridge, CA***
***(Photo Courtesy of Kiewit)***

***Figure 5.24 – Two single cell boxes cast together with four traveler frames, Creve Coeur Lake Memorial Bridge, MO (Photo Courtesy of Finley-McNary Engineers)***

Usually obtained from vendors, form travelers come with a detailed checklist of the construction steps involved in operation. This checklist must be consistently observed and checked during the construction process.

**Figures 5.25 – 5.32** below show an example of form traveler installation and operation, as performed on the US-281 Colorado River Bridge in Marble Falls, Texas (main span length of 410 ft).

Immediately following the eight installation photos, **Figures 5.33** and **5.34** detail a form traveler's major components from two different views.

***Figure 5.25 – Form Traveler Installation Step 1: Set Rails***
***(Photo Courtesy of Archer Western)***

***Figure 5.26 – Form Traveler Installation Step 2: Set Main Structural Frames (Horses) and Rear Truss (Photo Courtesy of Archer Western)***

***Figure 5.27 – Form Traveler Installation Step 3: Install Rear Tie-Down System***
***(Photo Courtesy of Archer Western)***

***Figure 5.28 – Form Traveler Installation Step 4: Set Front Truss, Inner Frame, and Formwork***
***(Photo Courtesy of Archer Western)***

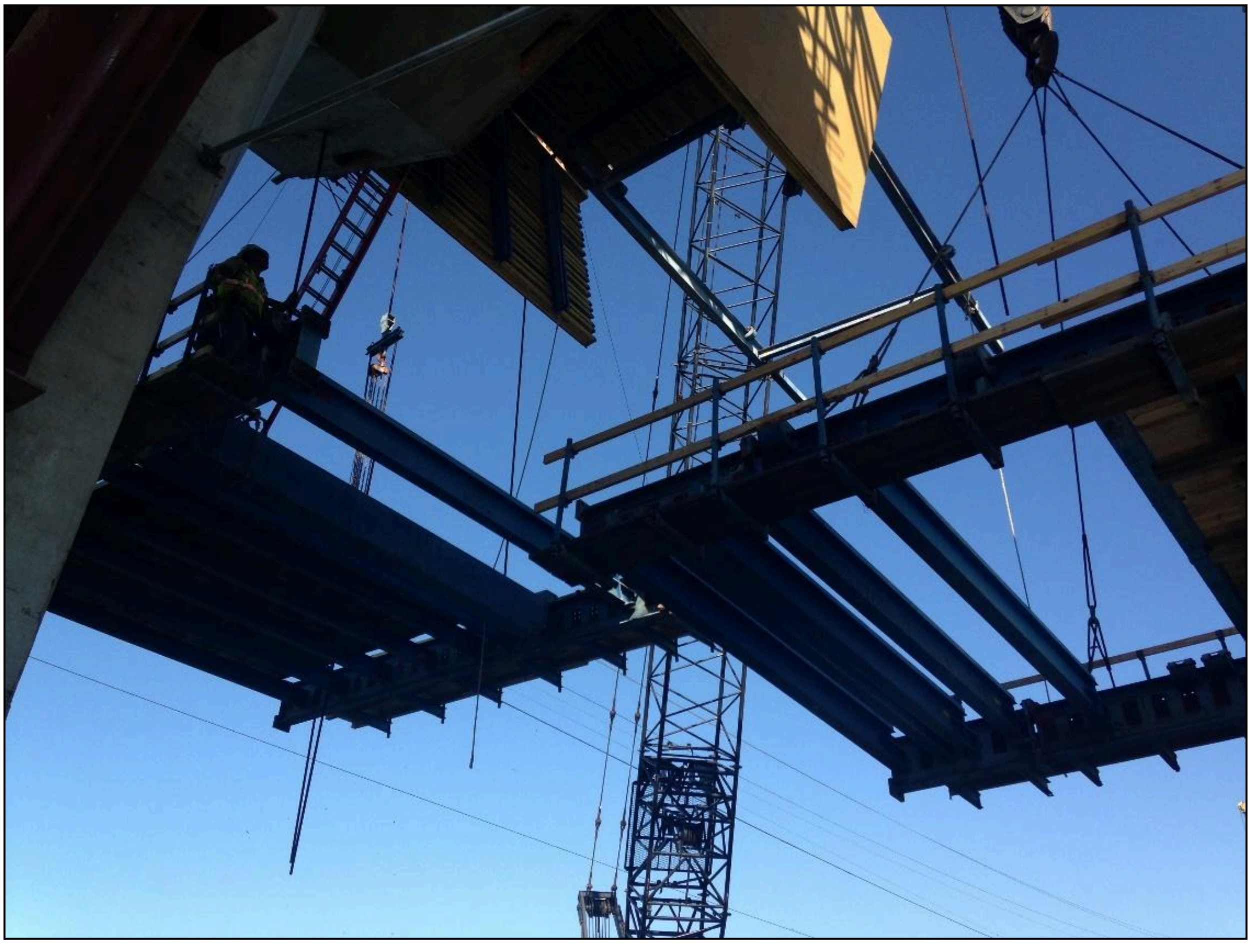


***Figure 5.29 – Form Traveler Installation Step 5: Set Bottom Deck and Formwork***
***(Photo Courtesy of Archer Western)***

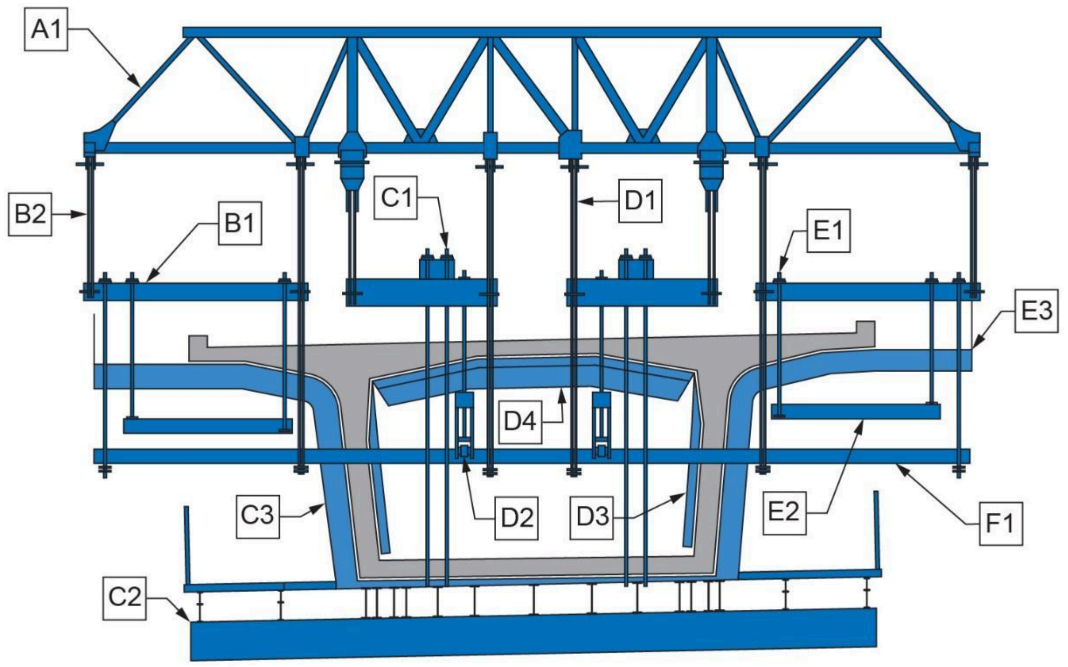
*Figure 5.30 – Form Traveler Installation Step 6: Set Outer Wings and Formwork*
*(Photo Courtesy of Archer Western)*

***Figure 5.31 – Form Traveler Operation: Traveler and Formwork Assembled***
***(Photo Courtesy of Archer Western)***

***Figure 5.32 – Form Traveler Operation: Nearing Mid-Span Closure***
***(Photo Courtesy of Archer Western)***

## Form Traveler Components

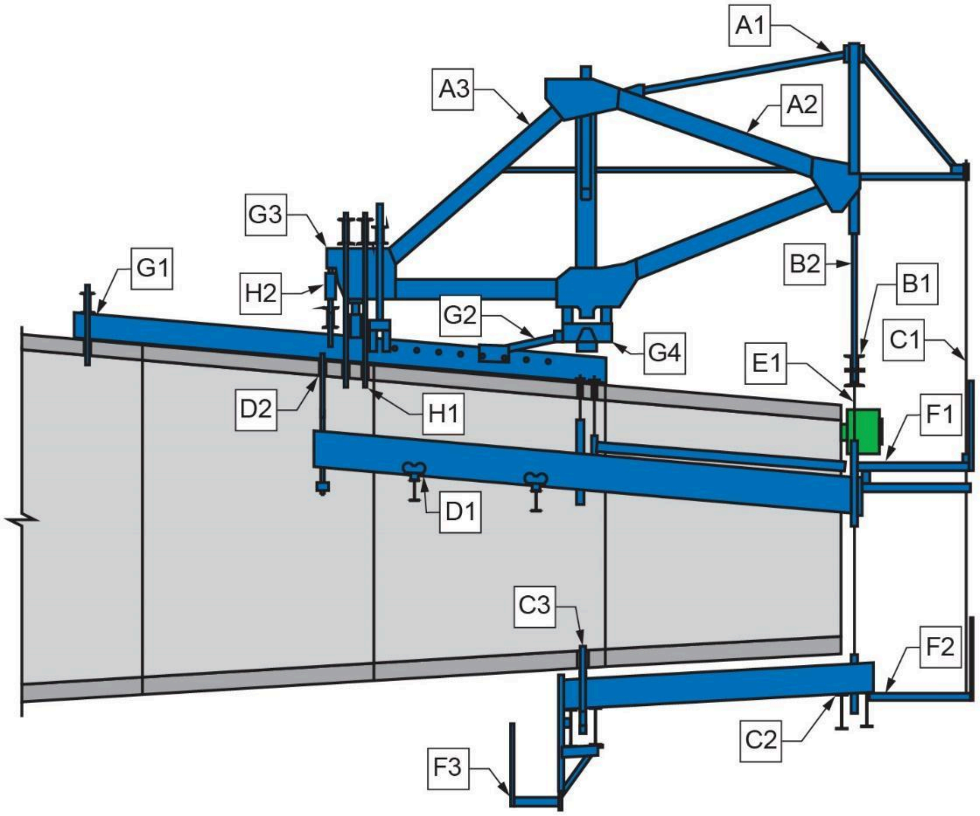
**Figures 5.33** and **5.34** below show a form traveler's major components as seen from two different views. Further detail about the major components and how they work together follows.



**Traveler Components**

- A. Primary Structural System
  - 1. Front Truss
  - 2. Main Frame and Rails (Not shown in this view)
- B. Vertical Suspension System
  - 1. Spreader Beam
  - 2. Hanger Channel Pinned to Front Truss
- C. Bottom Platform
  - 1. Front Suspsension Bars
  - 2. Bottom Platform Framework and Side Work Platform
  - 3. Exterior Wall Formwork
- D. Interior Formwork Assembly
  - 1. Front Suspension Bars
  - 2. Interior Framework
  - 3. Interior Wall Formwork
  - 4. Top Deck Crown Formwork
- E. Cantilever Formwork Assembly
  - 1. Front Suspension Bars
  - 2. Supporting Framework
  - 3. Overhang Formwork and Work Platform
- F. Work Platforms
  - 1. Upper Work Platform

***Figure 5.33 – Form Traveler Components:***
***End View as Seen from the Leading End of Construction***



### Traveler Components

- A. Primary Structural System
  - 1. Front Truss
  - 2. Main Frame
  - 3. Rear Truss
- B. Vertical Suspension System
  - 1. Spreader Beam
  - 2. Hanger Channel Pinned to Front Truss
- C. Bottom Platform
  - 1. Front Suspsension Bars
  - 2. Bottom Platform Framework
  - 3. Rear Tie-Down through Concrete
- D. Interior Formwork Assembly
  - 1. Interior Framework Rail and Roller System
  - 2. Rear Tie-Down Bars through Concrete
- E. Cantilever Formwork Assembly
  - 1. Front Suspension Bars
- F. Work Platforms
  - 1. Upper Work Platform with Post-Tensioning Jack in Place
  - 2. Lower Work Platform
  - 3. Rear Trailing Platform
- G. Launching System
  - 1. Main Rails and Rear Tie-Down Bars
  - 2. Hydraulic Launching Cylinders
  - 3. Rear Bogey Assembly
  - 4. Front Bogey
- H. Tie-Down System
  - 1. Rear Tie-Down Bars through Concrete Slab
  - 2. Pull-Down Ram to Release Tie-Down Bars

***Figure 5.34 – Form Traveler Components:***
***As Seen in Elevation***

### Vertical Suspension System

The vertical suspension system ([B1] and [B2] in **Figures 5.33** and **5.34**) is the structural system for supporting the leading end of the bottom platform, interior soffit formwork, overhang, and wall formwork. Vertical channel hangers are suspended from the front truss and connected to a series of horizontal spreader beams, which distribute the applied loads equally to the front truss. The front truss is supported in turn by the main frames secured to the existing concrete segment. Each of the formwork components is suspended from high-strength bars connected to the spreader beams on top and to a secondary structural support on bottom.

### Bottom Platform

The bottom platform ([C1] through [C3] in **Figures 5.33** and **5.34**) carries the concrete weight of the bottom slab and walls and provides a safe staging area. The bottom platform is held in place by its trailing end to the previous segment with a set of high-strength bars that pass through sleeves in the bottom slab. The leading edge is supported by bars suspended from the inside spreader beams. When the bottom platform is ready to be moved ahead, the trailing end must be released from the existing segment. A secondary set of bars, one on each side, is suspended from the rear truss and connected to the bottom platform, allowing it to move freely during launch to the next position.

### Interior Formwork Assembly

The interior formwork assembly ([D1] through [D4] in **Figures 5.33** and **5.34**) supports the concrete load between the web walls. High-strength bars are suspended from a set of spreader beams and connected to a framework running longitudinally inside the box segment. The rear end of the frame is tied down to the previous segment with bars similar to those on the bottom platform. The interior beams are a two-part system: they provide vertical support to the crown form, as well as a rail for the interior wall support. The interior walls are supported on a frame that is suspended on rollers that slide independently along the interior beams. When the form-traveler is launched to the next position, the interior wall forms must be left at the previous location because the web walls of the segment contain heavy vertical reinforcing that can only be installed from the interior of the girder -- which is not possible with the wall panels in place. When reinforcing installation is complete, the interior wall panels can be advanced forward on the roller assembly.

### Cantilever Formwork Assembly

The cantilever formwork assembly ([E1] through [E3] in **Figures 5.33** and **5.34**) supports the cantilevered portion of the top deck outside each web wall and provides access for construction activities such as post-tensioning of the transverse tendons. Bars on the front end of the traveler are suspended from a spreader beam and connected to the front end of a frame that runs longitudinally under the overhang. The cantilever assembly includes a system for supporting the exterior web wall form. The trailing end of the assembly is supported at two locations. It is tied down to the previous segment and is suspended from the rear truss with a high-strength bar.

### Launching System

The complete traveler assembly is supported on a pair of rails located directly above the girder web walls for direct load transfer into the superstructure. The rails provide a smooth surface to roll the traveler forward, bypassing any irregularities of the concrete deck.

Launching the form traveler system forward is a two-step process. First, the rails are "pulled' forward to the next segment position, stopping just short of the leading edge at the cantilever tip. Next, the complete assembly is "pushed" forward over the rails. The entire system moves incrementally forward via a set of hydraulic cylinders pinned between the main frame of the traveler and the rails. The length of the cylinders determines the distance traveled with each increment. The same set of cylinders launch the traveler and the rails; when the form traveler is launched to the next segment position, all components move simultaneously. See **Figure 5.35** below for a view of a pair of rails and launching system.

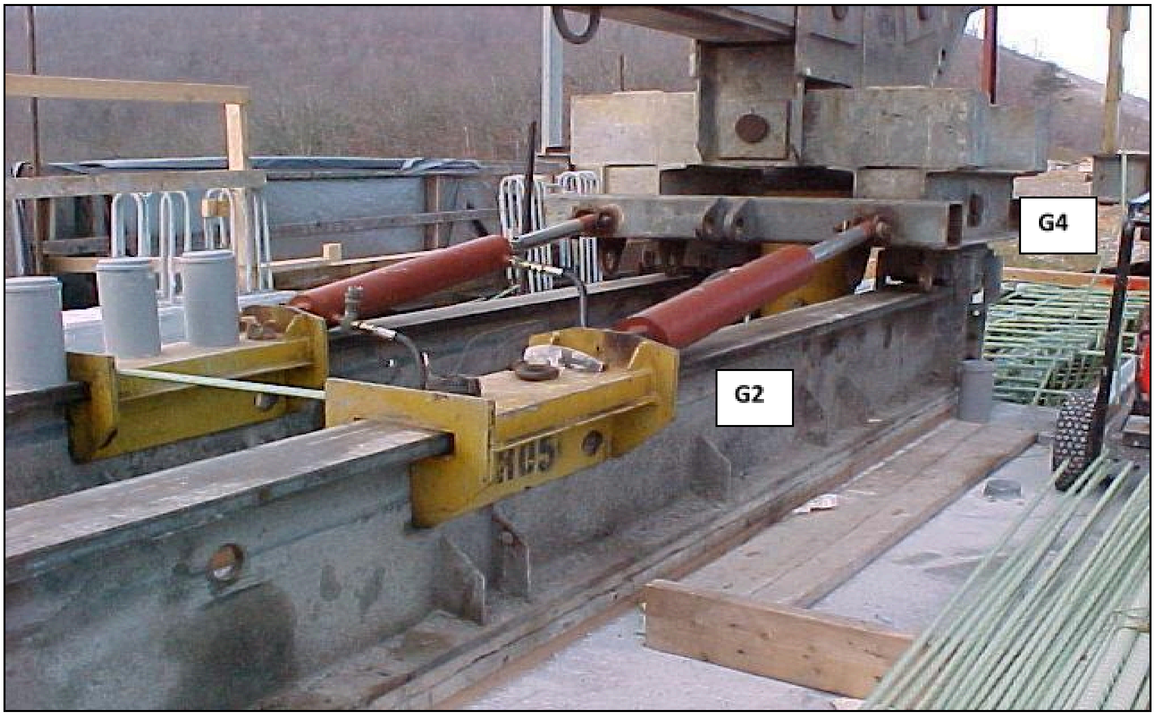


*Figure 5.35 – Launching Rams [G2] Have Pushed the Traveler Forward to the Leading Edge of Construction. The Front Bogey Assembly [G4] is on the Main Rails.*
*(Photo Courtesy of PCL Civil Constructors, Inc.)*

During launching, the traveler is top-heavy. It must be restrained from tipping over the leading edge using a rear bogy assembly with rollers that grip under the flanges of the rails, as shown in **Figure 5.35**. The trailing ends of the rails are tied down to the existing segment with high-strength bars accommodated by sleeves cast through the top slab of the segment. The leading edge of the traveler is supported by the front bogy assembly.

## Tie-Down System

When the traveler is advanced to the next segment position, it must be restrained from tipping over. As shown below in **Figure 5.36**, a rear tie-down system provides the main structural support to the traveler, using one set of high-strength bars for each main frame. The bars are pre-loaded to a specified force to prevent the traveler from moving during concrete placement. The front end of the traveler must be lifted off the rails so it will not roll forward. At the front edge of the cantilever tip and below the front bogy, a front leveling ram lifts the front rollers off the rails and supports the traveler weight during concrete placement.

Careful attention must be paid to the formwork at this juncture. The pre-load from the tie-down system can potentially travel through the formwork and must be accounted for in the formwork design.

With the traveler secured, adjustments are made to set the segment formwork to the correct elevation. Using the geometry control manual, elevations are calculated based on the segment number and construction step at that particular construction phase. Then, under strict tolerances, a project surveyor surveys the new position. Adjusting the length of the front suspension bars changes the leading formwork position; center-hole jacks are used for large adjustments and turning the appropriate nut with a wrench sets the final elevation.

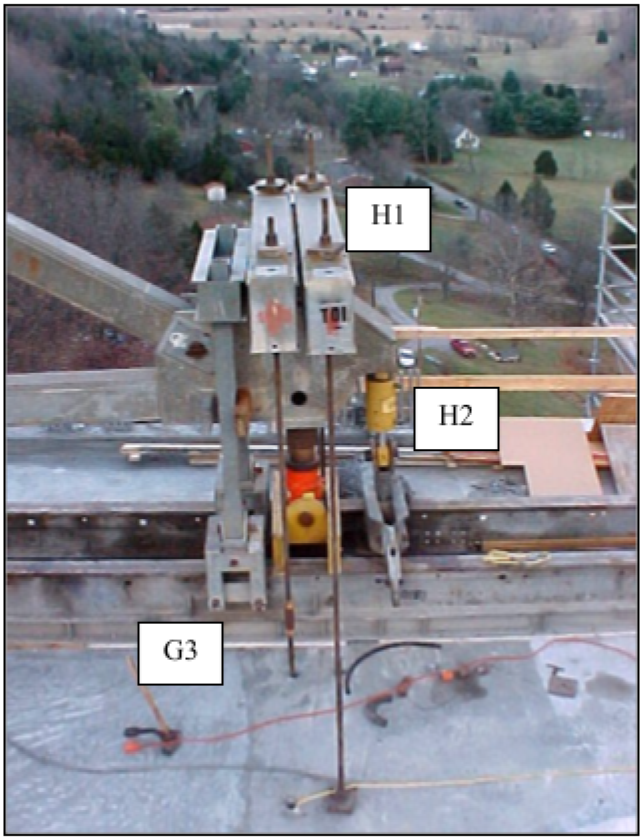


*Figure 5.36 – Rear Tie-Down System for Main Frame [G3], Rear Bogey Assembly [H1], Rear Tie-Down Bars, and Pull-Down Ram [H2]*
*(Photo Courtesy of PCL Civil Constructors, Inc.)*

The following steps summarize a typical launching cycle. Note that a traveler can require unique steps not listed. It is critical to follow the traveler supplier's specified step-by-step directions. (Numbers in brackets refer to major form traveler components as shown in **Figures 5.33** and **5.34**).

1. Launching the main rails to the next segment position, flush with tip of cantilever [G1].
2. Tying down the rear-end of rails with high-strength bars [G1].

3. Lowering the front leveling ram so that front bogey rollers are in contact with rails [G4].
4. Releasing all rear ties of the bottom platform and top deck form support [C3, D2].
5. Actuating the rear pull-down ram to engage safety clamp and release the tie-down bars [H2].
6. Releasing the pull-down ram to transfer tipping load to rear bogeys [G3].
7. Launching the traveler forward, then installing and pre-loading the tie-down bars at the next segment position [H1].
8. Installing and stressing rear ties of bottom platform, overhang, and top deck form [C3, D2].
9. Leaving interior form system behind and rolling it forward later to facilitate reinforcing installation [D1].

### Work Platforms

An upper work platform is suspended from the front truss by a series of high-strength bars; a lower work platform is supported by a fixed channel support on the bottom platform ([F1] through [F3] in **Figures 5.33** and **5.34**). These two work platforms provide access for construction of segment bulkheads, post-tensioning from the leading edge, and access to the traveler components. **Figure 5.37** below provides an end view.

***Figure 5.37 – End View of Form Traveler Work Platforms, Mon River Bridge, PA (Photo Courtesy of Walsh Construction)***

### Segment Casting Cycle

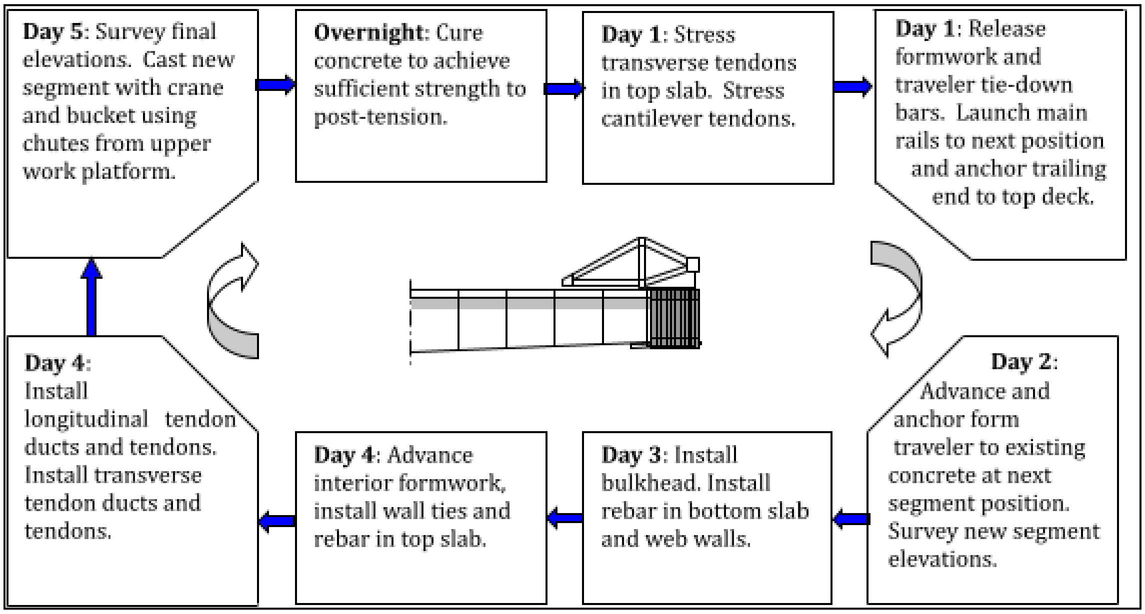
After the concrete is placed for a new segment, a repetitive casting cycle begins. The first step is to stress the transverse post-tensioning tendons located in the top slab before stripping the traveler formwork. If the transverse tendons are not stressed in a timely manner, longitudinal cracking may result. The traveler formwork must be stripped before the traveler assembly can be launched forward.

Before any of this work can begin, however, it is critical that the newly cast concrete segment will not crack under the large compressive force from post-tensioning. To ensure adequate concrete strength has been achieved prior to post-tensioning and launching the traveler, test cylinders are used to verify in-place strength.

Since curing the concrete is a time-dependent activity with the potential to delay the critical path of the project, high early strength concrete is typically used.

Geometry control is an important part of the casting cycle. As-cast surveys of the cantilever are used to evaluate the profile of the cantilever after key phases of construction. The survey should be done at a period of minimum thermal gradient (early morning) to minimize thermal deflections. The as-cast survey is evaluated against the theoretical casting curve to determine the setup for casting the next segment. The theoretical cast curve combines the plan geometry with the casting camber and structural deflection of the cantilever for the phase of construction being evaluated.

The daily activities of a typical five-day casting cycle are lined out in **Figure 5.30** below and in the text that follows.



**Day 5**: Survey final elevations. Cast new segment with crane and bucket using chutes from upper work platform.

**Overnight**: Cure concrete to achieve sufficient strength to post-tension.

**Day 1**: Stress transverse tendons in top slab. Stress cantilever tendons.

**Day 1**: Release formwork and traveler tie-down bars. Launch main rails to next position and anchor trailing end to top deck.

**Day 2**: Advance and anchor form traveler to existing concrete at next segment position. Survey new segment elevations.

**Day 3**: Install bulkhead. Install rebar in bottom slab and web walls.

**Day 4**: Advance interior formwork, install wall ties and rebar in top slab.

**Day 4**: Install longitudinal tendon ducts and tendons. Install transverse tendon ducts and tendons.

*Figure 5.38 – Typical Repetitive Casting Cycle*

__Day 1__ - The post-tensioning crew stresses the transverse tendons (**Figure 5.39**) while the form traveler crew simultaneously releases the formwork and traveler tie-down bars in preparation for advancing to the next segment. The cantilever tendons are also stressed at this time if they terminate at this location (**Figure 5.40**).

***Figure 5.39 – Stressing transverse tendons***
***(Photo Courtesy of NMDOT)***

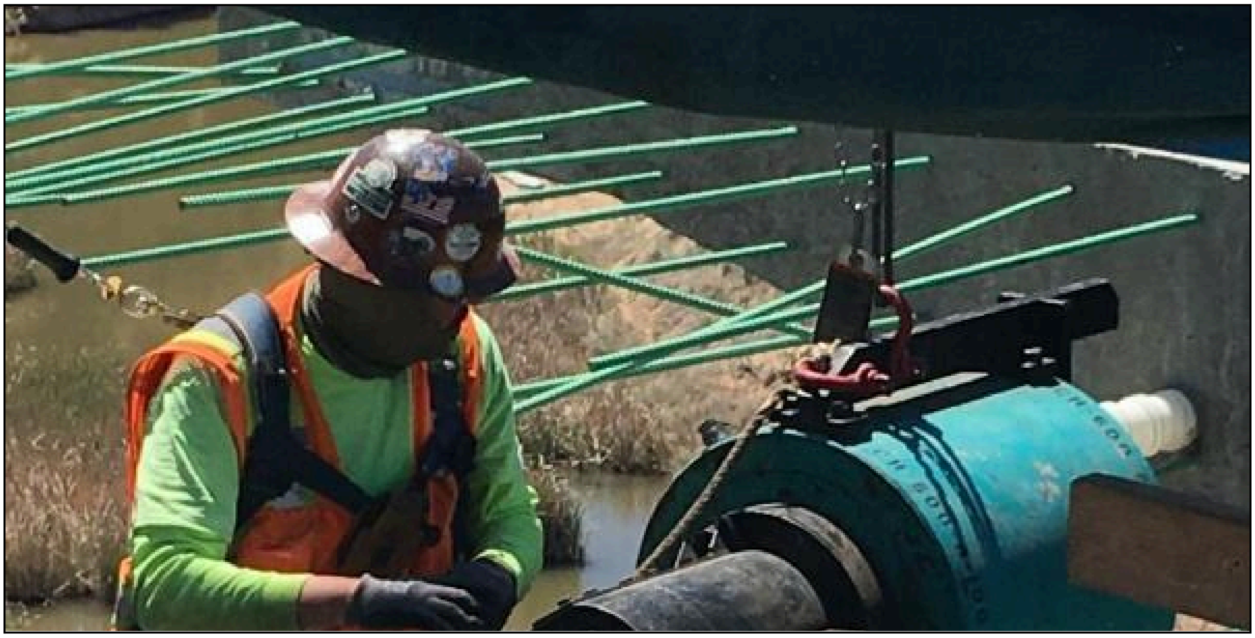


***Figure 5.40 – Stressing cantilever tendons***
***(Photo Courtesy of NMDOT)***

**<u>Day 2</u>** - The traveler crew advances the form traveler to the next segment position, trims the exterior wall form to the new height, and aligns the formwork to the correct elevation with the assistance of the project surveyor for geometry control. A carpentry crew then installs the bulkheads on the segment face.

<u>**Day 3**</u> - The reinforcing crew begins installation of the bottom slab and web walls of the box girder. All reinforcing steel for the segments is tied in place as the form traveler bracing and framework does not provide enough space to lift a preassembled cage into place. The reinforcing is placed as per the integrated segment shop drawings which includes the segment dimensions, post-tensioning layout, reinforcing size and spacing, traveler and form sleeves, embeds and any requirements for the segment (**Figure 5.41**).

***Figure 5.41 – Installing the post-tensioning ducts and reinforcing for the bottom slab and tendon anchor blister (Photo Courtesy of NMDOT)***

**Day 4 -** Once the reinforcing installation is complete on the bottom slab and walls, the crew begins installation on the top deck (**Figure 5.42** and **Figure 5.43**). The longitudinal and transverse post-tensioning ducts and tendon strands are installed but left unstressed. The interior walls are rolled out, cut to the correct dimensions, and form ties are installed. Coordinating the various crews is essential within the confined area of the segment.

***Figure 5.42 – Installing cantilever ducts for the top deck.***
***(Photo Courtesy of NMDOT)***

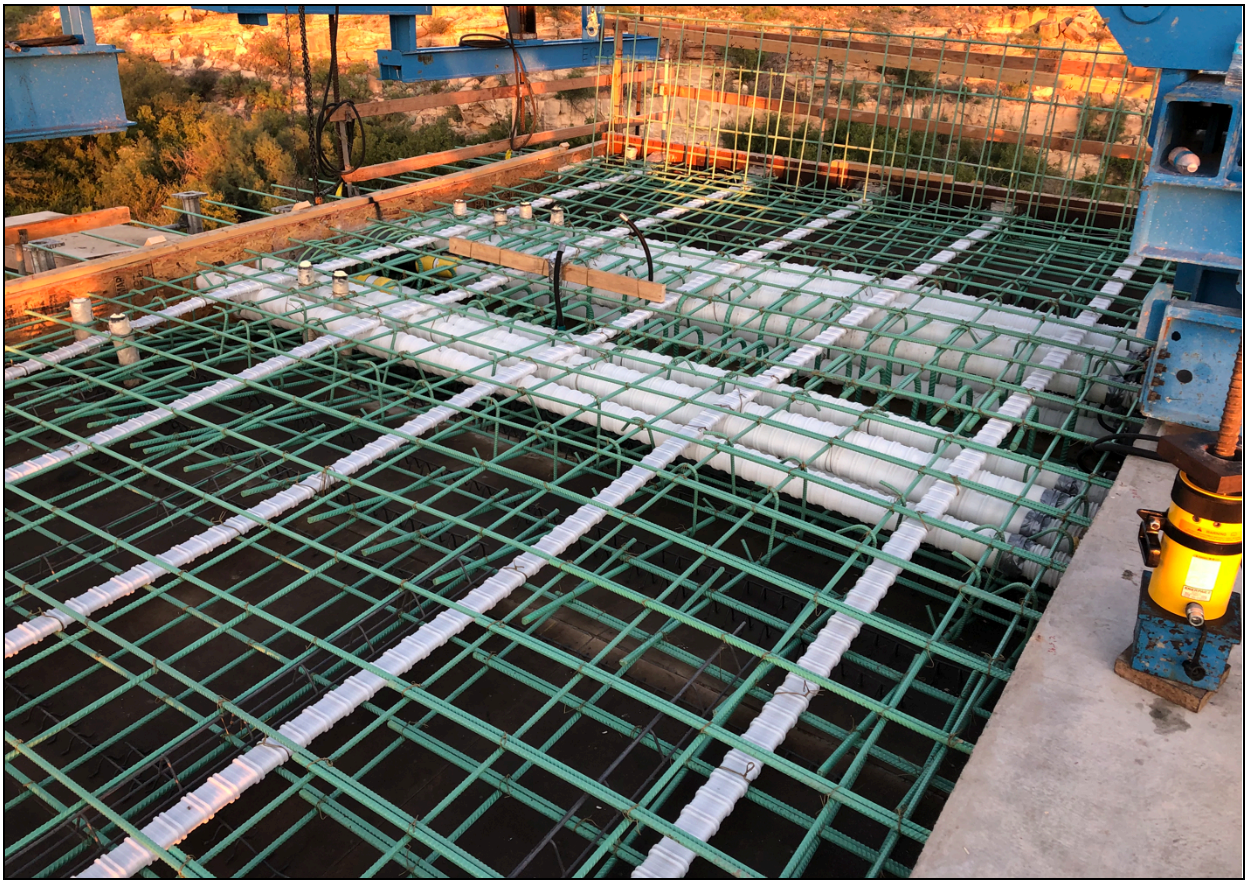


***Figure 5.43 – Installing reinforcing for the top deck.***
***(Photo Courtesy of NMDOT)***

**<u>Day 5</u>** – Final preparations for casting the segment and placing the concrete. The day begins early, before sunrise, with the project engineer determining the final elevation of the new segment with any required corrections. Within an hour of sunrise, the project surveyor checks the final position to eliminate any false readings caused by thermal movement of the cantilever.

Next, concrete is placed, typically in the following order: (1) the outside corners of the bottom slab and web wall, (2) the bottom slab, (3) the web walls and top deck. This is illustrated in **Figures 5.44** and **Figure 5.45** below. The concrete is consolidated with internal concrete vibrators. Field personnel must exercise careful quality control when placing the concrete. The first placement, at the outside corners, must be delivered with a low slump to "plug" the bottom of the open wall form against the added pressure of placing the web walls above.

***Figure 5.44 – Segment concrete placement***
***(Photo Courtesy of McNary, Bergeron, and Johannesen)***

***Figure 5.45 – Finishing top deck concrete placement.***
***(Photo Courtesy of Kiewit)***

With cast-in-place balanced cantilever construction, the same steps are happening on the opposite cantilever, typically offset half a cycle. For example, when one crew is casting the segment on one cantilever, a separate crew is setting the forms on the opposite cantilever. When post-tensioning is being stressed with the newly cast segment, reinforcing is being placed on the opposite cantilever segment. This allows segment casting and crews to alternate from one cantilever to the opposite cantilever.

The casting cycles times can vary based on segment size and complexity. As with any repetitive cycle, there is an initial learning curve that must be accounted for. The above cycle durations are based on typical segments after the initial learning curve.

### *Special Segments*

### *Midspan Closure Segments*

When the bridge contains two or more piers, you will be faced with making a mid-span closure. The closure segment is usually shorter than the typical segments. These segments are typically installed by either utilizing the form traveler to bridge the gap, or stiff-back members can be installed across the gap and the segment formed by hand.

Utilizing the form traveler to form and pour the closure segment usually requires coordination with the construction engineer and the form traveler supplier as the closure segments are normally shorter than a typical segment and will require tie down points at a different spacing than what was normally utilized. Additionally, using the form traveler for the closure segment will require locking the two cantilevers together with the form traveler. The form traveler supplier will be able to supply the forces that can be imparted on the system during this process. If aligning the cantilevers fall outside of the allowable forces from the form traveler supplier, or if schedule dictates that the form traveler be immediately moved to the next pier table, the stiff-back method is normally used.

The stiff-back (closure beam) method of forming the closure segments utilizes structural members to span the gap between the cantilevers, locking them in place. Once locked in place the stiff-backs are then utilized to support the formwork for the closure. Utilizing this method will require additional engineering, formwork and structural members, but as stated above, will free up the form traveler to be utilized on the next pier table. See **Figure 5.46** below for a view of a mid-span closure segment ready for concrete placement.

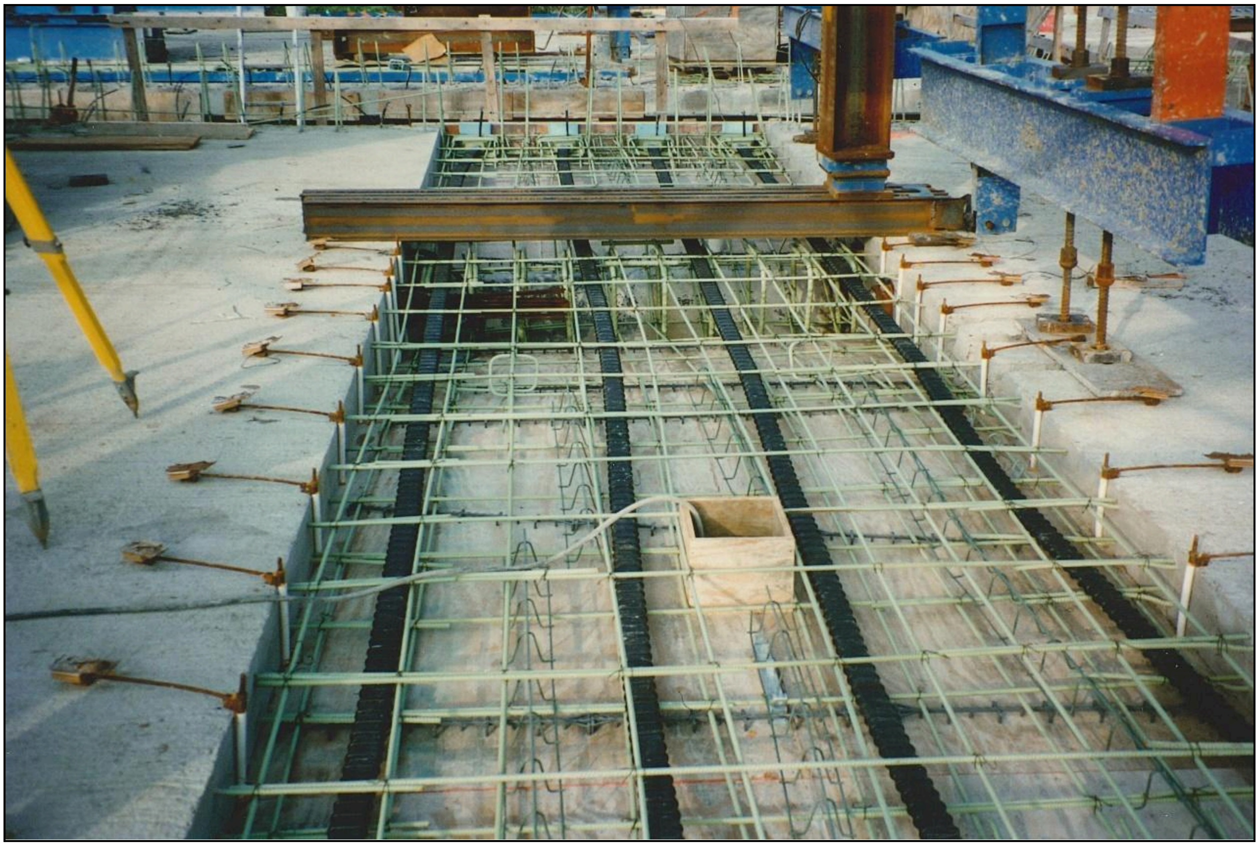


***Figure 5.46 – Midspan closure segment, Wabasha Freedom Bridge, MN***
***(Photo Courtesy of FIGG)***

### *Abutment Segments*

The abutment (or end) segments, which are situated at each end of a bridge, make the final connection between a completed cantilever and the abutment substructure. Segment depth at this location in the structure is typically constant. Abutment segments usually contain massive, thick diaphragms situated over the bridge bearings to transfer the vertical load of the end span and provide anchorage for the continuity tendons. For this reason, this area usually contains a high concentration of reinforcing steel and takes significant time to construct. Abutment segments are typically built in three separate lifts: (1) the bottom slab, (2) the web walls and diaphragm, and (3) the top slab and the deck overhang supported on shoring. Abutment segments are often supported on steel falsework that remains in place until the closure segment is cast connecting it to the end of the cantilever. See **Figure 5.47** below for a view of an abutment segment being constructed.

***Figure 5.47 - Abutment Segment Under Construction with the Falsework in Place (Photo Courtesy of Archer Western)***

# TABLE OF CONTENTS

# Chapter 6: Incremental Launching Segmental Bridges

## 6.1 Introduction

The incremental launching method has been successfully used in hundreds of long and short segmental bridges in Europe, Japan, and other parts of the world, although thus far, its application has been limited in North America. It has proven to be a cost-effective, high-quality solution for difficult bridges around the world.

***Figure 6.1 – Incremental Launching Segmental Bridge***
***(Photo Courtesy of PSM Construction USA, Inc.)***

Construction of an incrementally launched segmental bridge involves manufacturing a bridge superstructure by segments in a fabrication area set up behind one of the abutments. Each new segment is match-cast against the preceding segment. After the concrete is hardened and launch prestressing has been installed in the newly cast segment, the entire superstructure is moved forward on the piers one segment length to clear the casting cell for the next segment. This process continues until the first segment reaches the abutment at the other end.

**Figure 6.2** below shows a schematic view of the standard arrangement for an incrementally launched bridge.

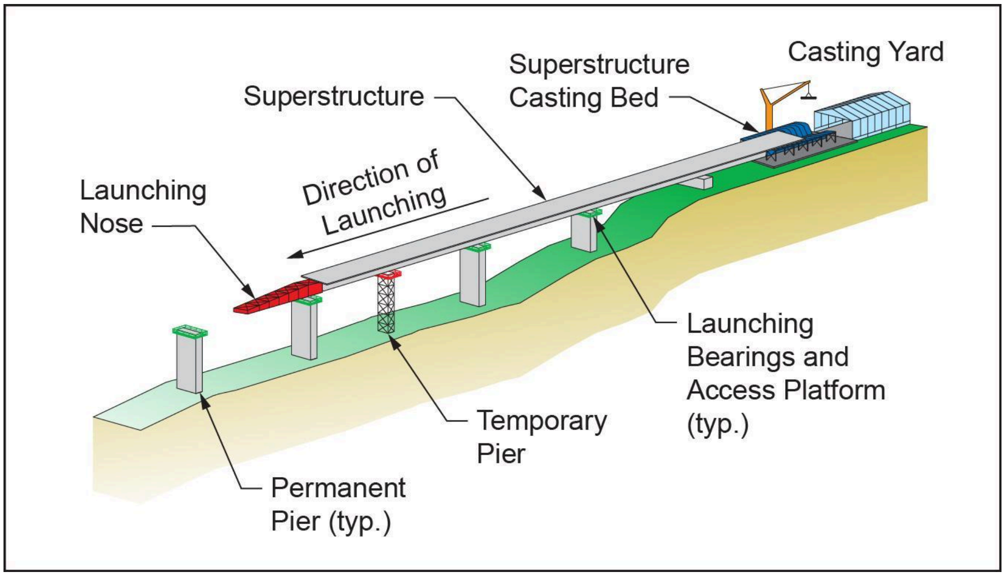


*Figure 6.2 – Schematic View of Incremental Launching Arrangement*

Incremental launching segmental bridges combines the advantages of cast-in-place and precast concrete bridge construction. They are relatively "compact" to build: they do not interfere with obstacles the bridge needs to pass over, or with the clearance needed for traffic underneath, and the casting yard required is the smallest of any type of segmental bridge – all attributes which are especially valuable in dense urban or environmentally sensitive areas. The casting yard can be easily sheltered for continued production during inclement weather, and yard industrialization can readily be adapted to the dimensions of the bridge. Other advantages include streamlined construction and labor, improved jobsite safety, and improved workmanship and quality control. Further, the construction equipment needed -- a launching nose, a hydraulic thrust system, and a casting cell -- is inexpensive and easily reused on future projects. The advantages of this method are further detailed in S**ection 6.2**.

Segmental launching is generally economical for prestressed concrete bridges of medium span, ranging from 100 ft to more than 200 ft, and is applicable to longer spans with temporary piers that halve the spans during construction. In the longest bridges, launching from both abutments is sometimes adopted to diminish the thrust force. This also permits halving the construction duration by working in two casting yards, although the equipment costs approximately double.

## 6.2 Advantages of Incremental Launching of Segmental Bridges

As outlined above, there are numerous advantages to the incremental launching method of segmental bridge construction. Most of the work is done in a stationary casting yard set behind one of the abutments, providing greater ability to control quality, safety, and cost. Because the superstructure moves forward on the piers, construction is carried out without falsework and is not affected by conditions under the bridge. There is no interference between the new construction and conditions on the ground, be it highways, rivers or structures. Because no impact is made on clearance, road and railroad traffic below the bridge may continue uninterrupted during construction with concurrence from the applicable agency.

*Figure 6.3 – Incremental Launching Over a Road – Japan*
*(Photo Courtesy of PSM Construction USA, Inc.)*

**Figure 6.3** above shows below-bridge traffic being maintained while spans are launched above.

Just a few of the advantages of incremental launching segmental bridges include:

1. Stationary fabrication streamlines construction and saves labor.

a. The casting yard, rebar assembly yard, stocking area, and batching plant (if needed) are located in a single, small yard. This is a valuable advantage in urban, congested, or environmentally sensitive areas.

b. Steel cages are partially prefabricated within the casting yard or in the workshop, so preassembly can be divided at different levels (e.g., web panels, deck slab panels, etc.) or integral. Parallel (rather than serial) activities performed at short distance from one another optimizes utilization of personnel.

c. Site industrialization can readily be adapted to bridge length and dimensions. If designed modularly, the necessary construction equipment -- a launching nose, hydraulic thrust system, and a casting cell -- can be reused for future projects. The casting cell can be designed with standard components.

d. Mechanized, concentrated fabrication requires a crew of 10-15 workers throughout the segmental construction. Yard industrialization reduces the time required for each activity.

e. Workers do not need to be transported to several locations and nearly all materials are delivered to one place, simplifying transportation.

f. Handling of materials inside a small yard is easy and labor-saving. A standard tower crane can further enhance handling efficiency .

g. Construction risks for workers are minimized since the casting cell is rigidly supported on the ground instead of being, e.g., suspended at the tip of a cantilever, and no activity takes place on the superstructure.

h. Sheltered fabrication allows work to continue uninterrupted by inclement weather. Winter construction is possible with heat insulation if other conditions allow.

2. Improved workmanship and quality.

a. Geographically concentrated fabrication allows clean and efficiently managed construction and labor.

b. Factory-like conditions and repetitive work can expedite workmanship and improve quality, with an even higher rate of progress possible with mechanization. The work rhythm can be coordinated to construct one deck segment per week, using weekends for curing concrete. Although deck segments can be as long as one-half of the span, alternative arrangements using shorter segments can be used to increase repetitiveness.

c. Mechanized fabrication enables precise control of geometry and the concrete cover, enhancing quality of construction.

d. The number of construction joints is minimized – two per span is typical. They have continuous reinforcement and they can be easily bush-hammered, sand-blasted, or pressure-washed before match-casting the next segment for structural continuity.

3. Improved safety.

a. Little work is done at the final bridge position. Most operations are performed on the ground, making the work simpler and safer than if done while suspended.

b. There is little or no interference with the clearance of highway or railroad traffic crossing below.

c. Performing construction behind an abutment minimizes impacts to third parties and the surrounding environment.

**Figure 6.4** below shows an incremental launching with a temporary pier over a six-track railroad in downtown Milan, Italy. Trains passed under the bridge every day without any speed restrictions, and the electrified lines were kept in service. Falsework for this application would be prohibitively expensive, due both to the complexity of the forms and the interference with the tracks.

***Figure 6.4 – Incremental Launching with Temporary Pier over Railway – Italy***
***(Photo Courtesy of Marco Rosignoli)***

## 6.3 Characteristics of Incremental Launching Segmental Bridges

### 6.3.1 Geometry

Due to the alternating bending moments and shear forces that affect the superstructure during launching, a typical span-to-depth ratio is approximately 17. This can be increased by using temporary piers, which also permits savings in launch prestressing (see **Section 6.5.3**). For high-speed railway bridges, the ratio is diminished to between 12 and 15, mostly because of deflection limitations in service. Maximizing the number of spans with equal or almost-equal length (excepting end spans) is preferable.

The most suitable cross-section is the single-cell box section. Double-cell box sections are used, although construction is somewhat more complicated with respect to shuttering and launch supports. Three- and four-cell cross-sections have been successfully launched, though even less commonly. (**Figure 6.4** in the previous section shows a triple-cell section.)

**Figure 6.5** below shows another cross-section, the double-cell fish-belly. Here it is a segment of a 2,700-ft long bridge with an architectural board-marked surface finish extracted from an industrialized casting yard. The cleanliness and order of the yard are evident in the photograph.

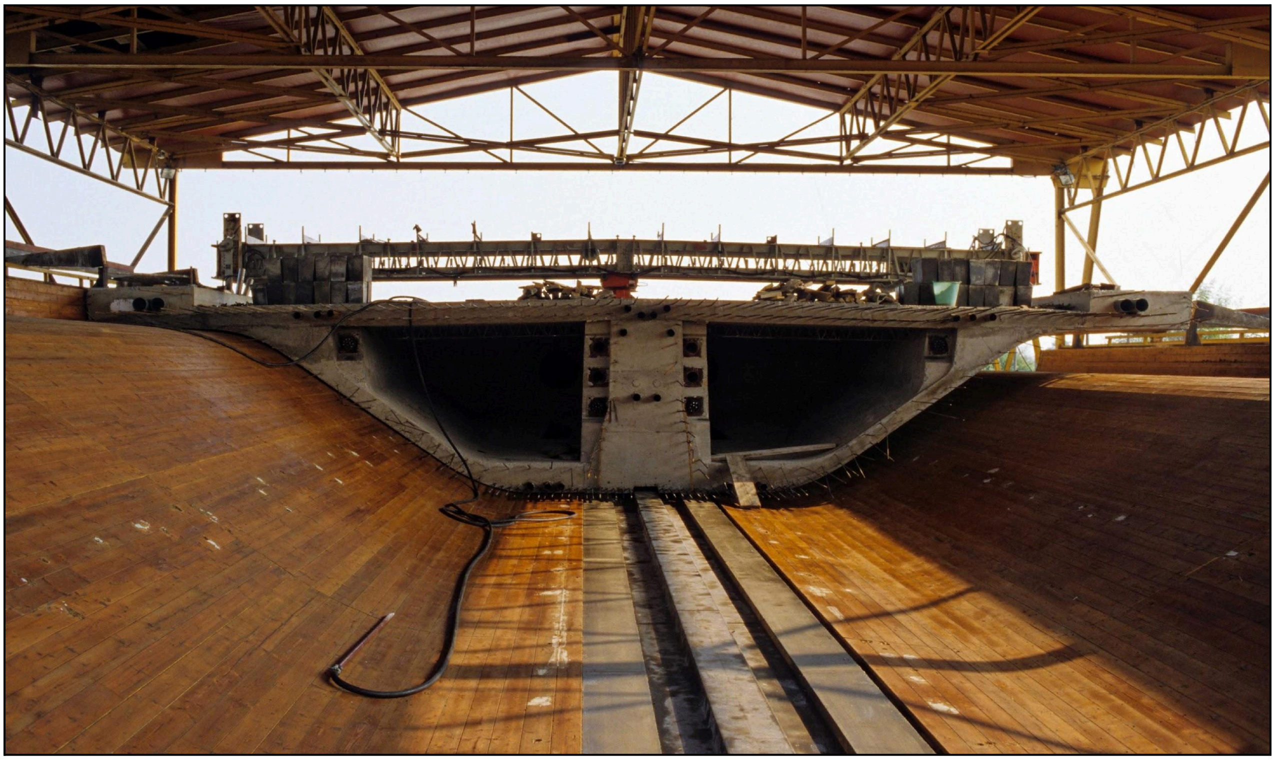


***Figure 6.5 – Double-Cell Fish-Belly Cross-Section – Italy***
***(Photo Courtesy of Marco Rosignoli)***

**Figure 6.6** shows a four-cell voided slab launched on three support alignments. This highly skewed, varying-width, simply supported span was launched over a railroad using a steel temporary pier to help avoid overturning. Three launching noses (see **Section 6.5.3**) were used, inexpensive prestressed concrete blocks fixed to the front deck end with prestressing bars and braced to each other with steel angles. The central launch alignment acted as a plan guide.

***Figure 6.6 – Four-Cell Voided Slab – Italy***
***(Photo Courtesy of Marco Rosignoli)***

Double-T beams (ribbed slabs) can be launched on short spans or onto arches. In spite of their simplicity, ribbed slabs are difficult to launch due to the raised location of the cross-sectional centroid. This makes controlling negative moments challenging, given the limited potential for tendon eccentricity.

The incremental launching method is normally reserved for either straight bridges or bridges curved on a constant radius. In the most complex cases, bridges with variable curvature have been launched with wide launch bearings and lateral temporary piers. Launching from both abutments with central closure permits use of two different curvatures forming an "S" curve.

The superstructure should be of constant depth. Minor adjustments in the vertical alignment of the launch surface can be attained by temporarily attaching shims to the girders. An example of incremental launching of a bridge with plan curvature is illustrated in **Figure 6.7** below. Especially in such cases, attention should be paid early in the design phase to the possible use of the incremental launching. The ideal geometries for launching are constant grades and crossfalls, and either straight or constant radius curves. Any other alignments will require some combination of section distortion and active support adjustments, such as shimming. Adjustments to simplify the erection method are easier to accommodate in the early stages of design.

***Figure 6.7 – Incremental Launching of a Bridge with Plan Curvature***
***(Photo Courtesy of PSM Construction USA, Inc.)***

### 6.3.2 Post-Tensioning

Almost every section of the superstructure receives alternating bending moments and shear forces from its own weight as it is launched forward. During launch, even mid-span sections which usually receive only positive bending moments have to resist negative moments and shear forces. These cyclic changes require temporary launch tendons to be laid out to compliment the final tendons. **Figure 6.8** below shows both temporary and final external tendons.

***Figure 6.8 – Temporary (Launch) and Permanent External Tendons***
***(Photo Courtesy of PSM Construction USA, Inc.)***

There are several approaches to providing temporary launch tendons and coordinating them with final tendons. All approaches fall into two broad categories, as outlined below and illustrated in **Figure 6.9** that follows.

1. **Launch tendons dictate the design**, and are supplemented after the launch by permanent tendons. In this approach, the temporary tendons are typically straight, imparting nearly uniform compression. The final tendons are added to address additional loadings in service and provide supplemental shear capacity.

2. **Final tendons required for service are designed**, and are supplemented with tendons as needed for the temporary condition. This typically results in a more complex tendon arrangement, as the draped tendons used in service typically need an opposing pattern in the temporary tendons to address the shifting demands during the launch. The temporary tendons may be removed after the launch

The two approaches provide different advantages, and the selection will be based on the project-specific drivers. In general, the first method is simpler for the layout of the tendons, with fewer deviations and complex details. It is also simpler during the launching phase. This is balanced against the improved structural efficiency and often smaller section that results from the second method.

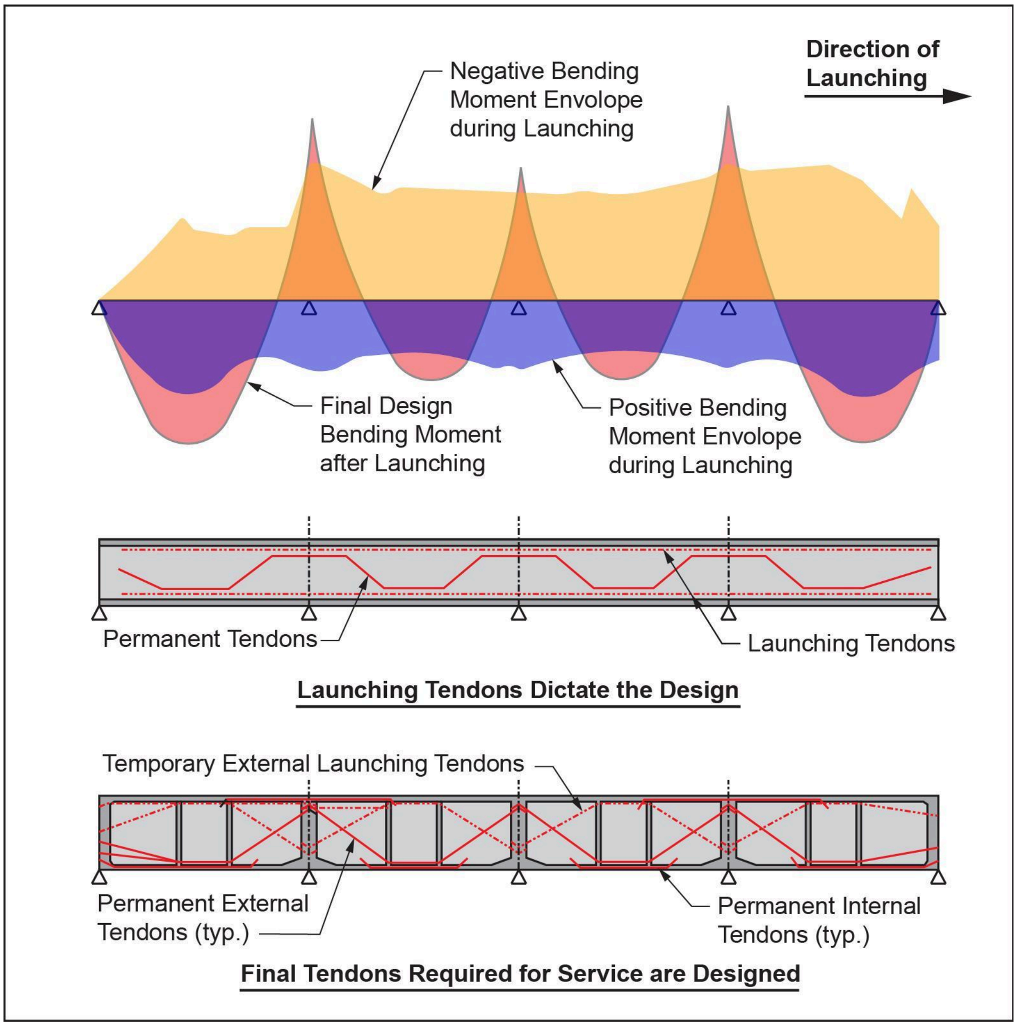


*Figure 6.9 – Bending Moment Diagram and Examples of Post-Tensioning Coordination*

### 6.3.3 Application to Precast Segmental Construction

The incremental launching construction method has been applied mainly to cast-in-place bridges, combining the advantages of the industrialized and repetitive work processes of this method with those obtained by minimizing construction joints. Nevertheless, the method is equally suited to precast segmental construction. Bridges composed of precast segments arranged along temporary support rails, connected by closure joints or epoxy, and incrementally launched offer several advantages including:

- Construction of most of the superstructure is independent of pier construction, as precast segments can be stored elsewhere.
- Yard operations are limited to the segment arrangement along the support / launch rails, joint sealing, and introduction of post-tensioning in each new section of the superstructure.
- The construction duration may be half that of cast-in-place, albeit with additional labor costs and the need for a precast yard.

### 6.3.4 Other Applications

A commonly used incremental launching technique is to launch the superstructure from one abutment towards the opposite one. Related techniques include launching from the opposite abutments with mid-span closure and launching followed by transverse shifting to clear the launch alignment for construction of new bridge strips. An application involving transverse shifting is shown in **Figure 6.10** below. The first half (28 ft wide) of the twin-box section is being shifted right on 167-ft spans; the box-girder is leaving the temporary piers.

***Figure 6.10 – Transverse Shift of the First Half of a Twin-Box Section on Launch Completion – Italy (Photo Courtesy of Marco Rosignoli)***

Incremental launching can be combined with other construction methods as well. Examples include bridge approaches where longer central spans are built by balanced cantilever construction (with or without stay-cables) and construction of the superstructure of arch bridges. Both are shown below in **Figure 6.11**.

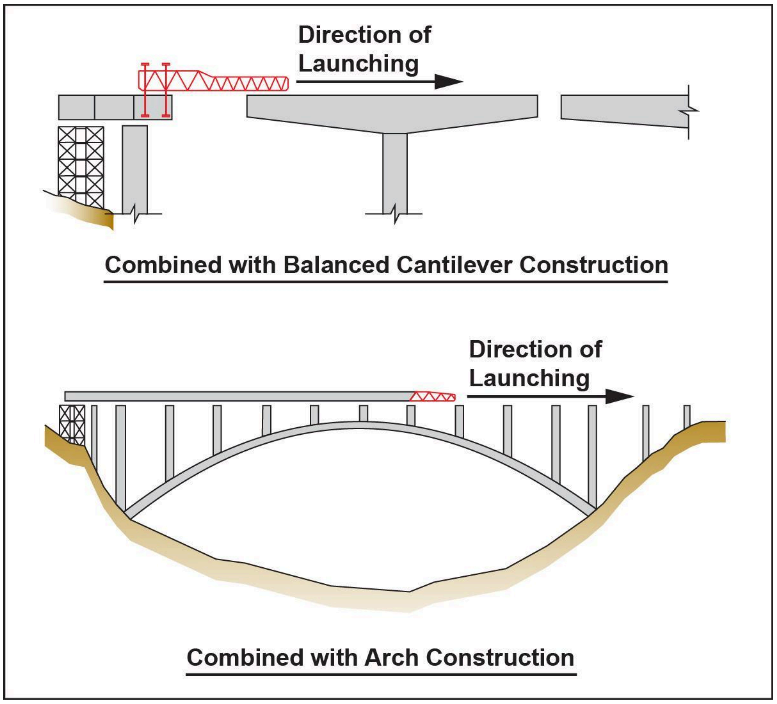


*Figure 6.11 – Incremental Launching Combined with Balanced Cantilever Construction (top) and with Arch Construction (bottom)*

Cable-stayed bridges can be built by incrementally launching the continuous superstructure onto temporary piers and permanently suspending it from a tower on launch completion. **Figure 6.12** below shows a cable-stayed bridge built in this manner and launched over active railways without interference.

***Figure 6.12 – Cable-Stayed Bridge: Launching the Superstructure on Temporary Piers Before Suspension – Italy***
***(Photo Courtesy of Marco Rosignoli)***

## 6.4 Typical Construction Sequence

Planning segment construction involves defining the casting sequence, arranging the casting yard, and pre-sizing the launch equipment. Optimum organization depends on the length of the bridge, the number and length of segments, and the construction schedule. All of these parameters influence the level of industrialization of the casting yard.

The casting yard is usually set behind one abutment. In the case of settlement or when no embankment is available, the formwork is supported by temporary supports. If the bridge has a longitudinal gradient, it is preferable that the superstructure be launched from the lower elevation, so that no braking equipment is necessary.

If the number of segments is large and enough space is available, it is convenient to create a rebar cage preassembly area. This is usually set behind the casting cell, with a gantry crane carrying the cage to the casting cell. Segment lengths between 35 ft. and 100 ft. are generally economical, depending on factors including the location of construction joints, typical span length, concrete volume, and available space. Longer segments shorten the construction duration but expand the casting cell. Construction joints should be located at a section of low bending moment; half of a span with construction joints at the span quarters is a common solution.

A typical work sequence for the incremental launching of segmental bridges with a box-section consists of the following steps.

1. Set bottom slab form and side forms.
2. Place reinforcing bars and tendons in the bottom slab and the webs.

3. Cast concrete in the U-section, cure it, and remove the internal web forms.
4. Set the inside form table for the deck slab.
5. Place reinforcing bars and tendons in the top slab.
6. Cast concrete in the deck slab and cure it.
7. After the concrete has reached the required strength, open the external forms and stress the launch tendons.
8. Launch the superstructure by the length of one segment.
9. Repeat the process for the next segment.

One full construction cycle typically takes one week to ten days. One week is generally preferred to allow the deck slab concrete to cure over the weekend. This means a complete span is cast every two weeks. If the bridge is very long, it may be convenient to divide the production into two areas, although this increases the total length of the casting yard. Therefore, a higher level of industrialization is generally preferred.

Accurate setting of the formwork is very important so that the sliding bottom surface is smooth and maintains the correct launching direction. Formwork typically consists of steel or plywood panels, depending on the number of cycles, i.e. the number of segments. The launching surfaces are generally match-cast onto neoprene-Teflon plates placed onto stiff stainless steel extraction rails. Load deflections of the extraction rails must be minimized.

During the launch, two people are generally necessary at every pier to insert low-friction plates between the launching bearings and the superstructure. On launch completion, after lifting the superstructure with hydraulic jacks, the temporary bearings are replaced by permanent bearings. Continuous final tendons, either external or internal, are then installed and prestressed afterward.

*Figure 6.13 – Casting Yard Behind an Abutment*
*(Photo Courtesy of PSM Construction USA, Inc.)*

## 6.5 Launching System and Equipment

Some unique systems and equipment are necessary for using the incremental launching method, as detailed below.

### 6.5.1 Launching System

There are several possible schemes for the system that moves the superstructure forward. Two of the most common are pulling launching and friction launching, both of which are described below. Any launching system, including redundancy measures, should be designed under local codes. Consideration should be given to backup measures to ensure that the launch will not be stuck in an unfavorable position for an extended time, for example in a cantilevered condition that may be vulnerable to high winds.

### (i) Pulling Launching

In pulling launching post-tensioning strands or bars are used to tow the superstructure. Center-hole jacks are set against a support structure anchored to an abutment. The other ends of the tensioning elements are connected to the superstructure with steel launching pins, beams, or brackets. Steel launching pins are attached to the rear end section of the new segment. If steel launching beams or brackets are used instead, they are connected to the webs or to the bottom slab by means of prestressing bars or anchoring bolts. The speed of launch depends on the jacks and pumps used, but is usually from 10 - 20 ft/h. This type of system is illustrated by **Figures 6.14 and 6.15** below.

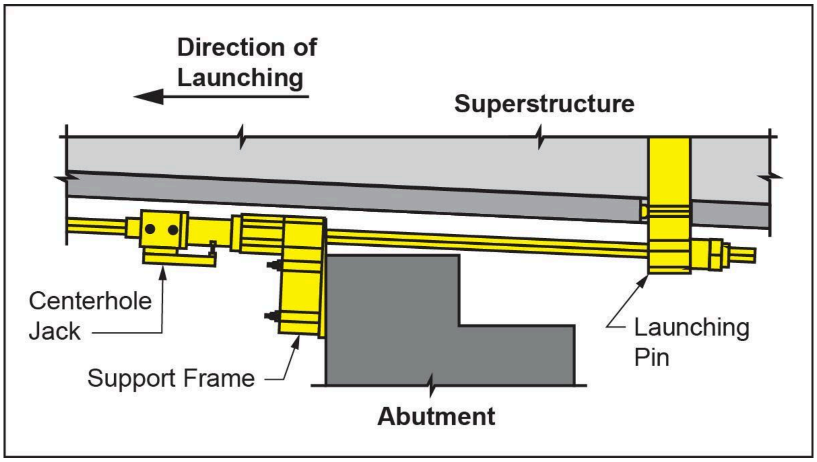


*Figure 6.14 – Pulling Launching System Scheme*

***Figure 6.15 – Pulling Launching System: Center-Hole Jacks and Supporting Frame Anchored to an Abutment***
***(Photo Courtesy of PSM Construction USA, Inc.)***

(ii) Friction Launching

In a friction launching scheme, one or more pairs of launchers -- composed of vertical jacks and horizontal pistons -- are placed under the webs of the cross section. After the superstructure is hoisted from the bearing blocks by the vertical jacks, the horizontal pistons push it forward. Friction transfers the thrust force from the vertical jacks to the concrete bottom surface. The superstructure is lowered back onto the bearing blocks by retracting the vertical jacks, at which point the horizontal pistons are retracted and the cycle is repeated.

***Figure 6.16 – Axial Friction Launching System***
***(Photo Courtesy of Marco Rosignoli)***

Friction launching offers many advantages over pulling launching, including:

- Since the thrust force is shared by the launchers, heavy superstructures can be launched by placing synchronized launchers on every pier. This is difficult to do in a pulling system, where the thrust force is transferred at one transmission point, creating stress concentration.
- The electrically controlled hydraulic system used permits synchronization of the action of the launchers and launch speeds up to 30 ft/h.

### 6.5.2 Launch Bearings and Lateral Guides

Before the incremental launching process is complete, the superstructure is supported temporarily by launch bearings made of concrete or steel, set on the top of the piers under the webs. The top of the bearings are covered by a polished stainless-steel sheet. **Figure 6.17** below shows a launch bearing in place.

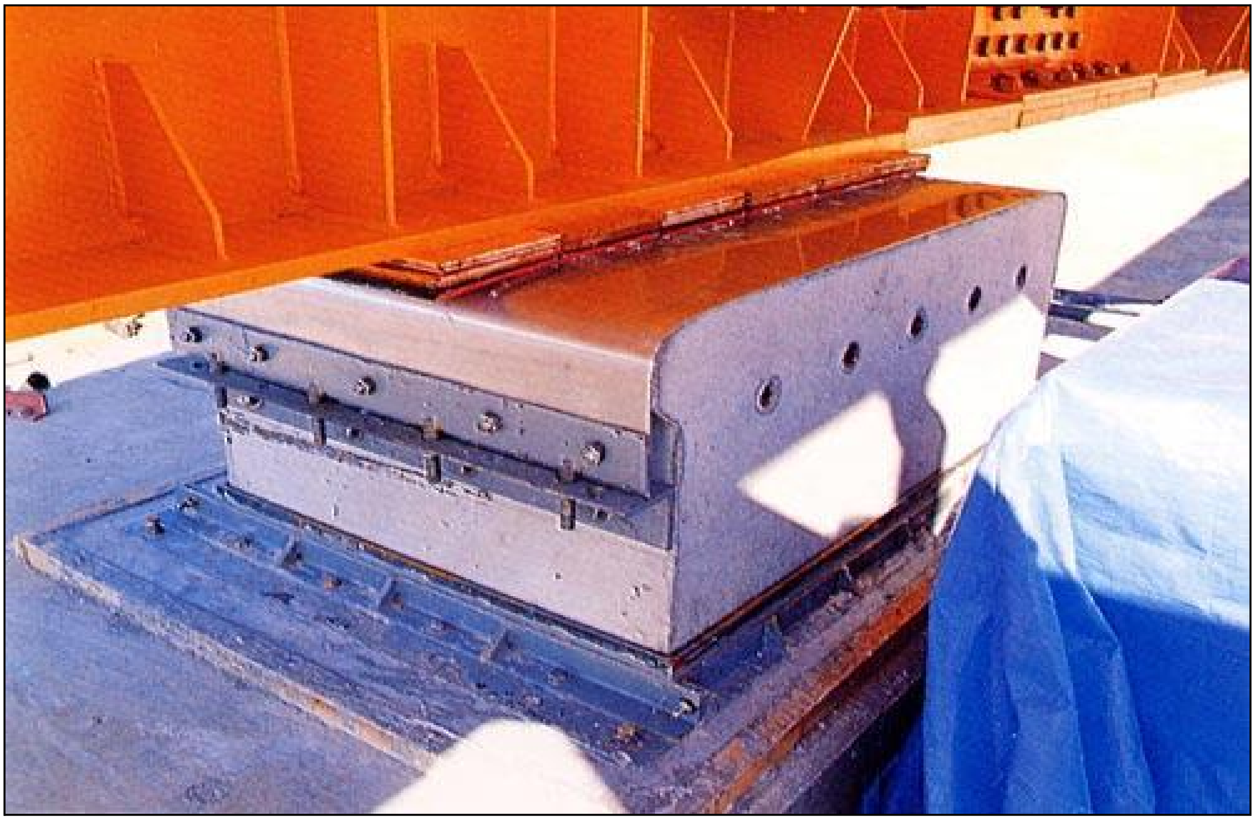


***Figure 6.17 – Launch Bearing Beneath the Launching Nose***
***(Photo Courtesy of PSM Construction USA, Inc.)***

Launch pads are inserted between the superstructure and the launch bearings. The launch pads are made of sandwiched neoprene sheets and steel sheets, with a Teflon plate glued to the bottom of the pad. The pads are continuously fed until the designated launching length is reached (see **Figure 6.18** below). Contact between the stainless-steel sheet and the Teflon plate reduces friction to between 2- 4%. The edges of the launching bearings are rounded so that sliding plates can be inserted without difficulty.

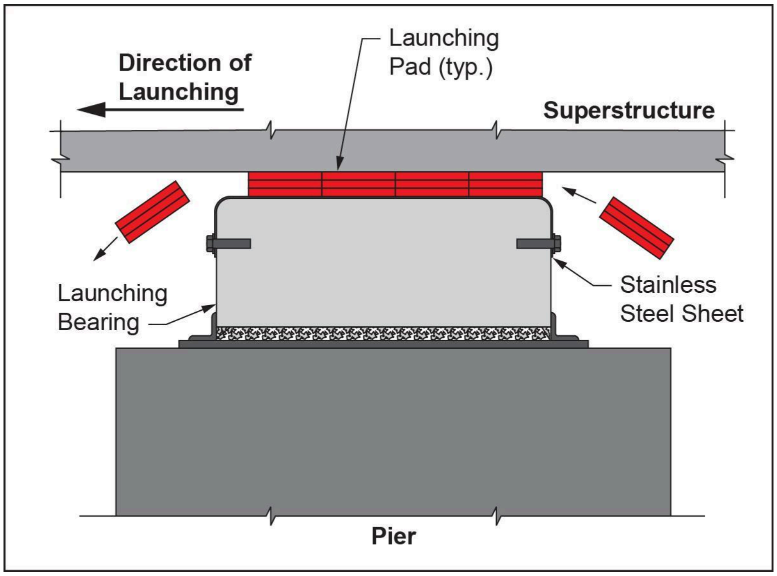


*Figure 6.18 – Launch Bearing and Launch Pads*

After launch completion, the launch bearings are typically replaced by permanent bearings, though some can be used as both launch and permanent bearings. An example of this type of “dual purpose” bearing is shown below in **Figure 6.19**.

***Figure 6.19 – Permanent Bearing Which Serves as Launch Bearing***
***(Photo Courtesy of PSM Construction USA, Inc.)***

Lateral guides are necessary to maintain the correct plan arrangement of the superstructure during launch. These are placed beside the launch bearings and surfaced with rollers or stainless steel (see **Figure 6.20** below).

Locking devices are important to support the superstructure longitudinally between subsequent launches, especially when a launch is performed at an incline.

***Figure 6.20 – Lateral Guide at the Permanent Pier***
***(Photo Courtesy of Marco Rosignoli)***

### 6.5.3 Launching Stress Mitigation System

The front of the cantilever receives the greatest negative moment before the tip of the cantilever touches a pier ahead of it. Following are three common ways to mitigate this launch stress.

(i) Launching Nose

The most common solution is attaching a lightweight steel nose to the front end of the superstructure to reduce sectional force in the cantilever. Braced double plate girders are commonly used to support concrete bridges. The nose is tapered toward the front according to the reduced bending moment it will receive. Because the nose and superstructure have to act monolithically, the connection between them is critical. To prevent a detrimental gap, the nose is usually connected to the webs of the superstructure via longitudinal post-tensioning. For optimal alignment, it is preferable to match-cast the first segment against the gusset plates at the end of the launching nose. As a rule of thumb, for maximum effectiveness, the length of the nose should be approximately 65 - 70% of the maximum span.

The launching nose is delivered to the site in pieces, which are assembled in front of the casting yard before the first segment is cast. When a friction launcher is placed at the abutment, the superstructure is pulled onto the launcher through the launching nose.

(ii) Cable-Stayed System

A second solution to reduce stress in the cantilever is supporting it from above with a temporary cable-stayed system. The pylon is hinged to the deck. Because of the need to continuously tighten and loosen the stays during launch and the complexity of the calculations involved. This approach is usually limited to projects with long spans and well-trained crews.

(iii) Temporary Piers

The third method commonly used for reducing launch stress is to place temporary piers halfway between the permanent piers to reduce the spans. This scheme either uses temporary pier at mid-span of the main span only (refer back to **Figures 6.4 and 6.20**) or one temporary pier per span for long multiple spans, as in **Figure 6.10**. This solution is particularly advantageous in combination with transverse shifting, as the temporary piers are along the launch alignment only, amplifying any savings from prestressing. For cable-stayed bridges, additional temporary piers may be used in the same span, as shown in **Figure 6.12**.

## 6.6 Summary

The incremental launching method is one of the most industrialized and effective forms of segmental bridge construction and numerous segmental concrete bridges around the world have been successfully completed by this technique. Recent developments include high-strength concrete, lightweight concrete, and precast technologies that can reduce launching weight and further reduce construction duration. As a result of these and other advantages, expansion of this bridge construction technique and its applications are expected to continue.

## 6.7 References

(1) Rosignoli, M., “Launched Bridges: Prestressed concrete bridges built on the ground and launched into their final position”, American Society of Civil Engineers, ASCE Press, 1998.

(2) Rosignoli, M., *Bridge Launching*, Thomas Telford, 2002.

## TABLE OF CONTENTS

# Chapter 7:
# Special Requirements for Construction of Concrete Segmental Cable-Stayed Bridges

## 7.1 Introduction

Cable-stayed bridges have been increasingly successful for spans ranging between roughly 500 ft. long to over 3,600 ft long, with the longest concrete cable-stayed span being 1,740 ft. long (see **Figure 7.1** below). Modern bridges use multiple stay cables for ease of erection and to reduce the weight of the bridge superstructures. In addition, cable-stayed structures must consider additional dynamic effects such as the loss of a stay cable or dynamic wind effects on the structure., and these conditions can be addressed with closer stay cable spacing or a more rigid superstructure. Cable stayed bridge structures are, therefore, highly indeterminate and, as a result, stage construction phases are more critical than for conventional bridges. How closely the final constructed state of stresses in the structure matches the design intent depends greatly on the accuracy of construction.

***Figure 7.1 – Atlantic Bridge, Panama***
***(Photo Courtesy of SYSTRA IBT)***

The primary challenge in the design and construction of a cable-stayed bridge is that every stay that is installed affects every other stay that had been previously installed. This is schematically shown in **Figure 7.2** below.

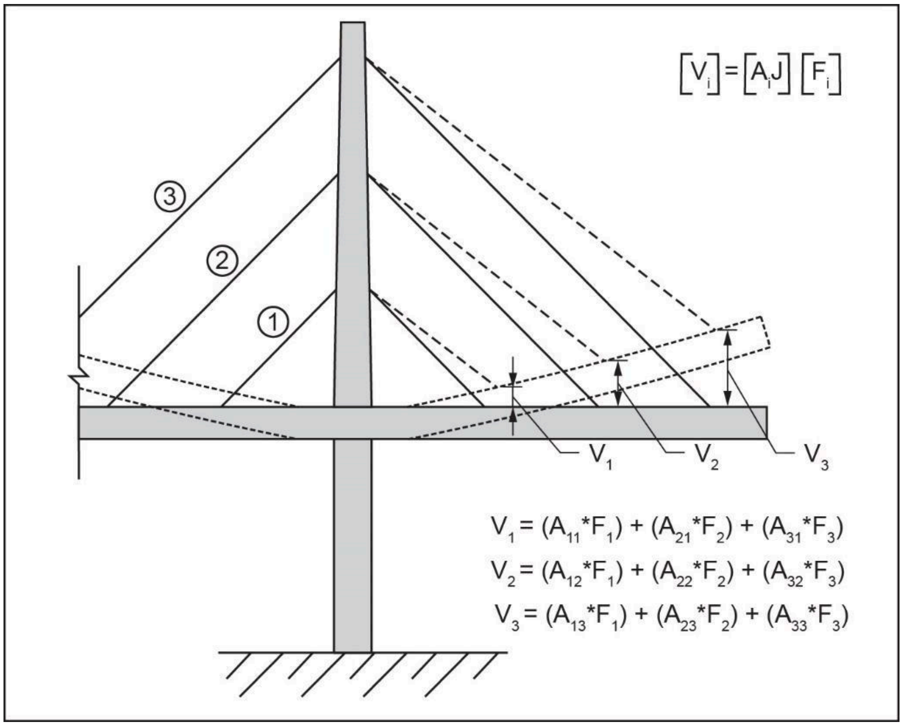


***Figure 7.2 – Stay Stressing Effects on Other Stay Cables***

Two analysis methods have historically been used to determine the necessary forces in the stay cables. The first is commonly referred to as De-Construction, where the final static configuration of the cable-stayed bridge is created and a Reverse Construction Process is done to determine the necessary stay cable forces when they are installed in order to achieve the final static configuration of the bridge. This more classical analysis method was commonly used on early cable stayed bridges, like the Pasco Kennewick Bridge shown in **Figure 7.3** below that was completed in 1978.

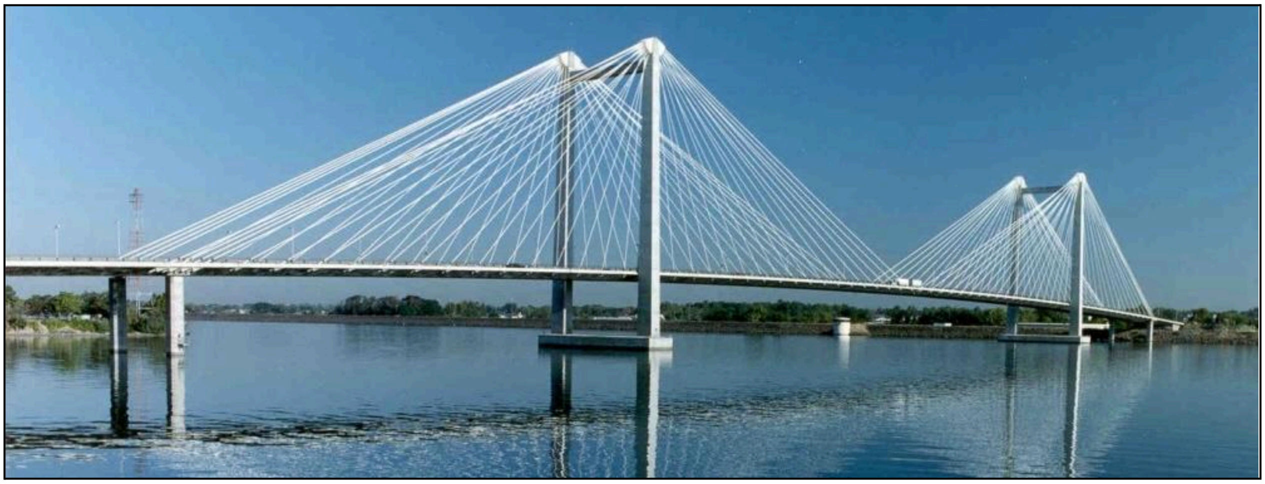


***Figure 7.3 – Pasco-Kennewick Bridge, Washington***
***(Photo Courtesy of Washington DOT)***

The second is commonly referred to as Forward Analysis, where an iterative Direct Construction Process is done to determine the necessary stay cable forces when they are installed in order to achieve a final static configuration of the bridge. A project's design criteria sets all of the requirements that the cable-stayed bridge must meet, both during construction and in its final in-service condition. The development of powerful computers that can utilize complex stage construction structural analysis programs over the last few decades has allowed this method to become the preferred method for cable-stayed bridge designers and construction engineers.

Concrete cable-stayed bridges offer a number of benefits to a project when compared to steel cable-stayed bridges. Concrete cable-stayed bridge superstructures are typically heavier than steel cable-stayed bridge superstructures, and this improves the aerodynamic stability of the bridge as it responds to the various dynamic wind effects on the structure. This also improves the fatigue performance of the bridge, particularly the stay cables, which enhances the service life of the bridge.

Concrete cable-stayed bridge superstructures are often stiffer than cable-stayed bridge superstructures made primarily with structural steel, and this reduces the amount the superstructure moves both during construction and over its service life. Smaller displacements during construction often result in more stable and safer worksite on the superstructure as it is constructed. It also reduces the number of necessary temporary superstructure supports and/or tie down cables needed to brace the superstructure to ensure its stability during construction. Smaller deflections during the service life of the bridge improves the bridge's response to transient loads (primarily from vehicle live loads and wind loads), which enhances user and pedestrian comfort during both normal operating conditions and more severe weather conditions.

Concrete cable-stayed bridges also reduce the number of specialty pre-fabricated elements needed to construct the cable-stayed superstructure. This often allows the contractor to build more of the superstructure with their own crews, which gives them more control over the quality of superstructure construction. It also reduces the contractors' dependence on specialty fabricators (which are often located far away from the bridge construction site), which allows the contractor to better control the construction schedule and budget and improves their ability to manage and/or reduce both schedule and budget risks.

The post-tensioning steel and rebar of the superstructure is also completely encased in the high strength and often high-performance concrete of the superstructure. Concrete cable-stayed superstructures are also post-tensioned in both the longitudinal and transverse directions. This compresses the concrete bridge deck in both directions, which significantly reduces any in-service cracking in the bridge deck as it responds to transient loads. This use of high performance concrete for the entire superstructure combined with post-tensioning it in both directions significantly reduces the chloride penetration into the structure, which increases the bridges durability and service life and makes it an ideal structure type for corrosive environments (i.e. coastal environments and northern environments that use large amounts or roadway salt during the winter months).

Once the initial choice of bridge superstructure material is made, the designer must decide on the construction method. If concrete has been selected, there are two main options for construction: precast segmental or cast-in-place with traveling forms.

Precast segmental construction fabricates precast concrete box sections and/or other concrete elements near or away from the bridge construction site and then erects them in their final position in the bridge's superstructure. Segments can be erected using either the balanced cantilever or uni-directional construction methods. Utilizing precast elements often shortens erection time, which shortens the overall construction schedule. Fabrication of the precast concrete box sections and/or elements in a casting yard also enhances the quality of the concrete construction and enhances the contractors' ability to control the curing conditions of the concrete that may have more complex thermal control plans. Wet joints and/or shims are typically needed to correct the precast superstructures geometry during construction because the geometry of the precast concrete box sections and/or other concrete elements were originally set in the casting yard, and onsite conditions different than those originally assumed often occur during construction.

Precast segmental construction is a very efficient choice if certain conditions are met:

- Site Access – Unless the superstructure is divided into twin box girders, the superstructure segments are often heavy (130-300 t). Heavy segments require easy access to the site, preferably by barge. For low-level bridges, a floating crane can erect the precast segments. For high-level bridges, it is easier to use a "beam-and-winch" method, in which a winch system on the deck lifts the segments off barges. If their weight is not excessive, segments can also be delivered from the top or hung beneath the deck.

- Initial Investment – Manufacturing large precast segments requires a significant initial investment in a casting yard, molds, and lifting equipment. This is justifiable when a sufficiently large number of segments are built.

Because of these constraints, most precast concrete cable-stayed bridges are relatively long or have a cross-section for the approach spans superstructure that has been extended into the main span. Some examples include the Varina-Enon Bridge (**Figure 7.4**), Korean War Veterans Memorial Bridge (**Figure 7.5**), and Veterans' Glass City Skyway (**Figure 7.20**).

Cast-in-place with traveling forms constructs the superstructure in its final position and also uses either balanced cantilever or uni-directional construction methods. This method eliminates the need for a dedicated fabrication facility for the project and reduces the size of construction equipment needed to transport materials to the portion of the superstructure being constructed. The erection time is typically longer than precast segmental construction because it is controlled by the curing time needed for each new bridge segment, and controlling curing conditions can be more difficult on site. However, the geometry of the superstructure can often be better controlled and adjusted to onsite conditions that differ from those that were originally assumed when the original casting curve was created because the geometry of each successive segment cast on site can be adjusted and the casting curve can be updated as necessary.

Cast-in-place with traveling forms is a very efficient choice if the following conditions are met:

- Proximity to Ground and Shore – Erecting the entire superstructure sometimes high above the ground and miles from shore can create challenges for supplying all of the necessary material to the tips of the cantilevers as they are constructed. Material supply plans need to be developed and carefully thought through to ensure construction material (particularly wet concrete) is delivered efficiently and safety as each new segment is constructed. These plans also need backup plans to ensure construction operations can continue if equipment fails or breaks down.

- Control of Cantilever Tip Loads – Traveling forms for cable-stayed bridges are often heavy pieces of equipment (200-500 t) that are placed at the ends of the cantilevers to create a place for the next cantilever segment to be built, and supports the wet concrete until it has cured to sufficient strength. Because of the flexibility of cable stayed superstructures, these heavy loads can induce significant temporary forces and deflections on the bridge that need to be considered in the construction analysis of the bridge.

Often, cast-in-place cable-stayed bridges have a cross section that is optimized to minimize weight and best managed the stage construction forces during construction. Some examples include the Centennial Bridge (**Figure 7.21**), the Tilikum Crossing (**Figure 7.22**), and the Sidney Lanier Bridge (**Figure 7.24**).

Every cable-stayed bridge has project-specific provisions related to the unique aspects of cable-stayed construction, but most reference the Post-Tensioning Institute's (PTI) "Recommendations for Stay Cable Design, Testing, and Installation," (referred to in this chapter as "Recommendations"). For a more complete understanding of the typical specific requirements for stay cables, this chapter of the Construction Practices Handbook should be read in conjunction with the PTI Recommendations.

*Figure 7.4 – Varina-Enon Bridge, Virginia*
*(Photo Courtesy of FIGG)*

*Figure 7.5 – Korean War Veterans Memorial Bridge, Delaware*
*(Photo Courtesy of FIGG)*

## 7.2 Cable-Stayed Structure

A cable-stayed bridge structure is comprised of three main components: pylon, deck, and stay cables. It can be thought of as a triangular truss, with the deck as the bottom chord (**Figure 7.6**). The stay cables are stressed at the time of erection to balance the weight of the deck. For subsequent loading conditions, the stay cables act as passive structural members, like the pylon and the deck.

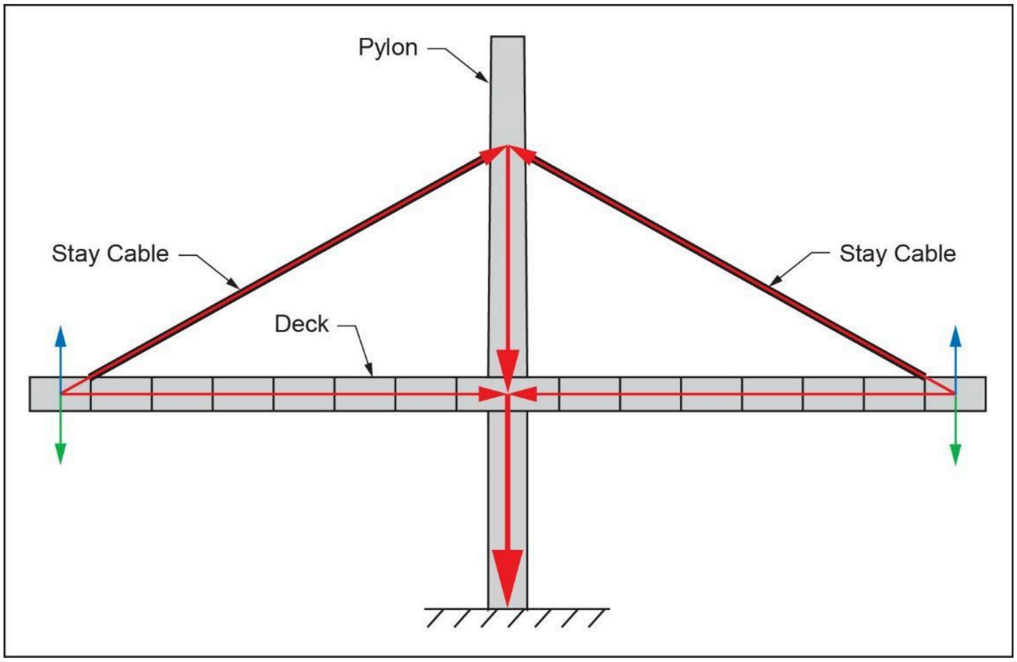


*Figure 7.6 – The Triangular Structure: Deck-Pylon-Stay Cables*

A cable-supported structure is often idealized as a beam on elastic supports (**Figure 7.7**). The stay cables can be idealized as springs that are "pre-compressed" at the time of assembly to provide adequate support to the deck without excessive bending. The amount of pre-compression and associated axial force is essential in determining the stresses at the end of construction. Typically, the designer balances the dead load shear with the stay cable forces to limit bending stresses in the superstructure, pylon bending and global deflections. Stay cable forces can also be adjusted to counteract bending due to long-term effects, superimposed dead loads, or live loads.

***Stays = Springs Pre-Compressed at Time of Assembly***

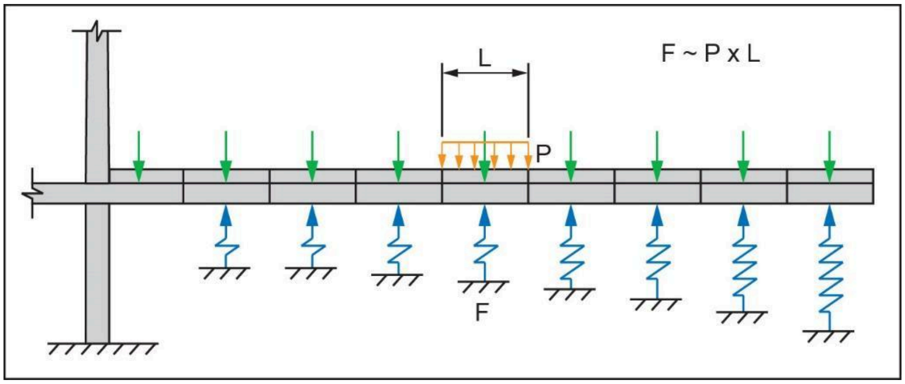


*Figure 7.7 – The "Beam on Elastic Supports" Analogy*

### 7.2.1 Cable-Stayed Bridge Superstructure

Modern concrete cable-stayed bridges are categorized as one of two types, based on superstructure.

1) "Rigid" Superstructure – These are superstructures whose bending stiffness is similar to or higher than the vertical stiffness of the stay cables. This includes box girders, which are used when

high torsion rigidity is required (e.g., when the structure is supported with a centralized, single plane of stay cables) or to improve aerodynamic stability.

2) “Flexible” Superstructure – These are superstructure types that are more flexible in bending than the vertical stiffness of the stay cables. It may be necessary to use two or more planes of stay cables support the superstructure to provide resistance to torsion.

The ratio of inertia between rigid and flexible concrete superstructures can be as much as 10:1 (**Figure 7.8**). A flexible deck tolerates imposed deflections more easily but is more sensitive to instability under high compression loads and is more susceptible to cracking. The dead load of the two structure types is usually equivalent.

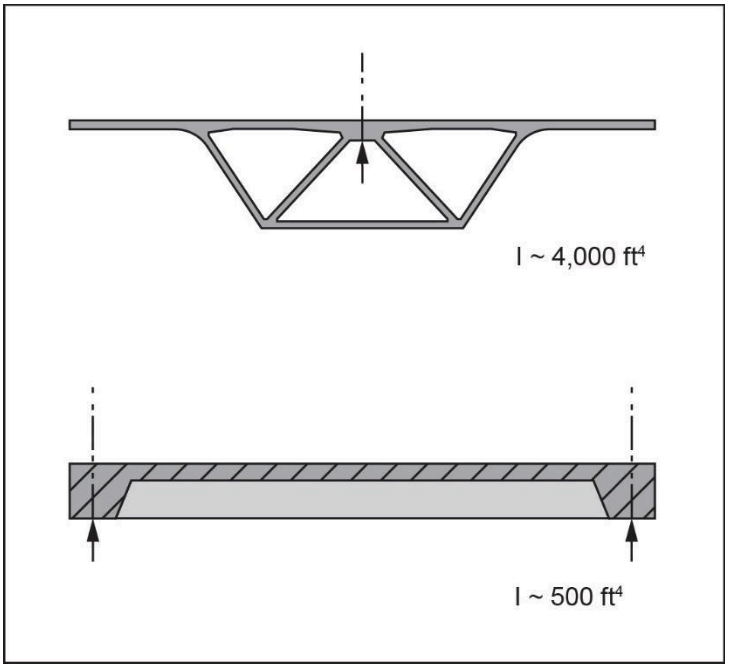


***Figure 7.8 – Deck Rigidity***

Both rigid and flexible concrete cable-stayed superstructures can be constructed using the precast segmental or cast-in-place with traveling forms construction methods. Additionally, both types of concrete cable-stayed superstructures can be connected to the towers/pylons by either a fixed connection (i.e. the superstructure is cast monolithically with the towers/pylons) or a flexible connection (i.e. the superstructure is supported by bearings and/or restrainers on the towers/pylons). The type of superstructure, construction method and superstructure to tower/pylon connecting is often determined by the designer.

### 7.2.2 Cable-Stayed Bridge Towers/Pylons

The terms “towers” and “pylons” are often interchangeable with respects to cable-stayed bridges. However, a generally accepted distinction between the terms is that a “pylon” is a single vertical structural element at the foundation that transfers the loads from the superstructure and stay cables directly to the foundation, and a “tower” contains two (or more) vertical structural elements that transfer the loads from the superstructure and stay cable to the foundation(s) through a frame action. A wide variety of tower and pylon configurations have been developed by different designers, and **Figure 7.9** shows a few examples that have been developed for concrete cable-stayed bridges.

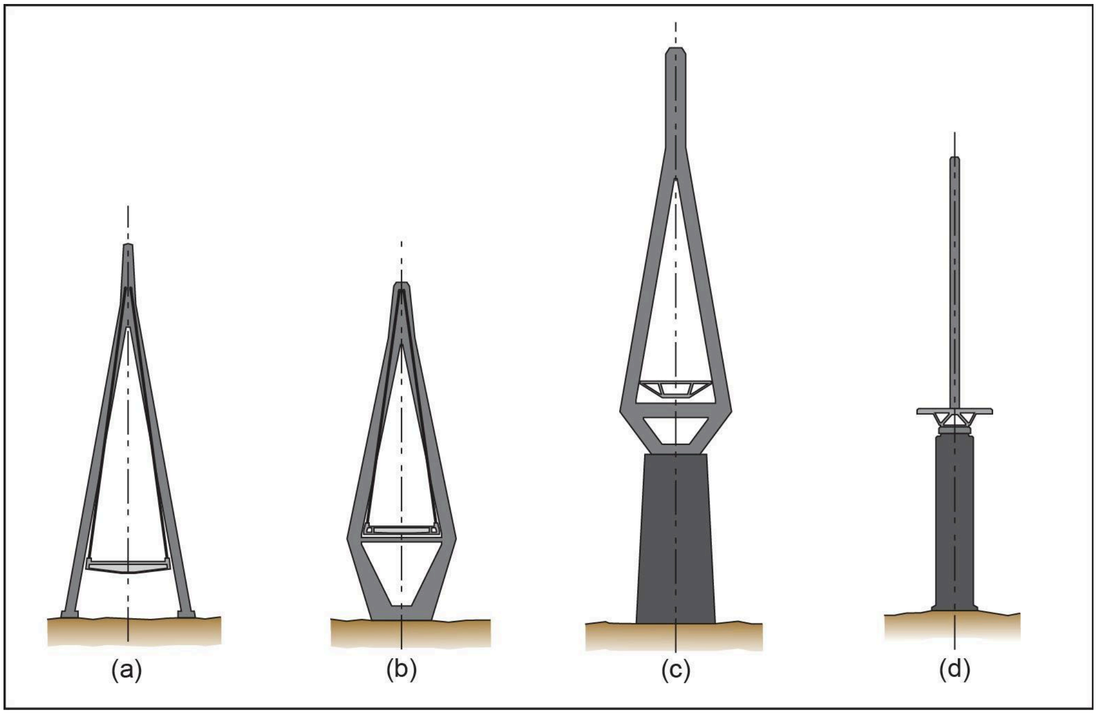


***Figure 7.9 – Examples Cable-Stayed Bridge Towers and Pylons: (a) A-Frame Tower, (b) Diamond Tower, (c) Modified Diamond/Delta Pylon, (d) Single Pylon***

Towers and pylons for concrete cable-stayed bridges will typically be made of concrete. The primary reason for concrete cable-stayed bridges needing to have concrete towers or pylons is the high level of structural stiffness needed in them to adequately support the concrete superstructure through all phases of construction and in its final in-service condition. Equivalent steel tower and pylon cross sections are generally made up of steel plates that are fractions of an inch to a few inches thick, and this results in tower and pylon cross sections that are much more flexible than concrete towers and pylons whos' walls are often feet thick. Although the steel towers and pylons are able to meet the necessary strength requirements, their flexibility introduces a number of challenges in meeting tension and compression requirements in the concrete superstructure (particularly during cantilever construction). This often leads to the use of higher concrete strengths and the addition of more post-tensioning in the concrete superstructure to meet stress requirements. More steel plates and/or thickening of steel plates in the steel towers or pylons are also needed to add stiffness, and additional supports, braces and/or tie-down cables are also needed to support the concrete superstructure.

Concrete towers and pylons will often contain elements that are heavily reinforced with large diameter mild reinforcing steel bars in combination with large amounts of post-tensioning tendons and/or bars for certain elements. The elements of the towers and pylons can be constructed using large forming systems for cast-in-place construction, or precast offsite and erected into their final position in the bridge.

### 7.2.3 Stay Cables

The stay cables in a concrete cable-stayed bridge are the primary structural elements that support the superstructure by connecting the superstructure directly to the towers/pylons. Longitudinally there are three basic arrangements of stay cables that are as follows:

1) Harp – Resembling the musical instrument, all stay cables are parallel to each other, having the same inclination angle, and their anchorages are equally spaced along the superstructure and supporting tower/pylon (See **Figures 7.4** and **7.5** for examples).

2) Fan – The angles of the stay cables vary from stay cable to stay cable, with the shorter stay cables anchoring in the superstructure near the tower/pylon being at steeper inclination angles and the longer stay cables anchoring in the superstructure far away from the tower/pylon being at shallower inclination angles (See **Figures 7.1** for an example).

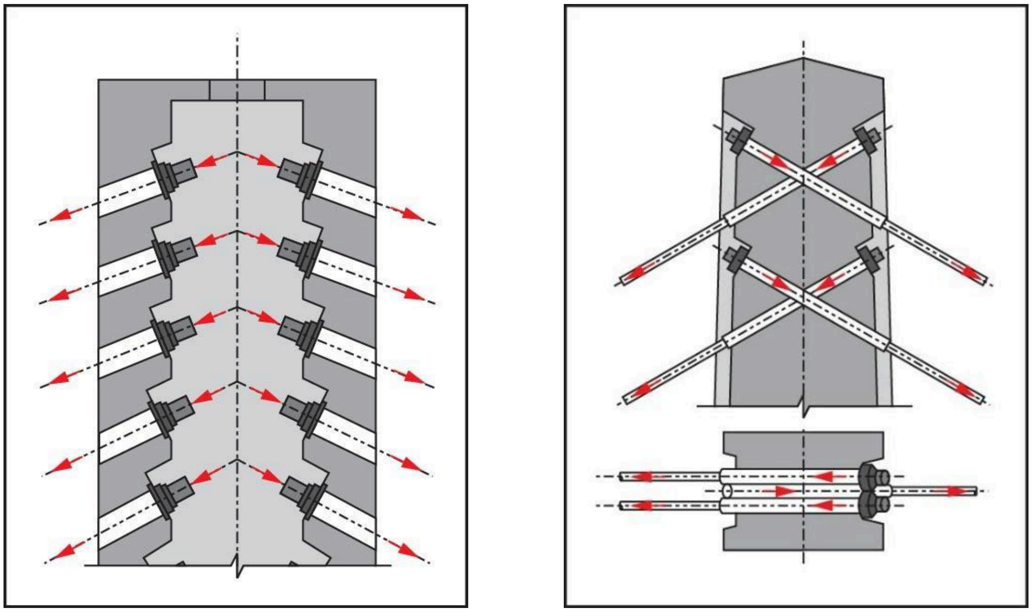
3) Radiating – In this arrangement, all stay cables converge at a common point at or near the top of the tower/pylon, resulting in an almost vertical inclination angle of the stay cables anchoring in the superstructure near the tower/pylon (See **Figures 7.3** for an example).

One or two planes of stay cables are commonly used to support the superstructure of a cable-stayed bridge, anchoring to either the middle or edges of the superstructure. However, three or more planes of stay cables have been used on cable-stayed projects with very wide bridge decks.

The inclined angle of the stay cables creates both a vertical force to support the superstructure, and a horizontal force towards the tower/pylon that is resisted by the superstructure. In steel cable-stayed bridges, these horizontal forces create buckling forces that a steel superstructure must resist with thicker plates and/or additional stiffener plates. However, in concrete cable-stayed bridges, these horizontal forces add compressive forces to the concrete superstructure that increases the concrete superstructures' capacity and ability to resist tensile forces. These horizontal forces from the stay cables also reduce the amount of longitudinal post-tensioning needed in the concrete superstructure that results in a more efficient design.

### 7.2.4 Towers/Pylons Anchorages

Two primary methods are used to secure the stay cables to the towers/pylons, and those are Terminal Anchors and Saddles. Terminal Anchors secure the stay cables directly to the towers/pylons, typically on the inside of the hollow cross section of the tower legs/pylon. The stay cables are not continuous though the tower legs/pylons, and this results in large tensile forces in the sides of the tower legs/pylons that need to be resisted with the addition of more reinforcing bars, post-tensioning bars and/or cast in structural steel members. One method that has been developed to mitigate these large tensile forces is to anchor the stay cables on the opposite faces of the tower legs/pylons, and this then compresses the tower legs/pylons together instead of trying to pull them apart. Both tower/pylon terminal anchor configurations are shown in **Figures 7.10** and **7.11** below.



*Figures 7.10 and 7.11 – Typical Stay Cable Tower/Pylon Terminal Anchors*

Saddles allow the stay cables to pass uninterruptedly through the tower legs/pylons, and each end of the stay cables are then anchored to the superstructure in the adjacent spans. In this configuration the stay cables are continuous through the tower legs/pylons, which eliminates any horizontal tensile or compressive forces in the tower legs. Saddles also impart radial compressive forces down into the tower legs/pylons. This configuration is shown below in **Figure 7.12**.

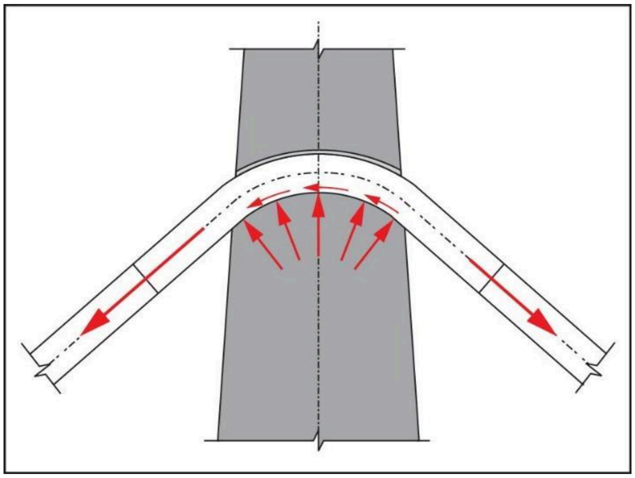


*Figure 7.12 – Typical Stay Cable Tower/Pylon Saddle*

Because both ends of a stay cable are anchored in the superstructure when a saddle is used in the tower legs/pylons, the stay cable can only be stressed at the superstructure. Alternatively, when terminal anchors are used in the tower legs/pylons, the stay cables can be stressed either at/inside the tower leg/pylon or at the superstructure.

### 7.2.5 Deck Anchorages

The Deck Anchorages connect the stay cable to the superstructure. For concrete cable-stayed bridges, there are two primary methods used to connect the stay cable to the concrete superstructure. The first method is for the stay cable to pass through the main longitudinal superstructure girder (commonly referred to as an edge girder in a cable-stayed bridge with two planes of stay cables), and anchors at the bottom of the edge girder. This type of connection allows the loads from the bridge deck to be transferred to the edge girders (commonly through transverse floor beams) and directly into the stay cables without the use of specialized elements to connect the stay cables to the edge girders. **Figures 7.13** shows this type of deck anchorage.

*Figure 7.13 – Typical Edge Girder Anchorage, Charles W. Cullen Bridge, DE*
*(Photo Courtesy Delaware DOT)*

The second method is for the stay cable to pass through an anchor block (typically located at the bridge deck), and anchors in the bottom of the anchor block. Loads from the bridge deck are transferred to the anchor block through a transverse framing system in the concrete superstructure. Anchor blocks can be used in concrete cable-stayed bridges with a single plane of stay cables or multiple planes of stay cables. **Figures 7.14** shows this type of deck anchorage.

***Figure 7.14 – Typical Anchor Block, Veterans' Glass City Skyway, OH***
***(Photo Courtesy of FIGG)***

Construction access, equipment and material delivery to the ends of the stay cables (particularly the stressing ends) needs to be carefully planned early on in order to develop efficient and safe stay cable installation operations.

## 7.3 Critical Construction Phases

As noted in the chapter introduction, cable-stayed bridges are indeterminate structures, with multiple possible combinations of stay forces and deck stresses when construction is complete. Additionally, construction may span several months, exposing the partially completed structure to significant loads from construction and environmental loadings. For these reasons, it is vital to have a fully engineered construction analysis performed by a construction engineer (who may or may not be the designer). The analysis should include each stage of construction, with variable loads applied appropriately throughout.

To ensure the designer's intent is achieved in the final bridge, realistic assumptions about the construction procedure should be made in the design of the bridge. These should be communicated to the contractor through clear plans and specifications. Important information the bridge plans should address include:

1) The final state of the structure at the end of construction -- This includes the geometry of the deck and towers, the forces in the stay cables, and the state of stress in the deck, pylons, and key members (bearings, tie-downs, foundations) as applicable.

**2)** Realistic loads during erection -- Typically, the loads center around the weight of the primary lifting equipment (the gantry) or form travelers. Designers should base weights on equipment used on previous projects.

**3)** Realistic assumptions about staging -- Generally, requiring significant simultaneous operations on both sides of the pylon is unrealistic or leads to excessive cost. The designer should provide reasonable capacity for unbalanced operations whenever possible.

**4)** Realistic assumptions for temporary supports – Cable stayed bridge often use temporary superstructure supports to control construction forces and deflections during erection that are typically designed by the contractor. Designers should provide the assumed stiffnesses used (compression and tension as applicable), and those assumed stiffnesses should be based on similar temporary supports used on previous projects.

**5)** Design criteria during erection -- This applies to loads, as well as performance criteria. Concrete decks are frequently only lightly pre-stressed, or not pre-stressed at all, at the beginning of each cycle. Clear design criteria, particularly for allowable tension in the concrete for all stages, should be established.

### 7.3.1 Deck and Stay Cable Stresses

It is essential that all erection phases be reviewed to ensure that stresses remain within allowable limits at each construction stage.

A typical erection cycle for a concrete segmental cable-stayed bridge consists of alternately erecting or pouring segments and stressing the stay cables. At the time of segment lifting or pouring (**Figure 7.15**), critical stresses are usually reached, meaning:

- Maximum negative bending in the deck.
- Maximum tension in the last erected stay cable (maximum allowable 0.65 GUTS under factored construction combinations).

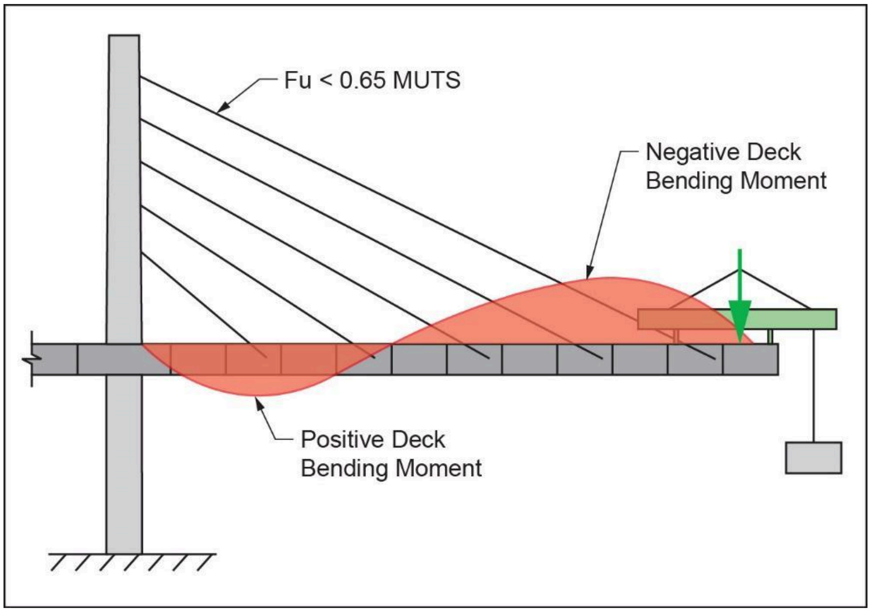


*Figure 7.15 – Critical Deck Bending During Construction*

Rigid superstructures better distribute the loads among the previously erected stay cables, reducing the negative moment in the deck while pouring or lifting segments. Precast segment lengths are typically shorter than cast-in-place, to limit segment weights and allow them to be trucked. If shorter segments are used, stay cable spacing is often set at two or three segment lengths to allow re-stressing of the stay cable between lifts and further reduce the moments in the deck. Stay cable forces and deck bending moments during construction are more critical when heavier erection equipment, such as a crane, is on deck. **Figure 7.16** provides an illustration. **Figures 7.17 through 7.21** are photographs showing the various stages of construction for several rigid superstructure concrete cable-stayed bridges.

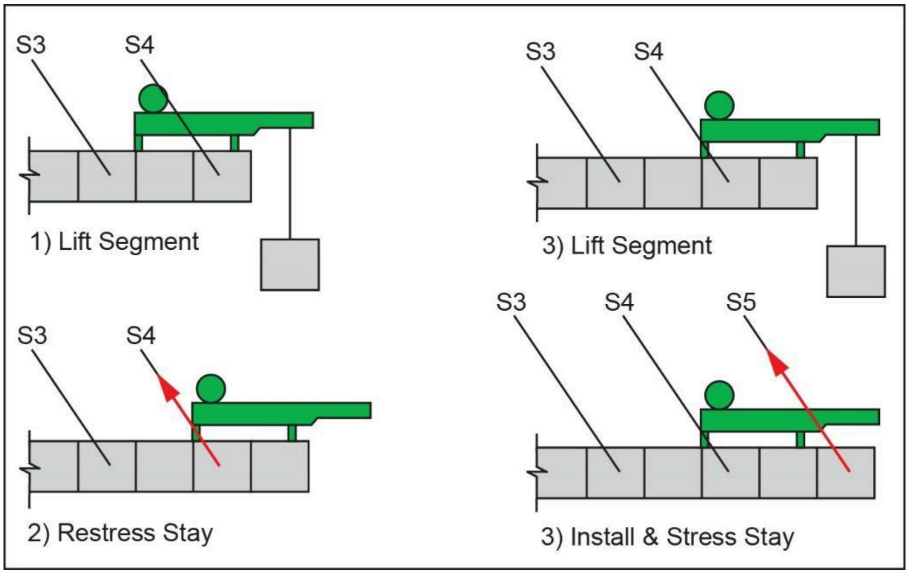


*Figure 7.16 – Typical Erection Phases*

***Figure 7.17 – Hodariyat Bridge, Abu Dhabi***
***(Photo Courtesy of SYSTRA IBT)***

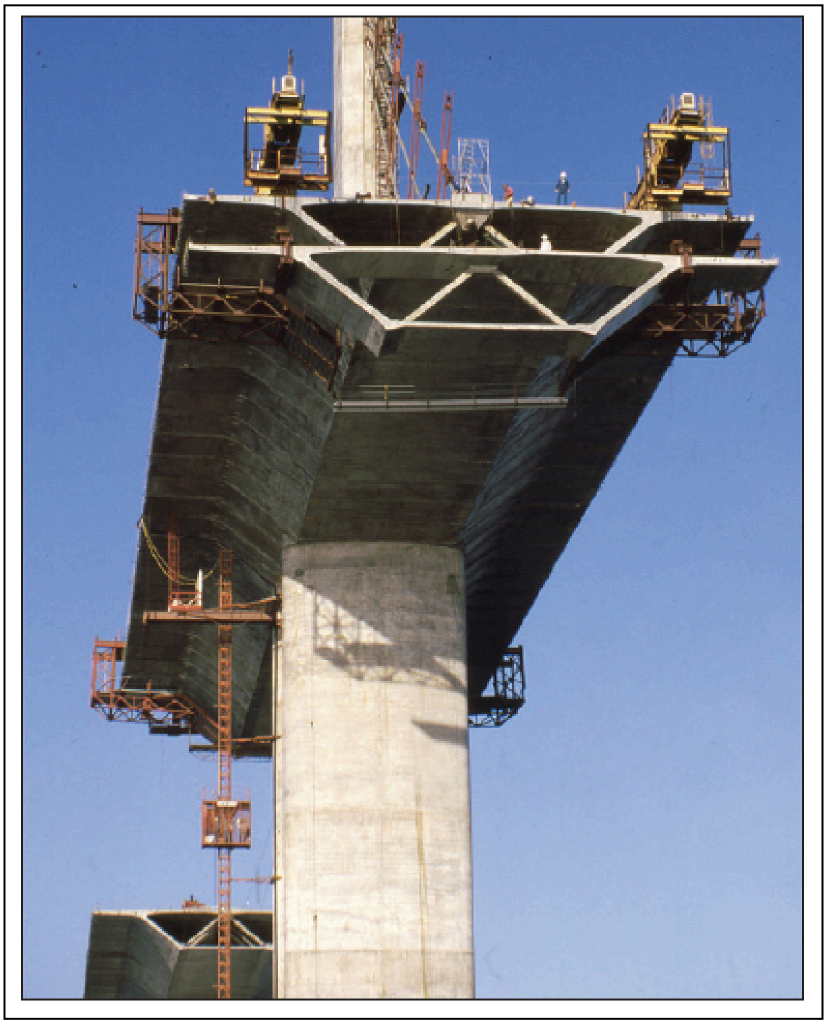


***Figure 7.18 – Sunshine Skyway, Florida***
***(Photo Courtesy of Figg & Muller Engineers)***

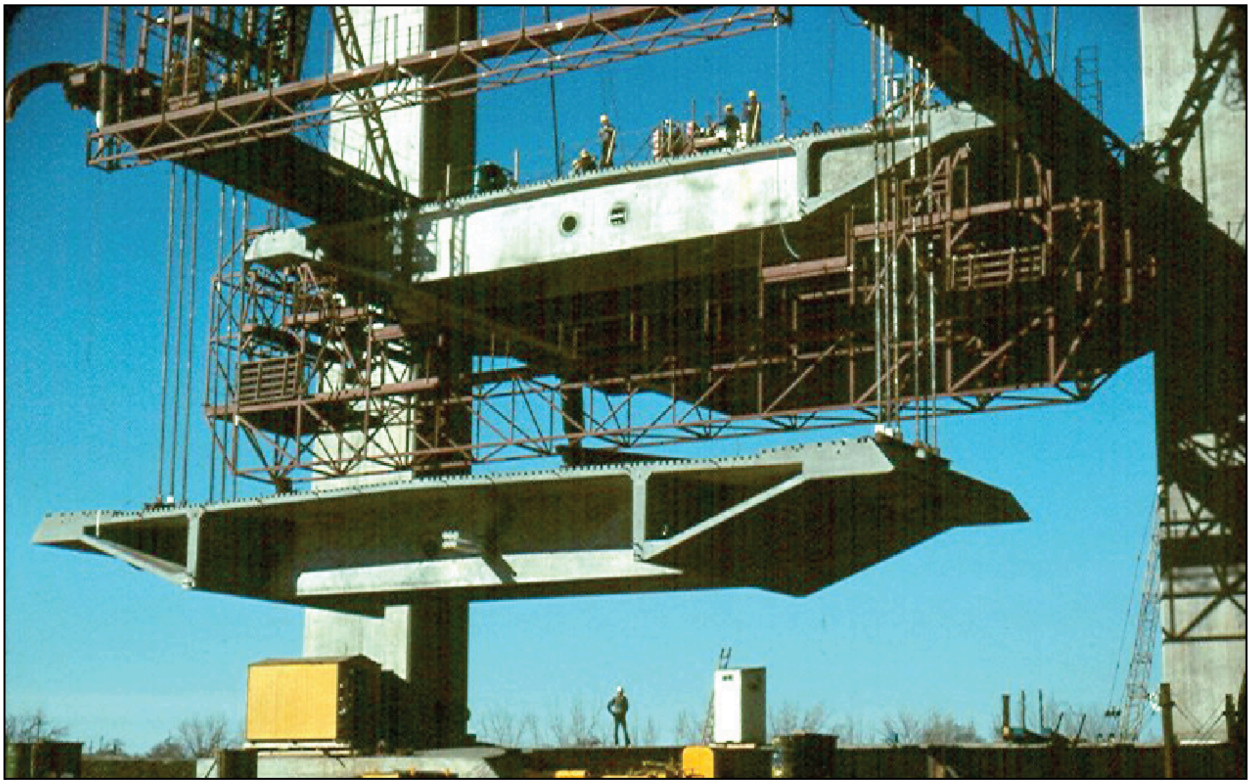


***Figure 7.19 – Pasco-Kennewick Bridge, Washington***
***(Photo Courtesy of David Goodyear)***

***Figure 7.20 – Segments Delivered Over Deck, Veterans' Glass City Skyway, OH***
***(Photo Courtesy of Bilfinger & Berger)***

***Figure 7.21 – CIP Box Girder with Traveler, Centennial Bridge, Panama***
***(Photo Courtesy of Bilfinger & Berger)***

Flexible superstructures, on the other hand, provide less resistance in distributing construction loads to previously erected portions of the bridge. Moments and stresses in previously installed stay cables must be reduced, since the long, unsupported cantilever can cause cracking under negative bending. One method is to connect the stay cable to the traveling form and partially stress it prior to pouring the segment. Alternatively, each long segment can be cast in two cycles, with an intermediate temporary stay attached after the first cycle to reduce stresses. **Figures 7.22 through 7.25** are photographs showing the various stages of construction for several flexible superstructure concrete cable-stayed bridges.

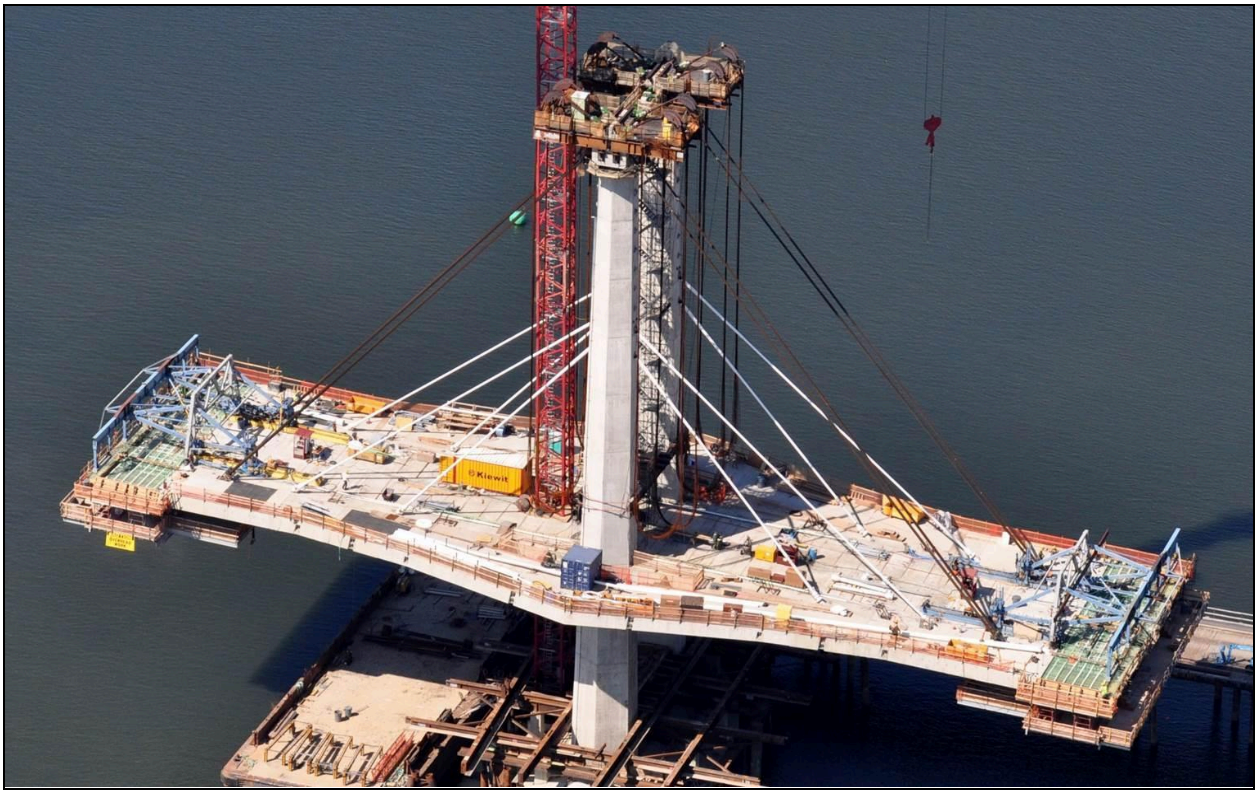


***Figure 7.22 – CIP Edge Girder with Traveler and Temporary Stay Used to Control Forces, Tilikum Crossing, OR***
***(Photo Courtesy of Kiewit)***

***Figure 7.23 – CIP Edge Girder with Traveler, La Plata River Bridge, Puerto Rico***
***(Photo Courtesy of Las Piedras Construction)***

*Figure 7.24 – Sidney Lanier Bridge, Georgia*
*(Photo Courtesy of Bob Webster)*

*Figure 7.25 – Traveling Forms on Shoring for Edge Girders, Puente de la Unidad, Mexico (Photo Courtesy of VSL Mexico)*

### 7.3.2 Unbalanced Loads

Overall stability of the partially completed bridge is critical during each stage of construction. Cable-stayed structures are usually built by the balanced cantilever method. The cantilevers can reach exceptional lengths, making asymmetrical wind conditions on either side of the pylon more likely. Asymmetrical dead loads can also result in critical moments in pylons and foundations.

The main loads to consider for overall stability during construction are:

- Unbalanced Segments
- Unbalanced Dead Loads
- Unbalanced Horizontal and Vertical Winds
- Unbalanced Construction Loads

At ultimate conditions, the dynamic effects of losing a segment and/or erection equipment on one cantilever and/or seismic loadings also must be considered.

Load combinations for checking stability during construction can be found in AASHTO LRFD Sections 3 and 5, as applicable. Static wind loads from AASHTO LRFD cannot be used alone, as dynamic effects and the resulting buffeting loads may be significant. Horizontal and vertical wind loads should be developed through wind tunnel testing or analytical wind studies and take into account the dynamic properties of the completed bridge. **Figure 7.26** provides an illustration of these loadings and **Figure 7.27** shows a scaled aeroelastic model of a bridge used for wind tunnel testing.

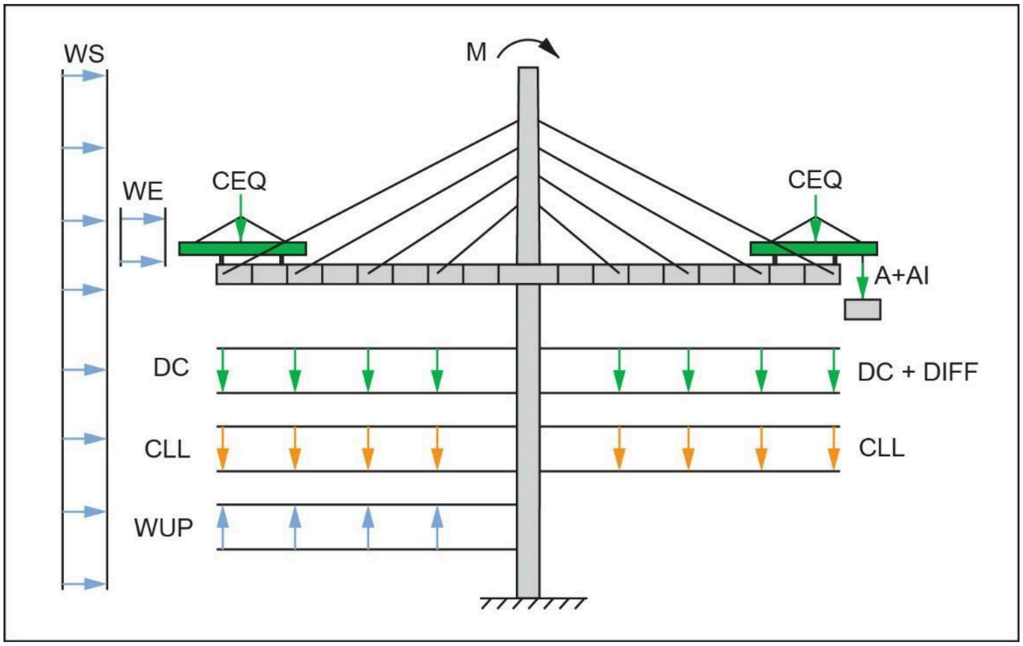


*Figure 7.26 – Unbalanced Loads*

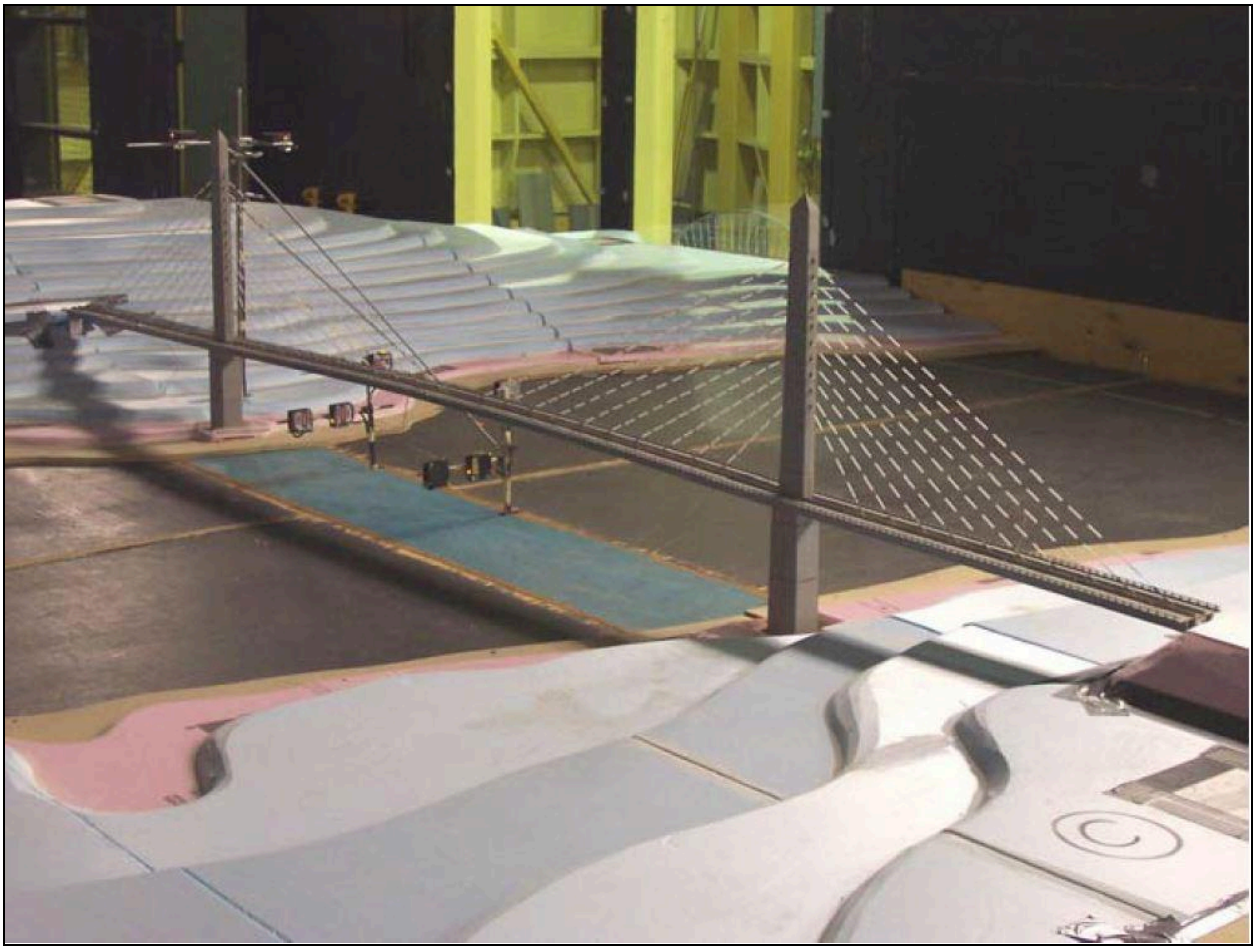


*Figure 7.27 – Scaled Aeroelastic Model of the Penobscot Narrows Bridge*
*(Photo Courtesy of Boundary Layer Wind Tunnel Laboratory)*

The aerodynamic stability of the structure during construction must also be checked as shown in **Figures 7.28** and **7.29**. Favorable deck damping helps aerodynamic stability. The length-to-width and width-to-thickness ratios influence the structure's behavior under wind conditions as shown in **Figure 7.30**. The "flutter" effect is avoided with a proper torsion-to-bending rigidity ratio as shown in **Figure 7.31**. Streamlining the deck, by using fairings along the edges or other means, also improve aerodynamic stability during construction. Temporary fairings during construction may be a practical solution even if not required in the final condition.

### *Wind on Long Cantilevers*

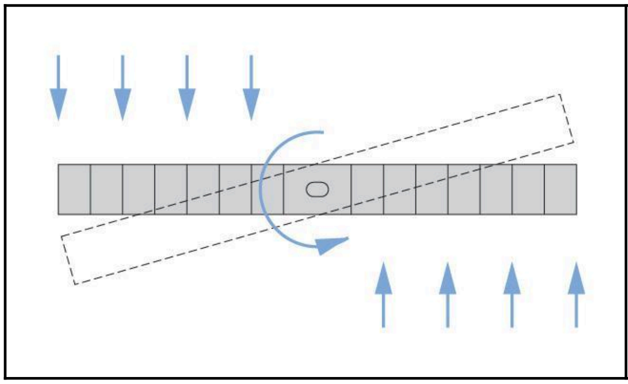


***Figure 7.28 – Horizontal Yawing***

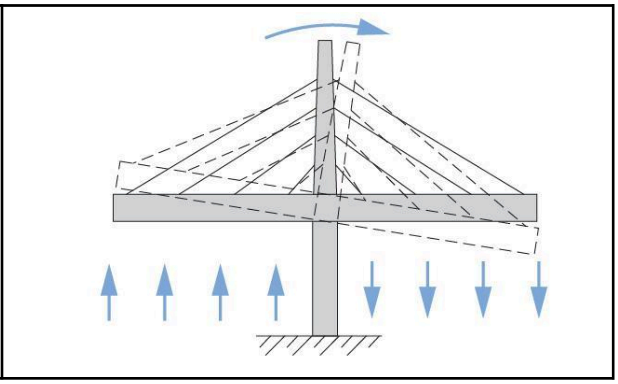


***Figure 7.29 – Vertical Rolling***

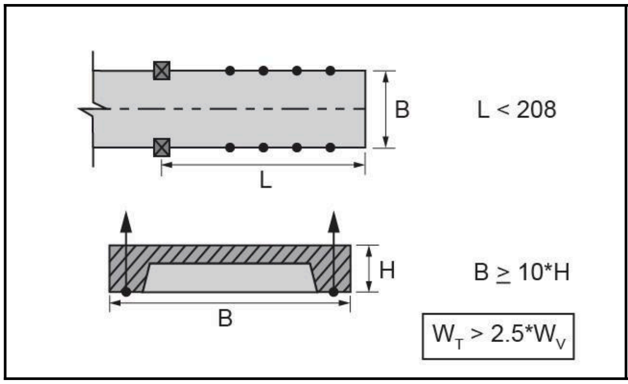


***Figure 7.30 – Aerodynamic Stability***

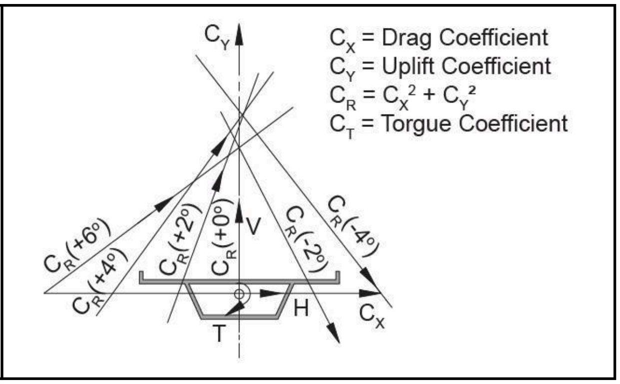


***Figure 7.31– Aerodynamic Coefficients***

The main goals of the wind tunnel testing are to:

- Verify the stability of the deck both during construction and in its final in-service configuration.
- Development of the buffet loads – which is the dynamic amplification of the static wind loads.
- Development of the Wind Loads during construction, which may have a very different behavior than the final in-service configuration of the bridge.
- Development of the damping recommendations to mitigate stay cable vibration.

Below are listed several ways to resist unbalanced loads during construction.

- Design a moment-resisting pylon, such as one with twin walls.
- Anchor temporary cables from the deck anchors into the pylon foundation to reduce moments in the pylon section at deck level.
- Connect temporary cables from outside anchors to temporary foundations to reduce

moments in the pylon foundation and control buffeting in the superstructure.

- Use temporary cables connecting from the top of the pylon to temporary foundations, thus reducing unbalanced moments in both the pylon and foundation.
- Connect temporary towers or bents to outside anchors in the superstructure to reduce moments in the pylon and foundation, and to improve stability during construction.
- Connect temporary stay cables from the top of the pylon to the leading edge of the cantilever to reduce moments at the ends of the cantilever when new bridge segments are lifted or cast.

Refer to Figures **7.32** through **7.38** for illustrations and photographs of some of these methods.

If temporary cables, restraints and/or towers/bents are used to control loads and deflections during construction, they need to be incorporated into the incremental erection model. This is done to ensure that the demands on them are not allowed to exceed the anticipated limits in the temporary members, and that the anticipated capacity of the permanent structure is not exceeded during each stage of construction.

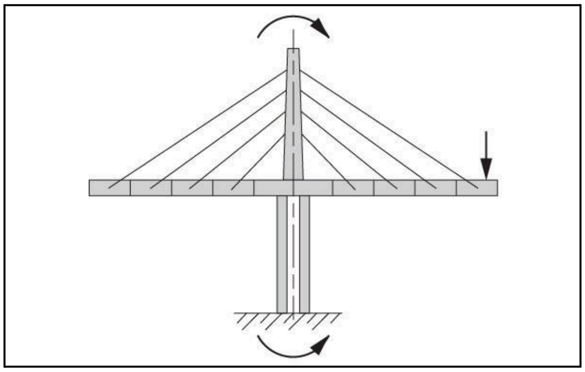


*Figure 7.32 – Moment-Resisting Pylon*

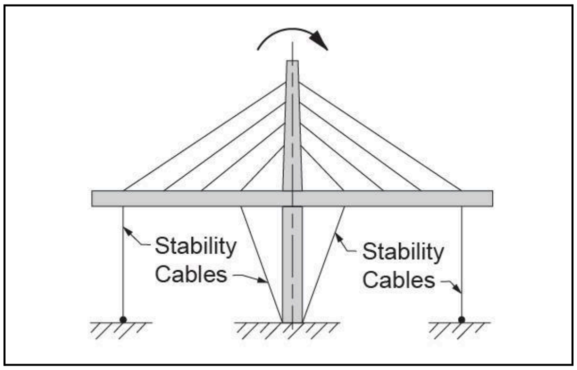


*Figure 7.33 – Stability Cables During Construction*

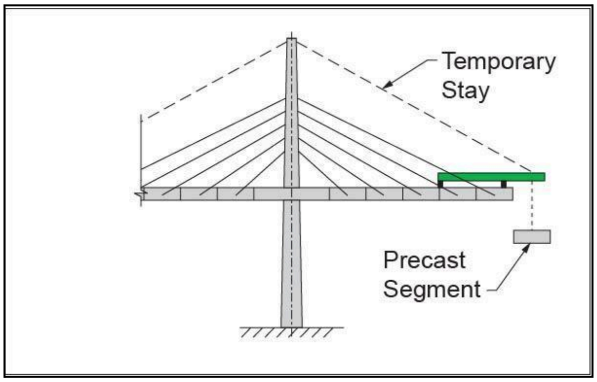


*Figure 7.34 – Temporary Stay*

***Figure 7.35 – Twin Wall Pier Pylon, Sunshine Skyway, FL***
***(Photo Courtesy of Figg and Muller Engineers)***

***Figure 7.36 – Pylon Stabilizing Cables, East Huntington Bridge, WV***
***(Photo Courtesy of David Goodyear)***

*Figure 7.37 – Temporary Backspan Bent, Veterans Memorial Bridge, TX*
*(Photo Courtesy of FIGG)*

***Figure 7.38 – Superstructure Stabilizing Cables, Sidney Lanier Bridge, GA (Photo Courtesy of FIGG)***

### 7.3.3 Other Critical Construction Loads

Plan view horizontal distribution of stay cable forces, sometimes called **Shear Lag**, must be considered during all phases of construction. Each construction phase should be checked for shear lag by calculating the spread of the horizontal component of the stay cable force into the section, with the vertical component effectively applied at the stay cable anchorage. This often reveals the need to add post-tensioning to the areas of the section furthest from the anchorage. See **Figure 7.39** for an illustration of shear lag.

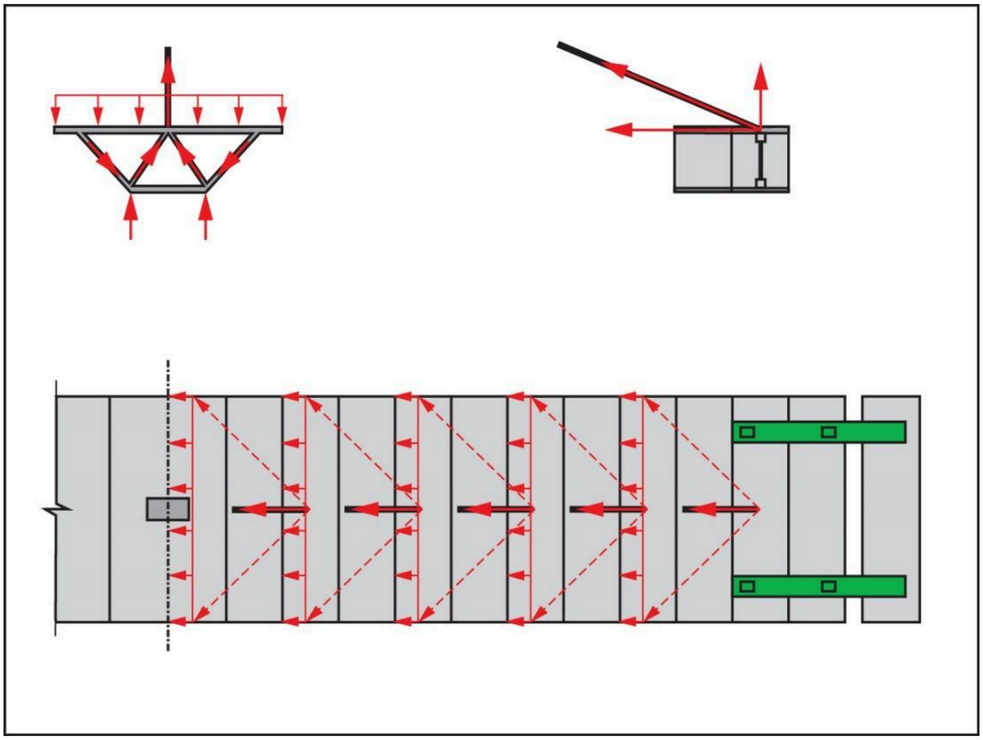


*Figure 7.39 – Shear Lag During Construction*

**Entrainment** may occur when compatibility tension is created behind the anchorage by stays that are stressed on a continuous structure, such as back spans that are pre-staged on falsework or temporary bents. This is analogous to intermediate pre-stressing anchorages as described in AASHTO LRFD Section 5. The effects must be accounted for analytically, and sufficient compression applied to prevent excessive tension behind the stay cable anchorages. **Figure 7.40** provides a photograph of a construction sequence with potential for entrainment.

***Figure 7.40 – Complete Back Span on Falsework – Potential for Entrainment, Charles W. Cullen Bridge, DE (Photo Courtesy of AECOM)***

**Stay cable vibration** can occur during construction when the periods of vibration of the stay cables and the partially completed deck are similar.

Stay cables are also sensitive to wind/rain-induced vibrations during construction and in service (see PTI Recommendations, Art. 5.2).

These vibrations must be studied carefully during design, and wind tunnel tests should be performed to evaluate possible countermeasures including:

- Hydraulic dampers at deck level and/or at the pylon level.
- Specially designed stay cable pipes with helixes or dimples to limit the influence of rain on stay cable vibrations.
- Steel ropes that connect stay cables to change their vibration frequency.

Not all of these may be practical during staged construction, but the risk of vibration should be understood, and suitable temporary control measures are made available.

### 7.3.4 Saddle Friction Forces

Unbalanced loads are also critical for stay cable anchorage saddles, which deviate the cables across the pylon without interruption. Early saddle systems installed all of the strands in a stay cable at once in one large single pipe in the pylon and stressed all of the strands together using large hydraulic jacks (similar to how external tendons are stressed through deviator pipes). Modern saddle systems install and stress each individual strand in a stay cable separately in their own pipe that is contained in the saddle pipe within the pylon. Saddles typically rely on friction or bond to transfer any unbalanced horizontal loads to the pylon. Sufficient friction must be provided between stay cables and saddle pipes to resist unbalanced loads with an acceptable safety factor (as per PTI Recommendations). This can be critical during early stages of installation, when tension in the cable may be relatively low. **Figures 7.41** provides an illustration of the necessary friction between the stay cable and pylon to resist unbalanced loads. **Figures 7.42** and **7.43** provide photographs of a prefabricated saddle prior to installation and an installed saddle with strands installed.

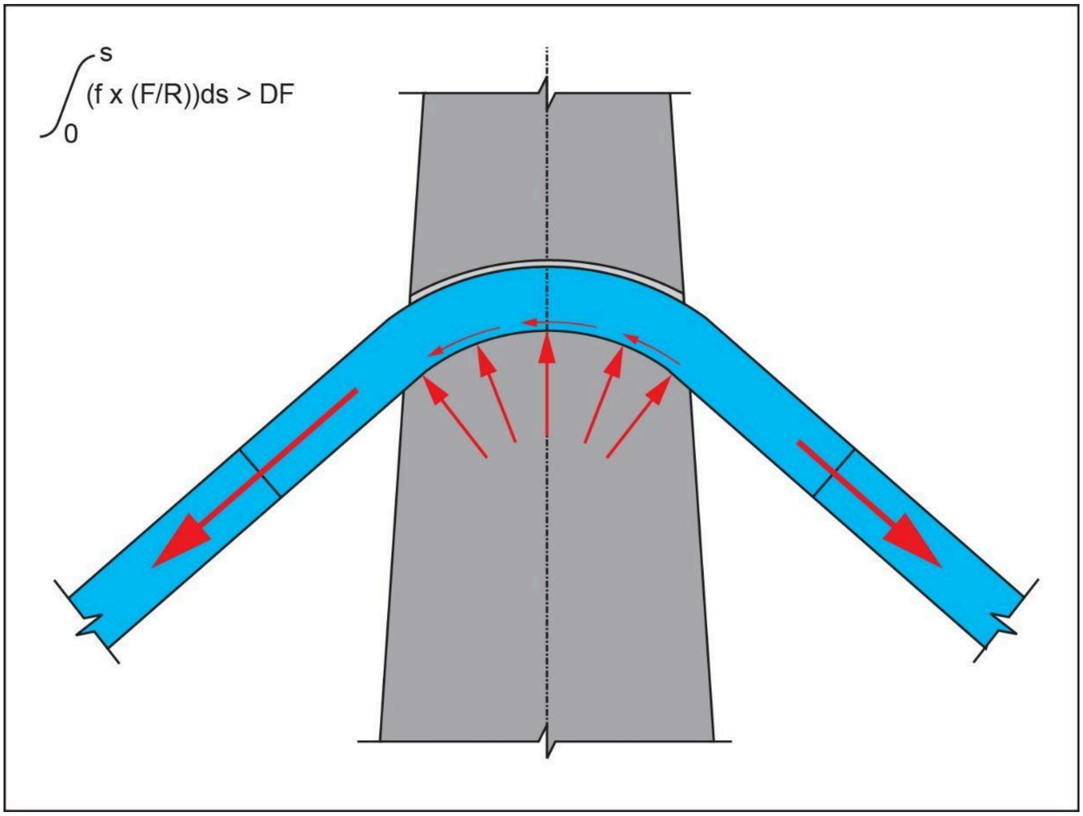


*Figure 7.41 – Unbalanced Stay Loads*

***Figure 7.42 – Prefabricated Saddle, Hodariyat Bridge, Abu Dhabi***
***(Photo Courtesy of VSL)***

***Figure 7.43 –Saddle in Pylon with Stay Cable Strands Exiting Saddle, Hodariyat Bridge, Abu Dhabi***
***(Photo Courtesy of VSL)***

### 7.3.5 Stay Cable Sag

All stay cables will have some amount of sag to them. Sag is basically the amount a stay cable dips below the chord line between the deck and tower/pylon anchorages from its own self weight. **Figure 7.44** below illustrates the basic concept of sag in a stay cable.

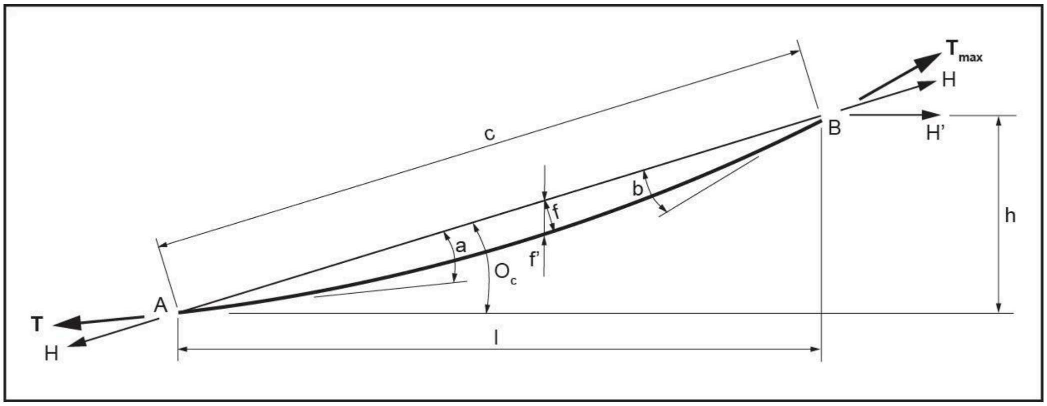


*Figure 7.44 – Stay Cable Sag*

The amount a stay cable sags is a non-linear function of the load level in the stay cable and its inclination angle. Consideration of sag is important in a cable-stayed bridge because the sag in a stay cable changes the orientation of the stay cable force vector (both at the deck and at the tower/pylon), making it different than the stay cable chord line. Geometrically this needs to be considered in design so that the stay cables are not kinked at the anchorages (which could significantly reduce their service life).

The sag ratio (i.e. the amount of stay cable sag divided by the stay cable length) is typically less than 1% when the cable-stayed bridge is in its final in-service configuration. However, the sag ratio can be greater than 5% while the bridge is being constructed. Different amounts of sag can not only affect the amount of force lifting on the superstructure, but it can also affect the stiffness of the stay cable (which is a non-linear function of the amount of tension in the stay cable and the change in the tangent versus chord angles at the anchorages). Sag considerations during construction can become even more complex if the superstructure has a steep vertical curve, where the inclination angle between the stay cable and the superstructure is very different between the back span and main span deck anchorages of a stay cable. Stay cable sag during construction can not only affect the bridges geometry during construction, but it can also affect the amount of force in the structure during construction. Consequently, it needs to be considered in the construction analysis of a cable-stayed bridge.

## 7.4 Geometry Control

Geometry control is an essential part of construction monitoring on a cable-stayed bridge. As with any bridge, adequate profile and alignment control are required, but with cable-supported bridges geometry control also must be used to verify that stresses in the structure and stay cable forces meet design expectations.

### 7.4.1 Casting Curves

As with any segmental structure, all segments must be cast following a pre-established casting curve to ensure the final profile matches the desired profile once all short- and long-term deflections have occurred. **Figures 7.45** and **7.46** illustrate some short- and long-term deflection considerations when developing a casting curve for a cable-stayed bridge.

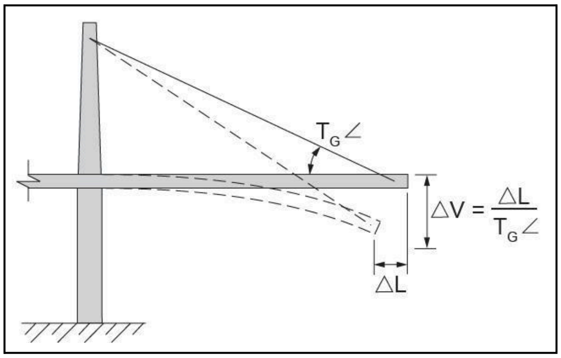


*Figure 7.45 – Effect of Superstructure Creep Shortening*

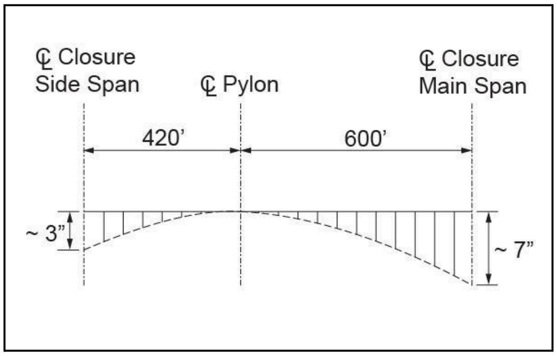


*Figure 7.46 – Long-Term Cantilever Dead Load Deflections*

Casting curves are influenced by several factors, which must be determined before the curve can be established. Some of these factors are listed below:

- The loads applied to the structure: dead loads, construction loads (both permanent and temporary), and stay cable forces.
- Construction schedule and sequence, including the step-by-step erection sequence.
- Material characteristics that include concrete creep and shrinkage, the elastic modulus of the concrete mix, and the apparent elastic modulus of the stay cables including non-linear effects due to sag.
- Bending, axial and/or torsional stiffnesses of the different cable-stayed bridge elements that include the superstructure, stay cables, towers or pylons, bearings, restrainers, foundations, back span piers and temporary support elements (such as restraining cables and/or temporary support bents).

Tests for creep and elastic modulus may take as long as six months, placing the mix design of the concrete squarely at the front of the critical path.

If any of these factors stray from design assumptions, a new curve must be developed. Any required tests – e.g., creep testing -- should be made at the beginning of the project so as not to delay casting operations.

Accurate casting curve development requires a time-dependent software package that accounts for the effects of concrete creep and shrinkage, steel relaxation, and actual construction phases and schedule as well as any significant effects of geometric non-linearity.

Segment weights should be monitored at the site by checking member dimensions and concrete unit weights, or by weighing segments (if segments are precast). Forms often swell slightly when concrete is placed. Even though this is accounted for when designing the capacity of an element, it can affect the geometry of a cable-stayed bridge if it is not monitored during construction.

Because of the factors above, the concrete mix design and erection methods will become critical path decisions relatively early in the construction schedule. **Figure 7.47** illustrates the basic casting curve for a precast cable-stayed bridge, and **Figure 7.48** illustrates the phase deflections that need to be developed and monitored for a cast-in-place cable-stayed bridge.

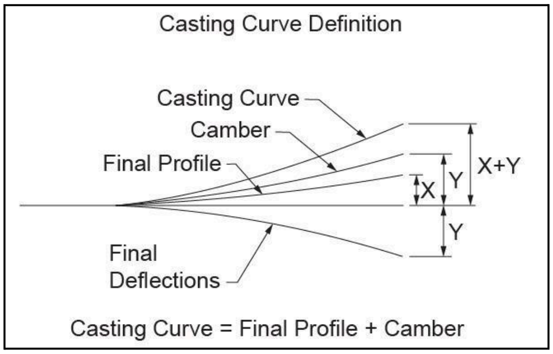


*Figure 7.47 – Precast Bridge*

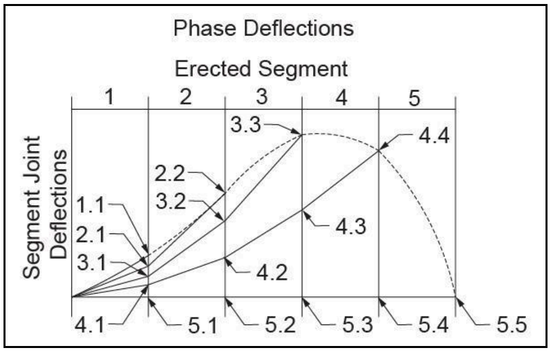


*Figure 7.48 – Cast-in-Place Bridge (Intermediate Cambers)*

### 7.4.2 Geometry Control for Precast Box Girder Segments

Segments are usually match-cast by the short line method, in which each segment is equipped with survey markers for elevation and alignment control. The marker locations are recorded in a casting cell reference system and "as-cast" plots are developed. A common system of geometry control surveying is illustrated in **Figure 7.49** below.

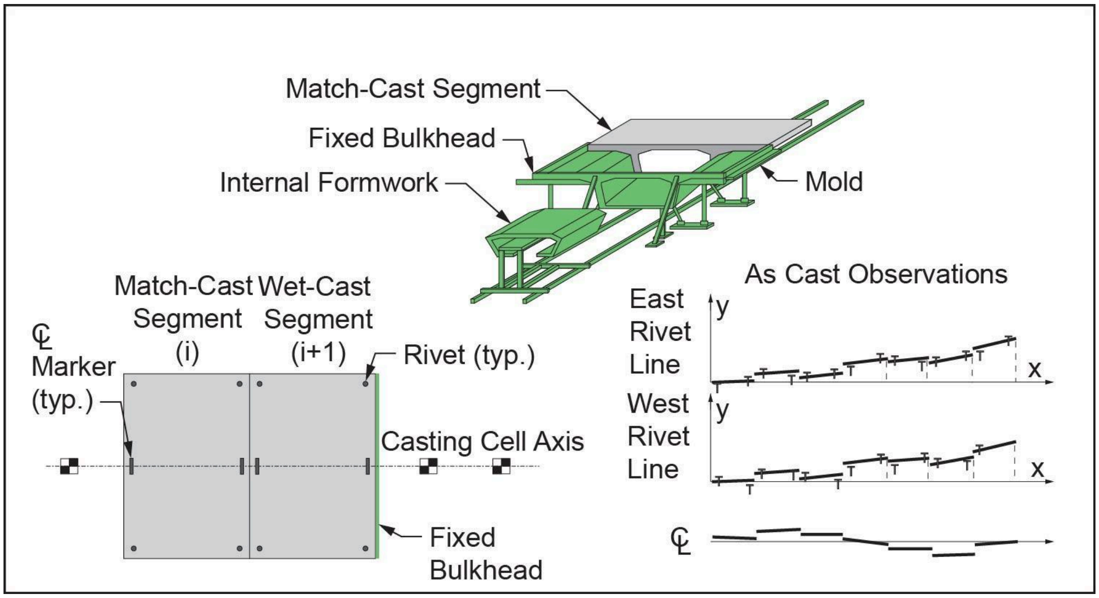
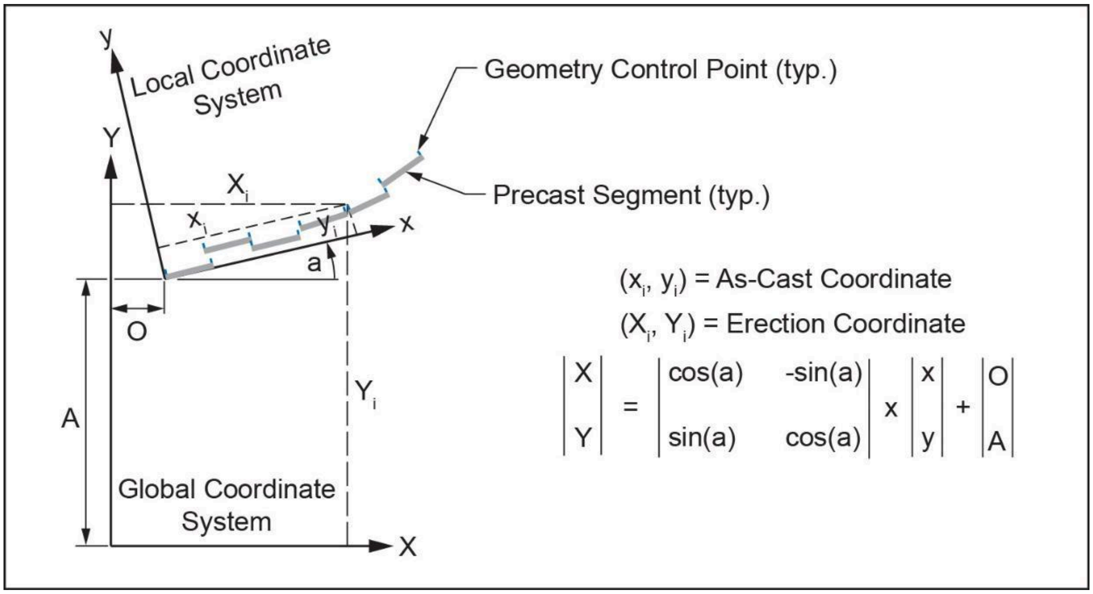


*Figure 7.49 – Short-Line Casting Method*

The relatively simple matrix operation shown in **Figure 7.50** below provides a simple example as to how to translate the as-cast coordinates into data that can be used by the erection site reference system.



$$\begin{vmatrix} X \\ Y \end{vmatrix} = \begin{vmatrix} \cos(a) & -\sin(a) \\ \sin(a) & \cos(a) \end{vmatrix} \times \begin{vmatrix} x \\ y \end{vmatrix} + \begin{vmatrix} O \\ A \end{vmatrix}$$

*Figure 7.50 – Coordinate Transformation*

It should be noted that a systematic error as "minor" as 0.001 ft on elevation measurements in the casting cell can result in significant discrepancies at the end of a cable-stayed bridges' cantilever because of the significant length that can be achieved. For example, a 600 ft long cantilever containing 60 segments that are each cast with an undiscovered 0.001 ft systematic error would result in a 1.8 ft (21.6 inch) elevation error at the end of the 600 ft long cantilever. It is also very important that the first segment of the cantilever be placed with a high degree of accuracy to avoid additional offsets at the cantilever end.

Deflections of the structure at each stage of erection should be obtained from the time-dependent software program and added to the as-cast survey marker elevations to provide expected elevations.

Similarly, the geometry of the pylon must be controlled during construction to verify that the maximum out-of-plumb and out-of-straight-line values assumed in the design for this compression member are not exceeded. The pylon may have a camber curve of its own, and tall pylons may require significant vertical camber at the deck level. These movements should be carefully integrated with expected deck elevations to ensure compatibility. **Figures 7.51** and **7.52** provide graphical descriptions of some possible allowable pylon construction tolerances.

**Pylon – Construction Tolerances**

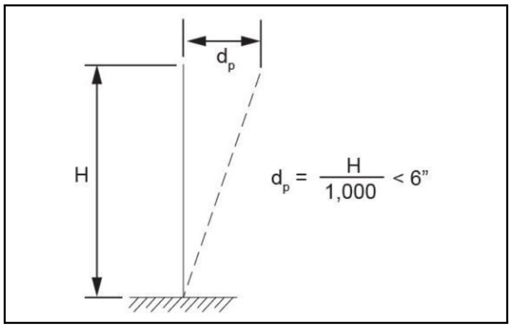


*Figure 7.51 – Out-of-Plumb*

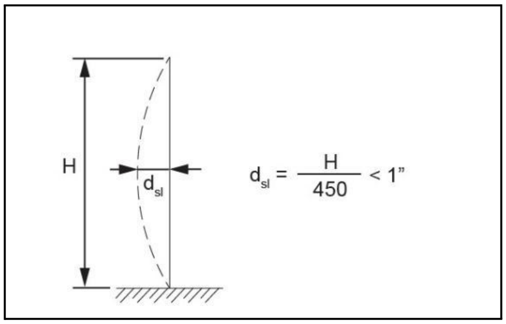


*Figure 7.52 – Deviation from Straight Line*

At each phase, the elevation of the cantilever tip should be plotted against theoretical figures. Movements of the deck and pylon that occur when lifting a segment or stressing a stay cable should be measured and checked against theoretical figures. The results of the measurements indicate the actual stiffness of the final structure. **Figures 7.53** and **7.54** illustrate the effects on the cantilever's geometry when lifting a segment and stressing a stay cable.

**Deck Deformations During Construction**

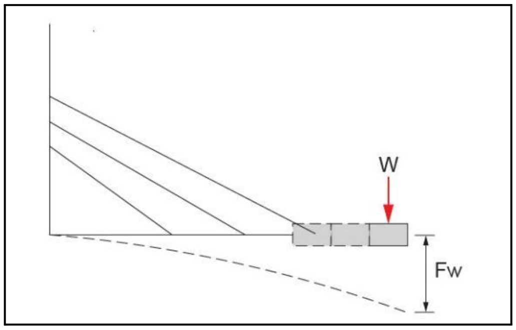


*Figure 7.53 – Lift Segment*

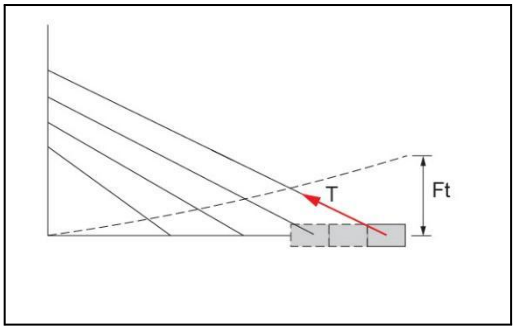


*Figure 7.54 – Stress Segment*

Bending of the overall cantilever can be checked by plotting actual and theoretical elevations at each joint at a given erection phase. After each deck survey, the inclination of the pylon should also be checked. If the pylon is out of position, it means the structure is subjected to unexpected loads -- affecting the deck survey.

It is imperative to verify that the last erected segment is not warped. This is done by comparing readings of the four (4) elevation survey markers after erection and in the casting cell. **Figure 7.55** illustrates a method to check warping during segment casting.

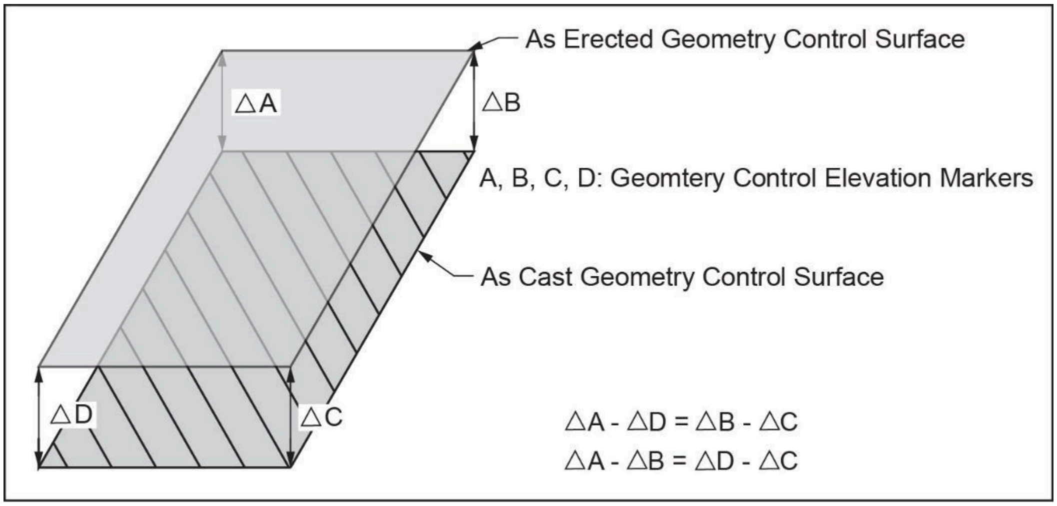


*Figure 7.55 – Segment Shape Control*

Accuracy of the stay cable jacking force is checked by measuring the elevation variations of a single survey marker over a full erection cycle (segment lifting, stay cable stressing, and re-stressing). Comparing these results against theoretical figures helps predict elevation gain or loss for the full cantilever. Loss of elevation, for example, may indicate a deficit of effective stay cable force or excessive downward deformation due to additional segment weight. Since total deck movement includes an equal number of upward and downward deflections, the influence of actual structure stiffness on the results is limited.

Thermal gradients within the superstructure and between the concrete deck and stay cables can affect stay cable forces and deck geometry. **Figure 7.56** illustrates this effect. The nominal stay cable forces used in design normally do not account for these thermal effects in the casting curve, primarily because the actual time of stressing in a particular day (i.e. early morning, afternoon, evening, etc.) is not known. One solution is to verify and adjust the stay cable forces early in the morning if the stay cable has to be stressed during the daytime. It is more practical to estimate the gradients at the time of stressing --with thermocouples, for instance. At each stage of erection, a correction of stay cable forces can be calculated to account for loss due to thermal gradients at the actual time of stressing. During daytime, thermal gradients create a downward deflection of the cantilever. When the gradient dissipates, the cantilever deflects back up, resulting in a loss of stay cable forces. Stressing during daytime therefore may require an increase of stay-cable jacking force.

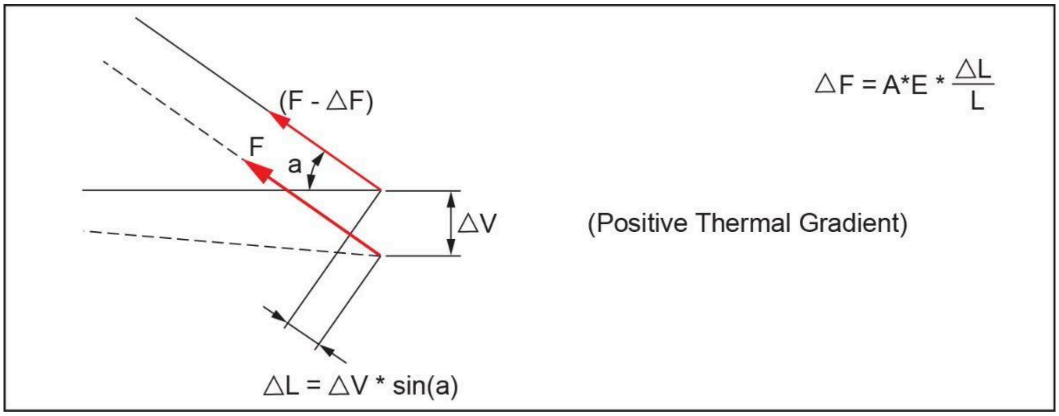


*Figure 7.56 – Thermal Effect Stay Force Correction*

Plotting cantilever tip elevations at each phase gives a good indication of the actual stiffness of the structure. The deck deflects up and down under stay cable stressing and segment lifting, and the deflection amplitude increases with the length of the cantilever. If the bridge is stiffer than assumed, the cantilever tip elevation will seem high after lifting a segment. After stressing a stay cable, the elevation of the cantilever will seem low. **Figure 7.57** below shows an illustration were the measured deflections of a stiffer than assumed cantilever are compared to the theoretical deflections.

Modifying stay cable forces to bring the deck to the theoretical elevation at each phase can result in unacceptable stresses in the superstructure. For this reason, a cable-stayed bridge with a rigid superstructure cannot be erected by following theoretical elevations only. Instead, erection should be governed by stay cable forces with a tolerance not exceeding allowable limits.

If cantilever tip elevations are low after stressing and lifting a segment, this indicates that the entire cantilever is aimed low or is deflecting excessively.

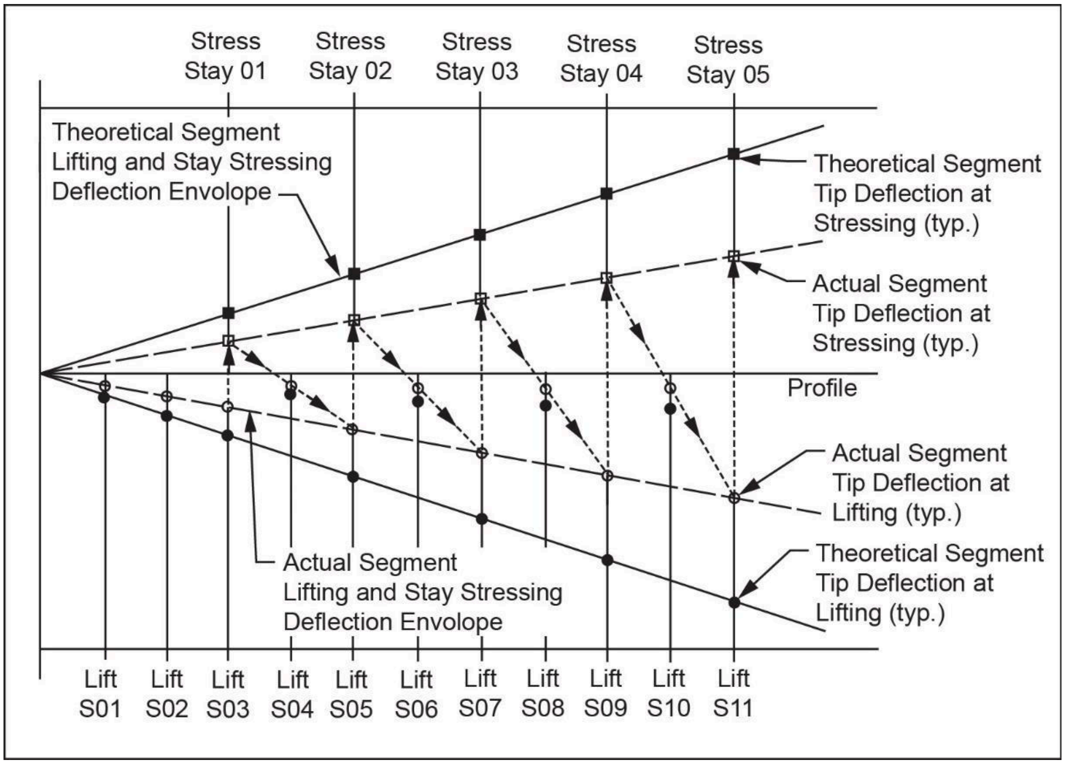


*Figure 7.57 – Plot Cantilever Tip*

## Bridge Instrumentation: Thermocouples and Strain Gauges

Important information can be obtained from thermocouples and strain gauges placed along the deck section, but valid results depend on taking the following precautions.

- Gauges must have the proper accuracy to detect long-term strains.
- Gauges must be installed properly and must not be disturbed during concrete pours.
- Gauges must be distributed across the width and depth of the section so that “average” axial stresses can be estimated. Refer to **Figure 7.58** below for a possible gauge location distribution across a superstructure cross section.
- A “zero” reading must be taken just after erecting or pouring a segment.
- Effects of creep and shrinkage must be dissociated by testing separately.
- The elastic modulus of concrete must be well understood to be able convert strains into stresses at different stages of construction.

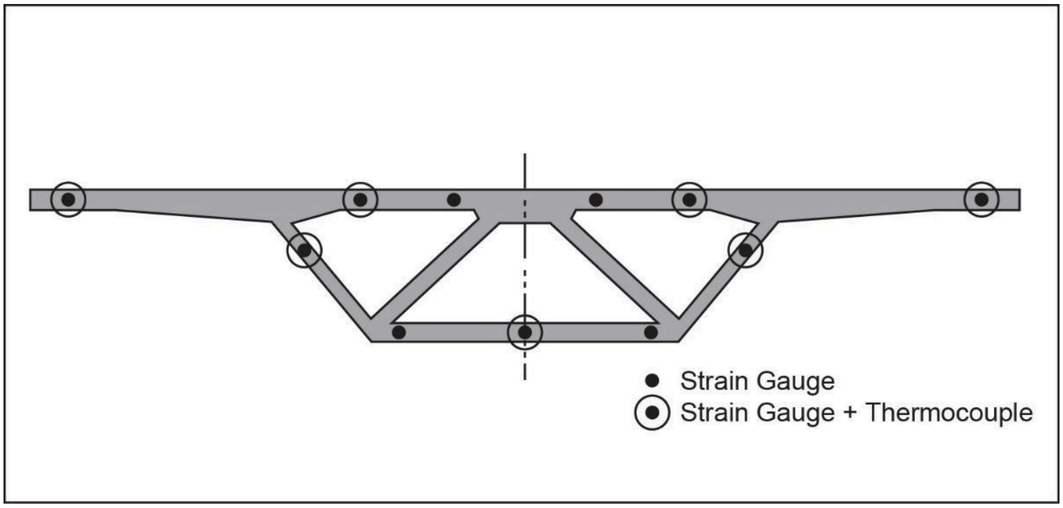
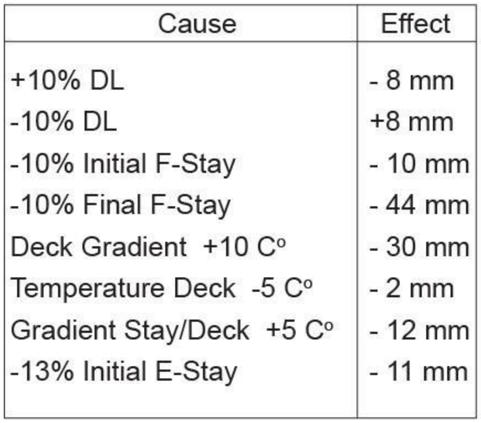


*Figure 7.58 – Bridge Instrumentation*

**Parameters Influencing Deck Deflections:**

A parametric study was made by the designers of the Coatzacoalcos Bridge (Mexico) for a 175-ft long cantilever. **Figure 7.59** below shows the sensitivity of the cantilevers' deflections to variations in design parameters.



| Cause | Effect |
|---|---|
| +10% DL | - 8 mm |
| -10% DL | +8 mm |
| -10% Initial F-Stay | - 10 mm |
| -10% Final F-Stay | - 44 mm |
| Deck Gradient  +10 C° | - 30 mm |
| Temperature Deck  -5 C° | - 2 mm |
| Gradient Stay/Deck  +5 C° | - 12 mm |
| -13% Initial E-Stay | - 11 mm |

*Figure 7.59 – Geometry Discrepancies L ~ 170'*

**Geometry Control – Correcting Discrepancies:**

Geometry discrepancies due to casting errors or inaccurate placement of the first cantilever segment and/or subsequent segments can be corrected by using plastic shims in the match-cast joints between segments. Shim thickness should not exceed 1/4 in.  Fiberglass mats are usually applied to prevent epoxy sag in the thicker part of the joint.

Geometry discrepancies due to additional segment weight or inaccurate stay cable jacking forces must be corrected by re-stressing the stay cables. Sometimes, stay cables along the cantilever have to be re-stressed to avoid excessive stresses in either the stay cables or the deck. Re-stressing is a complex operation because the cable-stayed support system is highly indeterminate.  This was shown schematically in **Figure 7.2** above as a linear superposition of stressing forces.  It should be noted that for many cable-stayed structures, additional non-linear effects can be significant. The designer calculates the jacking forces for each stay cable and re-checks the stresses in the structure at each stressing operation. If the geometry discrepancy is due to additional weight, the stay cable forces will need to be adjusted higher and the designer must verify that allowable stay cable forces are not exceeded for the bridge in service. It is advisable to provide additional stay cable capacity during design to account for such construction variations.

### 7.4.3 Geometry Control for Cast-in-Place Box Girders

Geometry control procedures for cast-in-place box girders differ slightly from those used for precast, in that local adjustments can be made with the traveling forms instead of by shimming the joints. Geometry discrepancies due to additional segment weight or inaccurate stay cable jacking forces still require re-stressing of the stay cables.

### 7.4.4 Geometry Control for Cast-in-Place Flexible Decks

Except for the initial casting stages close to the pylon, deck elevations can vary greatly with even a small variation in stay cable force. Since stresses in the deck are not affected as significantly by variations in deck geometry, it is logical to prioritize deck geometry control over stay cable jacking forces. This automatically compensates for variations in segment weights -- but it is important to record the stay cable forces to verify that allowable stay cable stresses are not exceeded. Again, it is advisable to provide additional capacity in the stay cables during design to account for these weight variations.

Since this erection procedure is guided by the deck geometry, it is essential to apply the stay cable jacking force at a time when the geometry of the structure is not affected by thermal gradients, i.e., before sunrise.

If erection is performed using a traveler, it is important to include the deflections of the traveler under the weight of the wet concrete. These deflections may be significant, particularly for longer edge girder decks. The flexibility of the traveler system should be well understood, and its performance verified in the field.

## 7.5 Stay Cable System Quality Control

### 7.5.1 Stay Cable Types

Most early stay cable systems had corrosion protection that was very similar to post-tensioning systems, using either grout or wax within a steel or polyethylene stay pipe to protect the bare bars, wires or strands (**Figure 7.60** is an illustration of some of the earlier stay cable systems).

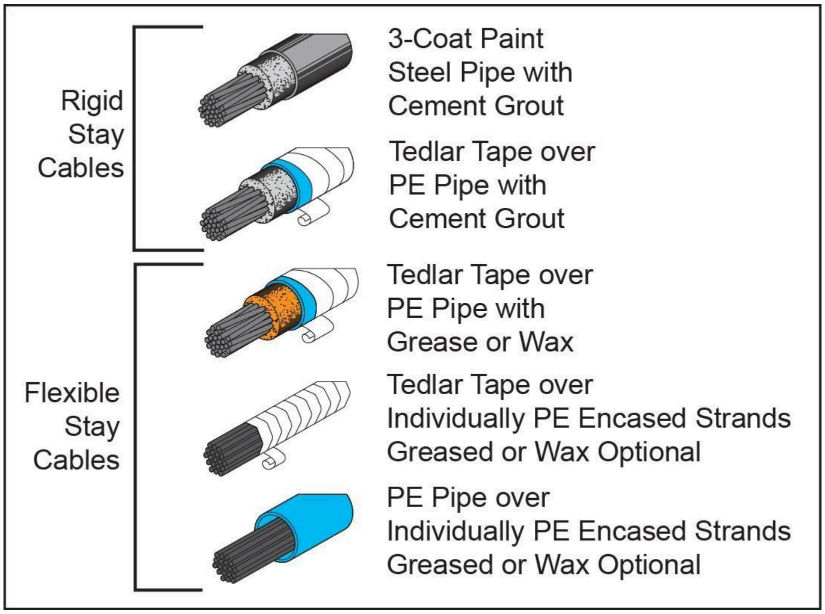


***Figure 7.60 – Early Stay Cable Systems***

The stay cable main tension elements (MTE) may be made up of high-strength steel parallel bars, parallel wires, parallel strands (PTI Recommendations), helical/locked coil strands or ropes (see **Figure 7.61** below for cross sections of these different MTE's). High-strength steel parallel bars and steel ropes have been used as stay cables because they are relatively simple to install and have simple corrosion protection requirements (when compared to the other stay cable systems). However, their steel strengths are lower (meaning they are heavier than high-strength steel wire or stands) and become increasingly more difficult to install for long stay cables. Parallel wires and helical/locked coil strands are more compact than the parallel strands, reduce wind loads on the stay cables and stay cable vibrations, which is an advantage for long span cable-stayed bridges exposed to high winds. These systems can also be fully prefabricated, which can simplify the installation of the stay cables on the bridge. Parallel strands are used for the vast majority of modern cable-stayed bridges because of their ability to efficiently meet various project design requirements for a wide range of stay cable lengths, and they are relatively simple to install. For these reasons, this section will primarily discuss the parallel strand stay cable system.

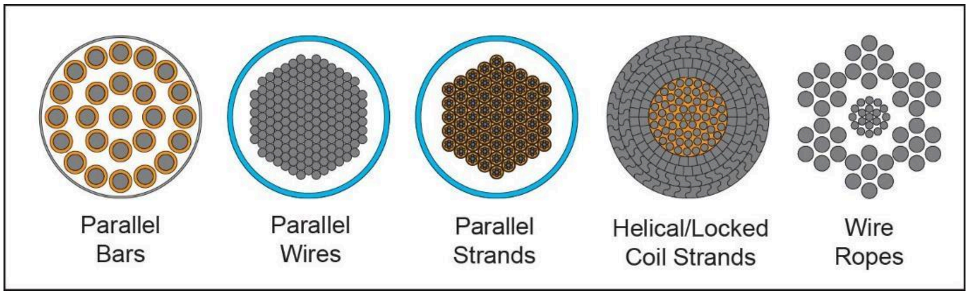


***Figure 7.61 – Cross Sections of Different Stay Cable MTE Types***

Modern parallel strand stay cable systems are made of individually protected strands and do not require cement grouting. Grouted stay cables were used in the past but proved to be more difficult and costly to install when compared to ungrouted stay cables. Additionally, it was found that the long-term durability of the grout was limited due to the flexibility of the long-exposed stayed cables in the environment that resulted in cracks in the grout over time.

There are two types of stay cable parallel strand protection systems within the stay pipe that are as follows:

- Bundled bare or galvanized strands with a corrosion-inhibiting coating and individual polyethylene sheathing (**Figures 7.62** and **7.63**).
- Individual epoxy-coated strands (**Figure 7.64**).

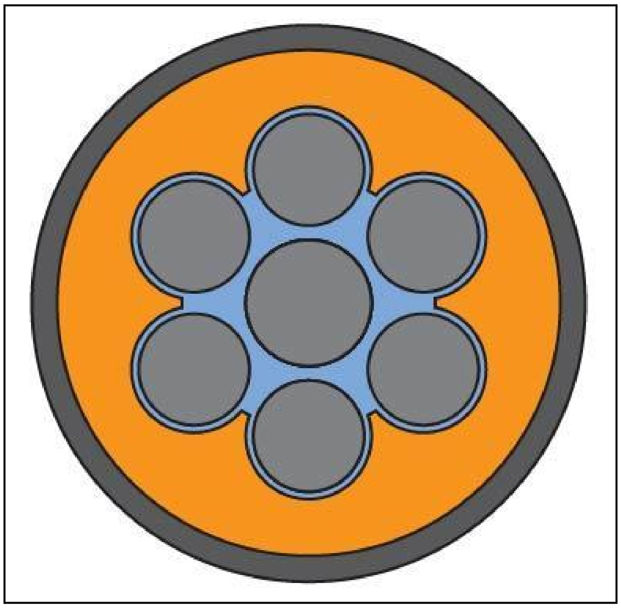


***Figure 7.62 – Individual Strand with Corrosion-Inhibiting Coating in a HDPE Sheathing***

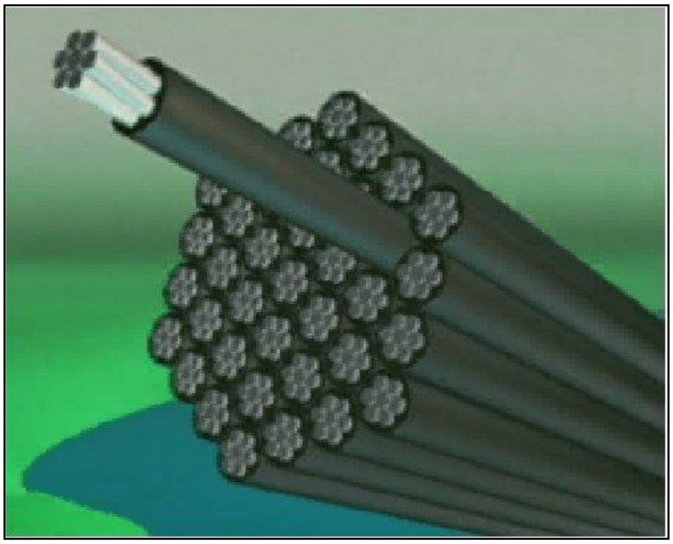


***Figure 7.63 – Bundle of Individual HDPE Sheathed Strands in a Stay Cable***

*Figure 7.64 – Individual Epoxy Coated Strands in a Stay Cable*
*(Photo Courtesy of FIGG)*

Modern stay pipes are made of structural steel (stainless or three-coat protection system) or high-density polyethylene (HDPE). The stay pipes are typically self-supporting when they are completely installed and held in place with restrainer plates or a flange connection at the towers/pylons. At the deck level, an expansion sleeve is connected to the stay pipe to allow the stay pipe to expand and contract with changing environmental temperatures. This is also particularly important for HDPE stay pipes since they have a different coefficient of thermal expansion than the steel strands they are encasing. There will also be an anti-vandalism pipe installed at the base of the stay cable, or s heavily reinforced pipe section that can protect the stay cable against significant vandalism attacks, sustained fire and blast loadings.

### 7.5.2 Bearing Plate and Guide Pipe Installation

In the most basic terms, a guide pipe (or recess pipe) provides a form for the stay cable anchorage system. A stay cable guide pipe is primarily used to orient the stay cable between the concrete superstructure and tower/pylon in a concrete cable-stayed bridge. Prior to casting the anchor block or edge girder in the superstructure or casting an anchor block in the tower (either in precast or cast-in-place operations), the guide pipe is typically bolted or welded to the anchorage bearing plate at a right angle. See **Figure 7.65** below for an example and **Figure 7.66** for a typical stay cable anchorage layout. After casting, the stay anchor hardware is then installed into the guide pipe and will bear against the bearing plate In some stay cable systems, a damping system is also attached at this point.

*Figure 7.65 – Bearing Plate and Guide Pipe with Anchorage Installed*
*(Photo Courtesy of AECOM)*

Precision is required in placing the guide pipe and bearing plate, as this determines stay cable alignment. See **Figure 7.67** for a photograph of a guide pipe being installed (Installation tolerances are provided in PTI Recommendations). Vertical and horizontal angles are especially critical, as offsets create bending stresses in the stay cable at the anchorage. This would result in damage or possibly a break in the strand(s) during construction, and/or could significantly reduce the service life of the stay cable. Tower and deck anchorages typically do not point directly at each other and are aligned to accommodate the sag of the cable in the final state, as specified in the design drawings.  The anchorage adjustable nuts or shims must stay in contact with the bearing plate. This needs to be done to avoid stress concentrations and deformation of either the adjustable nut or the socket, and it must be confirmed that the bearing area is perfectly flat.

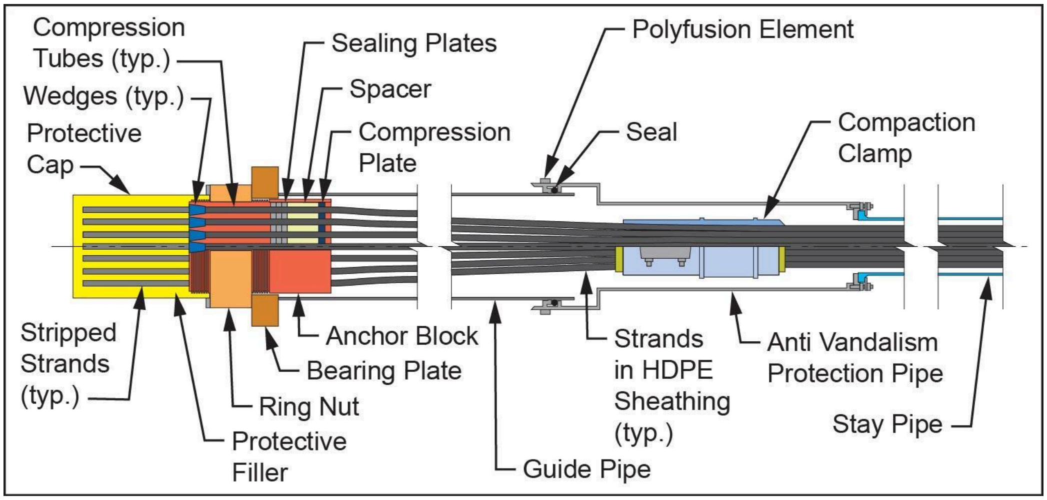


*Figure 7.66 – Stay Cable Anchorage Layout*

*Figure 7.67 – Guide Pipe Being Positioned in Deck Formwork*
*(Photo Courtesy of FIGG)*

### 7.5.3 Saddle Pipe Installation

When saddle pipes are used in the tower/pylons, they allow the stay cable to pass directly through them without interruption. As previously mentioned, a saddle fills two main roles by providing a form in the tower/pylon for the stay cable strands to later be installed and transfers the forces from the stay cables directly into the tower/pylon. Prior to casting the concrete in a section of the tower/pylon where a saddle is located, the saddle pipe is first correctly positioned and orientated. Typically, the saddle pipe is welded to a steel support frame that is then connected to a steel frame in the tower/pylon. Often it is bolted to the previously erected saddle pipe steel support frame, and the leveling bolts are adjusted to properly orientate the saddle pipe prior to tightening/locking them into position. Similar to the installation of the guide pipes and bearing plates, precision is required with the placement of the saddles to ensure the that the strands pass through them without any offsets that could create bending stresses in the strands. See **Figure 7.68** below for an example of a saddle positioned in a pylon prior to casting.

***Figure 7.68 – Saddle (Cradle) Positioned in the Pylon***
***(Photo Courtesy of FIGG)***

Old saddle systems were simply a large steel pipes that allowed the entire stay cable bundle of strands to pass through the tower/pylon. Today, the saddle pipes contain small pipes within them that allow each individual strand to pass through the tower/pylon through its own dedicated deviation pipe. Consequently, after concrete is placed for the tower/pylon segment, the annular space between the saddle pipe and individual strand pipes needs to be grouted. This is done to ensure that the forces from the individual strands are properly transferred to the saddle pipe and into the tower/pylon.

### 7.5.4 Stay Cable Pipe Installation

Stay pipes are typically delivered to the site in standard straight sections and assembled to their final required lengths on site. The exact procedure varies depending upon the pipe material. Steel pipes have to be butt-welded. Many of the welds in the steel pipe can be done with the pipe lying flat on the deck, but others require the steel pipe to be in the erected position. In either case, a detailed butt-weld procedure must be developed and approved. NDT checks of the welds are recommended.

HDPE stay pipes have become more popular in recent cable stayed bridges, both from the perspectives of cost and aerodynamic performance when compared to steel stay pipes. HDPE pipes are welded together by fusion, using a special device to maintain proper alignment of the HDPE pipe sections. Multiple HPDE pipe sections are welded together (typically horizontally on the deck) to make the appropriate stay pipe length that is going to be erected into position.

Different systems are used to lift and temporarily support the stay pipes prior to strand installation and stressing, but all are designed to prevent excessive bending of the pipes. Highlines can be used in conjunction with messenger cables to erect and temporary support the stay cable pipe while the strands are installed. Stay cable pipes can also be supported by the previously erected stay pipes with messenger struts. When using the highline erection and support method, multiple lifting clamps are attached to the stay cable pipe that is going to be installed. The stay cable is then lifted using a pre-planned procedure that uses the messenger cables to lift the clamps attached to the stay pipe at different speeds. This lifts the stay pipe off of the deck and rotates it to the correct installation angle, aligning it with the ends of guide pipe(s) and/or saddle pipe. **Figure 7.69** shows this installation method below for a steel stay pipe.

***Figure 7.69 – Steel Pipe Erection with Highline, Veterans' Glass City Skyway, OH***
***(Photo Courtesy of Bilfinger & Berger)***

A two-crane system can also be used to install stay cable pipes, and this is a common method used to install HDPE stay pipes. First the stay pipe is placed on rollers, spaced so that no part of the stay pipe is lying on the bridge deck. Clamps are installed on either end of the stay pipe and cranes are then attached to the clamps. The crane at the tower (typically a tower crane) lifts one end of the stay cable up to the guide pipe or saddle in the tower/pylon while the stay pipe roles along the bridge deck toward the tower/pylon on the rollers until it is lifted off of them one by one. When the end of the stay cable is near the tower guide pipe or saddle, the upper clamp is connected to come-alongs that will support the stay pipe while the strands are installed. Then the crane on the deck pulls the lower end of the stay pipe to the deck guide pipe, where the lower clamp is also connected to come-alongs that will hold the stay pipe in place while the strands are installed.

Note that the first strand typically needs to be installed and secured in the stay pipe prior to lifting the stay pipe at the tower because it will be used to support the length of the stay pipe during strand installation. HDPE pipes are most commonly supported along their length by the first strand that is installed. **Figures 7.70** and **7.71** shows HDPE stay pipes installations.

*Figure 7.70 – HDPE Pipe Erection, Penobscot Narrows Bridge, ME*
*(Photo Courtesy of FIGG)*

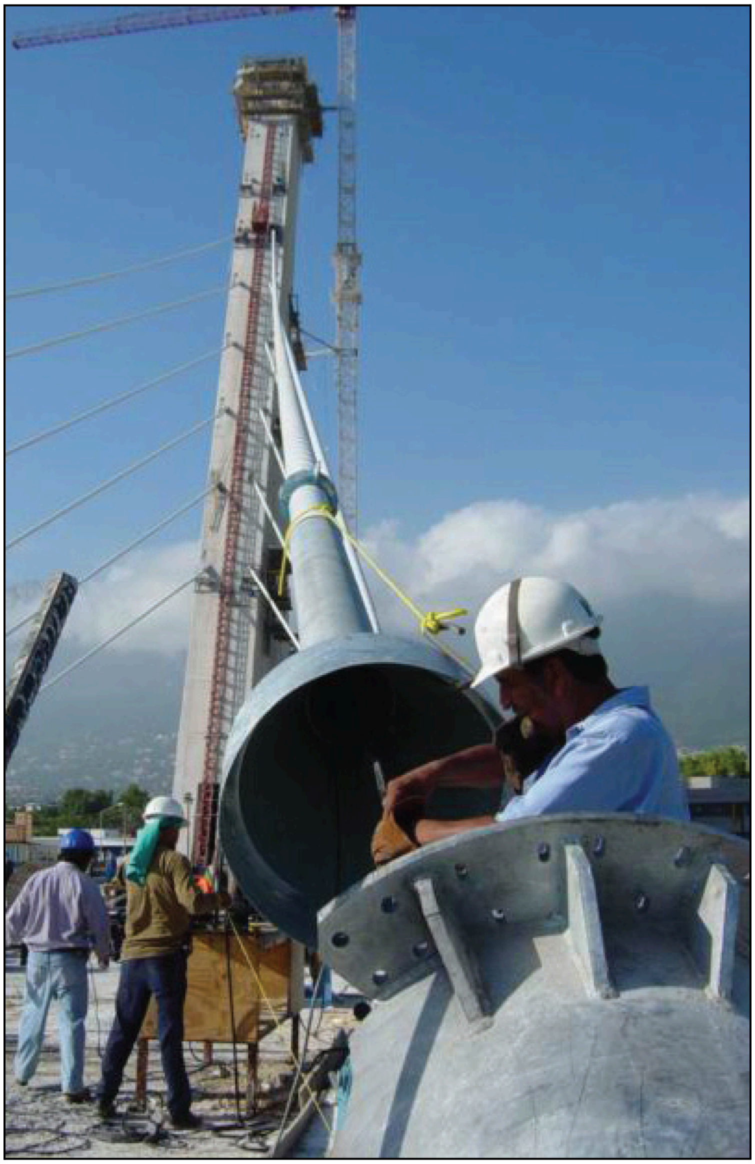


***Figure 7.71 – HDPE Pipe Supported with the First Strand, Puente de la Unidad, Mexico (Photo Courtesy of VSL Mexico)***

### 7.5.5 Installing Strands

The strands are delivered to the project on large spools. Often, the strand spools are delivered to the project site months or even years before they are actually installed, and it is important to ensure that they are properly stored and protected from the environment in accordance with the manufacturer's instructions (**Figure 7.72**). Early cable stayed bridges typically installed the strands in the stay pipe (by either pulling or pushing individual strands or pulling the entire bundle of strands through the stay pipe), and then stressed them all at once with a large stressing multistrand jacks. This method required very large equipment to install and stress the strands in the stay cable (**Figure 7.73**).

***Figure 7.72 – Stay Cable Strand Spools in Storage***
***(Photo Courtesy of FIGG)***

*Figure 7.73 – Bundle of Strands Being Pulled through the Guide Pipe*
*(Photo Courtesy of FIGG)*

Modern cable-stayed bridges now typically install and stress each strand individually. This greatly simplified and lightened the necessary stay cable strand installation and stressing equipment, and also greatly simplifies the future stay cable replacement operations. It is important to ensure that there is plenty of access to both ends of the stay cable. Typically, at the deck level, there will be an access platform that provides access to the bearing plate where the stay cable anchor will be installed. There will also need to be temporary access between the guide pipe and stay pipe because this is typically where the individual stay cable strands are installed in the stay pipe. Sufficient room on the deck needs to be provide for the strand spools, strand dispensers, cutting tables that is used to cut the individual stay cable strands to length, deviation wheels that are used to feed the strand into the stay pipe, and winch equipment that is used to operate the strand shuttles. Typically at the tower/pylon, there will be an access platform on the exterior of the tower/pylon that provides temporary access between the stay pipe and guide pipe (or end of the saddle pipe), as well as an access platform inside the tower/pylon if anchorages are located inside the tower/pylon.

Cable-stayed bridges with anchor blocks in the superstructure and towers/pylons can be stressed either at the tower or at the superstructure. Cable-stayed bridges with just anchor blocks in the superstructure and saddles in the towers/pylons can only be stressed at deck level and may need to be stressed at both ends. When the stay pipe is in position, the first strand will then be installed and stressed. It will be threaded into the top holes of the anchorages, the wedges will be installed, and the strand will be stressed to the required force.

After the first strand is installed and, in many cases, supporting the length of the HDPE stay pipe, subsequent strands will be installed into the stay cable. A strand shuttle is used to install each of the strands in the stay pipe by connecting to the end of the strand on the strand spool, and then pulling the strand from the bottom of the stay pipe at the deck up to the top of the stay pipe at the tower with a winch system (**Figure 7.74**). If there is an anchorage at the tower, the strand is threaded through the appropriate hole in the anchorage, and the wedges are set at the tower anchorage. If there is a saddle in the tower, the strand is threaded through the appropriate strand pipe in the saddle and then pulled down to the deck anchorage in the adjacent span (**Figure 7.75**). The length of the strand is monitored as it is being pulled, and with the predetermined length is met the strand will be cut on the cutting table. The other end of the strand is then threaded through the appropriate hole in the anchorage(s) at the at the deck, the wedges are set and the strand is stressed to the required force. This general process is repeated until all strands in the stay cable are installed. This strand installation process is commonly referred to as “mono-strand stressing”, and a more in-depth discussion on determining the required force in each strand is provide later in this chapter.

***Figure 7.74 – Stay Cable Strand Being Connected to the Strand Shuttle***
***(Photo Courtesy of SYSTRA IBT)***

***Figure 7.75 – Strands Being Threaded Through the Saddle (Cradle) Pipe***
***(Photo Courtesy of FIGG)***

It is important to note that the stay cables are not complete at this point, and typically they need to be restressed again. Restressing of the stay cables during construction is common for cable-stayed bridges and is often necessary to efficiently manage the forces on the bridge during each stage of construction and to efficiently manage the in-service forces on the bridge in its final configuration. Consequently, the stay cables will be in a temporary state until superstructure construction is complete, and it is important to appropriately protect the strands and stay cable components until their permanent corrosion protection systems are installed. The stay cables need to be monitored throughout construction, and additional temporary measures (such as installing temporary damper devices) may be required during the remainder of superstructure construction. **Figure 7.76** shows stay cables during construction with temporary protection measures in place.

***Figure 7.76 – Previously Installed Stay Cables with Temporary Protection during Construction (Photo Courtesy of FIGG)***

### 7.5.6 Installing Dampers

Once the installation of the strands is complete and they are stressed to their final forces, the dampers will then be installed. Historically, stay cables have seen large amplitude vibrations under light rain and moderate wind conditions. These amplitude vibrations generally get worse as the length of the stay cables increase, and these vibrations have significantly damaged stay cables in the past. Dampers are an important component in the stay cable system that basically counter the amplitude vibrations. They can be elastic, hydraulic, friction or mechanical systems, and are most frequently located at the base of the stay cables but occasionally can be at the top or at both ends. Instructions are typically provided by the stay cable supplier for installation of the dampers and they should be strictly followed.

Generally, there are two types of dampers that are commonly used in modern cable-stayed bridges, and those are friction dampers and hydraulic dampers. Friction damper systems are commonly connected directly to the stay cable strands and are located within the stay pipe or anti-vandalism pipe at the bottom of the stay cable. They are often connected to a support frame that is typically connected to a flange plate on the guide pipe. They are common in stay cable systems that utilize strands that are individually greased and sheathed, and are typically installed after the tension rings are installed on the strands (i.e. the tension rings pull all of the individual strands in the stay cable together to act as a single cable in the stay pipe). **Figure 7.77** shows an example of a friction damper being installed.

***Figure 7.77 – Friction Damper Installation (Photo Courtesy of BBR)***

Hydraulic dampers are typically connected to the stay pipe and connected to a support frame that is connected directly to the superstructure. Since hydraulic dampers are external to the stay pipe, an HDPE cheese plate typically needs to be installed inside the stay pipe where the damper connects to the stay pipe so that the amplitude vibrations from the strands in the stay pipe can be transferred directly to the damper connection on the stay pipe. They are common in stay cable systems that utilize either epoxy coated strands or strands that are individually greased and sheathed. Figures 7.78 and 7.79 shows examples of the different hydraulic damper components.

***Figure 7.78 – Hydraulic Damper and Frame Connected to the Superstructure***
***(Photo Courtesy of SYSTRA IBT)***

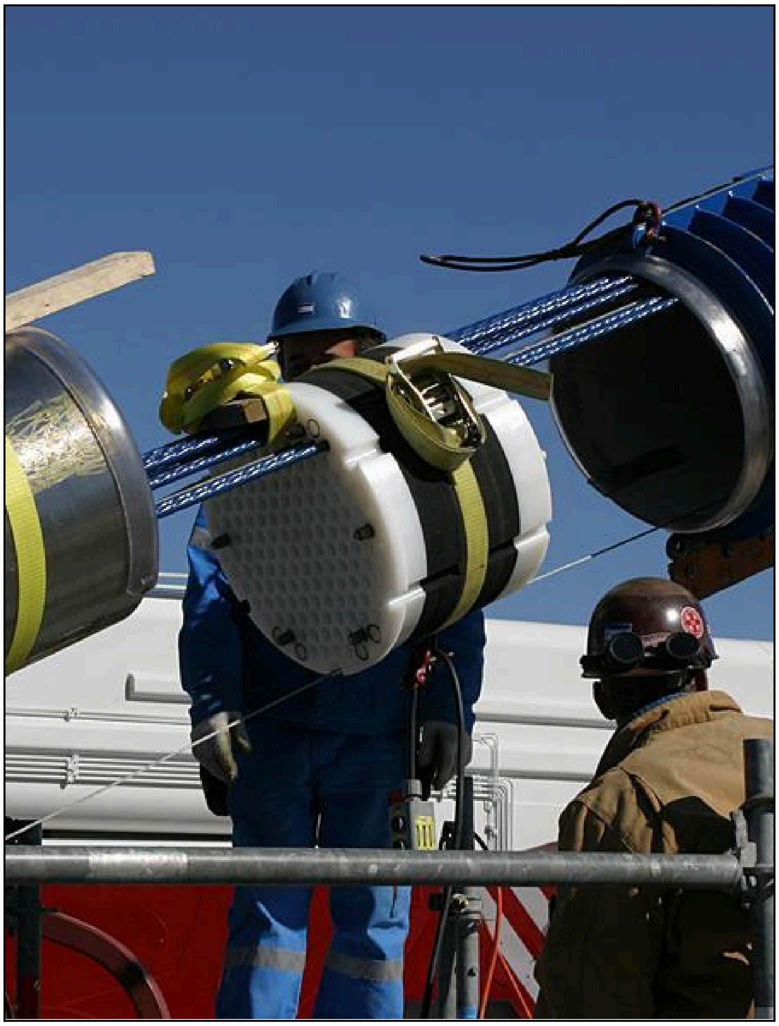


***Figure 7.79 – HDPE Cheese Plate Inside the Stay Pipe at the Hydraulic Damper Connection (Photo Courtesy of FIGG)***

### 7.5.7 Installation of Remaining Stay Cable Components

After the installation of the dampers, the remaining stay pipe components are installed and/or closed up to seal the strands in the stay pipe. The strand tails at the anchorages are then cut to their required lengths and are typically much longer than the lengths of strand tails on normal post-tensioning strands. This is done so that the strands can be easily restressed in the future (if needed), or fully de-tensioned in the future to facilitate individual strand replacement or the replacement of the entire stay cable.

The anchor caps are then installed on both ends of the stay cable to protect the ends of the strands. To further protect the ends of the strands, the anchor caps are typically filled with a wax resin material. The wax resin material typically needs to be heated to a few hundred degrees Fahrenheit to change it from a solid to pumpable liquid state. It is then pump into the bottom of the anchor cap until it replaces all of the air in the anchor cap. In some stay cable systems, the wax resin can also flow to the back side of the anchorage into the guide pipe to further protect the strands. **Figures 7.80** and **7.81** shows examples of the permanent anchor cap and wax resin that fills the anchor cap.

***Figure 7.80 – Typical Stay Cable Anchor Cap***
***(Photo Courtesy of SYSTRA IBT)***

***Figure 7.81 – Typical Wax Resin Cap within the Stay Cable Anchor Cap***
***(Photo Courtesy of SYSTRA IBT)***

## 7.6 Control of Stay Cable Forces

Stay cable stressing is one of the most critical operations performed during construction, as adequacy of the final bridge profile and stresses depends on it. Hydraulic jacks used to stress the stay cables must be accurately calibrated, so having a load cell onsite to check the jack calibration is recommended. At a minimum, a master gauge should be available and jack gauges checked frequently.

Measuring stay cable elongations during stressing verifies the correlation of stay cable forces and the design assumptions made for stay cable elastic modulus and the stiffness of the deck and pylon. Theoretical elongation figures must account for sag variation, deck movement, pylon movement, and elastic modulus of the steel.

In a parallel strand stay cable system, the seating of strand wedges should be compensated for at the time of stressing to avoid an accumulation of losses in stay cable forces. This is done by additionally stressing the stay cable by the amount of assumed anchor set – before releasing the pressure in the jack. The strands should be marked to ensure no strand slippage occurs after removing the stressing jack.

As noted earlier, modern parallel strand systems are not grouted and strands are individually protected. This allows installation and stressing of the strands one by one, which greatly simplifies operations at the site due to lighter installation and stressing equipment (handheld mono-strand jacks instead of very large multiple-strand jacks). Forces in the individual strands vary every time a new strand is stressed, with stay cable suppliers usually determining jacking force for the initial (pilot) strand from information supplied by the bridge designer (total stay cable force and pylon and deck movements under a given stay cable force). **Figure 7.82** illustrates wedge seating and **Figure 7.83** illustrates pylon and deck movement considerations. The stressing procedure should also result in equal forces between individual strands within a tolerance of +/- 2.5% of the desired force in the strands. This is achieved by continually monitoring the force in the pilot strand and stressing each subsequent strand to an equivalent force. **Figure 7.84** illustrates this monitoring and stressing process, and **Figure 7.85** shows a mono-jack stressing a strand in a stay cable.

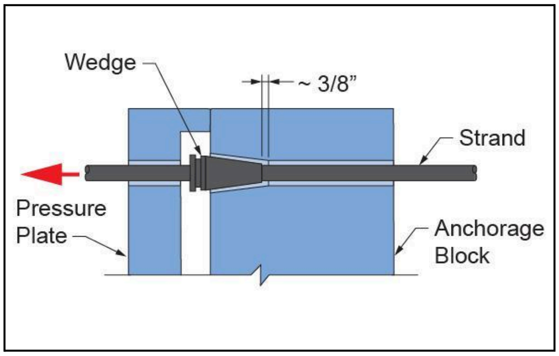


*Figure 7.82 – Anchor Set*

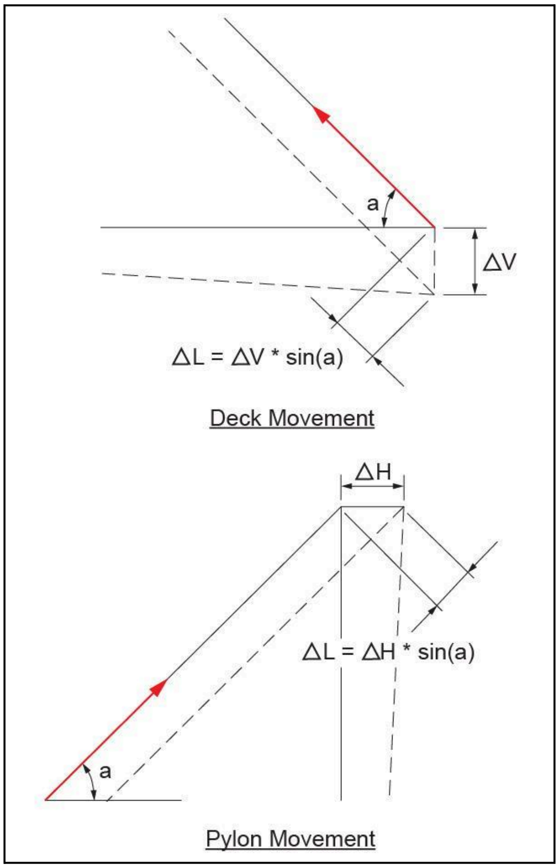


*Figure 7.83 – Stay Elongations*

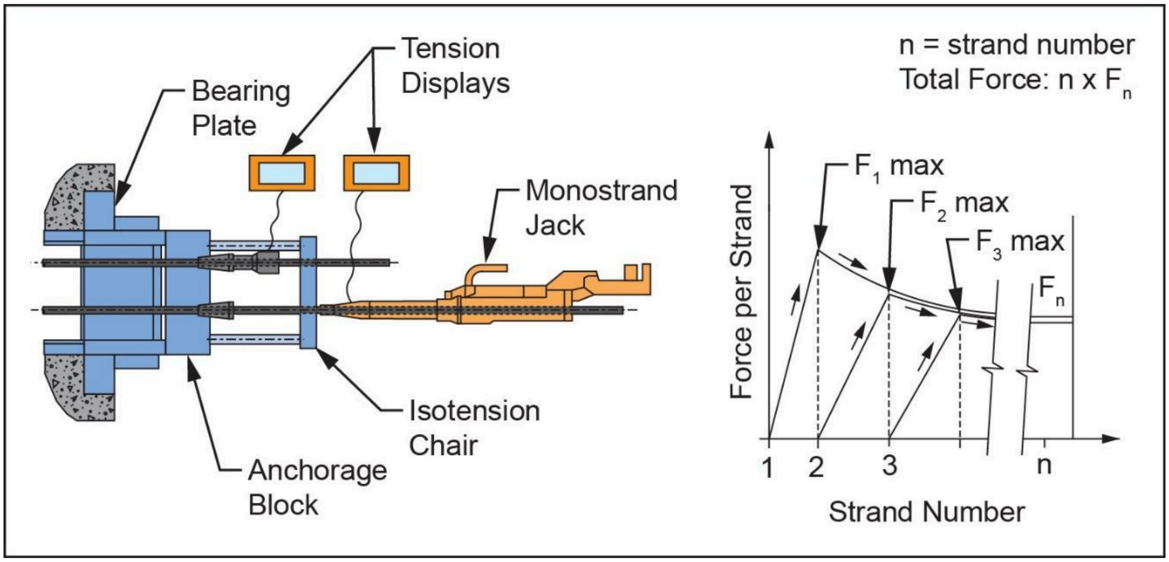


*Figure 7.84 – Isotension Principle Diagram*

*Figure 7.85 – Mono-Strand Jack*
*(Photo Courtesy of VSL Mexico)*

In some cases, it is desirable to use a multi-strand jack to install the entire cable at once. They are also needed when typical ring-nut anchors are used to adjust stay cable forces. Otherwise, multi-strand jacks are generally not used, when possible, due to the increased difficulty in handling, and the potential for needing multiple jack sizes to stress different sizes of cables. **Figure 7.86** below provides a photograph of a stay cable multi-strand jack.

It should also be mentioned that when elongations are so short (less than 15-25 mm), they would result in overlap of the wedge bite marks on the stay cable strands. Consequently, stressing with the anchorage ring nut and a multiple-strand jack is required**.**

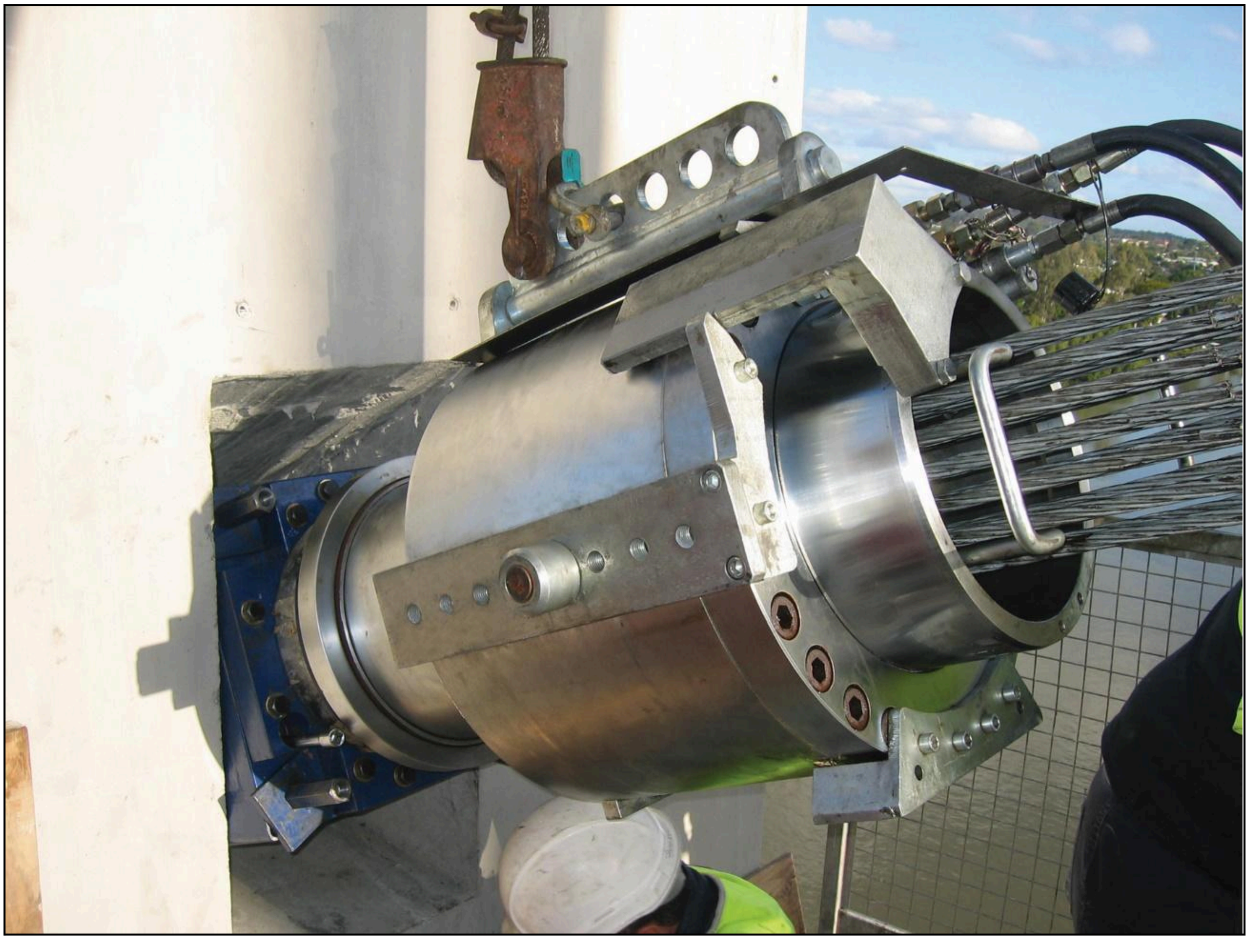


***Figure 7.86 – Multi-Strand Jack***
***(Photo Courtesy of BBR)***

## 7.7 Fatigue Testing

PTI Recommendations require fatigue testing of individual strands or wires, as well as testing of full-scale specimens. This is time-consuming and should be initiated early in a project to avoid delays. First, the stay cable anchorage system itself must be submitted and approved by the design engineer and owner. Then a testing procedure is submitted and approved. Only at that point can testing begin, subject to the availability of specialized laboratory equipment. If excessive wire breakage occurs, and the test does not meet specification requirements, the anchorage may have to be modified, and the entire test procedure started over. Since some stay cable anchorage components must be installed when segments are cast, it is preferable to have testing completed prior to casting. **Figure 7.87** shows a photograph of a fatigue test setup.

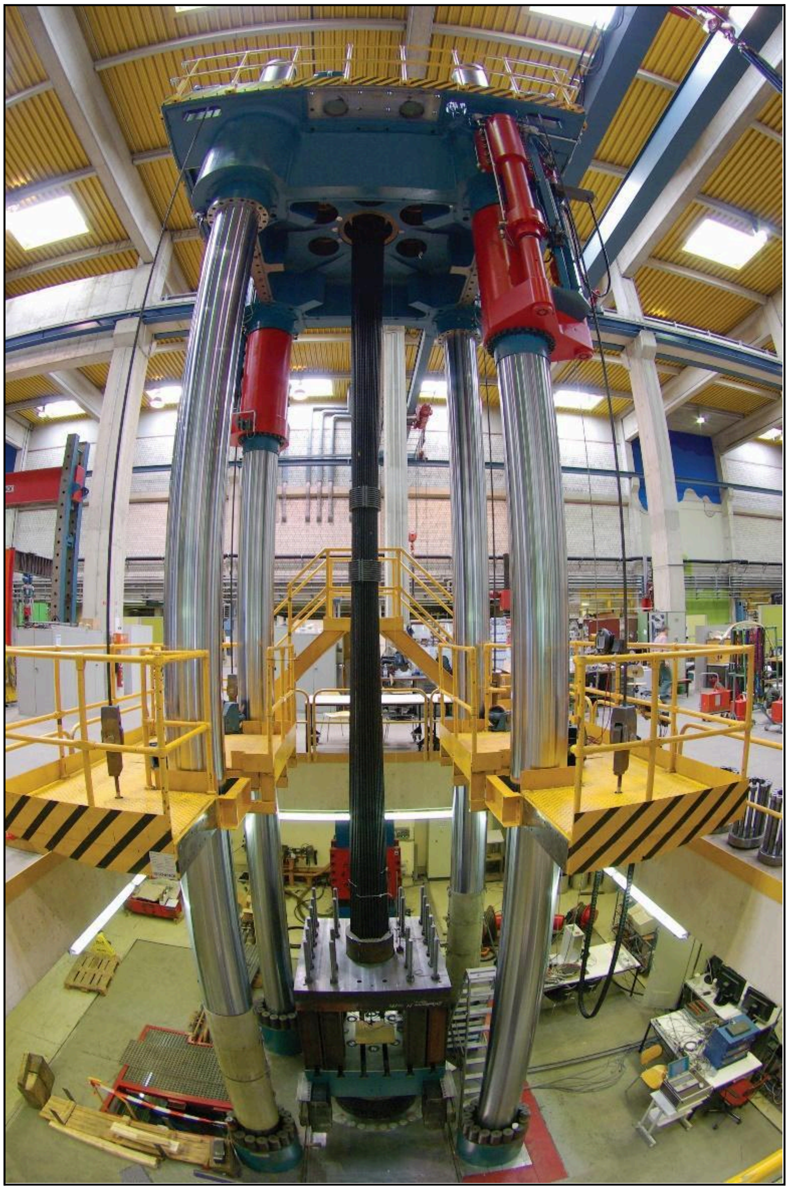


***Figure 7.87 – Fatigue Test Setup***
***(Photo Courtesy of BBR)***

## 7.8 Extradosed Bridges

### 7.8.1 Design Concept

A concept introduced by Pr. Jacques Mathivat in the late 1980s, extradosed bridges are externally post-tensioned bridges with cables placed outside of the girder, which allows greater eccentricity for the external cables. These bridges are generally considered hybrids of post-tensioned box girder bridges and cable-stayed structures, though the technical distinction between extradosed and cable-stayed bridges is not distinct. PTI currently does not make a sharp distinction between the two but instead allows for an increasing phi factor at the strength limit state as the stress range from live load decreases. Overall, the structural behavior of extradosed bridges is closer to box girder bridges than cable-stayed bridges.

The cables on an extradosed bridge are anchored or diverted by a short pylon above the deck that is about half as high as that used on a typical cable-stayed bridge (10% L versus 20% L). The improved efficiency of the external cables allows a reduction in girder depth and, as a result, a reduced dead load. The girders carry higher compression forces than a cable-stayed bridge does, due to the shallower angle of the cables. Also, there is less variability of stresses in the cables under service loads, so the cables are subjected to less fatigue.

Extradosed bridges have been economically used for spans of 300 ft. to 600 ft., with spans up to 900 ft. reached in Japan by using hybrid girders (concrete close to the pier, with a steel central span).

In summary, as compared to post-tensioned box girder and cable-stayed bridges, extradosed bridges feature:

- Reduced concrete box girder depth and lowered vertical profile.
- Constant-depth girders in place of variable-depth box girders, resulting in standardized precasting operations and reduction of precast segment weights.
- Reduced pylon height, which can help better meet a specific projects vertical clearance requirements.

Photographs of extradosed bridges are provided below in **Figures 7.88** and **7.89**.

*Figure 7.88 – Saint Croix Bridge, MN-WI*
*(Photo Courtesy of Structural Technologies)*

### 7.8.2 Construction of Extradosed Bridges

Construction of extradosed bridges is similar to that of box girder bridges since the external cables act more as post-tensioning cables than stay cables.

Geometry control is more critical for an extradosed structure than a typical precast box girder because the cantilevers are normally more slender and longer. The geometry is controlled during erection in a similar manner to cable-stayed bridges; however, discrepancies cannot be corrected by re-stressing the cables since such a large force increase is required to move the deck vertically. Instead, shimming or cast-in-place joints should be used, as used for a long box girder bridge.

The erection process is typically simpler because the cables are normally stressed only once, similar to post-tensioning cables. The shorter cables on an extradosed bridge are also easier to install when compared to long stay cables on a cable-stayed bridge.

The cables must also be replaceable, and double pipe systems are sometimes used at the anchorages and saddles. Alternatively, individually protected strands similar to stay cables can be used to facilitate cable replacement.

Because the cables are quite short, they normally are typically not sensitive to wind/rain-induced vibrations, as is the case with the cables on a cable-stayed bridge.

*Figure 7.89 – Pearl Harbor Memorial Bridge, CT*
*(Photo Courtesy of FIGG)*

## 7.9 Conclusion

The construction phasing of a cable-stayed bridge is critical. Important decisions need to be made at the site in a timely manner to avoid construction delays. Having a knowledgeable team, familiar with design and construction of a cable-stayed bridge structure, on site throughout construction is essential.

## References

- FIP Congress 1986-New Delhi, Cable Stayed Bridges, Keynote Lecture by Fritz Leonhardt
- Ponts Haubanés, Pr. René Walter-1985
- Construction and Design of Prestressed Concrete Segmental Bridges, Podolny-Muller-1982
- Construction and Design of Cable Stay Cable Bridges, 2nd edition-Podolny-Scalzi-1986
- PTI Recommendations for Stay Cable Design, Testing and Installation, Sixth Edition
- AASHTO LRFD Bridge Design Specifications

## Segmental Concrete Cable-Stayed Bridges in the United States

| Bridge Name | State | Date Completed | Main Span (Ft) | Superstructure Type | NBIS No. | ASBI Database No. |
|---|---|---|---|---|---|---|
| Pasco-Kennewick | WA | 1978 | 981 | PC, Edge Box Girders | 85555000000000 | 418 |
| East Huntington | WV | 1985 | 900 | PC, Edge Girders, Steel Floor Beams | 00000000006A215 | 449.1 |
| Sunshine Skyway | FL | 1987 | 1,200 | PC, Box Girder | 150189 | 375 |
| Dame Point | FL | 1989 | 1,300 | CIP, Edge Girders | 720518 | 067 |
| Varina-Enon | VA | 1990 | 630 | PC, Twin Box Girders | 10007 | 349 |
| Veterans Memorial | TX | 1991 | 640 | PC, Box Girder | 201240030603030 | 344 |
| Talmadge Memorial | GA | 1991 | 1,100 | CIP, Edge Girders | 5101690 | 115 |
| Cochrane | AL | 1991 | 780 | CIP, Twin Box Girders | 15430 | 002 |
| Korean War Veterans Mem. | DE | 1995 | 750 | PC, Twin Box Girders | 1902 082 | 372 |
| Sidney Lanier | GA | 2002 | 1,250 | CIP, Edge Girders | 12750200 | 114 |
| Penobscot Narrows | ME | 2006 | 1,161 | CIP, Box Girder | 6421 | 482 |
| Veterans’ Glass City Skyway | OH | 2007 | 612 | PC, Twin Box Girders | 4805909 | 444 |
| La Plata River | PR | 2008 | 525 | CIP, Edge Girders | 30001 | 487 |
| Pomeroy Mason | OH | 2008 | 675 | CIP, Edge Girders | 5300916 | 407 |
| Charles W. Cullen | DE | 2012 | 950 | CIP, Edge Girders | 3156 050 | 373 |
| Pearl Harbor Memorial | CT | 2015 | 515 | CIP, Extradosed Box Girder | 00174A (NB)<br>00174B (SB) | 423 (NB)<br>424 (SB) |
| Tilikum Crossing | OR | 2014 | 780 | CIP, Edge Girders | 22258 000 00000 | 408 |
| Oakley Collins | OH | 2016 | 900 | CIP, Edge Girders | 4401263 | 457 |
| St. Croix | MN | 2017 | 600 | PC, Extradosed | 82045 | 396 |
| Harbor Bridge | TX | 2025 | 1,661 | PC Twin Box Girders | 161780010106119 | 505.0 |

## TABLE OF CONTENTS

# Chapter 8:
# Segmental Substructures

## 8.1 Introduction

With the development of precast segmental columns, segmental technology was extended to be used in bridge substructures. The first bridge in the U.S. to use precast segmental columns is generally acknowledged to be the Seven Mile Bridge, built in 1982 in the Florida Keys (**Figure 8.1**). The project was located more than 80 miles away from the southernmost city on the Florida peninsula down US Route 1. The project's remote location with many of the in-water piers located miles from shore made it an ideal project to utilize precast segmental columns to reduce the construction environmental impacts, duration and cost.

***Figure 8.1 – Seven Mile Bridge, Florida Keys, FL***
***(Photo Courtesy of FIGG)***

Since then, many more bridges have been constructed using this technique, resulting in benefits including improvements in construction schedule, economy, and durability. The use of precast substructures can also help address projects with limited access and improve worker safety by limiting work near traffic or over water. In many cases, when site preparations, deep foundations, or extensive repetition of common piers provide adequate lead time for precasting column sections, conventional cast-in-place substructures and/or foundations can be re-designed as precast for significant project savings.

## 8.2 Project Examples

The bridges built using precast segmental columns represent a range of diverse approaches.

Many used simple, hollow rectangular column sections. The Varina-Enon Bridge, the James Burrows Edwards Bridge, Chesapeake and Delaware Canal Bridge, Garcon Point Bridge, South Norfolk Jordan Bridge, O'Callaghan-Tillman Memorial Bridge, the Route 36 Highlands Bridge, and Bayonne Bridge approach spans are among these. **Figure 8.2** shows a typical hollow rectangular column segment used on the Garcon Point Bridge.

Other bridges employed shapes specifically selected to meet structural, aesthetic, and/or other project requirements. A few such structures include the Sunshine Skyway, Linn Cove Viaduct, Albemarle Sound Bridge (**Figure 8.3**), U.S. 183 Austin Bridge, Foothills Parkway Bridges, Dallas-Fort Worth Automated People Mover and lift towers for the Sarah Mildred Long Bridge. The Route 36 Highlands Bridge is shown in **Figure 8.4** and Dallas-Fort Worth Automated People Mover is shown in **Figure 8.5** below.

***Figure 8.2 – Garcon Point Bridge Pier Column Segment, FL***
***(Photo Courtesy of FIGG)***

*Figure 8.3 – Albemarle Sound Bridge Pier Column Segments, NC*
*(Photo Courtesy of FIGG)*

***Figure 8.4 – Route 36 Highlands Bridge, NJ***
***(Photo Courtesy of J.H. Reid General Contractors)***

***Figure 8.5 – DFW Automated People Mover, TX***
***(Photo Courtesy of McNary Bergeron & Johannesen)***

The benefits of segmental construction can also apply to vertical construction. Precast segmental columns have been used for building and stadium construction. Examples of vertical construction using precast segmental columns include the Google Headquarters elevator and stairway cores in Manhattan, New York, (**Figure 8.6**) and the roof support columns for the SoFi Stadium in Los Angeles (**Figure 8.7**).

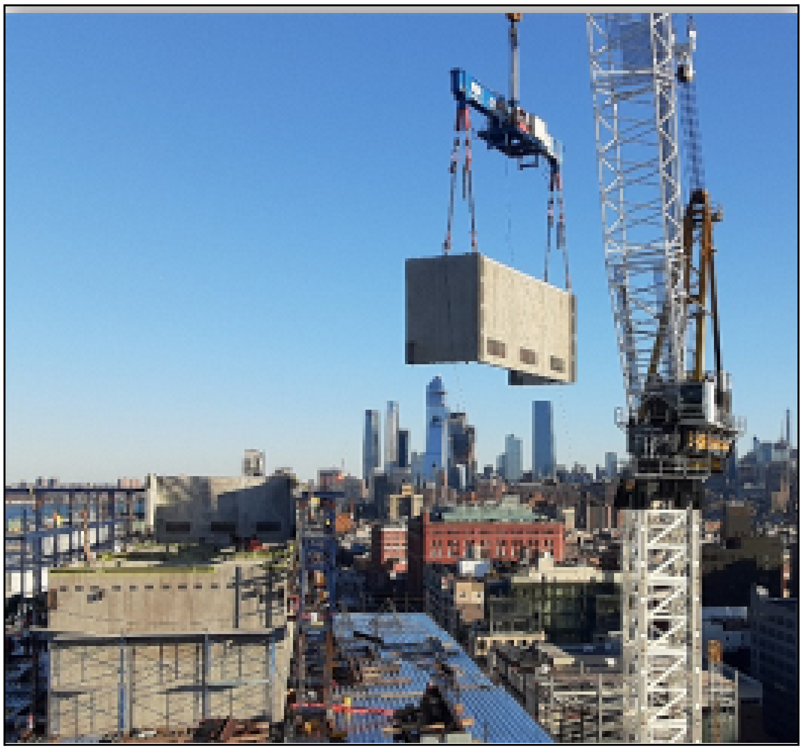


***Figure 8.6 – Google HQ Precast Elevator Core, NY***
***(Photo Courtesy of Rizzani de Echer USA)***

***Figure 8.7 – SoFi Stadium Roof Support Columns, CA***
***(Photo Courtesy of McNary Bergeron & Johannesen)***

The James Burroughs Edwards Bridge over the Wando River in South Carolina is of particular interest. The construction sequence for the main span of the superstructure called for temporary piers in the side spans. The contractor elected to use precast column segments for these temporary piers. After construction of the main span, they temporary piers were disassembled and used as permanent piers elsewhere in the project (**Figure 8.8**). This innovation resulted in a significant reduction in materials and construction costs.

Also of note is the Linn Cove Viaduct (**Figure 8.9**) on the Blue Ridge Parkway in North Carolina. To meet aesthetic requirements, the project specified hexagonal columns with concave surfaces, along with adding black iron oxide to the concrete mix so the columns would weather to the same color as surrounding rock outcroppings. The construction placement of the columns was also similarly unique. No heavy equipment was allowed on the terrain below the structure, so the superstructure was built forward until a pier location was reached. The pier column segments were then delivered across the completed portion of the superstructure and placed in their final position from above.

On the O'Callaghan-Tillman Memorial Bridge (Hoover Dam Bypass Bridge) spanning the Colorado River between Arizona and Nevada, the contractor used precast segments for the pier columns and the spandrel columns on the concrete arches. The columns were engineered to taper slightly toward the pier caps, with the tallest pier reaching about 300 ft tall. The temporary pylons that supported the stay-cable system during arch erection were precast as well. Because of their temporary nature, epoxy coating was not provided between the temporary pylon segments. The James Burroughs Edwards Bridge is shown in **Figure 8.8**, the Linn Cove Viaduct is shown in **Figure 8.9**, and O'Callaghan-Tillman Memorial Bridge is shown in **Figure 8.10** below.

***Figure 8.8 – Pier Column Disassembly, James Burroughs Edwards Bridge, SC***
***(Photo Courtesy of FIGG)***

***Figure 8.9 – Pier Column Segment Erection, Linn Cove Viaduct, NC***
***(Photo Courtesy of FIGG)***

***Figure 8.10 – Pier Column Segment Erection, South Norfolk Jordan Bridge, VA***
***(Photo Courtesy of FIGG)***

***Figure 8.11 – Precast Column Erection, Korean War Veterans Memorial Bridge, DE***
***(Photo Courtesy of Recchi America)***

*Figure 8.12 – Precast Column Erection, O'Callaghan-Tillman Memorial Bridge, AZ-NV*
*(Photo Courtesy of Obayashi)*

## 8.3 Precasting Operations

While segmental substructure precasting procedures vary based on contractor preferences, the basic operation comprises the following steps.

- Pre-tying reinforcing cage.
- Setting forms for match-cast pour and installing reinforcing cage and post-tensioning ducts.
- Establishing geometry by plumbing forms and match-cast segment, with corrections as required from previous match-casting.
- Pouring and curing concrete.
- Performing as-cast survey for new segment.
- Removing bottom match-cast segment to storage.
- Setting new match-cast segment in the casting bed.

Precast column segments are typically a constant cross-section, which makes reinforcing cages simple. They are usually made up of a series of transverse sets and vertical straight bars. The transverse sets are typically tie bars consisting of smaller bar sizes. Though current design code requirements have resulted in increased tie density, the reinforcing bar cages remain modular and are readily tied in assembly jigs off-line (see **Figures 8.13** and **8.14**).

***Figure 8.13 – Tying the Rebar Cage for the SoFi Stadium Column Segment, CA***
***(Photo Courtesy of McNary Bergeron & Johannesen)***

***Figure 8.14 – Precast Column Segment Reinforcing Cage***
***(Photo Courtesy of Cianbro)***

Precast column segments are most often cast in their actual vertical orientation, with each segment match-cast to assure a precise fit when they are epoxy-joined together during erection. Casting typically begins with the bottom segment and proceeds upwards, with the top segment being cast last. The first segment in each column is cast in the form at ground level, and the next one is match-cast on top of the first segment. The first segment is then taken to storage, the second segment placed in the bottom position, and the third segment match-cast on top of the second segment. This cycle repeats until a column is complete. The last segment, a pier cap segment, usually has a solid section with special reinforcing to accommodate the bearings and distribute the bearing and post-tensioning forces to the overall cross-section. **Figure 8.15** shows match-casting as part of the precasting operations.

The most common set-up for a match-cast pour involves four steps.

1. Setting a core form (forming the interior void) above and overlapping the match-cast segment.
2. Installing a reinforcing cage, along with post-tensioning ducts.
3. Setting the exterior form.
4. Surveying the form and match-cast segment into plumb positions.

If the as-built plumbness deviates from the last match-cast pour, the next pour cannot be set perfectly plumb. Instead, the forms must be offset to compensate for the previous as-built survey and allow the column as a whole to track a vertical line. Note that two orthogonal faces must be monitored to assure plumbness in both directions , while monitoring a third face will ensure there is no twist.

***Figure 8.15 – Match-Cast Pier Column Segment During Precasting Operations (Photo Courtesy of Cianbro)***

*Figure 8.16 – Precast Column Segment Concrete Finishing*
*(Photo Courtesy of Cianbro)*

The concrete is placed, directly into the top of the forms. Since the segments are cast in a vertical position, there are no slabs and only the small upper joint surface that requires finishing (**Figure 8.16**). Female shear keys are formed into the finished top surface of each column segment, creating male shear keys in the bottom match cast surface of the next segment. These shear keys ensure proper re-alignment of the segments during erection. All vertical surfaces are formed. Curing requirements are the same as for any other concrete element, and most contractors do not elect to steam column segments. The strength required to lift each segment to storage is usually a nominal 2,500 psi, and minimum strength for handling is readily achieved overnight.

Precasting operations for column segments are straightforward, generally producing a segment per day in each form bed. The limiting factor is the time needed for the concrete to achieve minimum strength for handling.

## 8.4 Erection Operations

Erection of precast columns proceeds very quickly, with some projects being able to erect over 100 linear feet of column per day for each column being erected. There may be variations based on contractor's means and methods, but the following process is typical.

The first step is to place and plumb the first segment on the footing. A keyway slightly larger than the segment cross-section is usually cast into the top of the footing (see **Figure 8.17**). The first segment is placed partially down into the keyway, but with a minimum joint of 1 to 2 in. between the segment and the bottom of the keyway. The segment is then plumbed by survey and shimmed off the bottom of the keyway to maintain the desired geometry (see **Figure 8.18**). The accuracy required depends on the height of the plumbed segment, since deviations in setting are projected to the top of the column. Therefore, if the individual segments are short, aligning a stack of multiple segments will result in better precision. Next, post-tensioning ducts between the footing and the segment are coupled. Finally, high-strength grout is poured into the keyway to join the first segment to the footing.

***Figure 8.17 – Footing with Keyway***
***(Photo Courtesy of FIGG)***

***Figure 8.18 – Aligning and grading the starter (bottom) segment to achieve the proper geometry and positioning for the column. In this photo, pockets for jacks were used to align and grade the starter segment.***
***(Photo Courtesy of J.H. Reid General Contractors)***

After curing the grouted joint, erection of the remainder of the segments can proceed. As with superstructure segments, column segments are joined using segmental bridge adhesive (epoxy) to seal the segment joints from water intrusion and improve structural continuity. Vertical PT bars are used to achieve the required epoxy contact pressure of 40 psi. In most cases, these PT bars are internal to the concrete and thus become part of the permanent post-tensioning in the structure.

Crew access for bar coupling, epoxy application, and bar stressing should be considered carefully. Taller columns may require access platforms attached to the segments with inserts installed prior to casting. Getting personnel to those access platforms is often achieved with manlifts.

Each segment is lifted into position directly above the previous segment to allow PT bar couplers to be engaged and making the vertical PT continuous through the new segment (see **Figure 8.19**). Safety blocking is installed, vertical bars are coupled, and epoxy is applied by gloved hand to the top surface of the previous erected segment. Safety blocking is then removed, and the new segment is lowered into place.

At that point, the vertical PT bars are stressed from atop the newly erected segment as shown in **Figure 8.20** to achieve a minimum uniform pressure of 40 psi for epoxy squeeze, or the minimum stress required for stability, whichever is greater. Typically, these PT bars are stressed when each segment is erected. Depending on epoxy working time, contractors sometimes have stacked 2 or more segments before stressing PT bars.

Excess epoxy squeezed from the segment joints can permanently mar the column finish and can be difficult to remove. This issue can be resolved relatively easily by covering the column exterior with one or two rows of duct tape just above and below the segment joint (see **Figure 8.19**). Excess epoxy flows onto the tape instead of the concrete, and when the tape is later removed the excess cured epoxy comes off cleanly.

Erected column geometry is monitored throughout the stacking process after each set of vertical PT bars are stressed. Since the column segments were match-cast, the geometry is monitored for deviations from the as-cast alignment.

***Figure 8.19 – Pier Column Erection with a Ground-Based Crane***
***(Photo Courtesy of FIGG)***

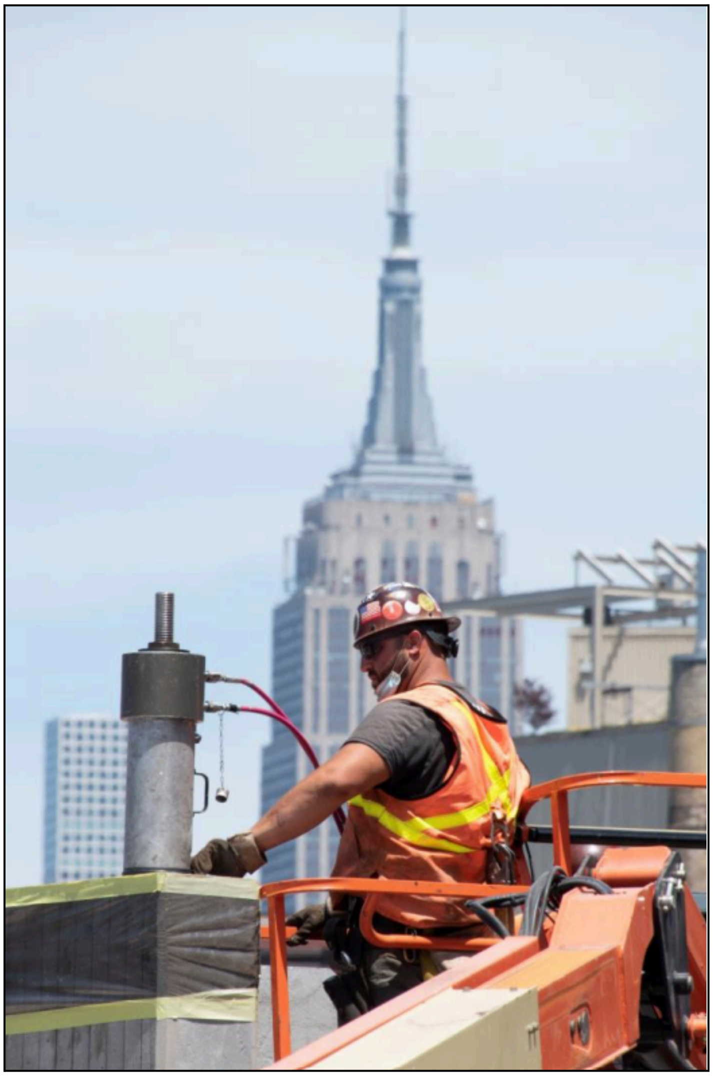


***Figure 8.20 – Stressing Vertical PT bars for Epoxy Squeeze between Precast Column Segments***
***(Photo Courtesy of Rizzani de Echer USA)***

After all segments in a column are erected, the permanent vertical post-tensioning is stressed (See **Figures 8.21** and **8.22** below). While either bars or strand tendons are acceptable, strand tendons are most often used for the major permanent post-tensioning. These tendons typically loop down through the footing and have both end anchorages located in the pier cap segment (see **Figure 8.25** below). They are double-end-stressed from the pier cap and typically internal to the concrete cross-section. Tendons external to the cross-section and running in the interior void can be used if the design prefers. These are typically unbonded tendons and require a different design basis. In all cases, the tendons are grouted after installation for corrosion protection.

There were instances in some of the early precast columns where an excessive amount of bleed water accumulated at the top of the vertical post-tensioning tendon anchorages and/or ducts. Over time this resulted in the deterioration of the strands at the tops of the columns, and the deteriorated tendons had to be replaced. The primary cause of the excessive bleed water in the grout was the use of regular cement grout that was mixed onsite (with minimal mixing requirements) and used in very tall precast columns.

Today, modern prepackaged thixotropic grouts are chemically manufactured with a number of additional admixtures that prevent the water from separating from the cement mixture. Post-tensioning tendon grout mixing procedures and requirements are also much more stringent today, and quality control testing for bleed water is now required during PT grouting operations. Additionally, extension tubes and cups are installed on top of the vertical post-tensioning anchorage caps to allow the grout to be pumped above the post-tensioning anchors. This gives inspectors the ability to monitor the grout in the tendon as it cures and, if any bleed occurs in the grout, it will occur above the post-tensioning anchorages.

*Figure 8.21 – Stressing Vertical Column Tendon, SoFi Stadium, CA*
*(Photo Courtesy of McNary, Bergeron, and Johannesen)*

***Figure 8.22 – Stressing Vertical Column Tendon, Route 36 Highlands Bridge, NJ***
***(Photo Courtesy of J.H. Reid General Contractors)***

## 8.5 Other Precast Substructure Elements

Segmental pier columns are the classic precast segmental substructure elements used on bridges, but other elements can be constructed as well. Accelerated Bridge Construction (ABC) methods have incorporated precast abutments, footings, and piers to speed on-site erection. These elements are often joined with post-tensioning after erection to complete their structural connection.

Precast footing shells have been used as falsework on marine projects to support large-volume concrete pours. Recent examples include the Audubon Bridge in Louisiana, Tappan Zee Bridge replacement in New York, and the Sarah Mildred Long Bridge connecting Maine and New Hampshire. On the Sarah Mildred Long bridge, the footing shells for the lift piers were precast in “tub” segments, set in place on top of drilled shafts and connected with post-tensioning to form a complete footing shell. See **Figures 8.23** and **8.24**.

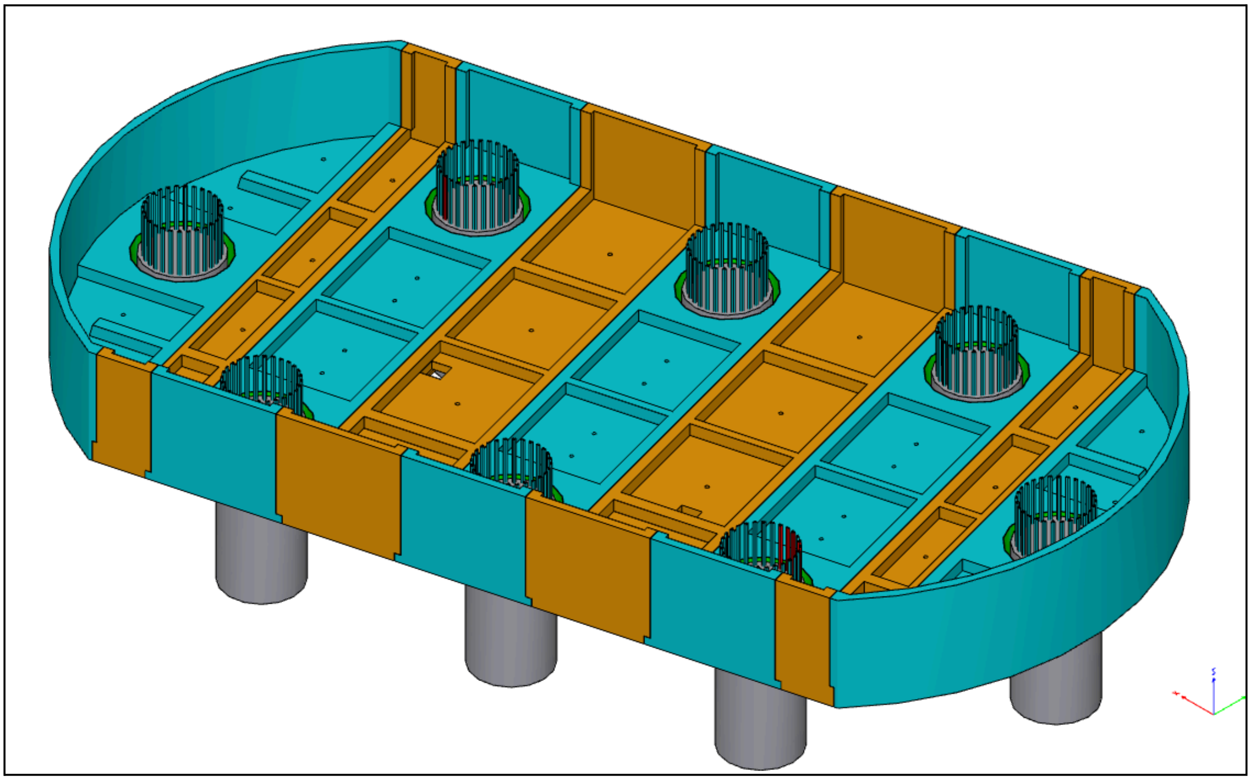


*Figure 8.23 – Precast Tubs Forming a Footing Shell on Drilled Shafts*
*(Graphic Courtesy of Hatcher Technical)*

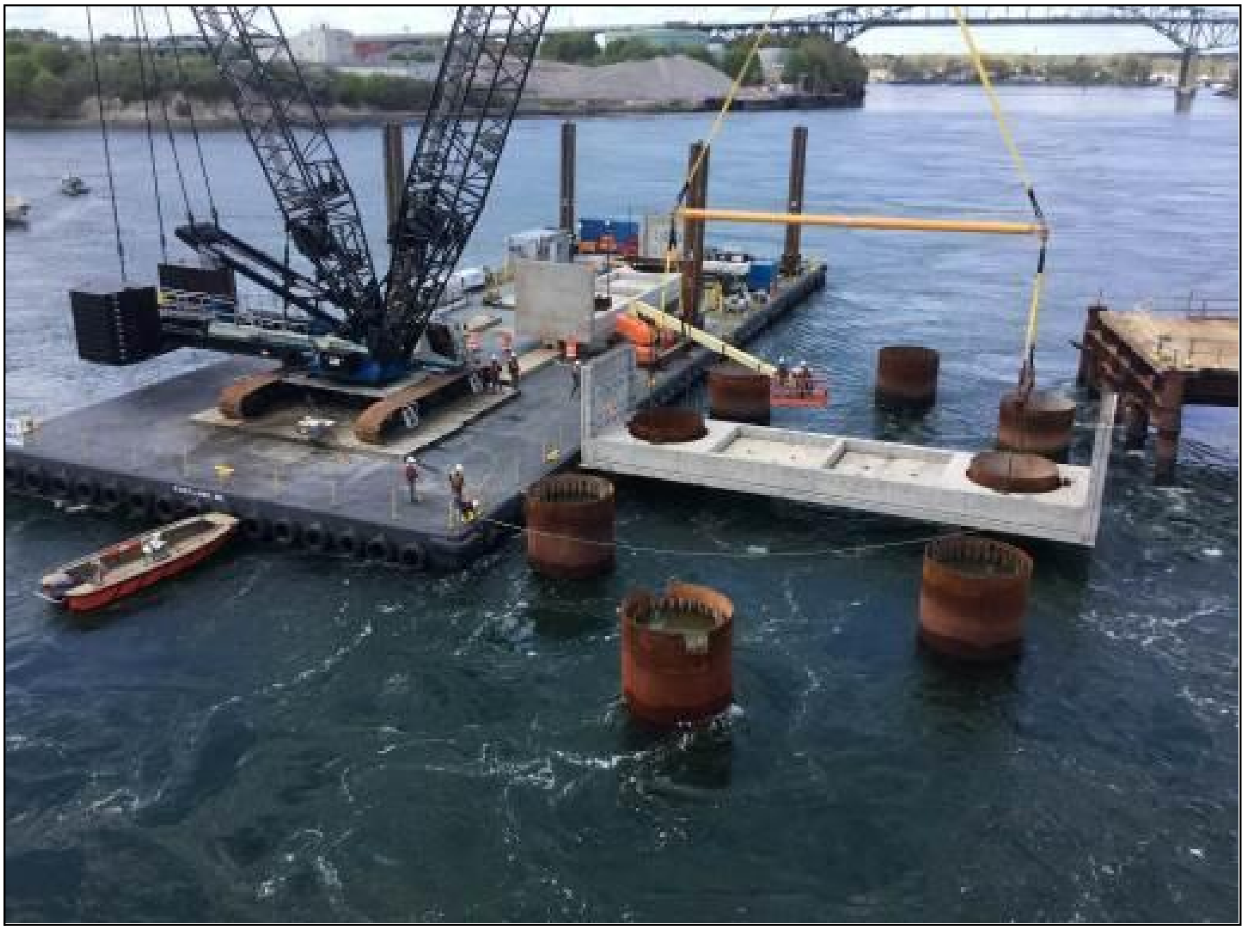


***Figure 8.24 – Installation of Precast Tub Footing Segment***
***(Photo Courtesy of Cianbro)***

## 8.6 Summary

Precast segmental substructures can be a very efficient solution when there is volume production of standard column shapes. Precasting may also be the optimal solution for unique sections requiring high-quality concrete, geometry control, or deep foundations with sufficiently long lead time that allows fabrication of column sections in parallel with foundation work. The major advantage of precasting column segments is the unsurpassed speed of on-site erection. Re-designing conventional substructures and/or foundations to precast segmental is often worth considering when feasible.

Precast segmental columns have thus far been used mostly in low to moderate seismic regions, but displacement-based seismic design is becoming more prevalent, potentially extending use of this type of construction to higher seismic regions. Research at the University of California at San Diego on the use of unbonded tendons in segmental columns subject to high lateral seismic displacements has shown the residual drift of these columns is much less than typical because the main vertical reinforcing (post-tensioning) does not yield, while still providing adequate displacement ductility. If employed, the shape of the column would need to be such that it adequately confines the compression zone, thereby providing for plastic hinging and displacement ductility.

The AASHTO-PCI-ASBI Box Girder Standards include details for precast box piers. These standard drawings can be found on the ASBI website, asbi-assoc.org, under the Resources tab. **Figure 8.25** shows a detailed drawing of the tendon loop connection of precast segmental piers to the foundation.

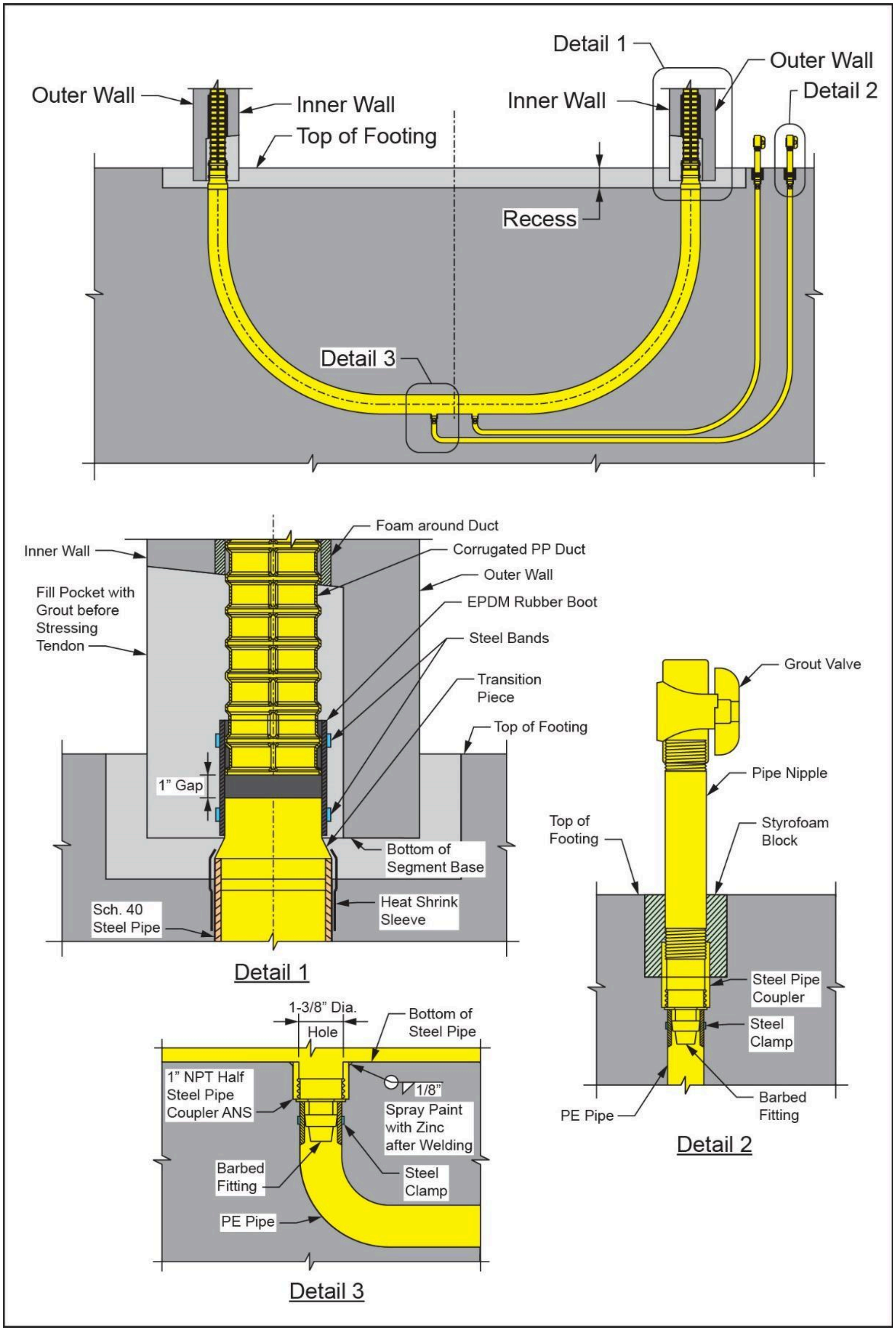


*Figure 8.25 – Loop Tendon Details in Footings*

## TABLE OF CONTENTS

# Chapter 9:
# Casting Yard Planning and Set-Up

## 9.1 Introduction

The planning undertaken and decisions made at the start of a project set the tone for the remainder of the job. On a segmental bridge project, many preliminary decisions regarding the location and setup of a casting yard should be made during the bidding process. Certainly, the casting method must be decided during bidding to estimate form infrastructure costs. One or more potential locations should be examined for acreage, existing site conditions, permitting, requirements for site preparation, required equipment, site access in and out, and site clean-up at the end of the project.

Schedule is always a driving factor. Immediately after project award, any long lead items including casting cells, batch plants, steam generators, and cranes should be ordered. Casting cells can take anywhere from twelve weeks to six months for delivery, depending on the number of forms required and the complexity of the segments. During this time, the casting yard needs to be finalized and prepared to accept the casting cells for erection upon their delivery. Site preparations may be as simple as clearing and grading, or may also address drainage installation, wetland issues, zoning requirements, utility installation, or docking/water access issues.

Another critical component is personnel. Project managers and/or plant managers are typically identified before a project starts, but a supporting cast may take time to assemble. This includes QA/QC inspectors, surveyors, form crews, reinforcing steel crews, post-tensioning and grouting crews, concrete finishers, equipment operators, and many auxiliary employees required to complete the daily work. The casting yard staffing plan should also give consideration to the long hours in the casting yard, and the potential need for multiple shifts.

A site-specific safety manual and mandatory employee safety training are two additional keys to success.

## 9.2 Production Methods

Precast segments are produced in structural groups of adjacent segments referred to as a “casting unit” or “casting run.” A casting unit can consist of either all segments of a span (typical with the span-by-span erection method) or all segments of either one cantilever arm or of both cantilever arms on one side of a pier (typical with the balanced-cantilever erection method). If all segments of both arms are cast at the same time, the pier segment can cast in the same long-line bed, as shown in **Figure 9.1**.

### 9.2.1 Match-Casting

Match-casting is a method whereby the fresh concrete of each new segment is cast against the already hardened concrete of the previous segment. A bond breaker (mixture of wax, soap, and talcum powder, or a manufactured chemical compound) is applied to the joint surface of each “match-cast segment” to ensure separation from the “wet-cast segment.” Assuming proper precautions are taken, match-cast segments come apart cleanly and erect together perfectly, with the joint being almost invisible. This technique makes segmental construction one of the most efficient methods for building large bridge structures.

Important separation precautions start with segment design. Protrusions make it physically difficult to break the bond and should be avoided. Any necessary protrusions, such as shear keys or post-tensioning block-outs, should have plenty of draft (slope) and be shaped to enable the pieces to be pulled apart. The bond breaker must be carefully and consistently applied, and the effects of weather on the bond breaker taken into consideration. Finally, segments must be smoothly and evenly pulled apart perpendicular to the match-cast face. Any force upward, downward, or to either side before separation may cause damage.

For correct fit at the time of erection, the joint faces must not be altered, except for a light cleaning that does not alter the joint face. This generally means no repair work should be done on the joint faces, and segments must be stressed in such a way that differential deformation cannot occur.

Both long-line and short-line casting use the match-casting technique. Both of these methods are described in more detailed below.

### 9.2.2 Long-Line Casting

Long-line casting is the original precasting method. The “long-line” refers to leaving segments in their cast location and traveling the forms ahead to the next segment to complete an entire “casting unit,” thus creating a “long line” of precast segments. A long-line casting bed usually comprises two main sections.

- A bottom form, or soffit, which is fixed and has the same total length as the entire casting unit --The soffit is made in the profile of the structure, with corrections for short- and long-term erection deflections. In other words, the soffit is set to the cambered geometry or casting curve.
- External forms, core forms, and a front bulkhead -- The external and core forms are the length of a single segment and are moved along the run. On variable depth structures, external forms usually have a fixed height equal to the deepest segment of the run, while the core forms and movable leading bulkhead are adjustable in height.

Advantages of this method include:

- Most geometry control is done during construction of the soffit, reducing much of the need for geometry control during segment production. However, as-cast surveys are needed to confirm the geometry when segments are erected.
- Segments remain in their relative position, so geometry control is simpler and more intuitive.

Disadvantages include:

- It requires a large casting area and a firm, non-settling foundation.
- Casting forms are rarely re-usable from one project to another.
- Variations in casting geometry are difficult to obtain. If the soffit is fixed, it can be made for one casting curve only, so all spans must have the same geometry or additional soffits must be

constructed. The soffit can be made to be adjustable, but the method then loses its advantage of simplicity.

See **Figure 9.1** for a schematic of a typical long-line casting operation, and **Figures 9.2** and **9.3** for examples.

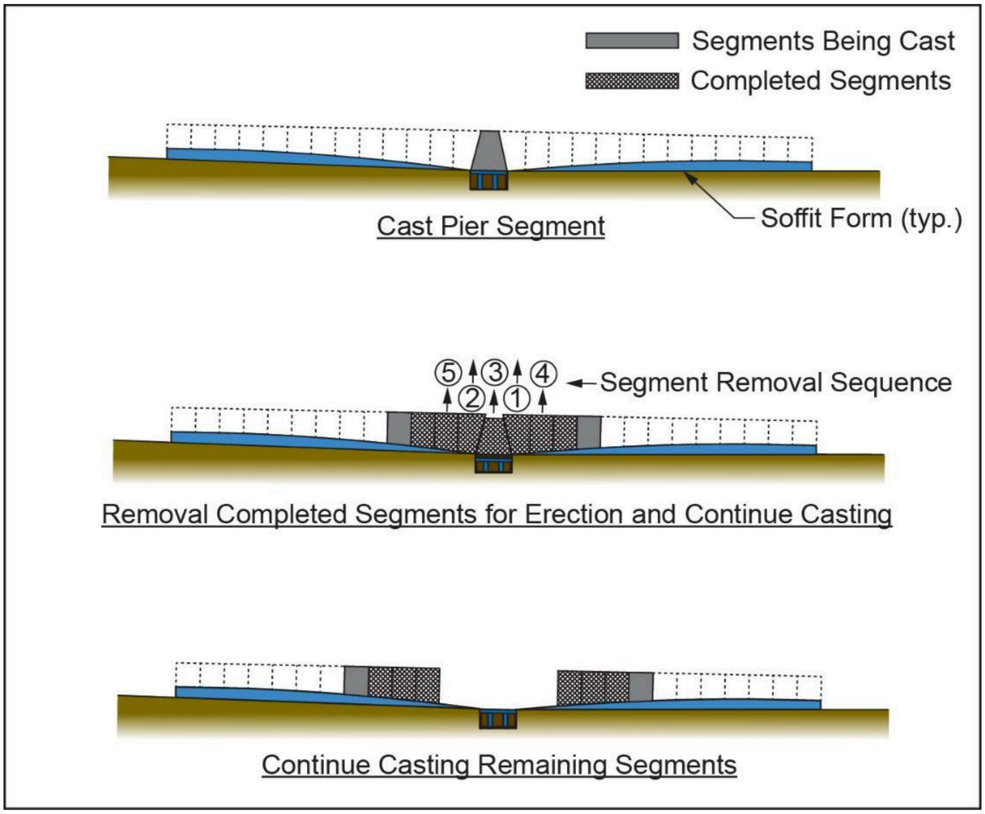


*Figure 9.1 – Typical Long-Line Production*

*Figure 9.2 – Long-Line Bulkheads and Core Forms Being Erected for Starter Segments, SW Line Bridge, WA (Photo Courtesy of Atkinson Construction)*

*Figure 9.3 – Simple Long-Line Casting Yard in Operation, SW Line Bridge, WA*
*(Photo Courtesy of Atkinson Construction)*

Variations are frequent, such as dividing the soffit into individual panels for each segment. The panels are still supported by a common stiff foundation but allow for slight vertical adjustments by means of shims or screw jacks. For the Skyway portion of the San Francisco-Oakland East Bay Bridge replacement project (**Figures 9.4 – 9.5**), 44 cantilever arms were cast using the long-line method, of which 10 had a curved alignment. The soffit consisted of individual forms for each segment, supported on short, adjustable shoring towers set on a concrete slab. Slight horizontal curvature adjustment was possible. Due to the weight of each segment (750T), settlements were accounted for in geometry control. Custom-designed software tracked the as-cast geometry and provided adjustments for the segments. This method demonstrated more versatility than traditional long-line casting, but the complexity detracted from the method's advantage.

***Figure 9.4 – Bulkhead View of Long-Line Bed, San Francisco-Oakland Bay Bridge Skyway, CA (Photo Courtesy of Flatiron Construction)***

***Figure 9.5 – Side View of a Long-Line Casting Bed, San Francisco-Oakland Bay Bridge Skyway, CA (Photo Courtesy of Flatiron Construction)***

### 9.2.3 Short-Line Casting

In “short-line” casting, the casting form is stationary and instead, segments move from the wet-cast position to the match-casting position, and then to storage away from the forms. A short-line casting cell schematic is shown in **Figures 9.6** and **9.7**.

Advantages of this method include:

- Space requirements (for the casting infrastructure) are reduced as compared to the long-line method.
- The manufacturing process is centralized.
- The system is extremely adaptable to geometry variations such as horizontal and vertical curvature and super-elevation transitions, which are obtained without increase in costs.
- The casting machines can be reused for other projects.

Disadvantages include:

- Increased cost for the casting infrastructure.
- Increased geometry control monitoring and survey costs.
- Match-cast segments must be placed to extremely tight tolerances, which can be time-consuming.

Illustrations of short-line forms in use are shown in **Figures 9.8 - 9.10**.

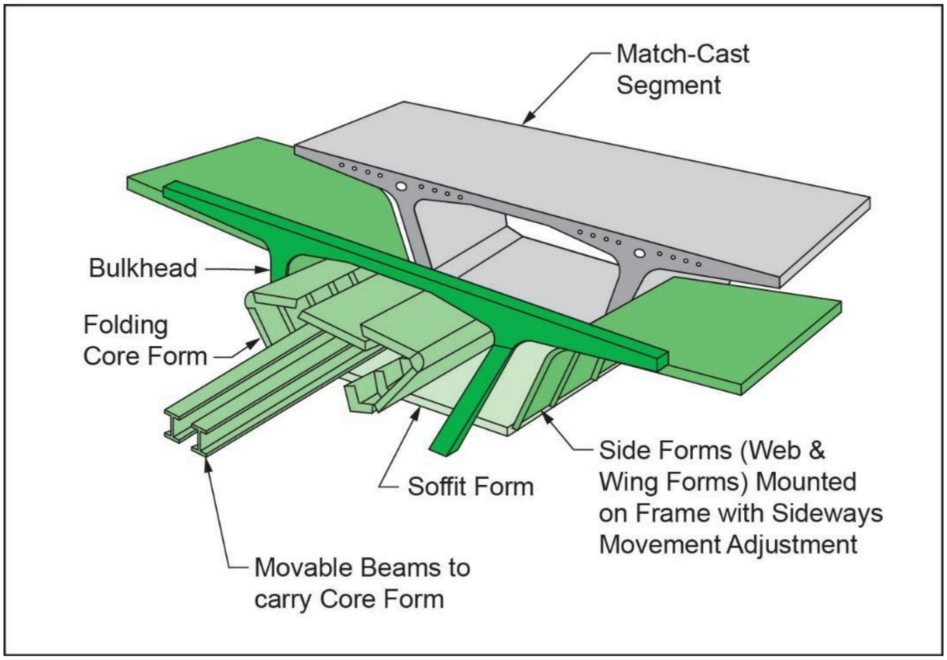


*Figure 9.6 – Casting Cell (Short-Line Method)*

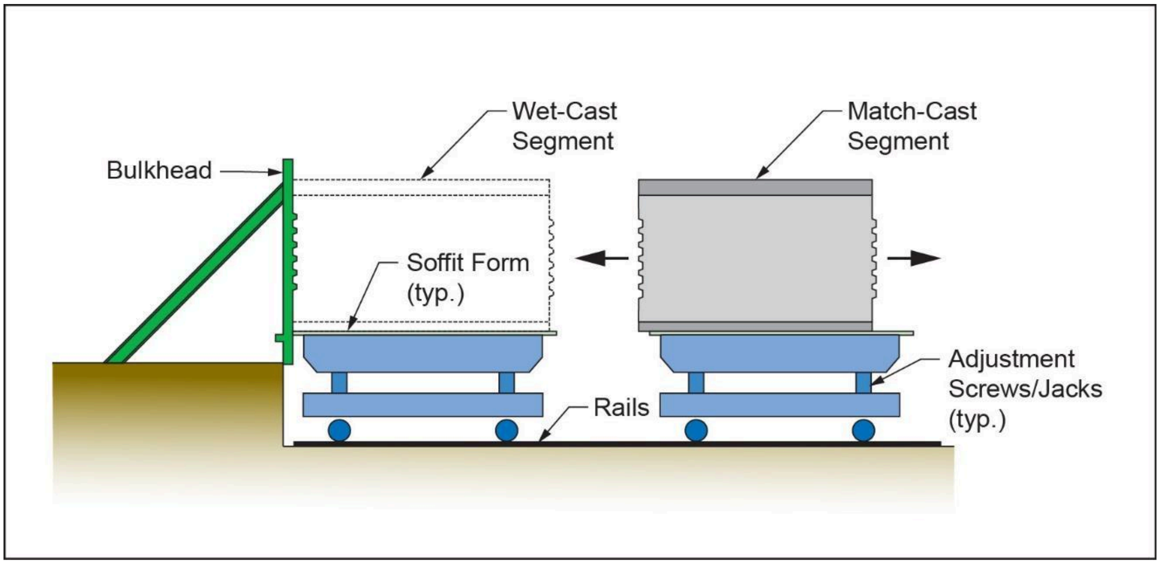


*Figure 9.7 – Casting Cell (Short-Line Method)*

*Figure 9.8 – Short-Line Form, Lee Roy Selmon Crosstown Expressway, FL*
*(Photo Courtesy of FIGG)*

***Figure 9.9 – Bulkhead and Wing Forms, Lee Roy Selmon Crosstown Expressway, FL***
***(Photo Courtesy of FIGG)***

***Figure 9.10 – Wing Form Supports, Lee Roy Selmon Crosstown Expressway, FL***
***(Photo Courtesy of FIGG)***

Due to the requirement to frequently and efficiently move segments out of the short-line system to begin the next cycle, casting yard layout is especially important in a short-line operation. Essential features are shown below in **Figure 9.11**.

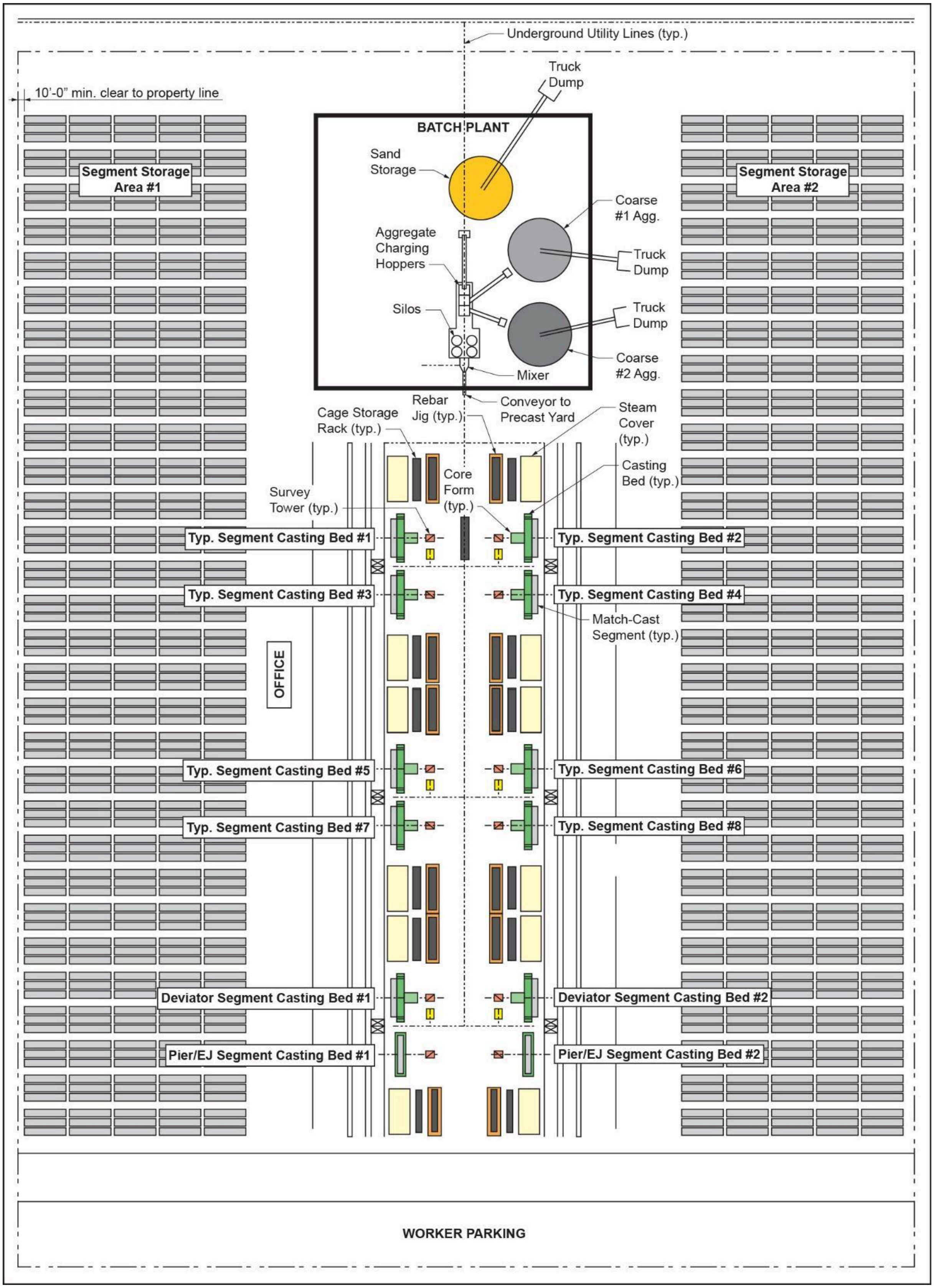


*Figure 9.11 – Typical Casting Yard Layout and Storage for the Short-Line Method*

### 9.2.4 Special Segment Casting

"Special" segments transfer the load from the superstructure to the substructure of the bridge. They contain some component of a diaphragm or heavily reinforced concrete wall to transfer the load. Special segments include pier tables, pier segments, and abutment segments.

Special segments have critical structural components that must be planned during the design, shop drawing, formwork design and purchasing phases. These might include an increased number of post-tensioning anchorages and ducts, heavier reinforcing densities, sleeves for temporary and future post-tensioning, personnel access, accommodations such as sleeves or block-outs for bearings and seismic restraining units, accommodations for drainage and utilities, or rebar couplers for secondary pours. Extensive conflict resolution for permanent materials and sleeves should be performed during design. Likewise, during form design, conflict resolution for formwork and placing aids (form stiffeners, ties, holes for sleeves and duct mandrels, etc.) is necessary.

In span-by-span erection, pier segments are typically cast in a casting cell that operates in short-line fashion. An adjacent typical segment is set in match-cast position and a core form is inserted to act as a solid wall form for the pier diaphragm. The fixed bulkhead for the opposite diaphragm wall form is nearly solid. A smaller core form may be inserted, or hand-set, between the two as an access passage.

Special segments are often cast "square," with both bulkheads parallel, to reduce geometry requirements and form adjustments These processes are better handled in casting of the adjacent typical segments.

There are several available methods for casting cantilever pier or abutment segments.

In short-line casting, there are three basic factors to consider:

- Short-line casting | Numerous special segments -- A custom bed can be designed to mass-produce a special segment type, similar to typical segment casting. A pier segment formed in this manner is shown in **Figure 9.15**.
- Short-line casting | Moderate special segments -- A "transformer cell" can be designed to cast typical segments and altered with special bulkheads to cast special segments, as well. This reduces infrastructure costs but loses several days in schedule each time the bed is converted.
- Short-line casting | Few special segments – Special segments can be precast independently of the casting cells in a stick-built or hybrid fashion, then used as match-cast segments in the short-line cell. An abutment segment formed in this manner in shown in **Figure 9.14**.

In long-line casting, there are two basic methods as illustrated in **Figures 9.1** and **9.2**:

- Pier segments can be first-cast with two bulkheads and used as the starter segment for both cantilevers.
- Segments may be first cast on both sides, with the pier segment between.

Reinforcing continuity with the substructure frequently requires these segments to be cast in place at the bridge site. They are not match-cast but require a "wet joint" between the onsite concrete and the precast concrete.

With hybrid methods that allow match-casting, a segment "shell" is placed over the substructure and supported by adjustable falsework. After precise alignment, voids in this shell can be formed and a diaphragm cast to create a monolithic structure offering the erection advantages of match-casting. **Figure 9.12** shows a special segment shell of this type being erected; **Figure 9.13** shows the same segment after the cast-in-place diaphragm is completed.

***Figure 9.12 – Precast Pier Segment Shell Over Seismic Reinforcing***
***[Note Voids for Placing Reinforcing and Concrete]***
***(Photo Courtesy of Atkinson Construction)***

***Figure 9.13 – Precast Pier Segment Shell Completed with Diaphragm***
***[Note Transverse and Longitudinal Post-Tensioning]***
***(Photo Courtesy of Atkinson Construction)***

There are critical considerations and quality control precautions when matching cast-in-place elements to precast segments.

- The precast segment requires temporary support that allows extremely precise alignment and restraint while the wet joint is placed. This usually requires embeds into the site cast, precast concrete, and temporary post-tensioning.
- The width of the wet-cast joint will determine reinforcing needs.
- Extremely detailed quality control is needed between the layout of ducts and sleeves in the cast-in-place elements and the layout in the precast concrete. <u>This cannot be overstated</u> and is challenging because the two are frequently built by different crews in different locations.

Another category of customized segments includes those with steel struts, precast concrete elements, or other variations that allow the structure to support greater loads in specific conditions. These elements may be exterior or interior to the segment. If these cases are great enough in number the segment forms can be adaptable to accept such special configurations; if few in number, a common solution is to place rebar couplers at the face of the concrete to allow for secondary pours to accommodate additions after leaving the casting bed.

*Figure 9.14 – Abutment Segment Form, SW Line Bridge, WA*
*(Photo Courtesy of Atkinson Construction)*

*Figure 9.15 – Completed Diaphragm Segment, Lee Roy Selmon Crosstown Expressway, FL*
*(Photo Courtesy of PCL Civil Constructors, Inc.)*

## 9.3 Casting Yard Location

### 9.3.1 Acreage

The property size needed for a casting yard depends on four main variables:

- Project schedule – Factors include lag time between beginning casting and beginning erection, casting versus erection rates, and contingency storage.
- Casting method – Either long-line or short-line, plus the construction of special segments.
- Structure characteristics – Include segment length and width. The more variability required in segment dimensions, the more complex the casting cells.
- Access – Access factors include gantry crane dimensions (determined by storage area aisle layout), amount of space between stored segments for work crews, whether the segments will be double-stacked, concrete batching and delivery, and material inventory. Adequate space should be set aside for the inventory of material required to maintain casting schedules. This includes reinforcing steel, post-tensioning, and embedded post-tensioning hardware.

It is important to first identify the various work stations and the anticipated footprint for each component of the casting yard. Assumptions concerning space requirements should be conservative and clearly stated in preparation of a bid. Take photos to keep a historical record of the property and to plan site remediation prior to handing the property back to the owner after completion.

Local building officials and planning board can identify the steps to obtain the necessary permits. The contractor should calculate the number of employment opportunities the casting yard will bring to the community to encourage cooperation.

**Determining the Size of Storage Needed**

An important factor in determining the total area needed for a casting yard is the number of segments required in storage before erection begins. This area is dependent on the size of the segments, the area needed for operating the transport vehicles, and the number of segments anticipated to be held in storage before erection begins. The minimum number of segments to be stored will depend on three factors: the number of segments cast per week, the number of segments erected per week, and the predicted start date for the erection. Unfortunately, these three factors are best determined by empirical knowledge. However, it is widely accepted that casting your first segment within 6 months of Notice to Proceed is considered great, within 9 months is considered good, and within 12 months is considered poor. The start of erection should begin when enough segments are cast so that the supply of segments is not depleted until the last span is erected. The following example demonstrates how to determine the area needed for segment storage.

A Segmental Bridge Project is advertised for bid. Time allotted for the project is 30 months. There are 103 spans with 7 segments per span; one pier segment and six typical segments, (7 x 103 + 1 = 722 segments). The segments are not complicated and one typical segment can be cast in each casting machine per day. Pier segments will require 2 days per machine. Also, erection shall utilize the span-by-span method and a rate of 2.5 spans per week is anticipated. Based on this information, one can plot the casting rate and the erection rate. By determining the start date of erection, one can predict how many segments will need to be in storage before casting begins (**Figure 9.16**).

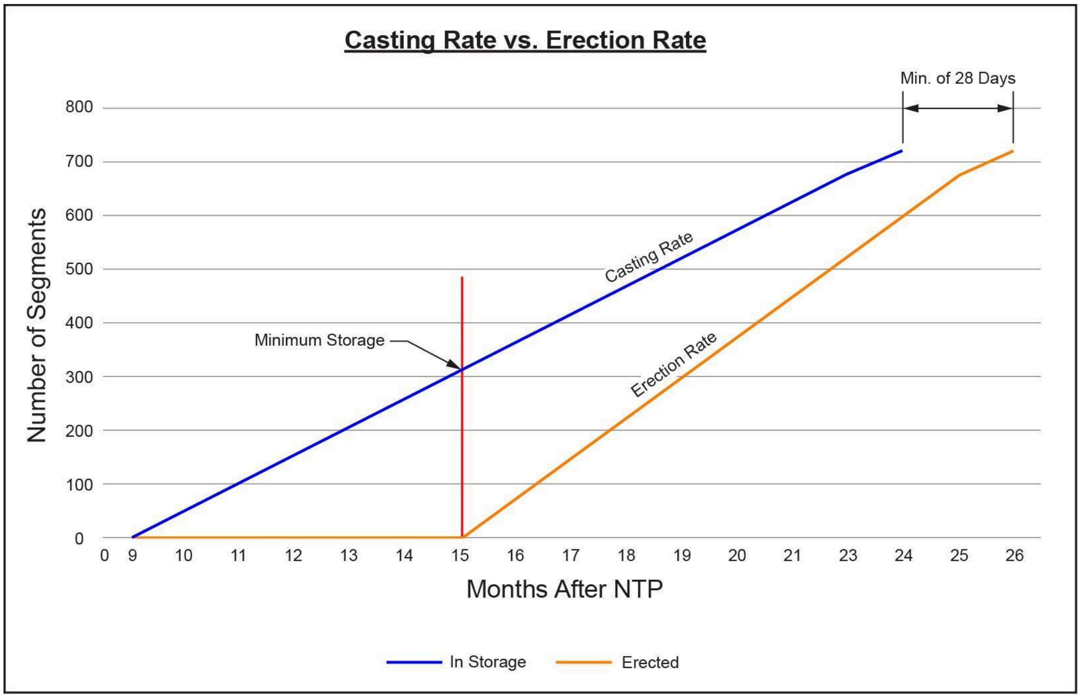


*Figure 9.16 – Casting Rate vs. Erection Rate Example*

Based on the graph above, casting should be complete 23 months after the NTP. Erection should start around 6 months after the start of casting and be completed 25 months after the NTP. This allows 5 months for paving, signing, striping, utilities, lighting, etcetera. Note that the minimum storage requirement for this scenario is 314 segments.

### 9.3.2 Indoor Casting Facilities

It is uncommon, but in some cases establishing a casting yard in an indoor or completely covered facility should be considered. The advantages of this scenario include the reduction or elimination of the effect of weather on the quality and production of segment casting, and the ability to provide more comfortable working conditions. Disadvantages may include a lack of suitable existing facilities, the high cost of building workable facilities, and significant limits on equipment access.

### 9.3.3 Utilities

Since the casting yard setup is usually on the critical path, assessing existing utilities and anticipated casting yard requirements is vital to estimating initial setup costs and scheduling impacts.
**Electrical** – Understanding the kilowatt draw requirements is necessary before discussions begin with the local utility company. A batch plant will very likely require a transformer addition or upgrade. This can be a long-lead item, so the need must be identified early.

Access to safe electricity will be required by every worker throughout the day. Location and draw should be planned for every work station and task. Electrical outlets should be placed near work stations, but be mindful that electrical cords can become obstacles across casting cell tracks, equipment roadways, and walkways. Portable generators may be useful in remote areas of the yard. Electrical facilities must be protected from the weather and ponding water.

**Water** – The contractor must consider the water needs of the batch plant, truck washout area, steam generator, and the sprinkler system requirements for any new buildings.

Water should be accessible near the casting cells for clean-up, and near the finishing and repair areas for material mixing. In freezing climates, accommodation must be made to prevent system damage.

**Internet** –Paperless project documentation and digital document transfers require high internet speeds that may not be available in remote areas.

**Compressed Air** – Compressed air may be required for form vibrators, tools, or cleaning purposes. Air plumbing piping should be steel for safety reasons.

**Steam/Indirect Heat** – Some form of heat will likely be required to accelerate curing to meet the desired casting cycle. The type of heat, required equipment, and delivery infrastructure must be considered. Similar to electricity, heat can be offered from a central source with a delivery system, or by portable equipment placed near the immediate need.

**Liquid/Gas Fuel** – Equipment will require liquid or gas fuel. Delivery and storage must be planned for, and fuel must be safely contained in storage and in equipment.

Utility infrastructure should be put below ground when possible, to reduce obstructions to equipment and people. This makes utility planning and installation the first step in yard layout.

## 9.4 Receiving/Delivery

Production cost versus segment delivery cost is the primary determining factor for establishing the casting yard's geographic location, distance from the erection site, and allowable travel route to the erection site.

### 9.4.1 Delivery of Segments – Via Land

Taking into account the size and weight of the largest segments, the contractor determines the proper truck/trailer combination for delivery. They may evaluate an existing fleet for options or discuss the project with a reputable trailer manufacturer or local trucking company. The state and local agencies responsible for transportation permits within their jurisdictions need to be contacted; they will evaluate allowable axle loads, axle layouts, and height or width restrictions. Scheduling, signage, escorts, police details, convoy allowances, hours of operation, bridge survey requirements and restrictions, and any upcoming construction projects along the intended route also need to be considered.

Local access may need to be improved; casting yard site roads must be graded or stabilized sufficiently to support large segment loads over the duration of the project.

Ideally, segments of the same span should be stored together. This makes it easier to track spans that are ready for delivery and allows completion of a span at a time without frequent relocation of crews and equipment. Such an arrangement must be planned and begun at the first segment to be successfully implemented.

### 9.4.2 Delivery of Segments – Via Water

For precast segmental bridge projects over water, a casting yard with water access for barge delivery is a strong advantage. The contractor must review existing marine haul-out facilities within a reasonable distance from the project (**Figure 9.17**), keeping in mind the size and weight of the largest segments will affect barge size, making vessel displacement an important factor. A water depth analysis should also be performed at the site, including tidal extremes, currents, and maximum wind and wave action. The contractor should have a good understanding of slip width requirements in the case that the casting yard's gantry crane can be modified to handle both casting and haul-out operations.

If dredging is required to regain water depth, a post-dredging inspection of the structural condition of all dock components is also required. After documenting any additional renovations, implementation can proceed. The contractor should schedule inspection milestones, load-test the facility and perform a dry run of all operations. Once the marine haul-out facility is operational, a maintenance program should be documented and managed with a detailed maintenance schedule.

Coast Guard, Environmental Protection Agency, Army Corps of Engineers, port authority, and state and local ordinances must be carefully researched to fulfill all the appropriate permitting requirements for construction, renovation, and shipping.

***Figure 9.17 – Loaded Barge Ready for Shipment***
***(Photo Courtesy of FIGG)***

### 9.4.3 Material Deliveries and Storage

#### Concrete Delivery

Typically, concrete is delivered directly to the casting cells via concrete mixer trucks. To maximize efficiency, the deliveries need to be carefully planned and scheduled. If an off-site supplier is selected, ensure enough trucks are allocated to provide a steady, sufficient supply of concrete. Segmental bridges are cast in high-strength, high-performance concrete that strengthens rapidly to achieve a fast casting cycle. Plus, each segment is cast monolithically, but requires multiple loads of concrete to complete. With this in mind, deliveries must be timely, as any fluid concrete time lost in transit from the batch plant to the casting cells can significantly affect workability and increase placement risk. And any factor that increases the possibility of delivery delay threatens segment quality and increases contractor risk.

If a batch plant is erected at the casting yard, a means of conveying concrete to the forms must be determined. Both new and used concrete trucks are readily available; criteria for selection depends in part on whether a central mixer is part of the batch plant (wet-batched concrete) or the truck must acceptably mix the concrete components (dry-batched). Once concrete arrives at the casting cell, concrete pumps (truck-mounted or stationary), booms, and conveyors may be useful for placement and are available in a variety of sizes. Crane and bucket are also acceptable means of placement.

It is important to protect the wet-cast cell from weather both during and after concrete placement. Tarps and overhead covers will affect concrete placement methods.

### Rebar Delivery/Trailer Storage

It is important to allow sufficient space for rebar delivery trailers. Storage for one-half to a full span of rebar for each casting cell should be available at the casting yard. The various rebar bundles should be stored in a manner that facilitates transport to the rebar jigs. Labeling the reinforcing steel using post mounted signage can increase efficiency by eliminating the need to look at rebar tags in search of the needed material.

Rebar laydown should be planned with the installer and close to the jigs. Access for equipment and workers should be designated. In smaller casting yards, rebar is typically transferred from the storage area to the rebar jigs by a forklift. Larger projects often employ utility trailers or tower cranes to increase workflow (**Figure 9.18**).

*Figure 9.18 – Material Laydown Design is Critical for Productivity*
*(Photo Courtesy of FIGG)*

**Fuel Storage**
Onsite propane, diesel, and gas storage requires significant precautions. Research the proper distance from storage area to work zone as mandated by OSHA, state, and local ordinances. Carefully follow all regulations including secondary containment, perimeter safety requirements, security fencing, and impact restraints. Sufficient total tank or tank farm capacity depends on equipment usage, local temperature extremes, hours of operation, and delivery frequency.

**Trash, Scrap, Recyclables**
A construction waste management plan should be developed. A casting yard produces wastewater from the batch plant, excess concrete, rebar and strand, lumber from shipping and formwork material, and miscellaneous cardboard and paper products. Keeping trash organized and sorted can reduce disposal costs.

**Hazardous Material Storage**
Many of the chemicals and fuels required in a casting yard need protection from temperature, stormwater, and accidental release. Waste fluids must be collected and stored for disposal and should be kept separate from unused material. Equipment access must be provided, as drums of these materials are too heavy to handle manually. Hazardous material storage areas should be clean, well-labeled, and allow easy access for safety and to encourage worker compliance.

**Post Tensioning Material Storage**
Knowing the specification requirements and manufacturer recommended storage criteria for post-tensioning material is critical. Post tensioning duct may need protection from UV rays, and grouting materials could require a temperature-controlled environment.

## 9.5 Site Preparation

### 9.5.1 Grading and Surfacing

The layout of the yard must be well understood before grading and surfacing take place. The foundations, light traffic access, heavy equipment access, storage, and parking areas all have different requirements. Generally, all organic matter should be removed and a compactable, well-draining surface course such as crushed rock installed, but requirements may be less stringent for segment storage areas. When grading, keep in mind that segment transfer equipment such as gantry cranes have a maximum slope they can travel.

Lack of proper drainage affects the safety and productivity of workers and equipment. Electrical supply and ice are major safety concerns related to ponding water and tracking water and debris into the casting cells and rebar jigs can impact quality. For this reason, the casting yard site plan should elevate the casting bed and rebar jig foundations above the surrounding terrain to mitigate water ponding in the work area. Stormwater retention basins, piping, and structures must be designed to meet the loading demands of the casting yard and should also consider maintenance.

A local geotechnical or environmental engineering company can develop records of designated wetland areas and site restrictions. Check environmental restrictions regarding workable perimeters around any wetlands. Cranes and other heavy equipment may not be compatible without considerable soil improvements.

### 9.5.2 Site Improvements

**Existing Environmental Concerns**
Property restrictions should be researched and a plan for mitigating potential issues developed. These issues should be evaluated during development, while casting, and final contractual obligations prior to property turnover. If a batch plant is installed on the site, groundwater monitoring wells may be mandatory.

Potential environmental concerns include:

- Concrete Waste
- High pH Water from Concrete Production and Washing Operations
- Stormwater Runoff
- Track-Out Caused by Truck Tires
- Overspray/Dripping of Form Oils and Bond Breakers
- Containment of Fuels, Lubricants, and Chemicals
- Storage of Spent Absorbents, Waste Petroleum Products, and Chemicals
- Dust from Segment Finishing Operations
- Existing Wetlands

**Form and Batch Plant Foundations**
The soil-bearing capacity and stability of the property must be analyzed to determine the best soil-bearing locations for foundations, especially for the forms and batch plant. Since this activity is always on the critical path, the initial planning must be thorough and occur before determining the form layout or receiving any loads.

### Buildings – Offices, Laboratories, and Inspector Facilities

Communication, troubleshooting, and quick resolution to construction issues are key components of a well-run casting yard. The office complex should be suitable for all parties, with buildings in proximity to each other, close to the center of the casting yard, and near the quality control (QC) lab.

Unless the property has an existing office space that can be economically configured to the project needs, consider mobile office trailers. They come in a variety of sizes and accommodations, and can be grouped together easily with stairs and decks to produce a useful working environment.

If a substantial structure is built, the QC lab might first be established in a temporary storage unit during concrete mix design testing and other start-up activities. The lab needs a compression machine for testing hardened concrete and grout cube testing. If project specifications call for 28-day concrete cylinder lab tests, controlled-environment curing equipment is also required.

Existing buildings can be valuable for dry storage (many materials must be protected from water and UV light before installation), heated storage (many chemicals must be kept within a safe range of storage temperatures), and waste management (used chemicals and contaminated materials must be categorized, protected, and stored with good equipment and personnel access). Dry and open storage requirements should be estimated and included in the casting yard layout plan. Depending on the climate zone, fabric structures, pre-engineered buildings, steel storage trailers, or existing structures may meet storage demands.

### Employee Parking

A suitable parking area with capacity for all employees and visitors. It should include all appropriate barriers, lighting and signage. Parking areas must be carefully determined since many aspects of casting yard operations are harmful to automobiles.

### Restroom Facilities

Restroom units should be located near worker break and parking facilities and busy work zones. For safety, keep facilities away from equipment access routes. Providing gender-specific units may be desirable or required by unions or local regulations. Depending on the number of site workers and length of the project, a larger restroom facility with a septic system may be cost-effective.

### 9.5.3 Post-Casting Work Areas and Access

***Figure 9.19 – Storage Yard Layout***
***(Photo Courtesy of Fueled Photography/PCL Civil Constructors, Inc.)***

Worker access to the casting area around the rebar jigs and casting beds is typically well planned, but even after casting is complete, access is still required for a number of critical activities that are often overlooked:

- Special Form Stripping
- Segment Curing
- Post-Tensioning
- Grouting
- Rigging
- Pointing and Patching
- Repairs
- Inspection

Consider these time-critical activities versus space available and determine if these tasks can be completed in the general casting area, in the storage area, or if an intermediate work area needs to be established. Each has advantages, but handling segments multiple times increases both man-hours and equipment time significantly, along with risk of damage.

Before casting begins, check segment structural integrity, dunnage configurations, and ground pressures to see if double stacking segments in storage is feasible. If so, notify the engineer to evaluate double stacking segments. If erection delays or other issues arise, this is a good option that keeps storage within the existing site (**Figure 9.19**).

## 9.6 Procurement

### 9.6.1 Forms

Choosing the right casting cells may be the largest factor in the profitability of a casting yard operation. The contractor should thoroughly discuss with casting machine manufacturers what is included in the “form package.” Any items not included may present unwelcome and expensive surprises during installation of the machine.

***Figure 9.20 – Segment Form Assembly***
***(Photo Courtesy of FIGG)***

Constant-depth casting cells, where both soffit width and web wall depth are constant, are the easiest to cycle daily. Segment length may vary, requiring that either the match-cast segment be moved on the soffit or that a soffit extension be used. The contractor should work with the designer to minimize segment variables, such as changing segment length, section thickness, and/or adding blister forms because they can greatly impact the cost and time of a typical cycle (**Figure 9.20** and **9.22**).

Variable-depth casting cells require the most changes to the forms, and changes in segment height and soffit width which require time to prepare the casting machine for the next pour. It is recommended that form components be kept light enough to be handled by hand. This reduces dependency on support equipment. Purchasing an additional soffit is also recommended to allow crews to assemble a day ahead, reducing change-over time each morning (**Figure 9.21**).

*Figure 9.21 – Variable-Depth Segment Form*
*(Photo Courtesy of FIGG)*

Typical casting beds have soffits that roll on high-capacity rollers or crane wheels. The track and embeds to hold the rollers should be included in the form package. Consider how the rolling stock will be moved, especially when loaded with a segment. Wire rope winches work well but can be a tripping hazard and require maintenance. Equipment such as a loader or forklift are options but can cause downtime while crews wait for support equipment.

Soffits for typical segments must adjust for horizontal curves and tight geometry control. Some casting cells come with two soffits and positioning frames; others have two soffits and one positioning frame that is moveable from soffit to soffit. Both horizontal and vertical hydraulic options should be considered, as manual adjustment is generally inefficient. Keep in mind, however, that hydraulic rams are powerful enough to damage concrete segments or the forms themselves. Physical limit switches or operators specially trained in form hydraulics reduce this risk.

Due to the large number of segments to be cast, skin thickness of the forms is important. Form steel skin should be at least 1/4 in. thick, including block-outs, or it may warp and distort over time.

Bracing for the web and wing supports requires base plates anchored to the foundation; both base plates and embeds should be included in the form package.

Stripping the wing walls is generally performed by lowering/rotating the web and wing forms away from the segment. Address any conflicts this movement may have with segment components and determine whether the forms can be moved manually or if additional hydraulics are required.

Shear keys forms can be fabricated from different materials. The most durable – but costly – is machined from solid steel bar. Solid steel keys withstand abuse from the rebar cage dragging across them, and are cost-effective if used many times. Other good options are bent steel plate and ultra-high molecular weight polyethylene, though both are more susceptible than solid steel to damage and misuse.

To cast a segment every day, the core form must be carefully detailed. The ability to rapidly configure the core for deviation segments, top blocks, and bottom blocks is critical. It is necessary to understand which form panels have to be removed or added to create each deviating configuration and minimize these form changes. Make sure all panels in the core have a slight draft (slope) to facilitate stripping. The core form may be retracted using hydraulics, moved manually, or a combination of both.

***Figure 9.22 – Pier Segment Form***
***(Photo Courtesy of FIGG)***

### 9.6.2 Batch Plants

When reviewing the cost benefits of obtaining concrete from an existing, independent, local concrete plant, verify they can provide the concrete mix using the specified material resources with equipment that meets project criteria. Also determine any batch plant components that need to be upgraded to handle segmental batching requirements (e.g., central mixer size, cement silos, aggregate bins, or admixtures.). The supplier should be located very near the casting yard to reduce the risk of delivery delay due to traffic.

If an acceptable existing supplier is not located, portable batch plants are a convenient and quick solution. Multiple national manufacturers can provide a set-up based on the project's specific needs. First identify the cementitious materials needed and the best available delivery method to the site. Then determine silo requirements based on the project's anticipated weekly usage and duration. The quality and volume of concrete required determines both cement and aggregate storage capacity needs, and the capacity needed in the central concrete mixer. Review all options of the computerized batching control system. Local climate dictates optional water chiller, ice machine, and boiler needs. Choosing the proper components and material resources is central to consistently producing a quality product and maintaining plant resale value.

Carefully inspect the manufacturer's proposals to determine proposal inclusions and exclusions. Missing items such as electrical wiring to components, installation of air lines, dust collection equipment, computer, or OSHA safety equipment can be costly. Admixture manufacturers will usually price admixture storage tanks, pumps, and plumbing, but exclude electrical feeds and air compressors. Depending on installation requirements, concrete foundations and winterization needs are usually excluded. The batch plant will need weigh hopper calibration, which may be mandated by local authority and NRMCA Certification prior to start-up; refer to http://www.nrmca.org/. Contact the Concrete Plant Manufacturer's Bureau (CPMB) or go to http://www.cpmb.org/MembersCPMB.htm for approved manufacturers.

Review state and local ordinances that can restrict batch plant design (i.e., height restrictions, noise ordinances, hours of operation, dust emissions, etc.) and shortcomings in case of excessive heat or extreme cold.

### 9.6.3 Curing Equipment

**Steam Generator**

The most common precast steam-curing is using live steam at atmospheric pressure. To minimize moisture and heat loss, it is generally performed in an enclosure -- insulated tarpaulins are frequently used. A typical steam-curing cycle consists of four distinct periods: (1) preset period, (2) temperature ramp-up, (3) holding the maximum temperature constant for a set time, and (4) decreasing the temperature.

Steam generator size and output capacity is determined by the quantity of forms, form layout, and the concrete quantity placed per day. In colder climates, concrete cubic yardage should include the match-cast segments since their temperature must be similar to concrete placement temperature. A 1,000,000-5,000,000 BTU unit services most casting yard applications, with larger custom units available. The manufacturer provides a piping design that optimizes the unit; any variation will drastically affect performance. Units can be outfitted with a variety of options ranging from simple manual controls to sophisticated computerized systems using thermocouples at each form. Computerized systems can be programmed to start the unit after concrete preset, provide the correct ramp-up to optimum temperature, and ramp down for proper release strength. Some can even be operated from the QC lab. Carefully weigh the cost/benefits of each option and whether or not the equipment can be expensed over multiple projects. Also, check the hardness of the local water in case a water softener is needed, as mineral deposits can gradually fill steam lines and plug valves.

### Alternate Curing Methods

Some project specifications allow Type 3 cement usage, which may result in a reduced external heat requirement. Form insulation techniques should also be considered. Economic options include a commercial blanket or batt insulation with a tough, moisture-proof covering. If insulated formwork is used, be sure that concrete temperatures do not become excessive. To maintain a humid environment, fogging and water sprinkler methods are options. A fine fog mist applied through a system of nozzles or sprayers raises the relative humidity of the air over flatwork, thus slowing evaporation from the surface.

Other curing methods include electrical, indirect diesel-powered, hot oil, microwave, and infrared curing. Electrical heating is especially useful in cold-weather concreting. Likewise, hot oil circulated under steel forms can heat concrete, and portable hydronic heaters can thaw subgrades and heat concrete without the use of an enclosure.

## 9.6.4 Cranes

Every aspect of casting, storage, and shipping operations is controlled by the service equipment chosen for the site. Project requirements must be well understood, as any areas left unplanned could be costly.

The process of selecting the proper crane(s) for the casting yard should take several factors into account, including yard complexity, productivity, and an overall cost-benefit analysis. Base equipment choices on the daily tasks assigned to each piece of equipment (**Figure 9.23**).

***Figure 9.23 – Gantry Crane Handling Segment; RT Crane Servicing Bed***
***(Photo Courtesy of Fueled Photography/PCL Civil Constructors, Inc.)***

Examine strongback (picking frame) and rigging needs carefully for safe and efficient operation. Design this equipment conservatively to handle the largest load; often the heaviest segment weight increases during the design process. Special segments frequently are the controlling load and may have different pick point spacing than typical segments. Design casting yard picking equipment and pick point spacing to mirror erection equipment pick points.

### Gantry Crane

When evaluating a gantry crane, consider the following:

- Lifting capacity – Determine the maximum segment weight first, keeping in mind that segment rigging and picking apparatuses must be considered in the total weight being picked. Make sure the crane will handle this amount and ideally, other uses or projects in the future.
- Overall height – Identify any casting yard problems associated with the crane's height. Are there building or utility wires that the crane needs to travel under?
- Wheelbase – This criterion establishes the storage area lane width. Decide how segments will be stored and maximize lane capacity.
- Maximum hook height – Calculate the maximum height a segment needs to be lifted above the ground, making sure to account for the strongback and rigging. If a segment must be lifted over segments in storage or a segmental form, this also influences hook height.
- Turning radius – Gantry cranes have a very large turning radius that affects travel lane width and segment storage layout. Use this data in planning the casting yard layout.
- Traveling speed – Impacts task timeframe and critical coordination factors.
- Drive train – Casting yards typically have rough terrain; consider cost benefits of all-wheel drive.
- Allowable slope – Gantry cranes may have a maximum slope they can travel, which may vary depending on the load. Yard grading must take this into account.

**Tower Crane**
Tower cranes can be very efficient for material handling and construction support, but since they are not mobile, they are limited in the number of operations they can service. As with any casting yard crane, yard layout is critical in optimizing a tower crane's usefulness.

**Rough Terrain or Tracked Crane**
A small wheeled or tracked crane is very versatile and can move quickly down a row of casting cells or rebar jigs. They are excellent for hoisting rebar to a jig, hoisting completed rebar cages to the form or storage, or moving heavy form panels or bulkheads, and they also can be used to pour concrete with a bucket.

**Purchase or Lease**
There are many quality crane manufacturers, both domestic and foreign. Check product availability, service requirements, and set-up requirements (some need a second crane) and have a manufacturer's list of recommended replacement parts included in the contract. For smaller projects, a used crane may be suitable.

A new or used crane also can be leased, and payments are fully tax-deductible operating expenses. If a larger crane is needed for a short duration, this may be a good option.

### 9.6.5 Auxiliary Equipment

A range of auxiliary equipment is available to increase productivity and enhance coordination efforts. Before making any selections, analyze the cost-benefit data (i.e., purchase price, availability, longevity factors, parts and servicing, and warranty information) and determine all safety requirements and mandatory training programs required for the casting yard.

**Telescopic Forklift**
A casting yard on rough terrain may benefit from a telescopic forklift. Its versatility is enhanced by attachments such as buckets, work platforms, and rigid and extendable booms that allow it to

unload trucks, service rebar jigs, hoist pre-assembled portions of rebar cages, move form components, and service auxiliary operations such as the segment finishing and repair. Review the forklift's maximum load height, load charts, specialized maneuverability options, precise load placement controls, and ease of operation.

**Aerial Personnel Lift**

Casting cells require work platforms for workers to access wing forms, bulkheads, etc. For cells with decks higher than 10 feet above ground, an aerial personnel lift should be considered. Safer than ladders, they include tie-off points for fall protection and allow crews to lift and install a limited amount of material or formwork without other equipment support. Examples of use include installing mandrels or cleaning ducts on the top slab of a variable-depth bed, or curing and rigging a segment from a tall casting cell. While not prohibitively expensive, the cost to rent or own an aerial lift should be weighed against the estimated man hours saved (**Figure 9.24**).

***Figure 9.24 – Tall Segment Forms May Require an Aerial Personnel Lift (Photo Courtesy of FIGG)***

**Front-End Loaders**

Front-end loaders are excellent all-around machines, especially when equipped with a quick-disconnect bucket and other similar options. They can keep batch plant aggregate bins full using a bucket and load and unload tractor trailers with forks. Front-end loaders may be used for yard maintenance to keep the storage area and construction roads flat.

**Segment Haulers**

These oversized loaders are an alternative to gantry cranes for moving segments in tight areas. They are limited in lifting height and load, but useful in certain circumstances such as where there is only access from one side of the segment staging area or there are slopes to be traveled that exceed a gantry crane's limitations.

**Air Compressors**

Compressors have many uses in the casting yard, including as vibrators and air tools for the segmental forms, batch plant equipment, QC lab equipment, and sandblasting. The resulting increase in labor productivity justifies having a centrally located compressor with a suitably sized holding tank. After yard layout has been determined, locate air supply line routes to each work zone. For safety and durability, compressed air piping is best made of steel and laid underground before foundations and beds are erected. Access to compressed air and valves should be considered for productivity; valves are typically desirable at ground and top deck elevation.

**Survey Equipment**

A one-second accuracy theodolite is used for centerline checks. Elevation readings are taken with a builder's level capable of reading to 0.001 ft. using an invar rod. Project specifications should be carefully reviewed for requirements.

Review geometry control provisions to optimize survey equipment set-up and devise a survey tower layout. Tower structures should be completely isolated from other structures to prevent transferring vibration, and both front and back sites should be anchored and protected from equipment to prevent movement. When setting up multiple forms, try to use each tower for more than one form. This reduces survey equipment needs and surveyor time and speeds up the casting cycle. To achieve the required accuracy, survey infrastructure must be located to meet the needs of the surveyor, including protection from wind, thermal effects, and vibration of neighboring equipment.

**Winches, Screeds, and Vibrators**

Winches are a popular means of moving match-cast segments to and from the casting position and moving core forms along the rails provided by the form manufacturer. Usually, a pulley system is used on the opposite side of the form so only one winch per segmental form is needed. Winch size is based on segment weight and a coefficient of friction of the rollers running along the rails, with an appropriate safety factor.

A variety of screeds are available that operate on air, gas, diesel, or electricity. Remember that the concrete should already have been vibrated using other methods; the screed's purpose is to level and consolidate the top surface only. Consider how heavy screeds will be moved between beds, where they will be stored, and what access is required alongside the wet-cast segment to allow safe access for operators.

Either internal or external vibrators can be used in precast segmental construction. The most common set-up uses only handheld internal vibrators, available in gas, 120v electric, high-cycle electric, and air-powered models. When using only handheld vibrators, concrete should be placed in 18-in. maximum lifts. When casting complex segments or in the case of congested rebar configurations, external vibrators may also be used to ensure proper consolidation and an aesthetic form finish.

Vibrator operator access to the more challenging corners of the segment must be planned in advance. Post-tensioning ducts or rebar must be frequently relocated by the designer or temporarily relocated and replaced during a pour to allow proper vibrator placement. Controls for external vibrators should be located near the pour for efficiency.

### Generator

Generators come in a variety of sizes to assist project startup, power backup, and daily casting operations. To determine the size needed, have the electrical contractor estimate total kilowatt usage of the batch plant, casting yard, and office.

Small, portable, gas-powered generators can be helpful in supplying electricity to work stations that move frequently, such as on a post-tensioning buggy or to a crew working in the segment storage areas.

### Sandblasting and Pressure Washing Equipment

Before shipment, the segmental match-cast joints need a light cleaning -- but the joint faces cannot be altered during the process. A sandblaster or a pressure washer can serve this purpose. If a sandblaster is used, either a stationary or mobile setup is acceptable. Review project specifications and the epoxy joint adhesive manufacturer's recommendations for required surface preparation to help determine sandblasting equipment, materials, and compressor capacity. Both pieces of equipment produce waste that can create an environmental hazard or access hazard for workers. Develop a management plan for the waste sand or water. Also ensure that blasting pressures for the sandblaster or pressure washer are kept at a level so as to ensure that the joint faces are not altered during the cleaning process.

### Lab Equipment

The concrete specifications should cite the AASHTO (American Association of State Highway Transportation Officials), ACI (American Concrete Institute), PCI (Precast / Prestressed Concrete Industry), and ASTM standards to be followed during approval and day-to-day casting operations. Since most projects are short duration, focus the onsite lab on the daily aspects of QC. An offsite AASHTO-certified laboratory is required for specialized testing such as petrographic analysis of the coarse and fine aggregates, alkali-silica reaction tests, modulus of elasticity tests, and creep and shrinkage tests. The AASHTO website (www.aashto.org) has a list of local certified labs.

Base the lab setup on casting yard requirements. Concrete mix design is typically the first task, involving the need for daily testing and strength gain verification. Other likely requirements include post-tensioning and grouting tests. Some projects also require plant certification by PCI or NPCA (National Precast Concrete Association). The two organizations are helpful in concrete lab setup, preparing a QC procedures manual, and addressing QC personnel certifications. Website addresses for the organizations mentioned are:

- http://www.aashto.org/
- http://www.aci-int.org/
- http://www.astm.org/
- http://www.precast.org (NPCA)
- http://www.pci.org/

## 9.7 Geometry Control

A geometry control manual should be developed to dictate daily surveying operations. The contractor's geometry control surveyor and the inspector's surveyor should maintain their own geometry control programs to provide independent checks. Complete geometry control recommendations can be found in Chapter 13 of this Handbook.

### Casting Curve

The casting curve is made of two important components:

1. The required geometric profile, which is actually the horizontal and vertical curvature and super-elevation shown on the plans.

2. The compensation of deflections – both deflections which occur during construction, and during the long-term creep and shrinkage. Deflections that occur during construction are shown in **Figure 9.25(b)**. During erection of a five-segment cantilever, both self-weight and post-tensioning deflections increase as the cantilever length increases. **Figure 9.25(c)** shows the situation at the end of erection. To maintain a horizontal profile post-erection, the casting curve should be precisely opposite the calculated deflection line.

**Figure 9.26** offers a four-panel illustration of structural deflections combined with the geometric profile. The required geometry of the structure is shown in **(a)**. Deflections occurring during construction are shown in **(b)**. The structural deflections are compensated in **(c)**, and finally, in **(d)**, added to the geometric profile to form the casting curve.

A casting curve should be shown on the contract drawings, based on the details and construction methods assumed in design. The contractor then verifies and modifies the casting curve as needed based on the details and construction methods actually selected. Note that erection equipment and construction loads have major impacts on erection geometry.

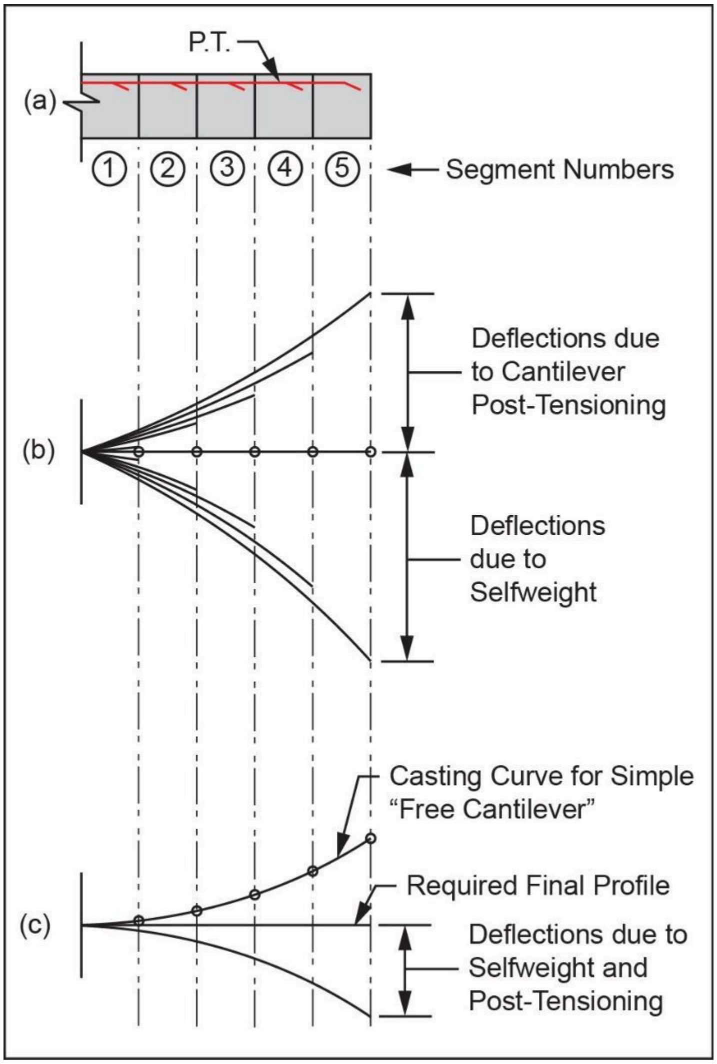


*Figure 9.25 – Simple Cantilever Casting Curve*

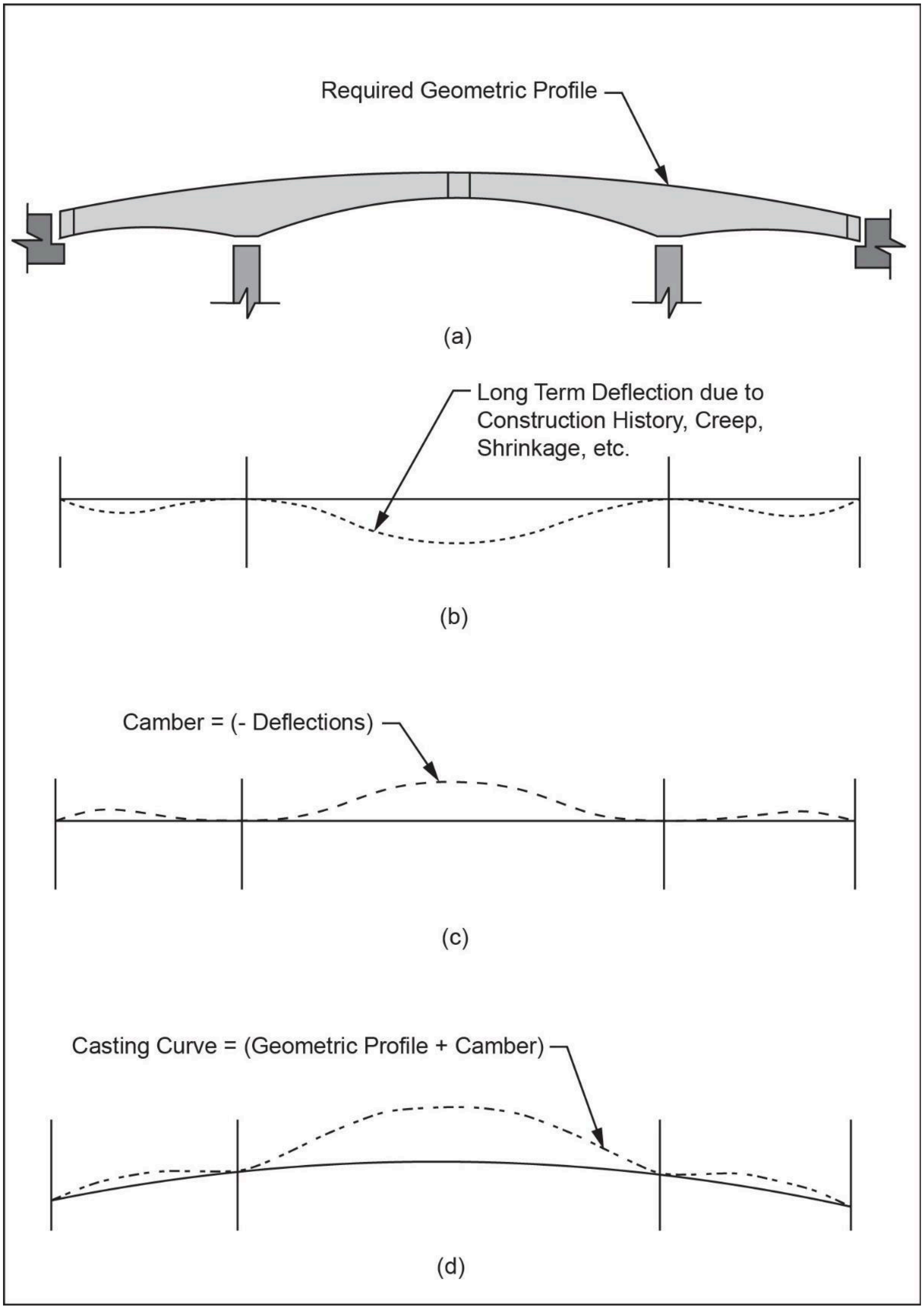


*Figure 9.26 – Casting Curve for Typical Cantilever Bridge*

## 9.8 Quality Control

The ASCE (American Society of Civil Engineers) manual “Quality in the Constructed Project” defines Quality Assurance and Quality Control as follows:

> “Quality assurance (QA), whether in design or construction, is planned and systematic actions necessary to provide adequate confidence that a structure, system, or component will perform satisfactorily and conform to project requirements. Quality control (QC) is specific procedures involved in the QA process.”

Proper Quality Control and Quality Assurance of all products produced in the casting yard is critical to the success of the project. Quality Control can be summed up as all the methods and processes that are used to verify the work is performed in accordance with the contract documents and to industry standards. It is important that all work products are subject to the QC and QA processes, and that these be properly documented.

Additional information on QA and QC can be found in Chapters 16 and 17 of this Handbook. However, for this chapter it is applicable to cite some major items that need to be considered in the Casting Yard.

Designated areas for concrete testing deliveries should be established. Storage for post-tensioning material, grout, embeds, and chemicals also have special storage requirements that must be inspected periodically.

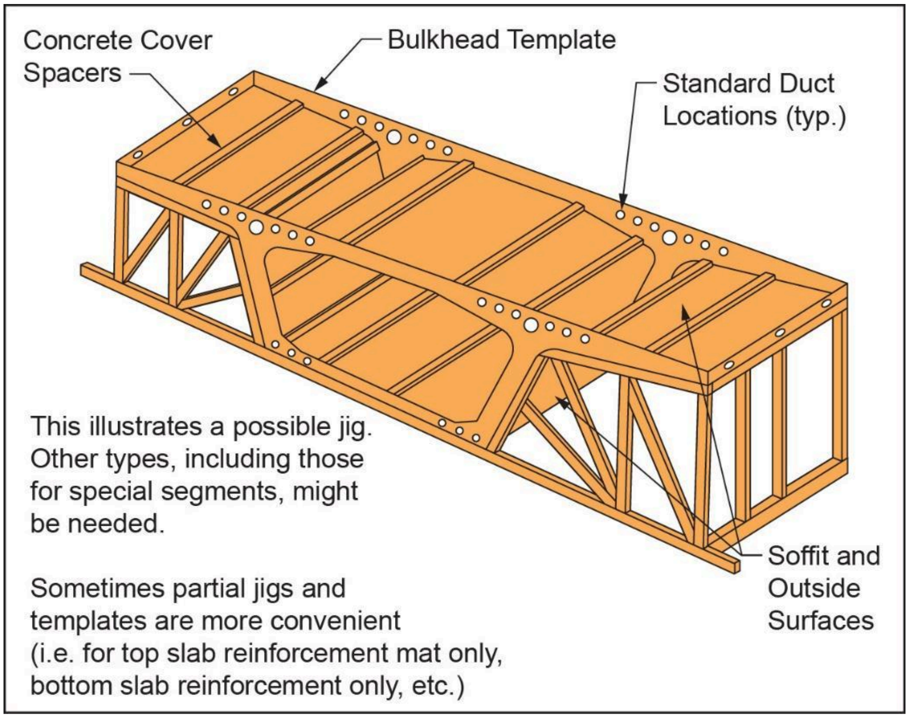
In the field offices, filing systems are needed for material mill certifications, individual segment files, shop drawings, submittal records, and pre- and post-pour records. The files may be either paper or digital, but the system must be well-organized and established before the project starts.

Manuals for quality control and repair procedures should be completed and approved before casting begins. The manuals should be issued to all personnel and address daily operational procedures, as well as responsibilities and standards all parties shall meet for a successful project.

The importance of QC and QA in a casting yard cannot be overstated. An unchecked quality issue in a casting bed may be repeated many times in many segments. If QC is not adequate, issues may not be discovered until segments are delivered onsite. And if a segment is delivered with an unidentified quality issue, it can have critical impacts to the schedule, crews, and expensive equipment until the issue is resolved.

## 9.9 Fabrication of Rebar Cage with Post-Tensioning

Achieving production of one segment per day requires prefabrication of the rebar cage, preferably with post-tensioning ducts and as much of the hardware installed as possible. This is readily accomplished with custom-built jigs and templates. A jig for a complete typical segment is illustrated in **Figure 9.27**.



This illustrates a possible jig. Other types, including those for special segments, might be needed.

Sometimes partial jigs and templates are more convenient (i.e. for top slab reinforcement mat only, bottom slab reinforcement only, etc.)

***Figure 9.27 – Jig for Fabrication of Rebar Cage***

The essential components of a jig are:

- A rigid frame of steel or lumber that accurately defines the main concrete surfaces (outside webs and slab soffits).
- Walls and floors for safe access and material support.
- Bulkhead templates cut and/or marked to the proper section size, with standard post-tensioning duct locations accurately defined.
- Wing cantilever and templates marked and fitted with locators as needed for transverse post-tensioning ducts, etc.
- Spacer bars or lumber laced to the walls and floors to provide correct concrete cover to rebar.
- Adjustments for variable-depth segments.
- Safety items such as handrails, fall protection, etc.

It may be advantageous to use partial jigs (i.e., one for the bottom slab and webs; another for the top slab) to produce cage components that can be fed into the main jig. Building two jigs per casting cell, or a single jig with a storage rack for additional cages, also reduces production risk by making one rebar cage ready at all times and limiting the impact of different cycle times and rebar fabrication errors. See Figure **9.28** for an example.

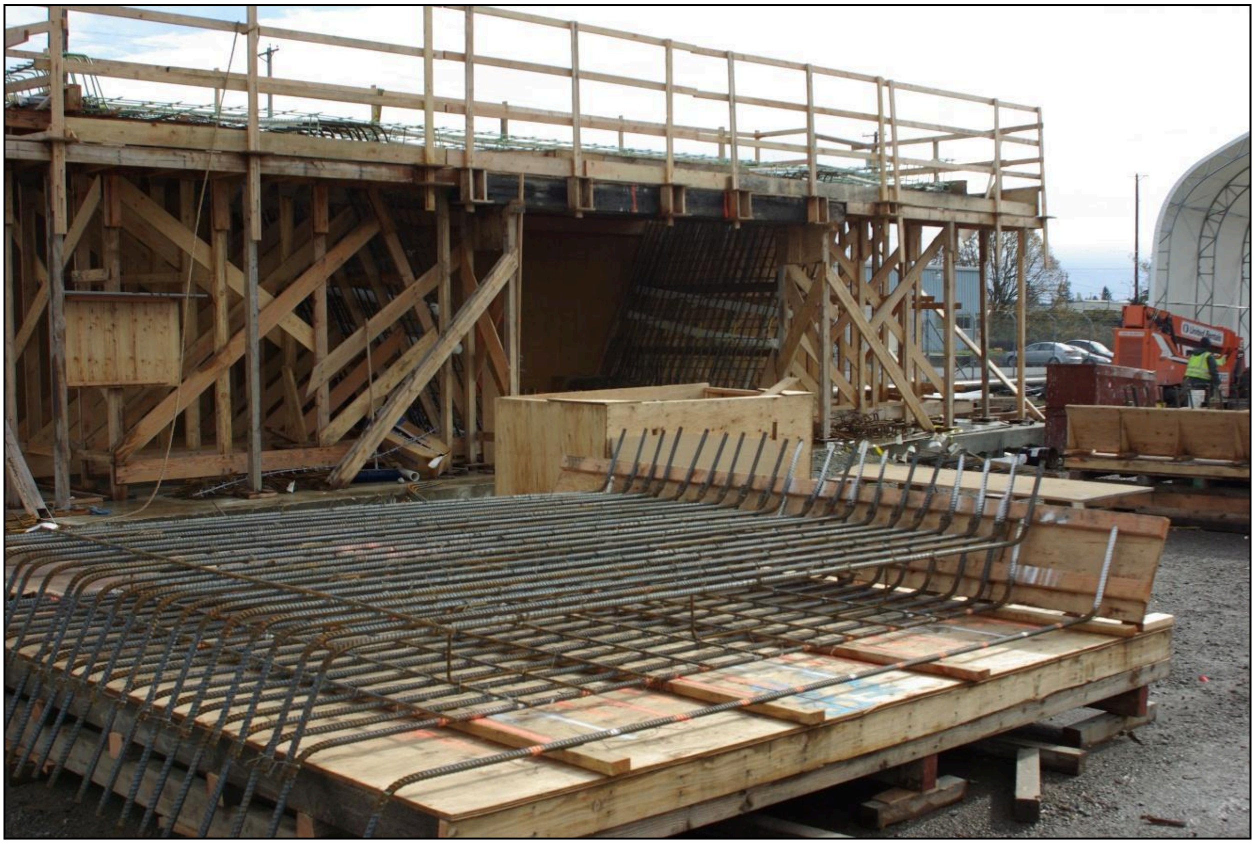


***Figure 9.28 – Rebar Jig in Use with Wall Component Jig in Foreground***
***(Photo Courtesy of Atkinson Construction)***

Using a jig allows rebar, post-tensioning ducts, and other hardware to be accurately fixed and marked for repeated use. For example, duct profiles can be traced onto the walls to ease assembly. String lines are used to check rebar, cover, and duct positions from open surfaces.

Rebar support materials must be well-planned and installed and secured in the jig. Slab bolsters or chairs must be installed at intervals that prevent the rebar from sagging toward the form and violating the required concrete clear cover. The spacing of chairs must be reduced significantly in areas with heavy reinforcing loads (such as at the bottom of web walls). Addition chairs should also be added in areas of tight reinforcing tolerances, such as below post-tensioning duct and areas that are especially difficult to access after the cage is placed. Designed to support vertical loads, bolsters and chairs perform poorly when side-loaded or dragged across a jig or form. They must be tied securely to the cage to prevent displacement during cage handling, and care must be taken to ease the cage onto the forms.

Plastic, plastic-tipped metal, or galvanized slab bolsters and chairs are common. Metal support materials are less likely to burst and allow the rebar to sag, but more likely to have their coatings damaged and produce unsightly corrosion staining on the surface of the segments. Eliminate this risk of corrosion by using plastic support materials, placing them at intervals that do not threaten their integrity and taking care to protect them during cage handling.

After placing the cage in the casting cell, final adjustments are needed. Segments can vary a little in shape or contain different post-tensioning duct and anchorage arrangements, and the rebar cage will deform during transportation from the jig to the casting cells.

For special segments (pier, abutment, and expansion joint segments), either the typical segment jig can be modified or a separate jig made. Sometimes the pier and expansion joint segments are cast in separate casting cells. If so and these segments are limited in quantity, it may be most efficient to fabricate the cage directly in the casting cell itself. See Figure **9.29** for an example.

Periodical checks of the accuracy of jigs and templates is required as they can deteriorate with repeated use and adjustments.

The key aspects of rebar jig construction are accuracy, accessibility, and durability. If jigs are not accurate, many hours will be lost adjusting the cages in the casting cells. The jigs are in the full-time work area for the ironworker crews in the yard; they must be able to safely move around them. Rebar bundles are heavy and hard, and will be slammed, dragged, and hoisted over all surfaces of the jig. The jig must be built to withstand this treatment hundreds of times.

Special care is needed on projects using epoxy-coated rebar. Contact surfaces of jigs and templates must be built or protected with material that will not damage the epoxy coating. Rigging must be completed with properly softened slings.

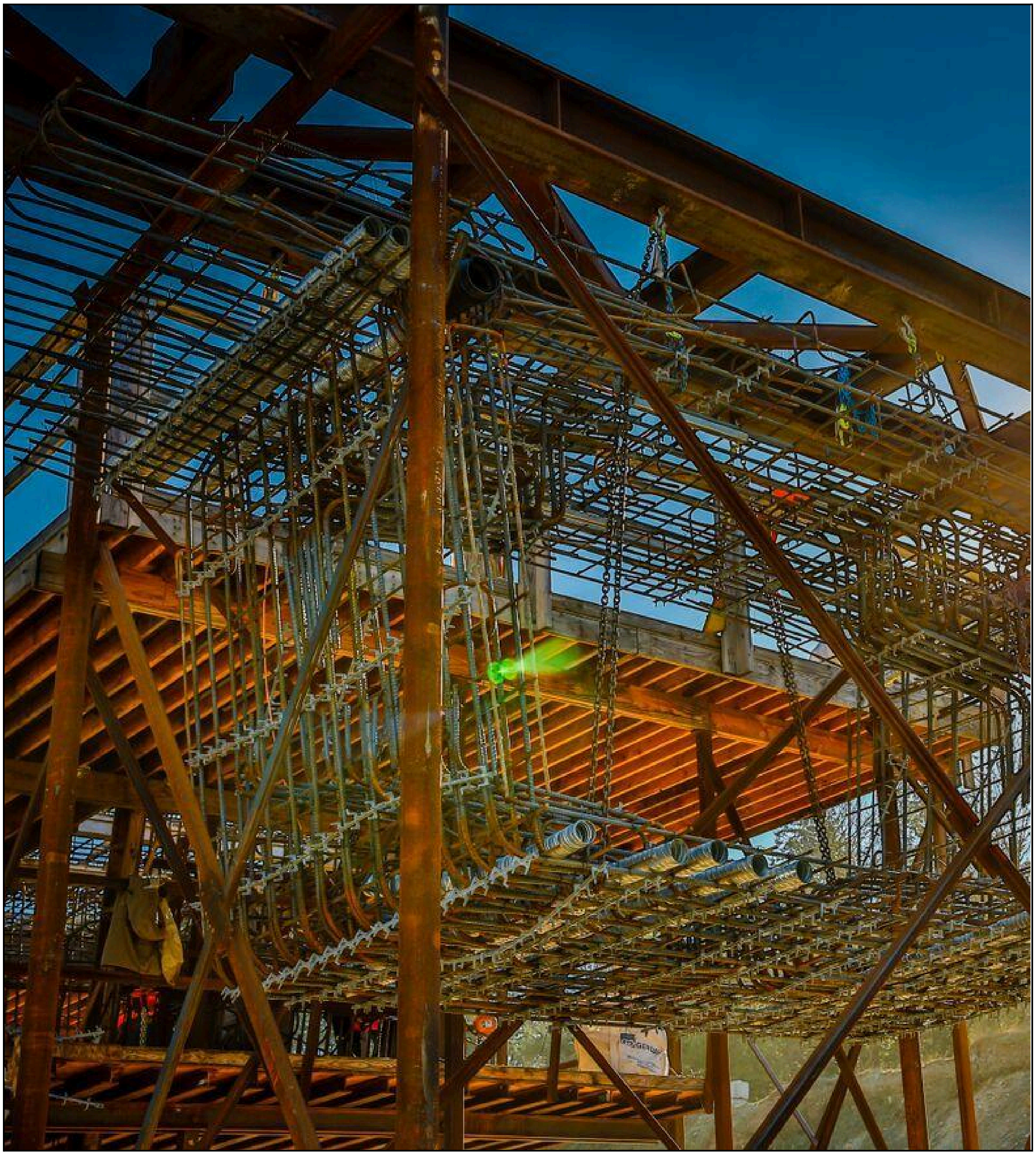


***Figure 9.29 – Rebar Cages Suspended in Storage Racks with Post-Tensioning Components (Photos Courtesy of PCL Civil Constructors, Inc.)***

## 9.10 Handling a Prefabricated Rebar Cage

Transport the rebar cage from the jig to a casting cell or cage storage carefully to avoid excessive distortion. It is typical to use a special picking frame (strongback) with picking eyes and rigging that can support the cage at many points (**Figure 9.30**). The rebar cage should be securely fabricated with adequate tie wire to maintain as much rigidity as possible.

A rebar cage is thousands of pounds of steel held together by tie wire. Hoisted cages must be handled with respect to maintaining their quality and the safety of workers.

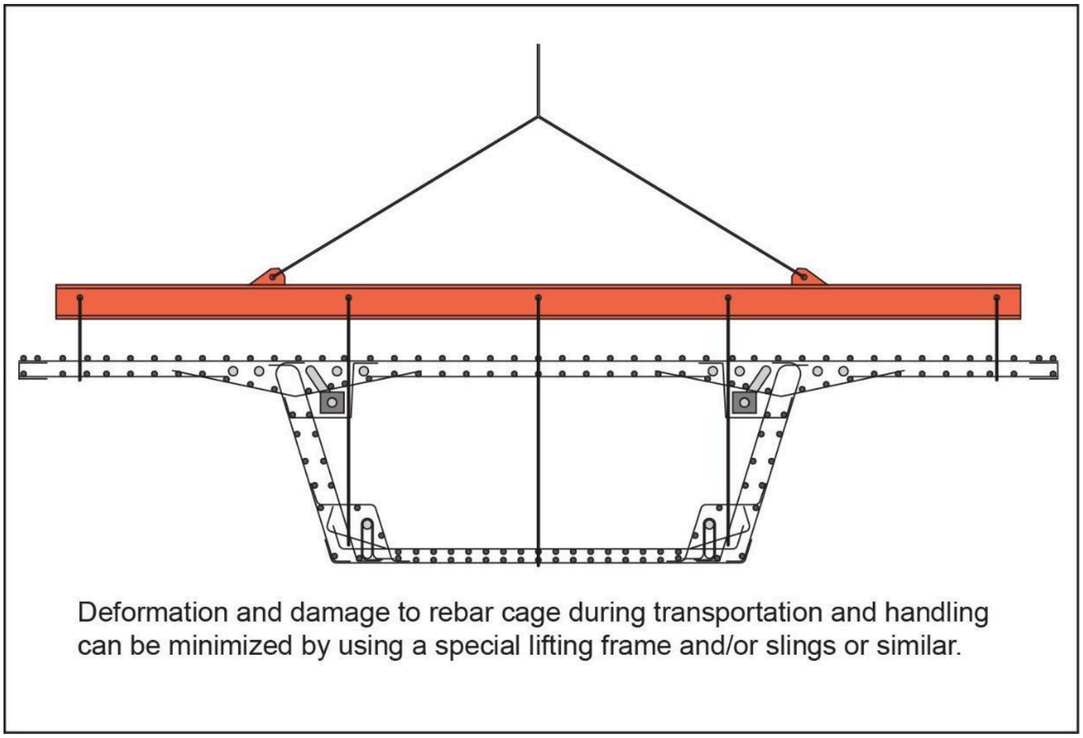


*Figure 9.30 – Handling a Prefabricated Rebar Cage*

## 9.11 Setting and Detailing a Rebar Cage and Post-Tensioning

Most of the post-tensioning hardware and ducts are installed in the rebar cage. Anchorages, on the other hand, are usually installed in the form due to their weight.

Once the wet-cast segment has been cleared, the forms must be cleaned and oiled. Block out forms are reset and anchorages installed. After the cage and prepared bed are inspected, the rebar cage is picked and set in the forms. Check the orientation of the post-tensioning distribution/bearing plates (provided on the shop drawings). In the case of repetitive plate arrangements, recess pockets are fabricated of steel plate. Once a steel recess pocket has been checked for dimensional accuracy, it will consistently provide the correct orientation. For uncommon recess configurations, wooden pockets can be formed but should be checked for accuracy with each pour.

***Figure 9.31 – Setting Rebar Cage in Oiled Casting Cell***
***(Photo Courtesy of PCL Civil Constructors, Inc.)***

After placing the rebar cage and anchorage in the cell, all post-tensioning ducts are securely connected to their respective anchorages and standard duct locations and alignments are checked. Be sure to provide adequate bottom support for the cage throughout; if it sags in any location, it is challenging to bring the post-tensioning ducts to their profile locations. Final inspection of the tendons and position of the bursting steel should be performed after the connection with anchors and match-cast segments are made. Mandrels are installed as stiffeners in each duct and should extend through the entire length of the segment to prevent deflection during concreting operations (**Figure 9.31**).

Note that post-tensioning installation tolerances are among the tightest in the casting yard; refer to the current PTI/ASBI M50 specifications. Because post-tensioning is usually anchored to rebar, it frequently controls the rebar installation tolerance. Support bars (non-structural rebar specifically to secure post-tensioning ducts) must be planned and precisely installed.

All aspects of installing post-tensioning ducts and anchorages should be detailed in accordance with the FHWA Post-Tensioning Tendon Installation and Grouting Manual, Chapter 3: "Post-Tensioning Duct and Tendon Installation." This manual can be found online at www.fhwa.dot.gov/bridge/construction/pubs/hif13026.pdf.

## 9.12 Setting the Match-Cast Segment

Before it is moved to the casting cell, the match-cast segment must be prepared. Form fins, rough areas, or damaged faces must be smoothed to prevent adherence to the wet-cast concrete. Also, an oil- or soap-based bond breaker must be thoroughly applied. There are pros and cons to each type. Oil-based products are commercially available and less susceptible to damage from wet weather. They are less visible after application, however, so it can be difficult to verify that all surfaces have been coated. Soap-based bond breakers are generally mixed on site with a thickening agent such as talc powder to a consistency that allows application to the vertical face without running. They provide a very positive membrane between two segments, but are more challenging to maintain through segment construction, especially if exposed to the elements.

The match-cast segment is set as close as possible to its desired position prior to placing the rebar cage, working with both a surveyor and a trained form technician. The rebar cage and ducts are properly adjusted, all inserts secured, all post-tensioning anchorages bolted to the forms and the ducts connected.

The next step is critical, though it can be time-consuming. To ensure no mortar leakage, forms are first brought tightly to meet the match-cast faces and then the surveyor fine-tunes the final casting position. This requires the full attention of the surveyor and the technician and must be planned for in conjunction with other tasks and cells (**Figure 9.32**).

***Figure 9.32 – Aligning the Match-Cast Segment in a Short-Line Casting Cell with Survey Tower in Background (Photo Courtesy of PCL Civil Constructors, Inc.)***

## 9.13 Placing Concrete

Concrete placement sequence is dependent upon many factors. A sequence that works on one cross-section may not work as well on a different section. It is often learned by trial and error. However, some important points to watch are:

- Make sure the forms are thoroughly cleaned, all joints are tight and sealed, all ducts are aligned and secure, and everything is in its proper place. The form should be lightly oiled for stripping, and the face of the match-cast segment coated with a bond-breaking agent.
- Place the concrete in the sequence shown in **Figure 9.33,** taking care to prevent concrete placed in the web from spilling into the bottom slab. This can easily displace rebar and ducts and pull concrete away from heavily reinforced bottom anchorages or the web itself, causing honeycombing. Some flow of concrete is unavoidable but can be minimized through good procedures. There are several acceptable ways to proceed, including the following practice.

1. Place the first concrete in the middle portion of the bottom slab, leaving 6 in. to 12” clear of the side forms at the bottom of the webs. This can be accomplished using either a delivery chute through a trap in the top slab soffit or a chute through the bulkhead end. Concrete consistency needs to be flowable enough to fill congested areas, while stiff enough to avoid blowout of the bottom slab during steps two (2) and three (3) in **Figure 9.33**.
2. Place the second concrete in the webs and vibrate it around the bottom corners to complete the bottom slab. The height of concrete lifts in webs should be no more than 24 inches. Some vibration from the inside of the segment to the outside corners ensures consolidation.
3. Place the concrete in the top slab working from the center and outside edges towards the web. Strike off the top surface and finish as described below.

- Use skips, chutes, or pumps to deliver concrete. Do not let it fall from excessive height, as this causes segregation, and the impact can damage ducts and displace rebar.
- Keep as continuous a delivery as possible; avoid holdups which can allow the concrete already placed to take on an initial set. Some deliberate short waits are necessary, especially after placing the bottom slab and web corner concrete so that it can stiffen just enough to take the weight of the rest of the web concrete – but be careful that overlong waiting doesn’t cause cold joints. Often, retarders are used in the concrete mix to simplify the casting operation.
- Use internal vibrators to thoroughly consolidate the concrete (**Figure 9.34**). Push the vibrator into the concrete to marry lifts at the last joint and slowly withdraw it from the same location. Do not move the vibrator sideways while still in the concrete. Do not use internal vibrators to move concrete around or to drag it from the webs into the bottom slab, as this will cause poor compaction and honeycombing. Limit contact of the vibrator with rebar and post-tensioning ducts, as this can cause damage or displacement.
- Make sure concrete is thoroughly vibrated in awkward areas, such as the corners around heavily reinforced anchorage zones and within spirals.
- Consult project specifications for specific placing and finishing tolerances and procedures.

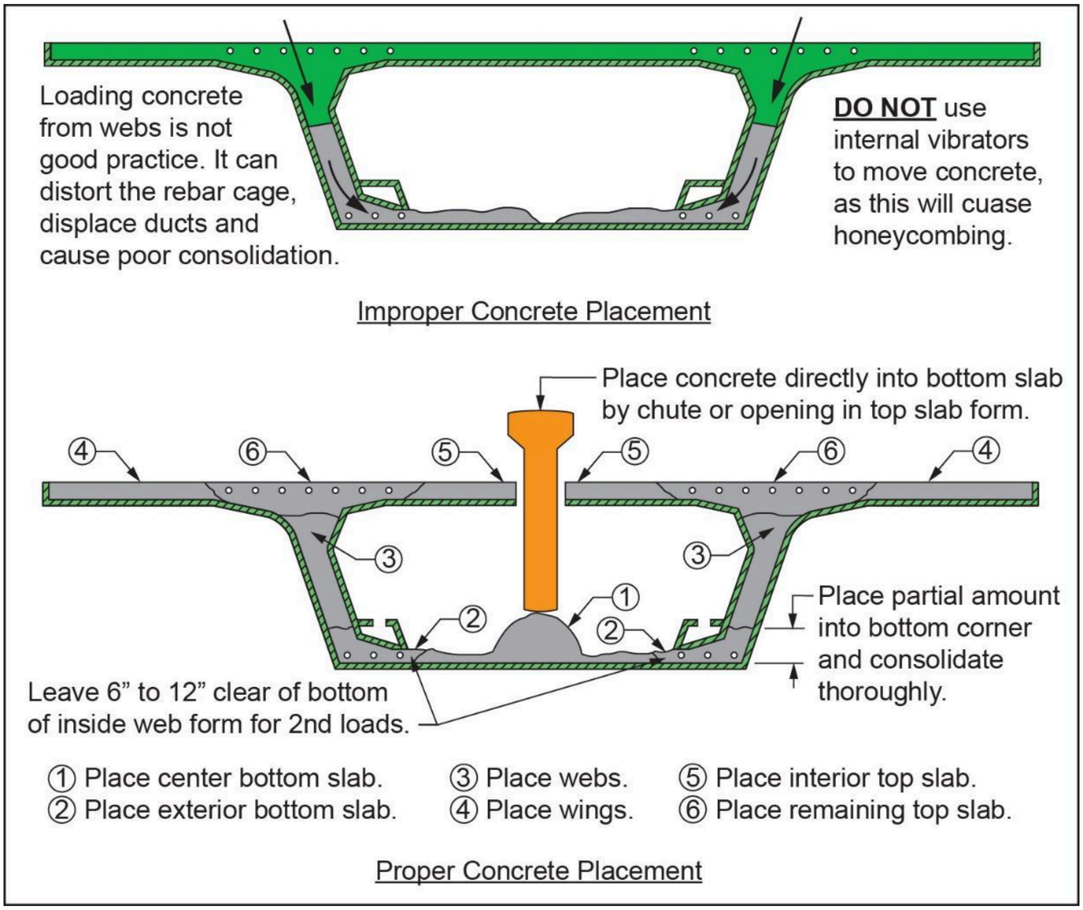


*Figure 9.33 – Placing Concrete*

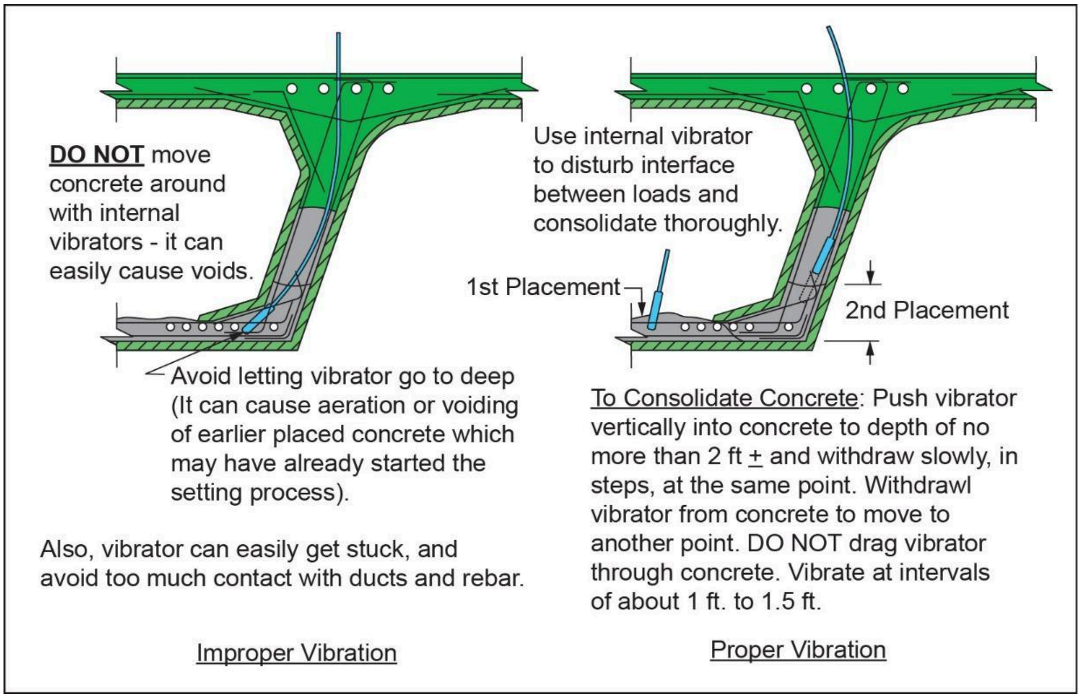


***Figure 9.34 – Use of Internal Vibrators for Consolidation***

## 9.14 Finishing the Top Surface

A good quality finish of the top surface of a structure is essential as this frequently serves as the riding and drainage surface. Some states now specify a 1/2-in. sacrificial thickness for grinding or milling, followed by mechanical grooving of the riding surface. This may be done immediately after erection or as a maintenance procedure in the structure's life.

Hand finishing has been used successfully on many segmental structures. This requires that a strong, straight screed board be extending from the top of the bulkhead to the top of the match-cast segment to strike off the surface to an accurate level.

Mechanical screeds also work very well, but the equipment must be used properly by trained and experienced operators (**Figure 9.35**). Make sure all depressions are filled and all high areas removed to give a uniform, dense, and even surface. The surface must be accurate and as smooth as possible before applying any required riding surface treatment, such as tining. Undulation should not be permitted. Good results have been achieved with both rolling and vibratory screeds. Mechanical screeding should be followed by using a straight edge, usually a stiff aluminum beam, by hand to check and correct any low or high spots. This should create an accurate and straight surface from the bulkhead to the match-cast segment.

After surface wetness has disappeared, the surface may be very lightly "touched up" with floats to produce a finer and smoother surface. This process must not move concrete or disturb the accuracy of the straight surface.

It is important to keep the concrete "live" by proper vibration and finishing. Adding water to stiff areas will create patches of weaker surface material, which will wear badly. Take advantage of workable concrete by performing initial leveling and finishing immediately after placement.

If the concrete is covered for curing, be careful not to spoil the top surface. Tarps should be supported to prevent contact. This is a matter of timing and requires assigning craftsmen to cover the segment when it has cured enough to be covered without damage.

The top surface of the bottom slab should be finished in a similar manner. Although the appearance of the surface finish is not as critical, it should be accurate. Mechanical screeds need not be used on the bottom slab.

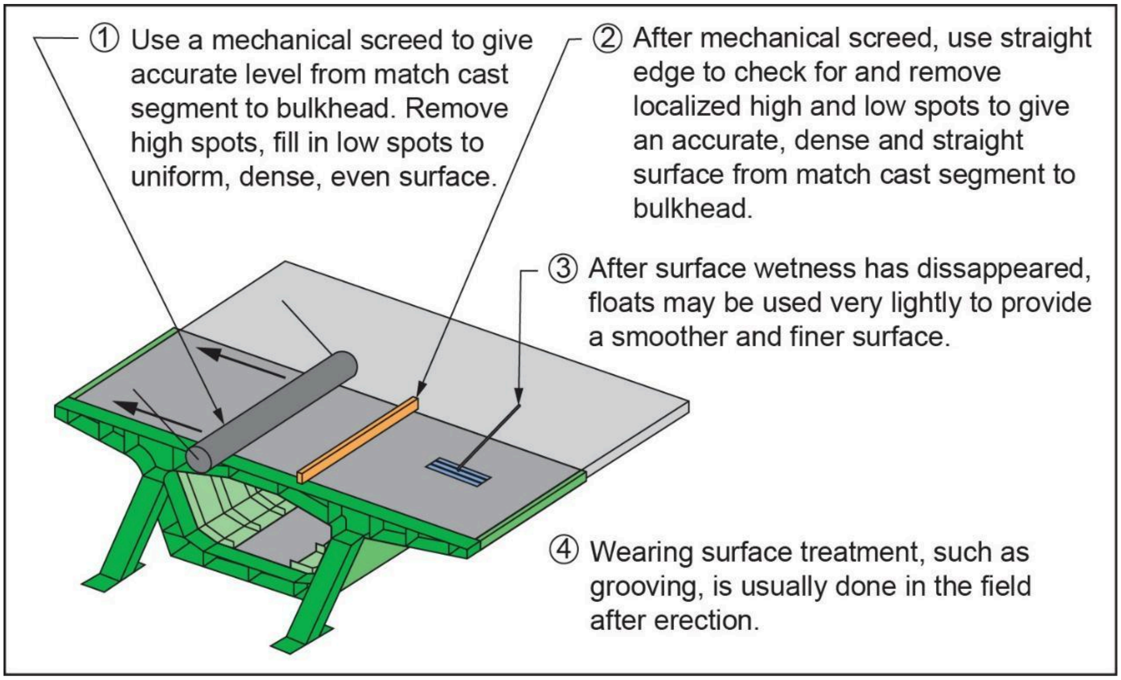


*Figure 9.35 – Finishing a Concrete Surface*

## 9.15 Curing

To achieve a production rate of one segment per day from each casting cell, it is essential that the concrete mix and the curing procedures provide the necessary strength gain. Project specifications or special provisions frequently prescribe curing procedures, but following those directions alone may not be adequate.

Curing procedures vary based on the type of cement used in the concrete and its chemical hardening processes, moisture content, temperature, and exposure conditions. Common practice involves covering each segment with tarpaulins and applying steam to maintain a controlled temperature and humidity level, but other methods may include the use of indirect heaters, rigid walls, burlap, insulation blankets, water, etc.

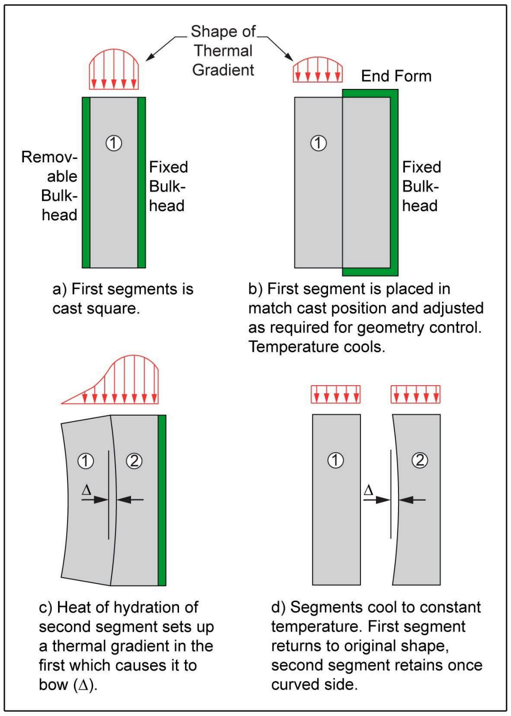
Curing must be continued after the stripping process to meet a target production rate of one segment per day per cell. This may be as simple as spraying the segment with a chemical compound to reduce moisture loss, or it may require monitoring the concrete and atmospheric temperatures and re-insulating the segment after form stripping to control cooling and limit differential temperatures. Computerized data loggers can be used to monitor the temperatures, as discussed further in the next section.

Curing requirements may be project specific for some segmental construction. and should be laid out in the project specifications. Even in a single casting yard, curing requirements change with the seasons, so a curing plan should be developed and communicated to all parties.

### 9.15.1 Banana-Shaped Segment Phenomenon

Proper curing is important to reduce the chance of cracking from thermal shock and can be highly dependent on ambient conditions. Curing methods can also potentially cause issues during erection, particularly for very wide segments. For segments having a width to length ratio greater than 6, the bowing of the match-cast segment has been observed due to a thermal gradient generated by the heat of hydration produced during the curing of the new, wet-cast segment.

While erecting the very wide but short segments (w/L = 9.7) for the San Antonio 'Y' project, crews reported the presence of small gaps between segment joints (top slab, near box centerline) that would not fully close during the application of the temporary post-tensioning. In the industry, this became known as the "banana-shaped segment" phenomenon. **Figures 9.36** and **9.37** show this effect.



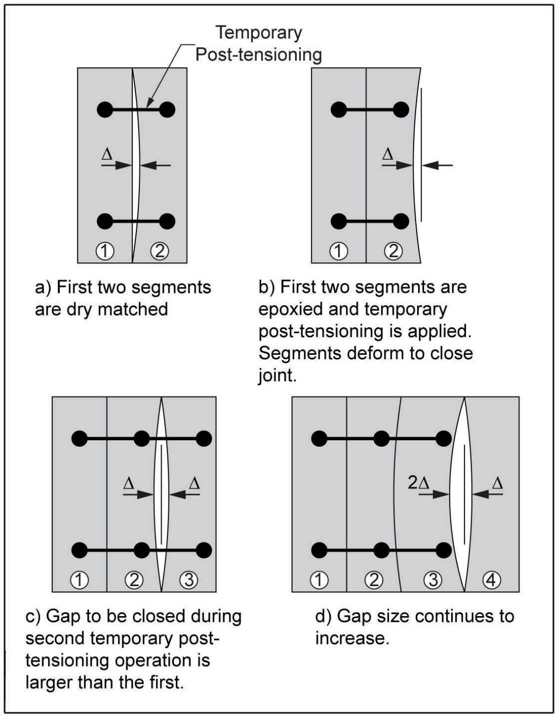
a) First segments is cast square.

b) First segment is placed in match cast position and adjusted as required for geometry control. Temperature cools.

c) Heat of hydration of second segment sets up a thermal gradient in the first which causes it to bow (Δ).

d) Segments cool to constant temperature. First segment returns to original shape, second segment retains once curved side.

*Figure 9.36 – Banana-shaped segment induced during curing*



a) First two segments are dry matched

b) First two segments are epoxied and temporary post-tensioning is applied. Segments deform to close joint.

c) Gap to be closed during second temporary post-tensioning operation is larger than the first.

d) Gap size continues to increase.

*Figure 9.37 – Effects of banana-shaped segment during erection*

Upon further investigation, it was determined the temperature induced deformation in the wet-cast segment was nearly 1/8" (Roberts-Wollmann, 1995). Thermocouples were installed in the top slab within the web and wing of two adjacent segments to record the thermal gradient between the wet-cast and match-cast segments showing nearly 40°F differential between the match-cast and wet-cast segments. The deformation of the match-cast segment was measured over several days, returning to its original, stress-free shape after 3 days.

Ultimately, to avoid this phenomenon, it was determined to either limit the w/L ratios to less than 6 or reduce the thermal gradient between the two segments. For high w/L ratios, the use of an isothermal curing enclosure for both segments is recommended. The application of external heating may be required in some climates. Keeping the entirety of the match-cast segment heated along with the wet-cast segment prior to and during wet-cast segment concrete placement and curing is critical to reducing the effects of this phenomenon.

## 9.16 Removal of Forms

Form stripping should not start until after the concrete reaches the allowable strength required by the design engineer. When "stripping strength" is achieved, it is acceptable to release the core form, ease off the side forms, and pull back the match-cast segment, but keep in mind:

- A separate "handling strength" may be required for lifting.
- Strength gain may slow after removal of the segment from its curing environment.
- If the reinforcing cannot support the weight of the unsupported top slab at stripping strength, the transverse post-tensioning must be stressed in part or in full before the core form is released – requiring a higher "stressing strength."

Concrete compressive strength can be verified by a number of methods. Traditionally, field-cured cylinders are tested, but computerized data loggers can now be embedded in a segment and used to calculate the degree-hours of maturity. This information is then compared to a pre-approved maturity curve developed for each mix design and closely correlates to total strength gain. Verification method(s) must be agreed upon with the owner and QA/QC personnel before casting begins.

Most casting cell forms are removable in whole pieces (**Figure 9.38**), but it is advisable to leave any special block-out forms in place for as long as possible, since their edges break very easily. Block-outs, shear keys, and other bulkhead forms can be left attached to the form, match-cast, or wet-cast in the segment during stripping. Leaving them attached to the bulkhead form eliminates having to reinstall them, but frequently another option is preferable to reduce breakage.

Stripping and pulling back the match-cast segment should be done with particular care. If bond breaker has not been properly applied, portions can easily break off either segment. Shear keys are especially vulnerable. To this end, the stripping crew must examine and understand the movement mechanism on the soffit. Loosening of jacks and tilting of the soffit can "lift" the newly cast segment (**Figure 9.39**), damaging the shear keys.

Match-cast segments may be separated by the following methods:

- Heavy-duty steamboat ratchets (hand-powered).
- Hydraulic jacks mounted on the soffit (**Figure 9.40**).

- Hydraulic jacks on the soffit table and on the top deck through lifting block-outs.

Below is a summary of the steps involved in form removal.

1. Confirm concrete strength.
2. Disconnect inflated duct liners or mandrels.
3. Remove wing bulkheads.
4. Release core forms, fold back, and retract.
5. Drop wing soffit and pull back web outside forms.
6. Strike and pull back match-cast segment, carefully avoiding damage to shear keys, etc.
7. Pull segment back from bulkhead, again using care to avoid damaging shear keys, etc.

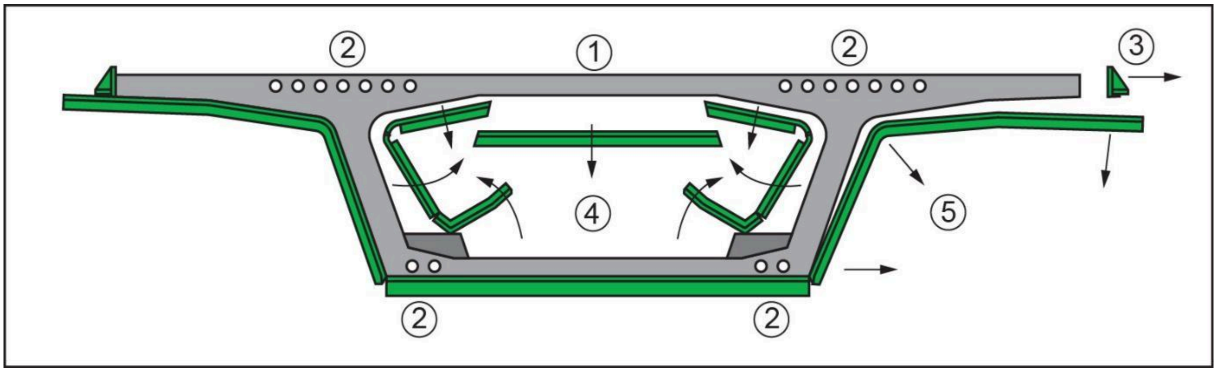
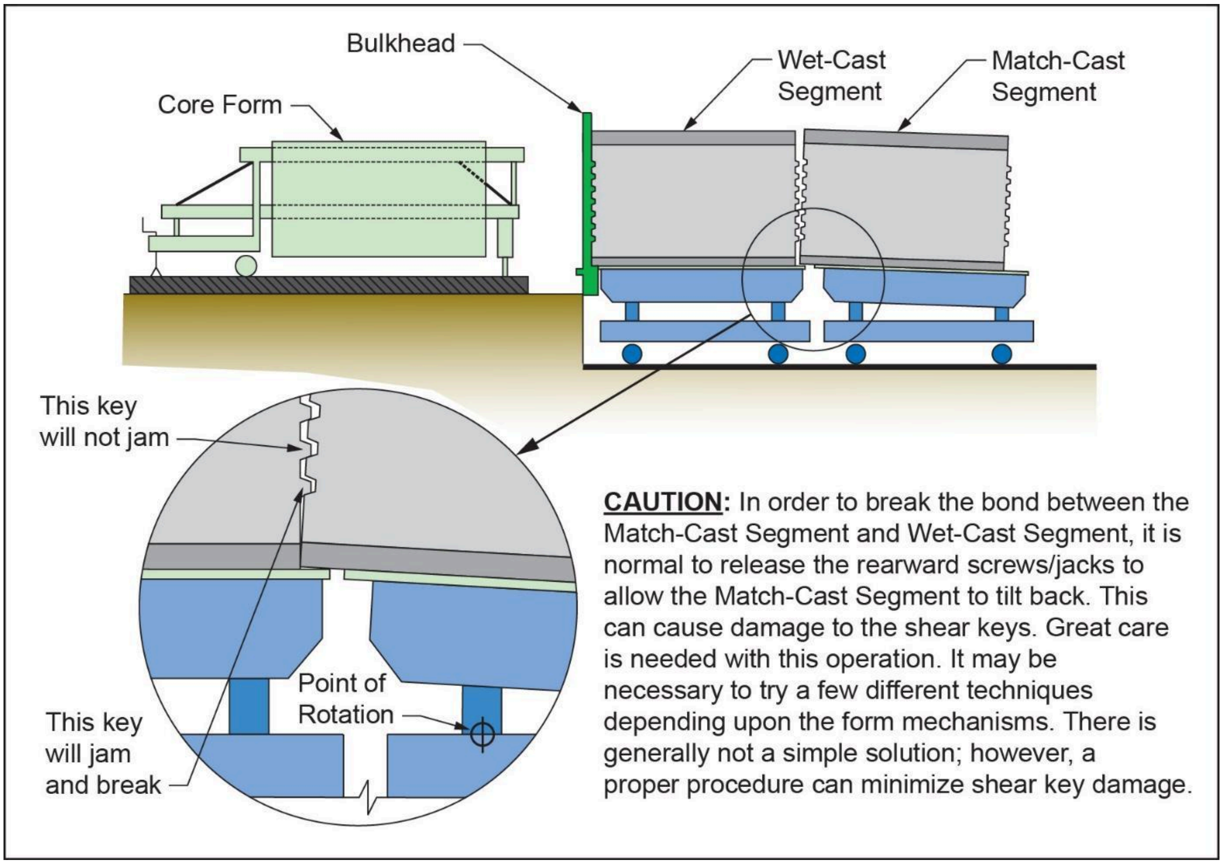


*Figure 9.38 – Stripping Forms*



**CAUTION:** In order to break the bond between the Match-Cast Segment and Wet-Cast Segment, it is normal to release the rearward screws/jacks to allow the Match-Cast Segment to tilt back. This can cause damage to the shear keys. Great care is needed with this operation. It may be necessary to try a few different techniques depending upon the form mechanisms. There is generally not a simple solution; however, a proper procedure can minimize shear key damage.

*Figure 9.39 – Striking Match-Cast Segment*

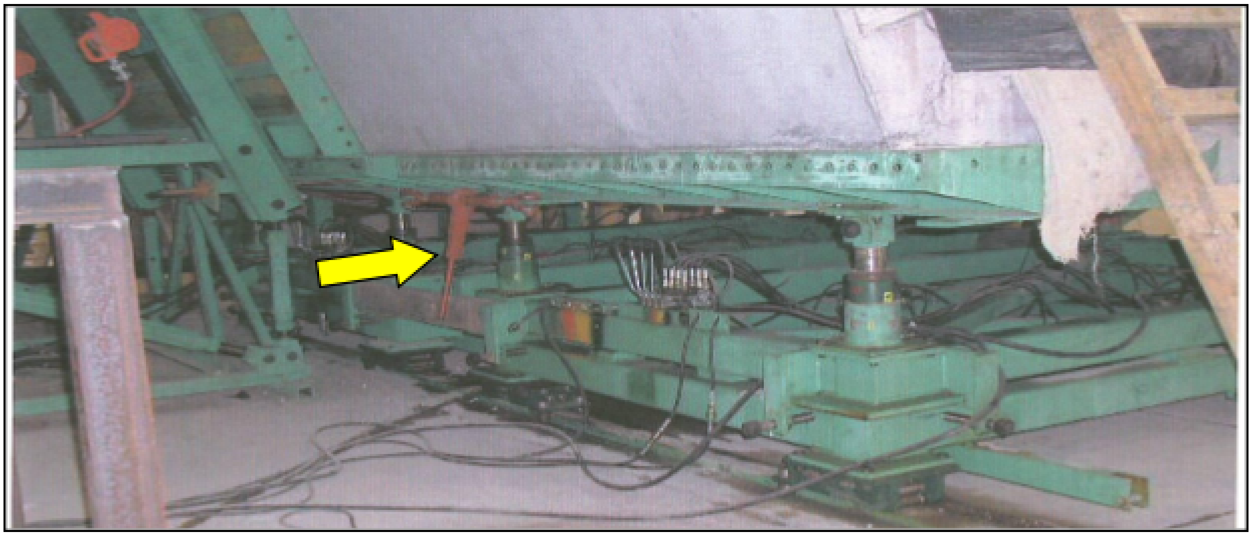


*Figure 9.40 – Device for Manual Separation of Segments*
*(Photo Courtesy of FIGG)*

## 9.17 Pointing, Patching, and Repair

With owners increasingly concerned about quality and structure service life, the cost of pointing, patching, and repair has become a substantial percentage of total production cost. As such, this phase of production must be planned, communicated, approved, and managed to meet expectations. Interior and exterior finishing standards should be agreed upon with all parties during production of the first few segments. It is advisable to complete standard point and patch tasks as segments are being produced, to minimize additional access and handling.

If segments are to be finished in storage, leave enough room to work around the segments with small hand tools. Workers should have adequate access to segment faces to lightly run a grinding wheel around the edges to remove any “fins” or burrs (**Figure 9.41**). If left untreated, irregularities can later create spalls when the segments are pulled together during erection.

A repair plan should be developed and approved by all parties before casting begins. It is impossible to mass-produce segments in a dynamic environment without encountering issues such as poor consolidation or finish, or breakage during stripping and handling. Having a good repair plan in place makes such repairs minor and not detrimental to the service life of the structure.

Repair materials and surface preparation are critical elements in repair service life, just as safe access to power and water (plus a well-communicated repair standard) are critical to productivity. As previously discussed, joint face repairs must be undertaken with extreme care. If necessary to prevent conflict with the matching segments, they must be recessed and the shallow void filled with joint epoxy at the time of erection. The design engineer determines the total area of a joint that can be affected by such a repair.

*Figure 9.41 – Work Access for Finishing Segments*
*(Photo Courtesy of Fueled Photography/PCL Civil Constructors, Inc.)*

## 9.18 Special Situations: Elevated Light Rail Transit (LRT) Construction

An aerial guideway presents all the issues of a typical precast segmental project, along with those associated with the special features required for light rail operations. Determining the cost impact of LRT features involves additional review, while coordinating the systems integration, requires upfront planning and adds to the QC/QA effort.

***Figure 9.42 – Precast Segment with North- and Southbound Steel Plinths Cast-in-Place On-Site (Photo Courtesy of Fueled Photography/PCL Civil Constructors, Inc.)***

### 9.18.1 Rail Components

The rails (commonly continuous welded rail) may be directly fixed to the guideway with elastic fasteners or raised above the deck via concrete plinths. Direct-fixation rail necessitates tight construction control. If plinths are specified, the contract documents specify the design criteria and usually they are cast in place once the structure is erected (**Figure 9.42**). Alternates methods such as using rebar couplers to avoid projected rebar or allowing plinth construction to take place at the casting yard may be allowed. The concrete surface treatments required for secondary plinth pour areas may be as simple as a raked finish but can sometimes be costly. Knowing the plinth reinforcing layout and secondary pour finish locations is critical to avoid costly remediation. Some projects require the plinth rebar to be fiberglass. Carefully review all project specifications for work within this application for segmental construction.

Identifying the design, location, and installation requirements of all LRT features is crucial. Accurately locating all special work, such as switchgear, grounding wires, high-strength rail, rail expansion joints, sleeves, and electrical conduits will require close review of shop drawing details to meet all the system integration placement requirements. This often necessitates a full-time electrician at the casting yard.

Integrated shop drawings, while important for all segments, are especially critical for cantilever segments containing LRT components. Most LRT components are located in the top deck and frequently conflict with cantilever tendon locations. Since both have very tight tolerances, conflicts revealed during segment construction can have damaging schedule consequences (**Figure 9.43** thru **9.45**).

***Figure 9.43 – Plinth Steel Added to the Rebar Cage***
***(Photo Courtesy of Fueled Photography/PCL Civil Constructors, Inc.)***

*Figure 9.44 – Rebar Added for Center-Mount OCS Pole*
*(Photo Courtesy of Fueled Photography/PCL Civil Constructors, Inc.)*

*Figure 9.45 – CIP Plinths with Final Preparation Before Rail Placement*
*(Photo Courtesy of Fueled Photography/PCL Civil Constructors, Inc.)*

### 9.18.2 Rail Crossover

An aerial guideway with northbound and southbound tracks must implement crossovers, which are congested with additional rebar and systems integration requirements (**Figure 9.46**). Production for these areas of tight construction control may not meet the target rate of one segment per cell per day. Tolerance requirements should be clarified early to avoid casting delays and QC/QA shortfalls. Meeting with the project LRT consultants prior to casting these segments is warranted.

***Figure 9.46 – Crossover Rail Layout Prior to Secondary Concrete Pour***
***(Photo Courtesy of Fueled Photography/PCL Civil Constructors, Inc.)***

### 9.18.3 Grounding Requirements

Since DC stray current can cause corrosion of the transit system infrastructure, grounding safeguards must be built into the structure. The contract documents may require grounding the post-tensioning system and steel reinforcement to eliminate the cumulative effects of stray current and increase design life. Each tendon normally requires grounding only at one post-tensioning anchorage. One method is to prep an area on the backside of the post-tension anchor and attach the ground wire with an exothermic weld. The individual copper jumper wires are crimped together and attached to the top slab reinforcement mat. These welds can be fragile, and care must be taken not to damage them during segment construction (**Figure 9.47**).

The PTI/ASBI M50 specification requires a PL-3 tendon, which includes hardware that allows it to be electrically isolated, thus eliminating the transmission of stray current and the need for grounding. The FHWA is currently developing specifications and guidance for this emerging technology.

*Figure 9.47 – Grounding Wire Exothermic-Weld to PT Anchor*
*(Photo Courtesy of Fueled Photography/PCL Civil Constructors, Inc.)*

The upper layer of reinforcement of the top slab also may require grounding. One approach requires tack-welding all or a portion of the reinforcement mat and then attaching a ground wire with a crimping tool. This technique entails use of ASTM A706 weldable rebar, which therefore should be specified in the contract documents.

Project specifications may require all metallic embeds to be grounded, including patron barriers, handrails, expansion joints, access hatches, etc., to fight corrosion and ensure safety. Grounding continuous items like handrails may mitigate the grounding requirement to every 40 ft. Such requirements are project specific. Verify whether a copper jumper wire is necessary or if additional rebar pieces and tie-wire will suffice. An itemized checklist with specific frequency requirements helps mitigate cost and inspection needs (**Figure 9.48**).

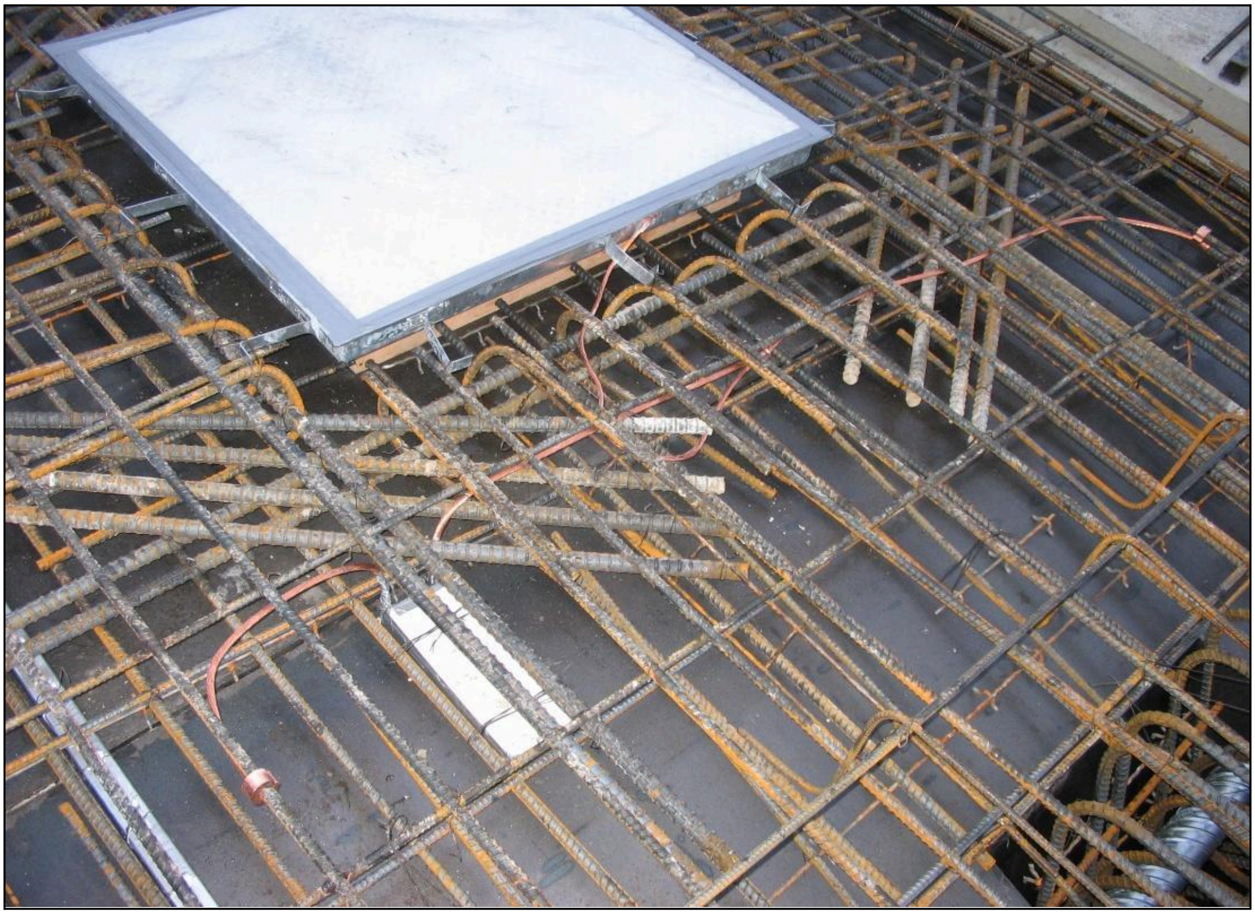


***Figure 9.48 – Grounding Wire Exothermic-Welded to Access Hatch***
***(Photo Courtesy of Fueled Photography/PCL Civil Constructors, Inc.)***

**Item 1** shows the exothermic connection of the copper grounding wire.

**Item 2** is a foam block-out allowing the ground wires to be connected to the conduit system within the precast structure.

### 9.18.4 LRT Conclusion

Light rail is an exciting and growing sector of the transportation industry that is similarly increasing the applications for segmental construction. LRT projects add complexity to segmental construction, but with proper focus on details, they are highly successful. Fully integrated shop drawings are a necessity to avoid delays in the field. Designing rail and electrification details after the structure design is complete can delay shop drawing production if not properly managed. Such additional considerations may require more managerial oversight and QA/QC presence than standard highway projects, but the extra effort pays off in the casting yard.

## 9.19 Summary – Casting Yard Planning and Set-Up

The overarching goal in setting up a casting yard is efficiency. Quality, schedule, and cost all directly correspond to the efficiency of the crew and operators.

Organization has a large impact on efficiency, from the first unloading of material trucks to looking for segments at time of delivery at the erection site.

It is important to emphasize that creating an efficient yard must begin when a contractor first decides to pursue a precast segmental project. During the pre-bid phase, a comprehensive plan for materials, equipment, real estate, and personnel acquisition should be in place.

Immediately after the letting, the successful contractor should finalize and enact the pre-bid plan. Hiring key personnel, negotiating with suppliers of long-lead items such as casting machines, and choosing vendors early ensures the casting yard can move quickly into production.

Means of delivery, overall project quantities and breakdowns, scheduling restraints, and material storage requirements must be discussed in detail to properly plan material flow. Proper organizational skills and inventory control procedures help meet casting cycle needs, reduce labor costs, and eliminate delays. Allocating the right personnel and equipment to handle the daily workload, inventory control and documentation, and QC/QA interface must not be underestimated.

With proper planning in place, the best casting yards are characterized by a drive for continual improvement until the last segment is cast. By focusing daily on safety, quality, innovation, and production, successful segmental casting yards ensure this construction method has a growing future in the transportation industry.

## 9.20 References

(1) Roberts-Wollmann, C., et al, "Temperature Induced Deformations in Match Cast Segments," PCI JOURNAL, V. 40, No. 4, July-August 1995, pp. 62-71.

# TABLE OF CONTENTS

# Chapter 10:
# Procedures for Handling, Transporting, and Erecting Precast Segments

Regardless of the erection method, a precast segment is typically handled multiple times: within the casting area; during transport to the storage area; and when it is taken to the bridge site for erection.

This chapter describes the most commonly used methods for handling, transporting, and erecting precast segments. The designer should verify the structural integrity of segment for these different loading conditions and at least one acceptable option should be shown on the contract drawings.

## 10.1 Methods of Lifting Precast Segments

Precast segments can be lifted using any one of the following methods.

### 10.1.1 Lifting Frames with Holes Cast in the Top Slab of Segments

Depending on the segment weight and design, four (4), eight (8), or 10 or more bars may be needed to lift it. Lifting bars are typically high-strength bars ranging in diameter from 1.25 to 3 in.

Lifting bars, couplers, and nuts can be reused -- unless they have been over-stressed, bent, or otherwise abused. Assuming they are in good condition, the number of reuses should be limited per the manufacturer's and/or specialty engineer's recommendations.

Lifting bars should never be welded or exposed to arcing and must be removed before performing any welding on the lifting frame.

Lifting holes are most often positioned through the top slab, near the inside or outside of the webs. The holes may be formed using corrugated post-tensioned duct pieces, tapered inserts, or other methods as specified by the engineer.

Exact positioning of the holes is critical, along with a restraining device to hold the forms in place during concreting operations. It is important to develop a quality control procedure to verify the correct layout is used. If the holes are not positioned correctly, or if they move during the concrete pour, the bars may get overloaded, the segment may not hang properly, or the lifting frame may not fit. To accommodate any planned variations in the lifting-hole layout, multiple positioning devices may be required.

Using the formed holes, the lifting frame is secured to the segment with post-tensioned bars (**Figure 10.1-2**). Segment slope and crossfall can be adjusted by changing the connection points on the lifting frame, varying the sling length, or hydraulically adjusting the relative positions of the frame and the segment.

The post-tensioned bars' stressing requirements must be followed when securing the frame to the segment. The system could be designed to rely on the friction developed between the frame and the segment to ensure that the bars are working in tension. If the bars are not stressed properly, the frame may slip and shear the bars.

After a segment is erected, the lifting holes should be plugged with an approved non-shrink grout or another material specified by the engineer. The hole forms finish used in the casting yard can be used as a surface to help ensure proper bonding between the plug and the segment, and to prevent the plug from falling out.

Access for forming, pouring, stripping, and finishing the bottom of the holes, especially holes outside the webs, may entail use of rolling platforms, personnel lifts, or other movable platforms. Access to lifting holes located inside of tall or sloped segments may additionally involve sophisticated movable scaffolding.

### 10.1.2 Lifting Frames with Inserts Embedded in the Segment Webs and Protruding Above the Top Slab: High-Strength Bars, Looped Strand Bundles, and Special Inserts

Lifting devices that can be embedded in the webs include high-strength bars, looped strand bundles, or other special inserts. Below is information on each.

**High-strength bars:** Assemblies of high-strength bars, plate, nuts, and couplers are encased in a post-tensioned duct. When placing the assemblies, care must be taken to ensure the bottom nut and upper coupler are fully engaged on the bar.

Without a means of visually confirming accurate assembly and placement, there is a risk of accidents since nuts, couplers, or bars may be improperly engaged or secured. With sufficient quality control, however, using these assemblies is safe. Note that the lifting bars, couplers and nuts cannot be reused because they are embedded in concrete.

After a segment is erected, the bars may require trimming to provide adequate concrete cover, and the post-tensioned duct encasing the bars must be grouted.

Throughout the project, both bars and couplers (and exposed rebar) need protection from damage. Additionally, if they protrude above the deck, or are recessed in holes, they can be tripping hazards.

**Looped strand bundles:** If looped strand bundles are used to lift the segments, the loop embedment length and details must be properly designed. The top of the loop should be encased in a metallic, lightweight pipe section bent in a “U” shape to ensure the load is evenly distributed among the strands. The bottom of the loop should be secured to the web rebar as detailed on shop drawings, the strand loops properly positioned in the segment, and a recess form used around each loop penetration. Proper positioning of this recess form may be problematic and hard to maintain during the pour.

After erection, the loops are trimmed inside the recess to provide proper concrete cover and the recess is filled with the specified grout or patching material. The recess detail should be analyzed carefully to ensure the patch will not pop out under traffic.

Special inserts: Other types of special precast handling inserts may also be engaged, in which case the manufacturer’s specific recommendations should be followed.

With any of these inserts, developing and maintaining precise positioning is critical. Quality control procedures should first verify the layout is correct; then, during concreting operations, a restraining

device used to firmly hold the inserts in place and plumb. Otherwise, the inserts may get overloaded, the segment may not hang properly, or the lifting frame may not fit. More than one positioning device may be needed to accommodate any planned variations in the insert layout.
Embedded rebar to lift the segments should not be used.

### 10.1.3 Clamshell Style Lifting Frames

Clamshell style lifting devices (**Figure 10.1-1**) are an effective way to handle segments without the need for embeds or holes. This method is very common for the span-by-span erection method where the segments do not need to be placed in their final position.

### 10.1.4 Lifting Slings or C Hook Frames

Lifting slings are an economical segment handling alternative except for balanced cantilever erection, or when segments must be placed in their final position prior to disconnecting from the erection equipment. Made of braided wire rope or nylon, these flat straps (**Figure 10.1-3**) do not require the use of lifting holes or imbedded inserts.

Slings are commonly used in precast segmental erection involving underslung trusses or falsework. Wood, plastic, or rubber softeners or shoes should be used around the segment edges to prevent damage to segment or sling.

Another segment-handling system that does not require the use of lifting holes or embedded inserts is the C hook lifting frame (**Figure 10.1-4**). The frame gets quite heavy when handling large segments, which may affect the type and size of erection equipment selected.

In some situations, a combination of these devices may be used to handle a single segment. The segment could be lifted with a sling in the casting yard and during transport and then erected with a lifting frame at the erection site.

## Segment Handling Methods

*Figure 10.1-1 – "Clamshell" Style Lifting Frame*
*(Photo Courtesy of FIGG)*

*Figure 10.1-2 – Lifting Hole-Style Lifting Frame*
*(Photo Courtesy of Parsons)*

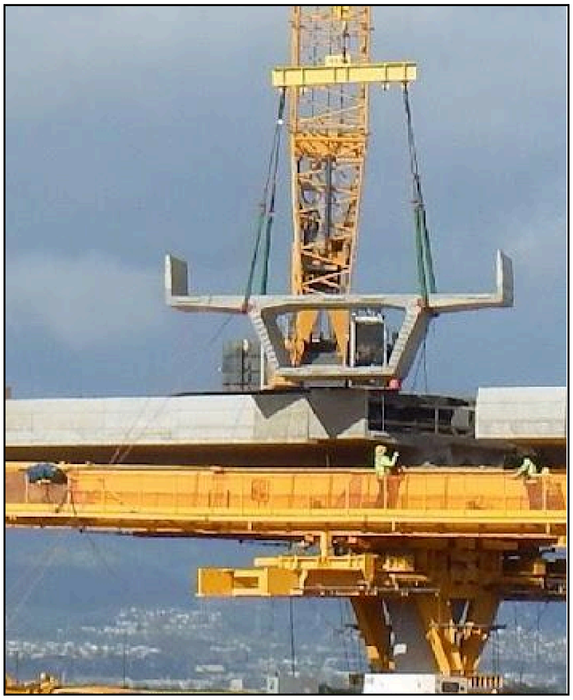


*Figure 10.1-3 – Sling-Style Lifting Frame*
*(Photo Courtesy of FIGG)*

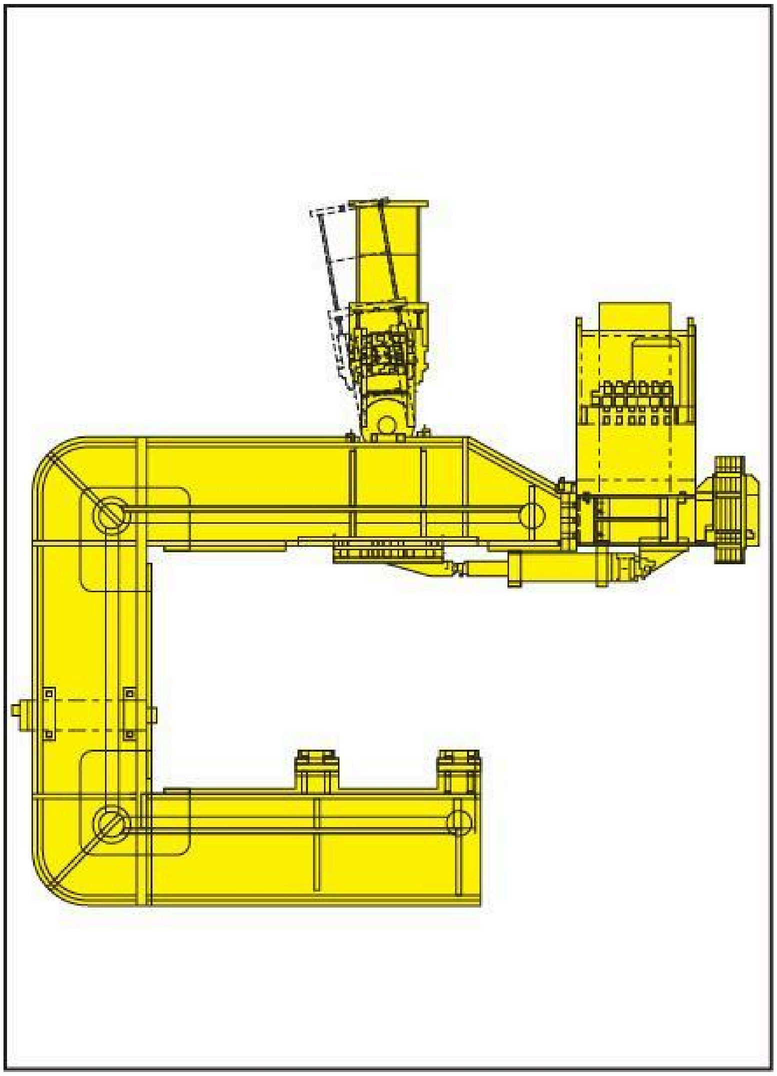


***Figure 10.1-4 – C Hook Lifting Frame***

## 10.2 Handling and Transporting Precast Segments in Precast Yard

### 10.2.1 Handling from the New-Cast Position to the Match-Cast Position

The first time a new segment is handled is when it is being moved from the new-cast position against the bulkhead to the match-cast position. The main operations that affect this handling are, in order of occurrence:

1) **Loosening the sides and bottoms of the inner core form**– Before performing this operation, the concrete should have attained the minimum strength requirements identified in the casting manual. None of the form elements supporting the concrete should be disturbed and the segment should not be exposed to excessive vibration. Typically, minimal or no post-tensioning is required. It is essential that an as-cast survey of both the new- and match-cast segments be performed before starting any loosening or stripping activities on the forms. Loosening of some non-critical or non-load bearing might be acceptable if approved in the casting manual.

2) **Separating the match-cast segment free from the new-cast segment --** The segments should be separated as indicated in the casting manual and in accordance with the recommendations of the form designer. Typically, the soffit table under the match-cast segment is tilted slightly as the tables are pushed apart using horizontal hydraulic or mechanical jacks. Since the separation takes place while the concrete is still relatively green, the shear keys are especially vulnerable to breakage. The use of heavy equipment to pull the segments apart should be avoided when separating the segments as this might result in shear key breakage.

3) **Rolling the match-cast segment away on its soffit** -- Once the segments are separated, the match-cast segment is rolled on its table using a winch, a hydraulic system, or a loader. Segment is typically moved to a finishing area or a ready rack/stand prior to being moved to storage area allowing the table to be moved back into position.

4) **Lowering the inner core form is lowered and retracted and lowering the wing forms –** This operation takes place when the concrete has reached the appropriate strength and, if applicable, the transverse post-tensioning is fully stressed. (The post-tensioning may be stressed in stages.) The form elements supporting the concrete are removed, the core form is folded and retracted, and the wing forms are lowered.

5) **Separating the new-cast segment from the bulkhead** -- Depending on the form design, the new-cast segment may be separated from the bulkhead using the same method as for the separation of the match-cast segment. Segments must be handled carefully to avoid shear key breakage.

6) **Rolling the new-cast segment on the soffit form** -- Once the new-cast segment is separated from the bulkhead, it is rolled on its table using a winch, a hydraulic system, or a loader, forward to enough so the soffit from the match cast segment can be positioned in the formwork. The rebar cage is then installed. The segment is rolled again, set, and adjusted in the match cast position.

### 10.2.2 Handling and Transporting of Precast Segments from the Casting Area to the Storage Area

Finishing work may take place in either a separate finishing area or in the storage area. Access should be provided for transverse post-tensioning and grouting, cleaning the joint faces, point and patch, secondary pours, and repair of small defects. If secondary pours are needed, runways must be wide enough to accommodate concrete trucks or other delivery methods.

Before lifting the segment, the concrete should have reached the specified lifting strength, and the required transverse post-tensioning should be stressed. Once it is properly connected to the lifting frame or to the slings, the segment is moved to the storage area. The storage area should be prepared in advance to prevent settlement under the segments.

Commercially available equipment can be used but, depending on site conditions, yard layout, optimization of the operations and economics, custom-built equipment may be more suitable (**Figure 10.2)**.

*Figure 10.2 – Straddle Carrier Transporting Segments to Storage, Baldwin Bridge, CT*
*(Photo Courtesy of Perini/Homsi)*

***Figure 10.3 – Overhead Crane, Singapore LRT***
***(Photo Courtesy of DEAL/Rizzani de Eccher USA)***

The segment lifting frame dimensions and weight should be considered in determining the necessary capacity of handling equipment. Safety details including wheel guards, engine kill switches, travel alarms, and air horns, as well as clear communication between the operator and the spotters, are essential to safely maneuvering large handling equipment in the storage area's narrow runways.

Three typical methods of moving segments in the storage yard are outlined below.

- **Cranes With or Without Tractor-Trailers or a Special Carrier** – Depending on project needs, the availability of equipment, and economics, large cranes may load segments onto tractor-trailers or special carriers, or they may crawl with the segments directly into the storage area. Not the most efficient method, it requires a storage area layout that can accommodate large runways for the travel and swing radii of the cranes and transporters.

- **Rail-Mounted Gantry Cranes (Figure 10.3)** – If the storage yard is rectangular and all segments can be stored on a long and narrow strip of land, a rail-mounted gantry crane offers an ideal solution. This equipment, which can typically straddle several segments, can operate in very narrow runways and optimizes use of the storage area. If electricity is available, a rail-mounted gantry can be operated using power and control cables running off the permanent power grid. This is usually more economical that equipping the crane with a generator.

Rail-mounted gantries require relatively flat terrain and proper ground preparation under the rails that include means for correcting ground settlement under the tracks.

- **Rubber-Tired Straddle Cranes** – If the storage area is square or irregular, a rubber-tired straddle crane may be needed. This type of crane typically straddles one or two segments and requires multiple runways wide enough for safe operation of the equipment between the rows of segments. Straddle cranes are often equipped with four-wheel steering and four-wheel drive, which are helpful for negotiating tight turns in the yard.

The tire pressure exerted by these cranes is quite high and requires proper soil preparation. Additionally, runways should be constantly monitored and repaired as ruts and depressions affect equipment operation and cause premature wear and tear on the drive and steering mechanisms. Proper drainage must be provided throughout the casting yard to avoid water ponding in the runways.

The path and turning radius of straddle cranes must be considered when laying out the casting yard. The crane manufacturer should be apprised of the soil conditions and terrain to properly specify the drive and steering systems.

Soil conditions in the storage area must be analyzed and properly prepared to minimize settlement under the weight of the segments.

Crane mats or concrete pads may be needed to spread the load. Segments should be stored on hard timber blocks using a three-point support configuration (see **Figure 10.4**) to avoid cracking or warping of the segment which would lead to complications in segment fit-up during erection and affects the final geometry of the bridge. Note that hard timber blocks may stain the concrete if the segments are stored for prolonged periods. It is suggested to wrap the timber directly in contact with the precast segments with plastic to minimize this effect if the segments will not receive any additional finishing or coating

Due to their sloped bottom soffits, variable-depth segments require more complex cribbing to keep the segments vertical and provide proper stability.

The storage area should be monitored periodically, especially after heavy rain, to check for settlement of the segment supports. If settlement is observed that could jeopardize segment stability, or if the three-point support configuration has been compromised, the segments should be relocated and the problem corrected.

Double stacking segments, though not always permitted, may be possible depending on segment design (**Figure 10.5**). This practice requires the approval of the design engineer. If approved, it is essential that the designer check the effects of localized loadings to avoid cracking. All segments should be checked periodically for damage resulting from double stacking. Double stacking severely variable-depth segments is not recommended.

Barrier rebar projections must be considered. Segment handling equipment must have adequate room to clear two segments with rebar projections on dunnage, plus a segment with a lifting frame and rigging under the hook.

Non-symmetrical segments may crack under their own weight, requiring special storage requirements.

Finishing work may take place in either a separate finishing area or in the storage area. Access should be provided for transverse post-tensioning and grouting, cleaning the joint faces, point and patch, secondary pours, and repair of small defects. If secondary pours are needed, runways must be wide enough to accommodate concrete trucks or other delivery methods.

***Figure 10.4 – Segment Storage Using Three-Point Support Configuration to Prevent Warping***
***[Note Support Under the Webs]***
***(Photo Courtesy of Elie Homsi)***

*Figure 10.5 – Double Stacking of Segments*
*(Photo Courtesy of Elie Homsi)*

## 10.3 Transporting Precast Segments from the Precast Yard to the Erection Site

Before transporting a segment to the erection site, it is important to ascertain that all quality control (QC) documents are properly completed and the segment is accepted for incorporation into the bridge. At a minimum, each segment should be inspected to verify:

- Proper concrete strength is achieved.
- Specified curing duration is reached.
- Transverse post-tensioning tendons are fully stressed and grouted per the contract documents.
- Patching and repairs are completed and accepted by the QC inspectors.
- Permanent and temporary post-tensioning ducts are checked for obstructions, layout, and placement.
- All inserts are correctly placed.
- The segment is properly identified and oriented.
- The match-cast face is pressure-washed or lightly sandblasted.

Depending on site conditions and location of the casting yard relative to the erection site, segments may be transported by water or by land.

### 10.3.1 Transport via Water using Barges

If the casting yard is remote from the project site, or the bridge is being erected over water, delivering segments by water using barges should be investigated. Note that this usually requires double-handling the segments, especially if a portion of the superstructure is over land.

#### 10.3.1.1 Loading

If easy access to a navigable waterway exists, the decision to use barge delivery should take the following items into account:

1) Any permitting issues restricting waterway access from the specified property.

2) Water depth adjacent to the edge of the project, dredging permit requirements, and buried utilities near the property shoreline.

3) Abutters' issues.

4) Waterway width and the risk of blocking the channel during segment loading.

5) If applicable, the structural integrity and fitness of any existing bulkhead; permit requirements for improvements if found deficient.

6) Equipment and segments' lateral loading of the bulkhead.

7) If needed, design decisions and permitting for a new bulkhead, with three basic options:

    a. A bulkhead parallel to shoreline – This option is easiest to permit but may block the channel during barge loading.
    b. A barge loading slip dug out inside the property line – This may require a large slip to accommodate the large barges used.
    c. Loading finger piers protruding into the waterway – The least expensive, but most difficult option to permit, this consists of two rows of piling with runways. Lateral stability and side loading should to be investigated, especially in waterways subject to ice loading.

With a slip or finger type bulkhead, barges can be loaded directly with the straddle crane used in the storage yard.

If a bulkhead parallel to the waterway is selected, segments are delivered to the bulkhead area by the straddle crane and loaded onto the barge using a crane with capacity to reach the centerline of the barge. This requires additional sets of segment storage pads and lifting frames at the bulkhead to stage segments during the transfer from the straddle crane to the loading crane.

If the casting yard does not have ready access to a navigable waterway, segments are transported to a waterway as described immediately below, in **Section 10.3.1.2**.

#### 10.3.1.2 Transport

First, the integrity and fitness of the barges designated for segment transport must be checked and certified by a qualified engineer or marine architect.

American Bureau of Shipping (ABS) certification may also be required.

The hull of the barge must be checked and strengthened as necessary to accommodate the segment loads.

A proper cribbing and tie-down system must be provided to secure the segments during transport, with variable-depth segments requiring a more complex and adjustable system.

The depth of the waterway, especially outside the navigational channels, must be checked and cleared of any obstructions. The potential effect of tides, seasonal variations and prevailing winds on water depth should also be evaluated.

Barge towing is weather-dependent: freezing rivers and waterways can have major impact on segment delivery. The weather forecast should always be checked prior to loading and moving the barges and all logistics of transport, on-site mooring, and storage studied in detail. The planned route of the loaded barges and tugboat should be checked for overhead obstructions, low clearance bridges, movable bridge schedules and operational reliability, etc.

**Figure 10.6** shows a barge transporting a segment hauler; **Figure 10.7** shows segments being transported directly by barge.

### 10.3.1.3 Unloading

Once the segments are delivered to the erection site, it is necessary to pressure wash the exposed faces, especially the match-cast faces, and any exposed steel or secondary pour-back area to wash off salt spray. If the post-tensioned ducts were not properly sealed prior to the trip, they will need to be flushed with potable water and dried with oil-free compressed air.

If the segments can be delivered within reach of the erection equipment, they can be unloaded directly from the barge.

Area wave action and swells may make connecting the lifting frames to the segments difficult, requiring special attachments to guide, hold, and secure the frame to each segment as the lifting bars are being tightened and stressed. Pinch- point type injuries and falls present a serious concern during this operation.

To prevent the frame from bouncing on the segment as it is being secured, proper alignment of the winch cables inside the block sheaves should be verified prior to lifting the segment off the barge.

Proper access and fall protection should be provided for safe access in reaching the top slab inside the box, the top of the segments, and the areas to be pressure washed.

If the segments are being stored on barges near the erection site, proper mooring must be provided, properly permitted, and designed to withstand local wind, water flow, wave, and swell conditions.

*Figure 10.6 – Barge Transporting a Segment Hauler*
*(Photo Courtesy of Elie Homsi)*

***Figure 10.7 – Barge Transporting Segments***
***(Photo Courtesy of Flatiron Constructors, Inc.)***

In some cases, the barges needed to accommodate the load will be too large and deep to access the erection site. In these situations, segments can be transferred to smaller barges or unloaded and transferred to a land hauler. Either situation can incur significant additional expense.

If the segments must be transferred from the barges to a land hauler, an unloading/staging area near the erection site must be set up with either a bulkhead parallel to the shoreline, a slip, or finger piers. Water depth and dredging permits should be investigated.

A bulkhead is the most likely solution. This will require the segments to be unloaded from the barge with a crane and then loaded onto a tractor-trailer or a special hauler and transported to the erection equipment.

Alternatively, a low-profile rough terrain straddle crane with rubber tires can be used to move the segments from the unloading area to the staging area, and from there to the erection equipment.

The haul road should be designed to accommodate the segment hauler's horsepower and turning radiuses.

### 10.3.2 Transporting Precast Segments Off-Site by Land

If the casting yard is not at the bridge location, segments are transported by land using either a tractor-trailer or special haulers. **Figures 10.8 - 10.11** show segments being moved from the storage yard to the erection gantry. **Figure 10.12** shows an 85-ton diaphragm segment being delivered to a project site.

#### 10.3.2.1 Loading

Segments can be loaded onto the hauler with the same straddle crane used in the storage yard. Typically, a section of the storage yard is designated as the loading area, with easy truck access and gantry crane rail crossings.

### 10.3.2.2 Transport

Several issues should be considered in analyzing segment transport to the erection site:

- The weight and dimensions of the segments often exceed the legal load limits for the local streets and highways.
- Over-weight and over-dimension permitting procedures vary from one locality to another.
- Clearance and load rating of existing bridges on the transport route
- The haul route may cross overpasses, buried utilities, underground box culverts, etc., which may all have different load ratings.
- In some regions, no over-weight permits are issued in the spring due to ground thawing concerns. During that time, no segments, heavy loads, or equipment can be moved outside the project limits.
- Police and / or special escort vehicles may be required.
- Localities with traffic congestion concerns or sensitive abutters may impose additional restrictions on hauling time.
- Overhead clearances along the haul route such as underpasses, power lines, traffic lights, overhead utility lines, etc. should be checked. The barrier rebar on top of the segments is usually the controlling element in determining necessary clearance.
- The distance from the casting yard to the erection site and the availability of haulers may necessitate setting up a staging area at the erection site.

Depending on the segment load and the permit requirements, multi-axle tractor-trailer combinations may be used to haul segments. Extra-heavy segments may require self-leveling, all-wheel steering hydraulic haulers pulled by specialized tractors that have massive counterweights for extra traction. Some of these haulers are self-propelled, but these move at very slow speeds and may be restricted from highways. Rail can be used if available at both the casting yard and the erection site, but the relative unreliability of the rail schedule and the project team's inability to control railroad operations make it a risky choice.

### 10.3.2.3 Unloading

Segments should be delivered directly to the erection equipment whenever possible, but in some cases, double-handling the segments and storing them onsite cannot be avoided.

In these cases, if staging areas are set up and a crane is used to unload the segments, both the crane and haulers will be needed later to load and transport the segments to the erection equipment. Alternatively, the haulers can be unloaded with a low-profile rough terrain straddle crane that can also deliver the segments to the erection equipment.

If segments are delivered on top of completed spans, the superstructure should be checked for loaded hauler or straddle crane reactions. Any exposed rebar on the upper deck could also need protection from the hauling equipment.

Haul roads should be designed to accommodate the segment hauler's horsepower and turning radiuses.

### 10.3.3 Transporting Precast Segments On-Site by Land

In addition to the methods for off-site transport, if the casting yard is located close to the erection site, segments can be transported to the erection equipment directly by low-profile haulers or special mega-haulers. When the casting yard is on the erection site, the same equipment can pick up each segment from the storage area, transport it along the bridge alignment and unload it at the erection equipment without the assistance of other cranes or equipment.

If a low-profile rough-terrain straddle crane is used, it should be able to pick up a segment from the storage area, travel with it along the haul roads and over the completed spans and fit under the tail of the overhead gantry to unload the segment. Typically, the straddle wheel gage is designed to match the segment web spacing. Alternately, the segments can be placed on the ground under the gantry or within reach of either the crane or the winch-and-beam system.

If the full span method is used in casting the superstructure (the entire span is cast in one element), customized handling and transportation equipment is necessary. Full span casting is typically applied to exceptionally long bridges, such as high-speed rail structures and major viaducts or bay crossings.

*Figure 10.8 – Gantry Loading a Segment on a Segment Transport Vehicle, Baldwin Bridge, CT*
*(Photo Courtesy of Perini/Homsi)*

***Figure 10.9 – Truck and Segment on a Trailer, Baldwin Bridge, CT***
***(Photo Courtesy of Perini/Homsi)***

*Figure 10.10 – Delivery of a Segment to the Launching Gantry, Baldwin Bridge, CT*
*(Photo Courtesy of Perini/Homsi)*

***Figure 10.11 – Segment Being Lifted by the Launching Gantry, Baldwin Bridge, CT***
***(Photo Courtesy of Perini/Homsi)***

***Figure 10.12 – Delivery of an 85-Ton Diaphragm Segment (note barrier wall rebar height), Boston Central Artery Project, MA***
***(Photo Courtesy of Unistress Corporation)***

***Figure 10.13 – Delivery of a 42 ton segment with tarping to protect the bottom of the segment from contamination during transport***
***(Photo Courtesy of Parsons)***

## 10.4 Erection of Precast Segmental Bridges

### 10.4.1 Factors for the Selection of Precast Segmental Bridge Erection Methods

The main factors influencing the selection of the project's optimal erection method and equipment discussed are:

- Access and Site Conditions
- Project Schedule and Construction Duration
- Superstructure Design
- Project Team
- Equipment Availability

Each of these five actors is outlined below in more detail.

**Access and Site Conditions**
Access and site conditions are probably the most significant factors in determining the most efficient erection method.

When working over land, multiple factors should be considered, from environmental issues such as wetlands and protected habitats to interferences with local traffic, businesses, and railroad crossings.

When working over water, factors to consider include:

- Water conditions (depth, flow, ice, etc.).
- Any required permits.
- The feasibility and cost of constructing access trestles.
- Wave action and barge during connection of the lifting beams to the segments.
- Saltwater splash on the match-cast faces and inside the post-tensioned ducts.
- Proper design, analysis, and certification of transport barges.
- Appropriate knowledge and permitting of loading and unloading facilities.

Likewise, the availability of suitable nearby real estate affects the erection and segment delivery method options. The distance from the precast yard to the bridge site impacts the number of transport vehicles and the need for staging areas and double-handling or barge docking facilities at the erection site. Similar to the casting yard, when a limited storage area exists and double-stacking is being considered, note that segments must be checked for loading condition, and proper dunnage and soil preparation must be performed to avoid differential settlement.

The route from the precast yard location to the erection site will dictate the size and type of segment that can be transported, especially if the route includes low overhead clearance or weight restrictions. Local ordinances and permit requirements and costs also must be factored into a casting yard location.

The transport route from the casting yard to the erection site must be checked for overhead clearances (e.g., power lines and overpasses) and underground structures (e.g., utilities and culverts).

Transport permit requirements vary widely from one location to another and seasonal restrictions may apply.

### Project Schedule and Construction Duration

The project completion date is typically specified in the contract documents and may require an accelerated schedule. This in turn typically involves extra manpower to perform simultaneous work on multiple fronts and/or specialized or expensive equipment – added expenses that are justified if the owner offers early-completion incentives. At times, the construction sequence and traffic phasing require multiple headings to keep up with the project completion schedule.

### Superstructure Design

Geometric characteristics of the superstructure including span length, pier height, horizontal curvature, maximum grades and cross-slope, as well as the consistency and repeatability of these characteristics throughout the project, have a major impact on the erection method selected. Projects with small segments or very tight radius curves require the use of cranes; large projects with a repetitive span layout favor underslung trusses or overhead gantries. Short projects with very high piers and heavy segments may require a beam-and-winch set-up to erect the heavier segments.

It is important to verify that the superstructure and substructure can carry the additional construction loads introduced by the erection equipment. Ground- or barge-mounted cranes introduce minimal construction load into the structure versus overhead gantries, which often introduce some of the most significant loads the bridge will support during construction. Different overhead erection equipment can produce very different loading conditions that must be considered.

**Project Team**
The experience of the entire project team, including the owner, designers, inspectors, construction managers, and the contractor is another major factor impacting selection of an erection method. The more experienced the team is, especially the contractor, the more feasible a sophisticated erection method may be if deemed the most efficient way to construct the project.

The availability of skilled labor in the project market also should be considered.

**Equipment Availability**
The availability of erection equipment (cranes or specialized equipment), new or used, competition among suppliers, and the availability of steel fabricators – all impact the cost and delivery schedule of erection equipment and, therefore, the selection process.

The additional costs associated with mobilizing, assembling and commissioning new specialized equipment or refurbishing and modifying existing equipment should not be underestimated in terms of money and time. More expensive specialized equipment benefits from the economy of scale of larger projects, where the initial investment is depreciated.

### 10.4.2 Erection Methods for Precast Segmental Bridges

Precast segmental bridge erection methods can be classified by bridge type as follows:

Erection Methods for Span-by-Span Type Bridges (Span by Span construction discussed in Chapter 3)
Underslung Trusses with Crane on Ground or Barge Mounted on Water
Erection on Underslung Trusses with Crane or Derrick/Lifter on Deck
Erection with an Overhead Gantry
Full Span Erection with Winches / Strand Jacks
Full Span Carrier / Erector
Full Span Erection on Shoring Falsework

Erection Methods for Balanced Cantilever Bridges (discussed in Chapter 4)
Balanced Cantilever Erection by Crane on Ground or on Water
Balanced Cantilever Erection by Overhead Gantries
Balanced Cantilever Erection with Beam and Winch/Strand Jacks
Balanced Cantilever Erection with Special Erectors

Below is a discussion and comparison of these various erection methods.

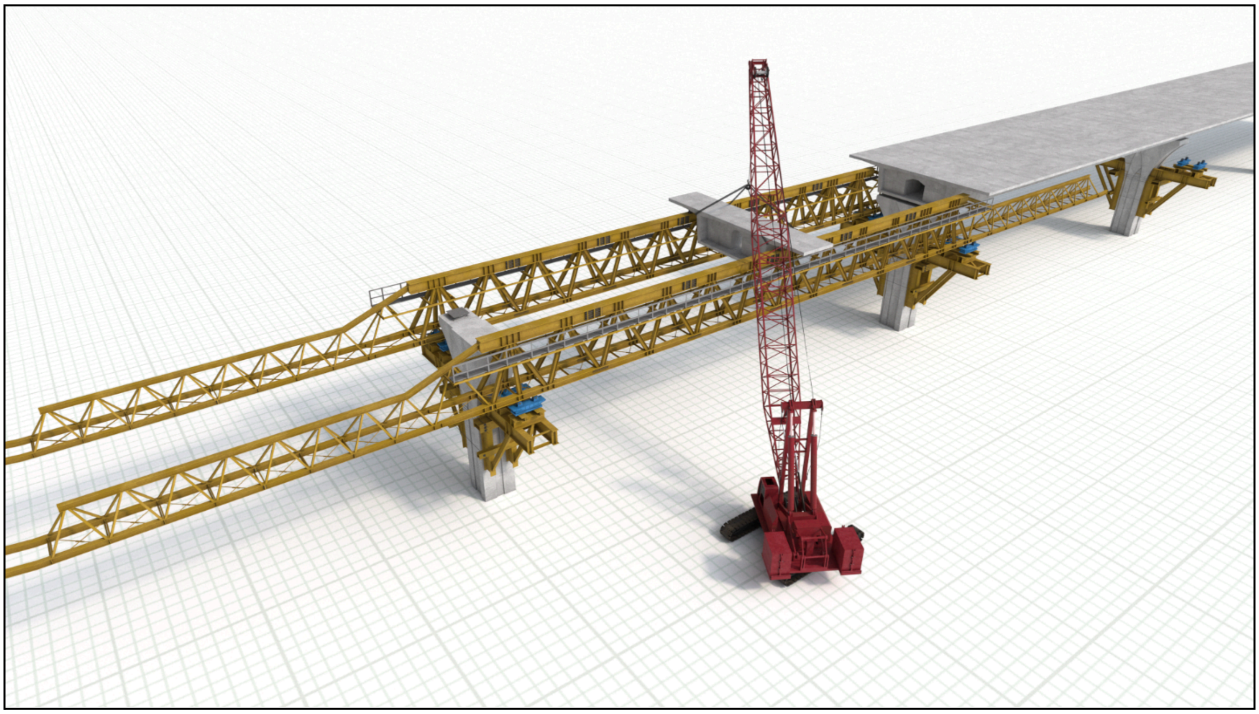


*Figure 10.14 – Crane Erection of Span-by-Span Bridges on Underslung Trusses*

### 10.4.2.1 Erection Methods for Span-by-Span Bridges

#### 10.4.2.1.1 Underslung Trusses with Crane on Ground or Barge- Mounted on Water

- Relatively economical solution if ample room exists for ground-level access.

- Requires access along the bridge alignment throughout the erection phase for the following operations:

– Foundations and Substructure Construction
– Pier Bracket Installation and Relocation
– Segment Delivery
– Erection Crane Access and Swing Radius
– Material Delivery
– Support Operations

May significantly increase cost of work over water due to need for trestle and /or barges and tugboat for access.

- Weather-dependent, especially if performed on the water.

- Requires special loading and unloading facilities for work over water.

- Governed by maintenance of traffic (MOT) rules if working on land.

- Pier brackets supporting the trusses typically cycled and erected on the leading pier by the erection crane.

*Figure 10.15 – Crane Erection of Span-by-Span Bridge on Underslung Trusses*
*(Photo Courtesy of Flatiron Constructors, Inc.)*

- Underslung trusses relocated using any of the following methods:

  - **Winches and self-launching of long trusses** – The long trusses are designed to be self-contained; they self-launch from pier to pier using winches mounted to the deck or the truss.
  - **Jacks and grips to push long trusses forward** – The long trusses are designed to be self-contained; they self- launch from pier to pier using a hydraulic jacking mechanism mounted to the superstructure and a perforated rail attached to the truss.
  - **Crane and "C" hook to relocate short trusses** – The short trusses are fitted with a "C" hook allowing cranes to relocate the truss span to span.
  - **Crane dragging trusses on pier brackets rollers or on C hook trailers** – Long trusses are relocated from pier to pier using a ground-based crane to partially support the nose-end of the truss while the tail of the truss rolls on the pier brackets. The truss is then pulled forward toward the next pier. Short trusses are fitted with a "C" hook attached to trailers on top of the deck and relocated pier to pier using a ground-based crane that partially supports the nose end of the truss and pulls it forward while the rear of the truss is supported by the "C" hook. This method should be avoided even if shown in the contract drawings. Dragging the trusses with cranes is very delicate and risky because of the high potential of side-loading the crane boom.
  - Various combinations of the above may be used.

#### 10.4.2.1.2 Erection on Underslung Trusses Using Crane or Derrick / Lifter on Deck

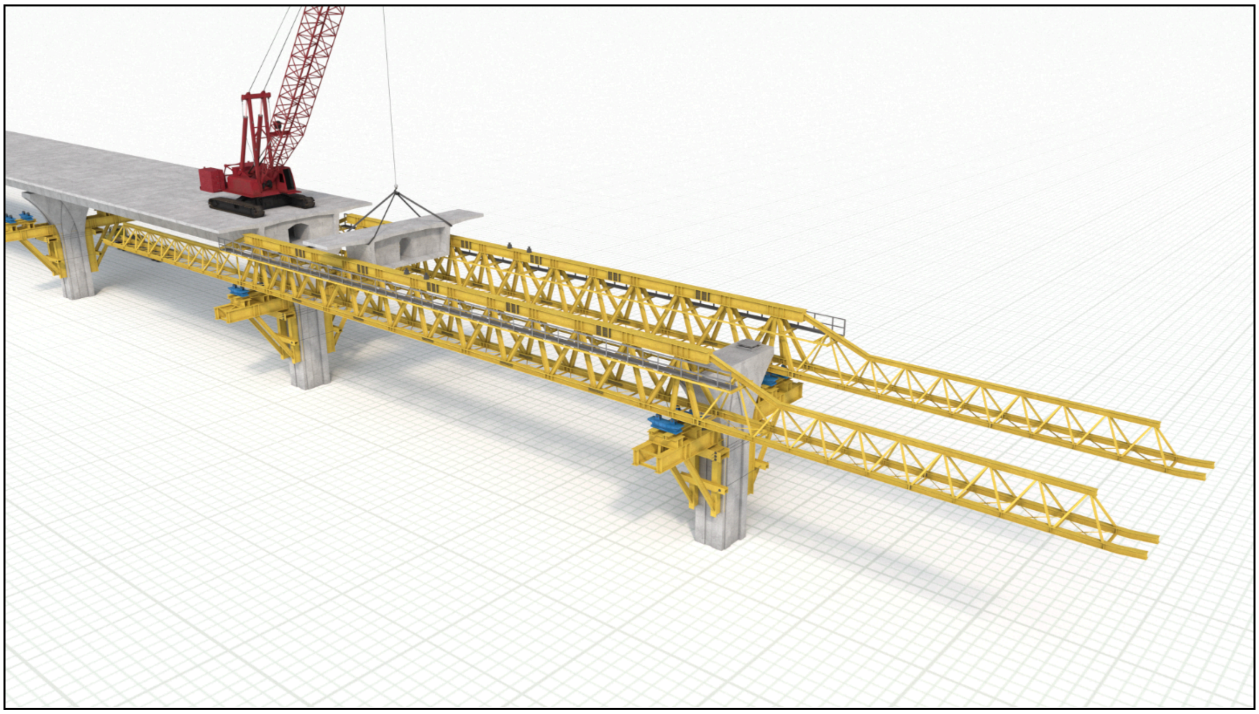


*Figure 10.16 – Span-by-Span Erection on Underslung Trusses Using a Crane or Derrick / Lifter on Deck*

- Requires access to the pier locations throughout the erection phase for the following operations:

– Foundation and Substructure Construction
– Pier Bracket Installation and Relocation

- Deck must be able to handle the loads from segment deliveries and crane.

- Same options for relocation of underslung truss as when crane is on ground or barge-mounted (described above).

- Speed of erection and erection cycle times are majorly impacted by precast yard location and distance from bridge site due to the travel time needed to haul the segments.

- Bridge length and distance segment haulers have to back up also impact operations if segments are delivered behind the erection crane on the new bridge.

- Difficulty of self-launching the pier brackets likely means separate ground- or water-based equipment required to install and remove brackets. Additional sets of pier brackets may need to be purchased to speed operations.

#### 10.4.2.1.3 Span-by-Span Erection with an Overhead Gantry

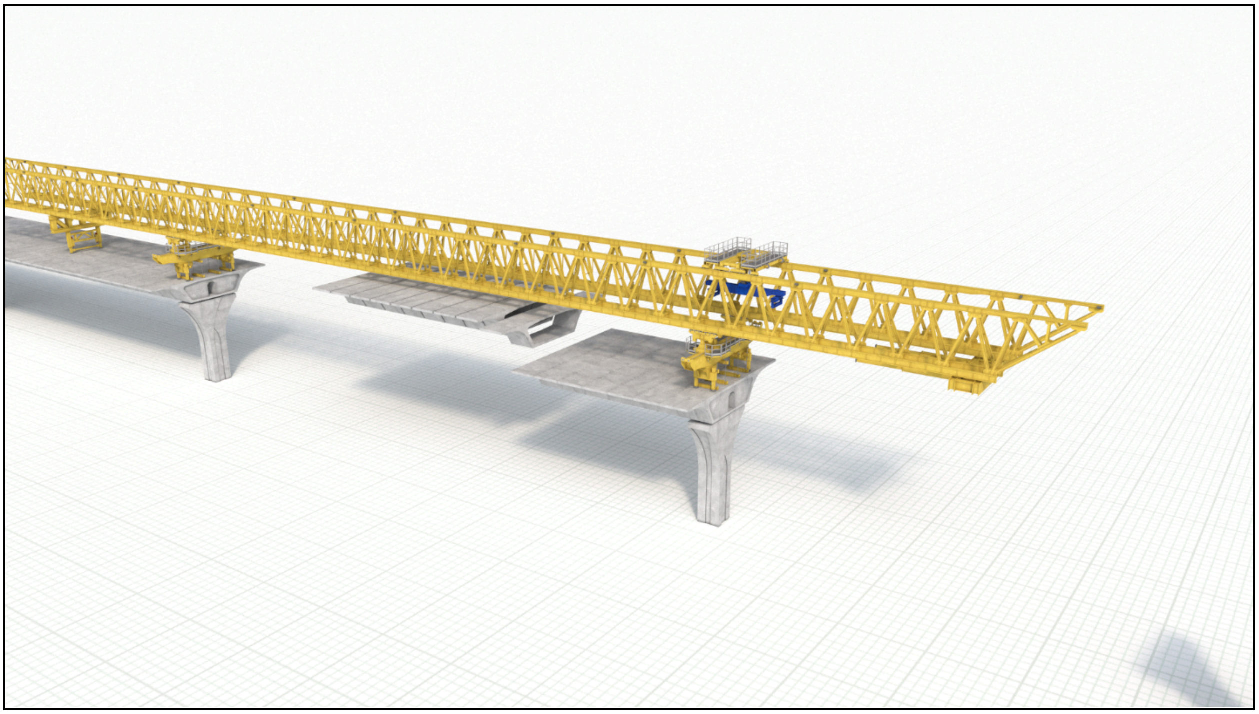


***Figure 10.17 – Span-by-Span Erection Using an Overhead Gantry (OHG)***

- Often efficient for light rail applications, where total span weights are relatively low; also successfully used on highway bridges.

- Good for erecting short spans and abutment spans if OHG is already on site for balanced cantilever spans.

- Access to pier locations must be provided for the foundation and substructure construction.

- Depending on OHG design, all major segment erection operations performed from the OHG and / or the constructed deck.

- Typically, more complicated and expensive than underslung trusses.

- Segments can be delivered from ground or water level or from behind OHG on the newly erected structure.

- To speed erection operations, segments can be stored under the OHG on the bridge alignment.

- Some OHGs are hinged (referred to as articulating gantries) to accommodate tighter radii.

- The use of an OHG typically provides a greater clearance envelop under the structure.

- Requires checking for overhead clearances such as overpasses and power lines.

- OHG generally self-contained and self-launching during relocation from pier to pier; may need assistance by a crane to relocate some of its supports

***Figure 10.18 – Span-by-Span Overhead Gantry Segment Erection, Honolulu Light Rail, HI***
***(Photo Courtesy of Traylor Bros., Inc.)***

***Figure 10.19 – Span-by-Span Articulating Gantry, Honolulu Light Rail, HI***
***(Photo Courtesy of Traylor Bros., Inc.)***

#### 10.4.2.1.4 Full Span Erection with Winches / Strand Jacks

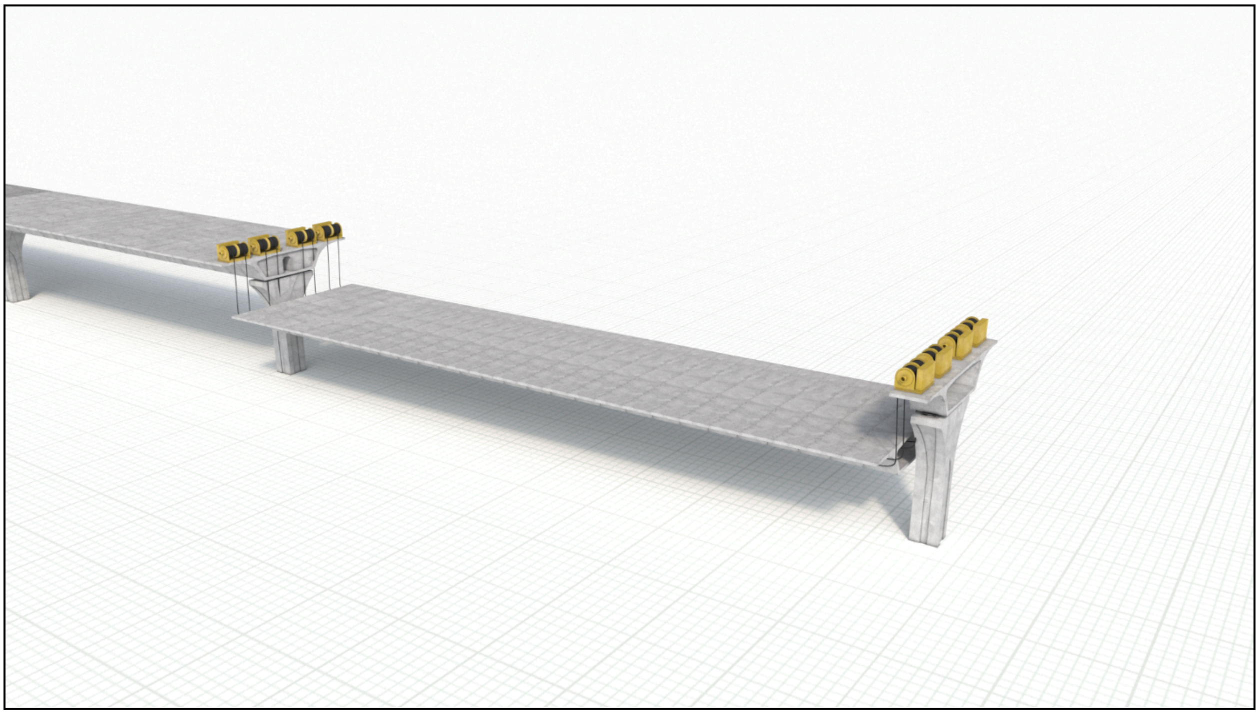


***Figure 10.20 – Full Span Overhead Erection with Winches***

- Access along the bridge alignment must be maintained throughout the superstructure construction phase and during the following operations:

– Foundations and Substructure Construction
– Casting or Assembly of Superstructure
– Winch Assembly, Installation, and Relocation
– Segment or Concrete Delivery
– Construction Equipment Access
– Material Delivery
– Support Operations

- Uncommon method.

- Superstructure segments either; precast and assembled on the ground under final positions; cast in place full span on the ground, under the final positions; or delivered on barges. Also requires the pier segments to be cast or erected prior to this operation for the setting of the winches.
- Requires additional temporary bottom slab post-tensioning to carry span self-weight during lifting.

#### 10.4.2.1.5 Full Span Carrier / Erector

*Figure 10.21 – Full Span Carrier / Erector*
*(Photo Courtesy of DEAL/Rizzani de Eccher USA)*

- Access to pier locations must be provided during foundation and substructure construction.

- Typically used on light rail projects, where the span weights are relatively low, but also applied to larger structures.

- Significant initial equipment investment in equipment dictates use on very large and repetitive projects where cost can be depreciated over many spans.

### 10.4.2.1.6 Full Span Erection on Shoring Falsework

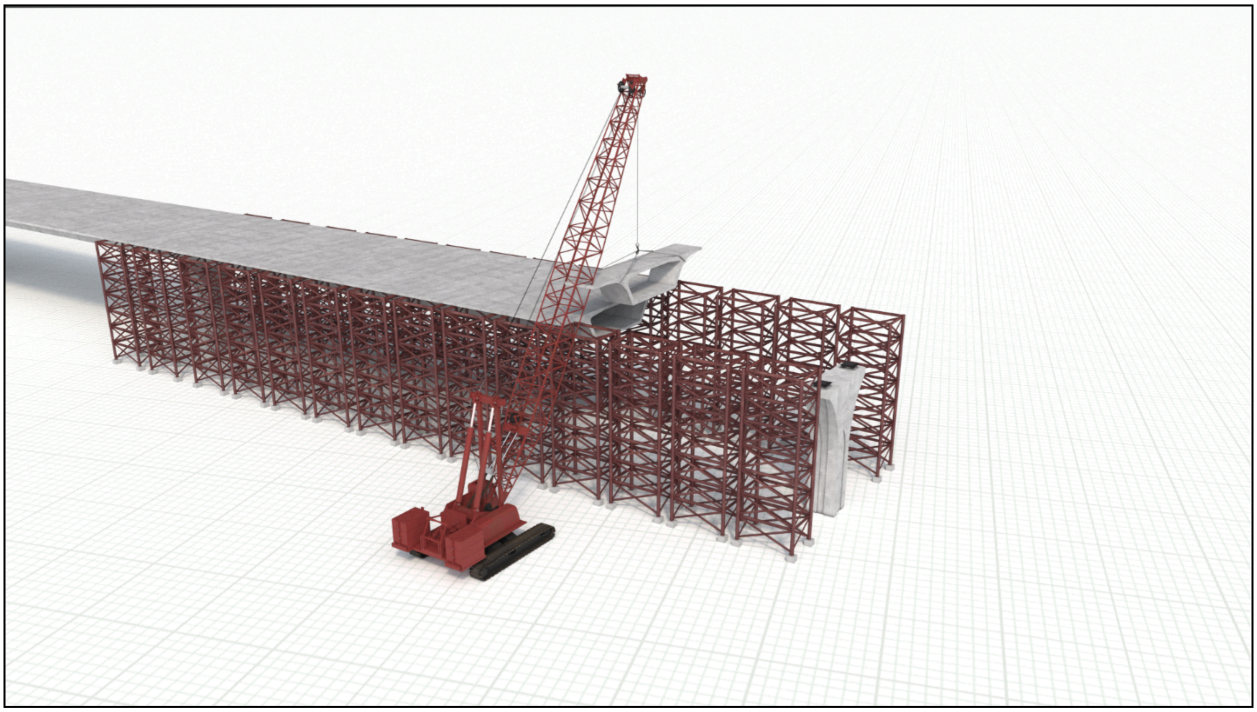


*Figure 10.22 – Full Span Erection on Shoring Falsework*

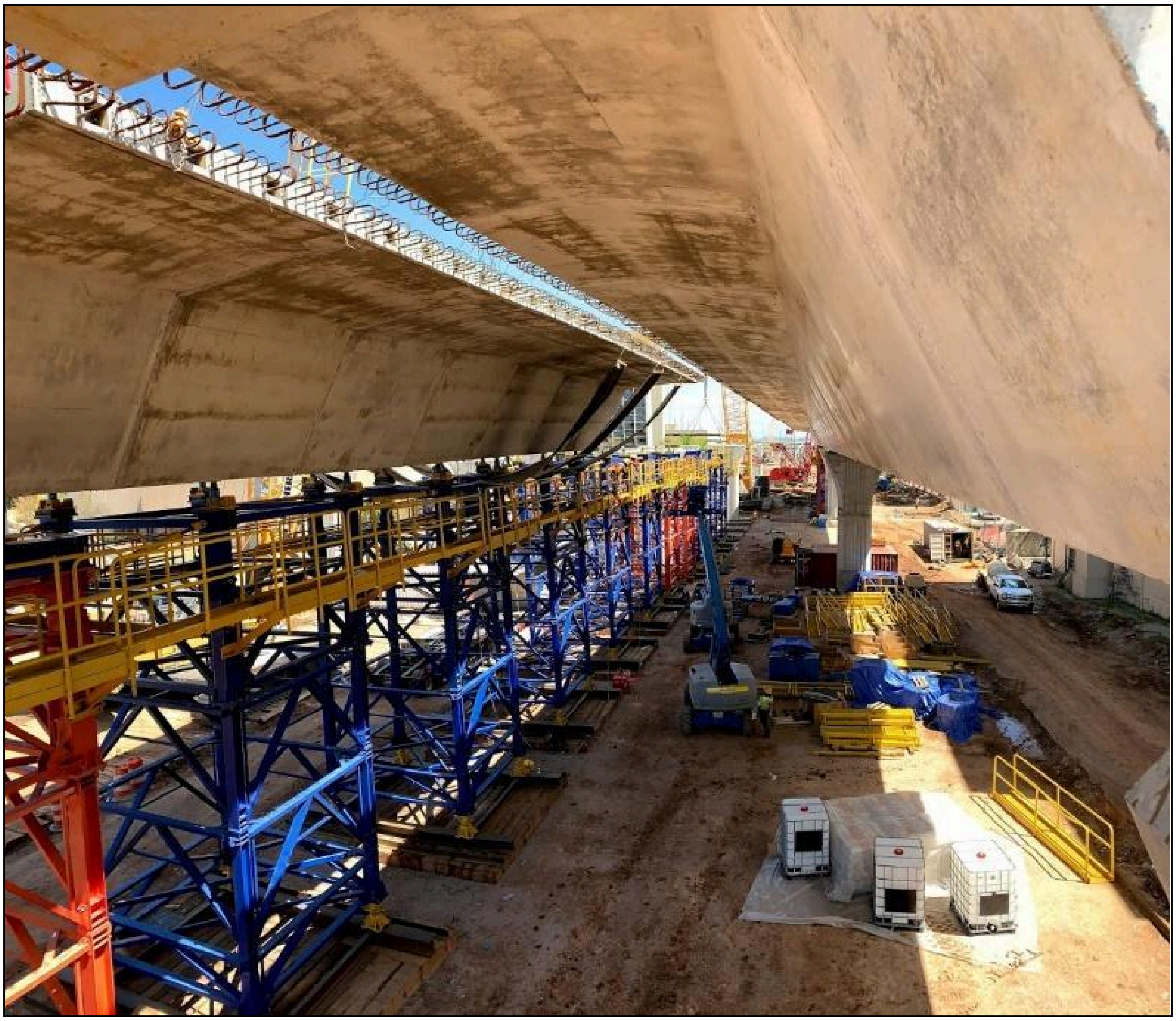


***Figure 10.23 – Full Span Erection on Shoring Falsework, I-59/I-20 Project, AL***
***(Photo Courtesy of McNary Bergeron & Johannesen)***

- Access along the bridge alignment must be maintained for the following operations:

- Foundations and Substructure Construction
- Shoring Assembly and Relocation
- Segment Delivery
- Erection Crane Access and Swing Radius
- Material Delivery
- Support Operations

- Can accommodate very tight radii.

- Use of commercially available scaffolding and cranes minimizes investment in specialized equipment, making it very competitive for small projects.

- Very labor intensive: ground preparation; construction of tower bases; erection, adjustment, and bracing of towers; installation of header beams; installation of jacks; dismantling system and relocating to next span.

- Slow relative to span-by-span erection on trusses or via gantry unless two or more sets of falsework are used.

- Feasible if MOT is not an issue; more complex falsework system is required over traffic or railroads.

### 10.4.2.2 Erection Methods for Balanced Cantilever Bridges

#### 10.4.2.2.1 Balanced Cantilever Erection by Crane on Ground or on Water

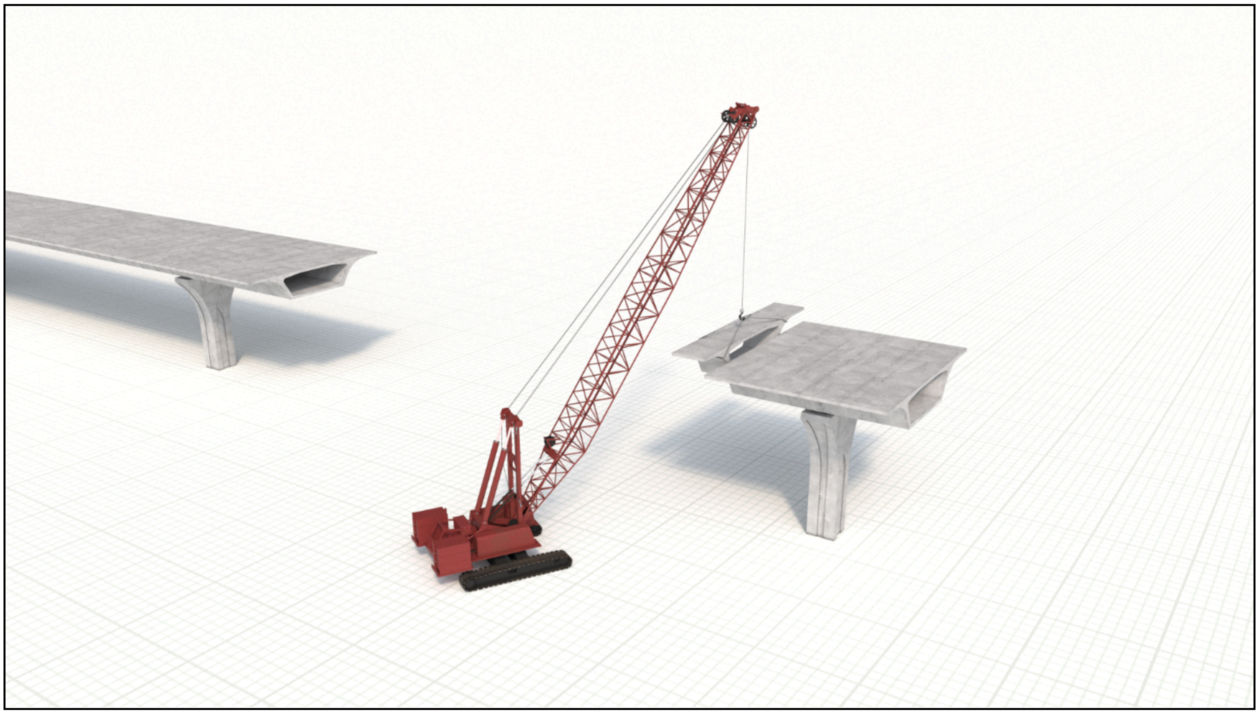


***Figure 10.24 – Balanced-Cantilever Erection by Crane***

- Requires access along the bridge alignment throughout the erection phase for the following operations:

– Foundations and Substructure Construction
– Pier Bracket Installation and Relocation
– Segment Delivery
– Erection Crane Access and Swing Radius
– Material Delivery
– Support Operations

May significantly increase cost of work over water due to need for trestle and /or barges and tugboat for access.

- Weather-dependent, especially if performed on the water.

- Requires special loading and unloading facilities for work over water.

- Governed by maintenance of traffic (MOT) rules and ground access conditions if working on land.

- Less efficient personnel, material delivery, and post-tensioning operations if working over water.

- Use of readily available cranes eliminates investment in specialized equipment; most economical solution for balanced cantilever erection with easy ground access. Cranes will experience more than usual track wear from walking back and forth and cutting into spans.

- Imposes the lightest construction loads on the superstructure.

- Can accommodate tight radii and steep grades.

- Crane should be sized to erect the pier segments based on heaviest segment.

- Requires extra attention to mid-span segments where crane can get boom-bound while erecting from the side of the bridge.

- With ground-based cranes, erection may proceed pier to pier without waiting for the closure pour and continuity post-tensioning activities.

- With multiple cranes, erection can proceed simultaneously on several headings.

- Unlike specialized erection gantries and trusses, the same cranes can support activities throughout the project – and, after completion, they can be readily used after on other projects.

*Figure 10.25 – Balanced-Cantilever Erection by Crane*
*(Photo Courtesy of Flatiron Constructors, Inc.)*

***Figure 10.26 – Balanced-Cantilever Erection by Barge-Mounted Crane***
***(Photo Courtesy of Flatiron Constructors, Inc.)***

#### 10.4.2.2.2 Balanced Cantilever Erection Using Overhead Gantries

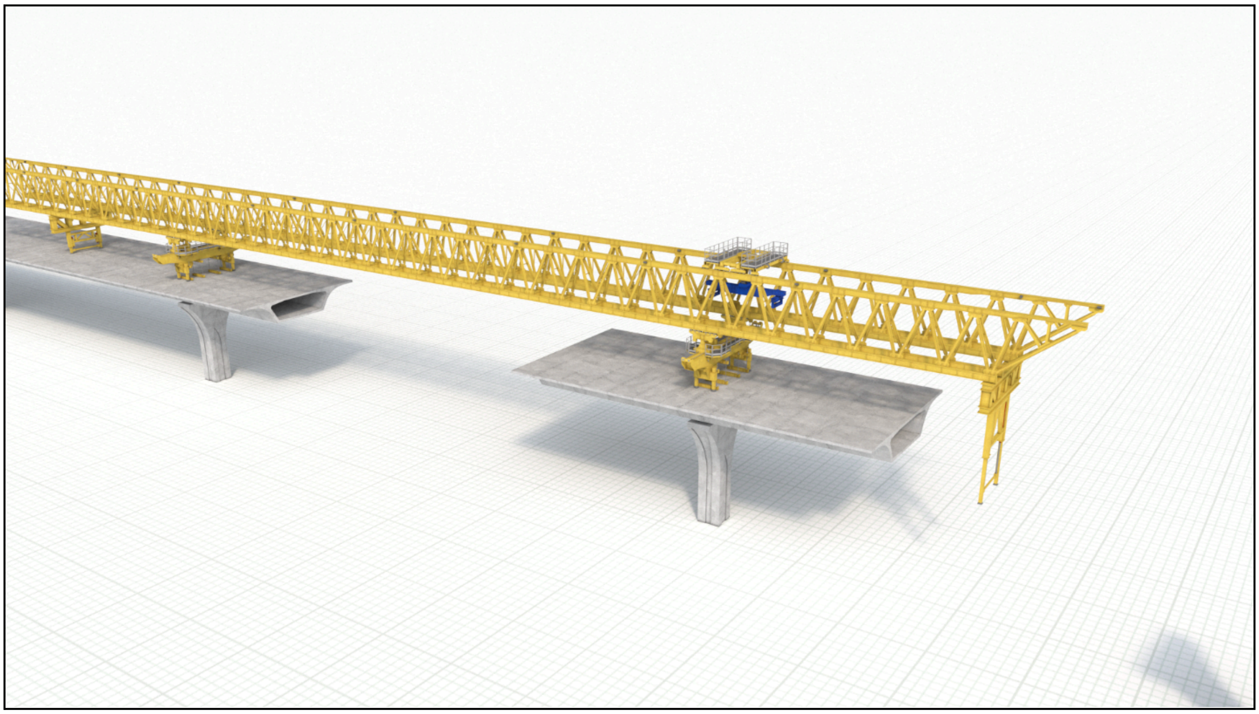


***Figure 10.27 – Balanced-Cantilever Erection Using an Overhead Gantry (OHG)***

- Requires access to pier locations for foundation and substructure construction.

- Depending on OHG design, all major segment erection operations performed from the OHG and/or the constructed deck, including:

– Personnel Access to Work Area
– Pier Bracket Erection
– Pier Segment Erection
– Installation of Post-Tensioning Platforms
– Overhead Service Cranes
– Material Delivery
– Pier Access
– Closure Pour Forming, Pouring, and Stripping Support
– Built-In Finishing Bridges

- Cost-benefit analysis needed to determine which options make economic sense.

- Very cost-effective when:

– Bridge is Long with Repetitive Spans
– Ground-Level Access is Restricted
– Existing Gantries are Available and Require Minimal Modifications

- Gantry reuse is feasible if designed properly with versatility for future projects in mind.

- Requires checking project alignment including assembly area for overhead obstructions such as power lines and overpasses.

- OHGs tend to be manufactured overseas, entailing additional time for shipping, customs, and trucking to the project site.

- Long lead-time on certain components means major spare parts should be ordered in advance and available on short notice.

- Best to identify local electricians, hydraulic mechanics, and suppliers of metric odds and ends early and involve them in commissioning.

- **Assembly and commissioning of custom-made OHGs typically take longer and cost more than anticipated**.

- Depending on project layout and construction sequences, may involve relocating OHGs from one alignment to another using one of four common methods:

– Dismantling, Trucking, Reassembling, and Re-Commissioning OHG
– Self-Launching OHG Back and Repositioning in the New Alignment
– Reconfiguring OHG for Reverse Operations and Re-Commissioning
– Loading Entire OHG on Special Transporters to Move It

*Figure 10.28 – Balanced-Cantilever Erection by Overhead Gantry*
*(Photo Courtesy of Perini/Homsi)*

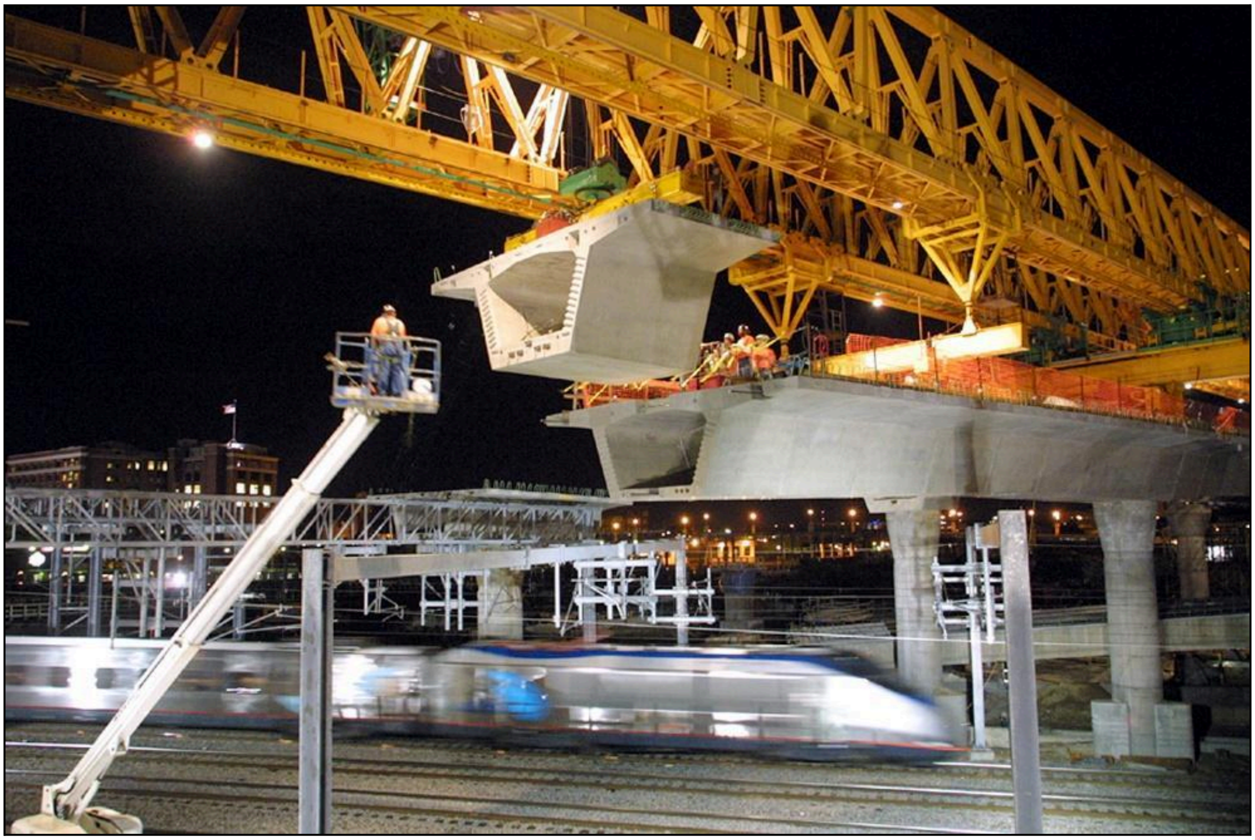


***Figure 10.29 – Balanced-Cantilever Erection by Overhead Gantry***
***(Photo Courtesy of Flatiron Constructors, Inc.)***

#### 10.4.2.2.3 Balanced Cantilever Erection with Beam-and-Winch / Strand Jacks

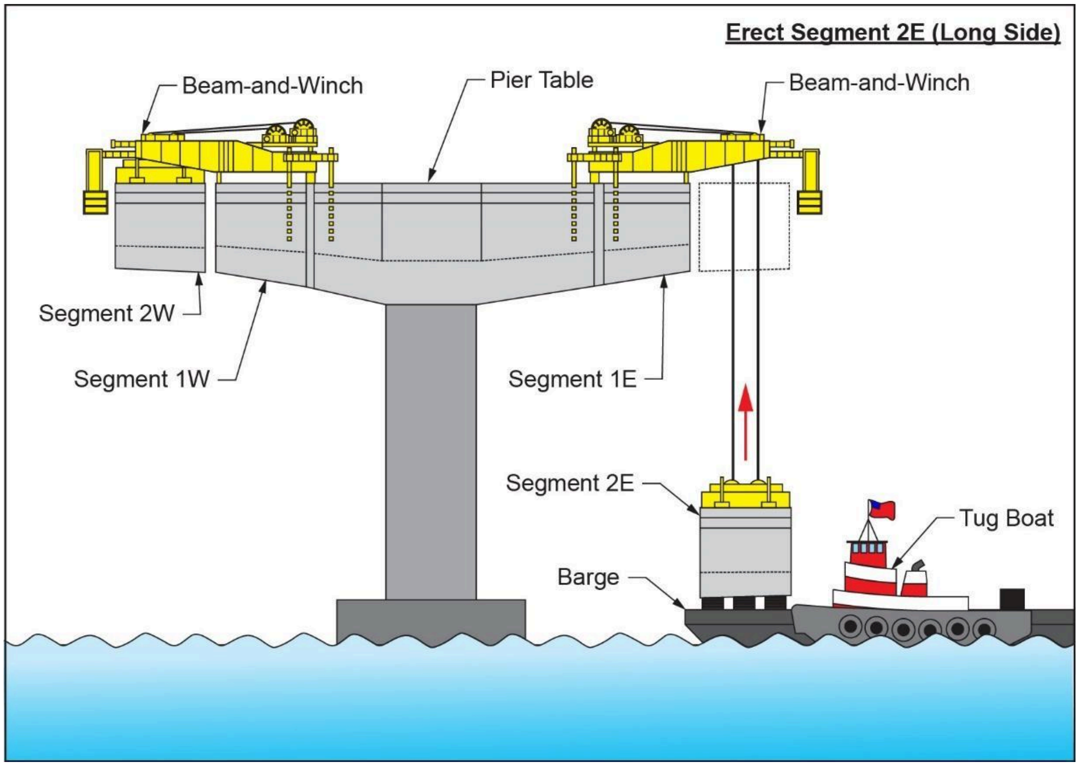


*Figure 10.30 – Balanced-Cantilever Erection Using Beam-and-Winch (Graphic Courtesy of Flatiron Constructors, Inc. / Kiewit)*

- Access along bridge alignment must be maintained for the following operations and throughout the erection phase:

– Foundation and Substructure Construction
– Segment Delivery
– Material Delivery
– Support Operations

- Requires each segment be delivered right under its final position, adding cost if segments are over shallow water or land obstructions.

- Very dependent on weather and water conditions for spans over water.

- Requires special loading and unloading facilities for transferring segments onto and off barges.

- Personnel, material delivery and post-tensioning operations are less efficient than with an overhead gantry.
- Using winch-and-beam, erection can proceed pier to pier without waiting for closure pour and continuity post-tensioning.

- With increased number of winch-and-beam setups, allows erection to proceed simultaneously on several headings.

- Typical winch-and-beam assembly can weigh as much as a segment, requiring a large crane for relocation from pier to pier.

- Capable of lifting very heavy segments very high; may be more economical than equivalent crane or OHG.

- Separate operation needed to erect precast pier segments or falsework for a cast-in-place pier table.

- Superstructure must be checked for ability to handle erection loads caused by equipment.

- Project schedule may be impacted by equipment design and fabrication lead times, as well as commissioning duration.

***Figure 10.31 – Balanced-Cantilever Erection using Beam-and-Winch, San Francisco-Oakland Skyway, CA (Photo Courtesy of Kiewit/Flatiron/Manson Joint Venture)***

### 10.4.2.2.4 Balanced Cantilever Erection Requiring Specialized Erectors

Unique site conditions may require special erection equipment to be developed, designed, and fabricated. If so, a qualified designer must verify that the new equipment conforms to applicable U.S. codes. Since most special erection methods are prototypes, longer fabrication, commissioning, debugging durations should be anticipated.

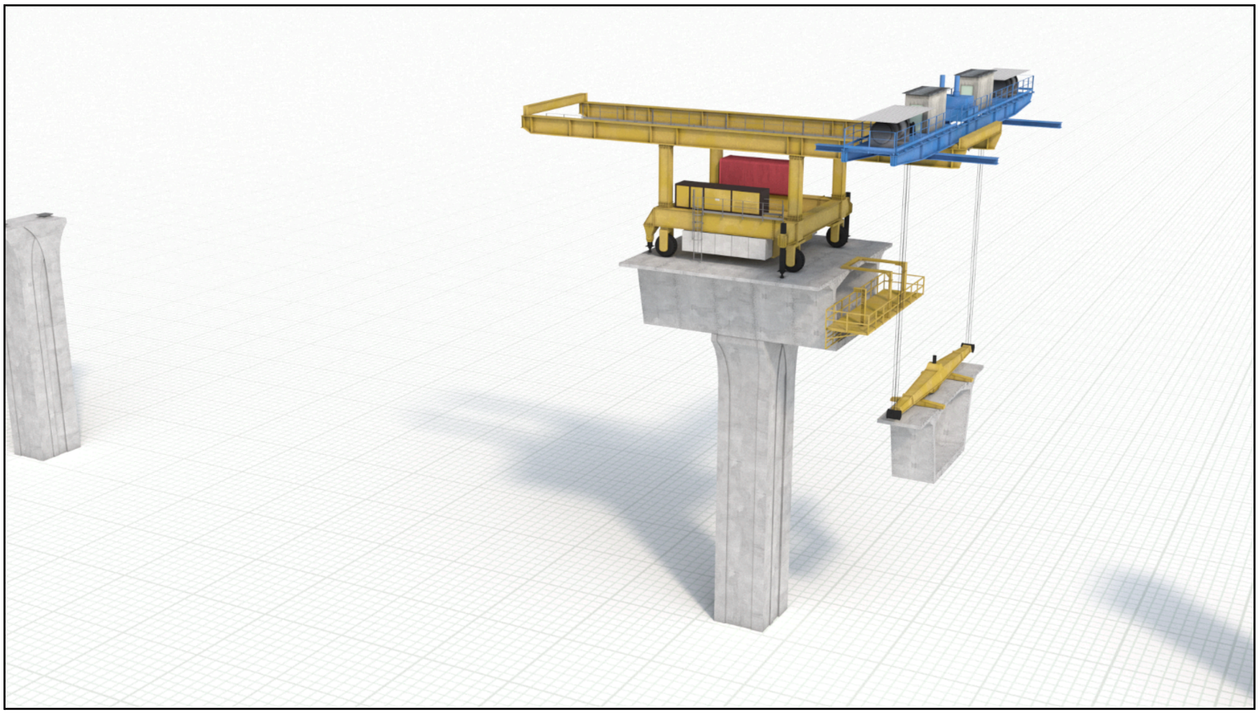


*Figure 10.32 – Specialized Erector*

***Figure 10.33 – Specialized Erector in Use, Dallas High Five Interchange Project, TX***
***(Photo Courtesy of DEAL/Rizzani de Eccher USA)***

## 10.5 Closing Remarks

Safety is always a priority on a construction site, furthermore, using specialized erection equipment requires a higher level of dedication and attention to details. Some of the items that require additional consideration include:

- A properly trained labor force.
- Thorough, clear checklists and procedures.
- Proper Quality assurance.
- Experienced site supervision and construction staff.
- Experienced construction engineer.
- Inspectors as a "second set of eyes."

The repetitive nature of segmental work can cause team members to become less focused, increasing the risk of an accident through carelessness. Cross training of the staff, rotating the duties, frequent refresher training sessions, active communication protocol are some of the steps that can be implemented to prevent this type of accident.

Numerous erection methods are available. The optimal method for the project should be selected based on the project specific conditions including:
Design
Schedule
Construction Sequence
Equipment Availability

Contractor Experience

Specialized equipment, means and methods, and temporary structures should be designed to U.S. standards and in conformance with OSHA.

Design-Build projects, and Design-Bid-Build projects which allow redesign or value engineering to suit the contractor needs and expertise, lead to optimization, creativity and more competitive bidding.

# TABLE OF CONTENTS

# Chapter 11:
# Post-Tensioning Details and Procedure

## 11.1 Permanent Post-Tensioning

Permanent post-tensioning tendons are installed and stressed as erection of segments proceeds. Both internal and external tendons may be used. External tendons, located in the interior space of the box girder inside a polyethylene sheathing, are attached to the structure at the pier diaphragms and at deviation blocks. Internal tendons, located in ducts inside the concrete slabs and webs, are commonly used in balanced cantilever erection.

In addition to the information presented below, refer to **PTI/ASBI M50.3-12**, jointly published by the Post-Tensioning Institute and ASBI, for a comprehensive guide specification on grouted post-tensioning.

### Anchorage and Duct Installation

Most post-tensioning suppliers include multiplane anchors for longitudinal and transverse post-tensioning. These “special anchorages” come with spiral and other reinforcement. It is important to install all local and general zone reinforcement following the supplier’s shop drawings. The spiral should be tied and secured to the nearby reinforcement and aligned with respect to the tendon path. Ducts must be installed so that no kinking occurs along the length of the tendon path, with a waterproof connection to prevent concrete blockage inside the duct. Installation of an inlet and an outlet is required for grouting the tendons. Proper consolidation of concrete around the anchorage area is critical to transfer the post-tensioning force to the concrete structure.

### Stressing Operation and Safety

Because post-tensioning stressing operations create very high forces in the tendons and surrounding concrete, requiring precautions to be taken to prevent personal injury or damage to the structure. Prior to starting stressing operations, anchorages and surrounding concrete must be inspected. The work area should be cleared of debris to allow unobstructed movement of the stressing crew.

All operating and safety instructions for the stressing equipment should be thoroughly read and understood. Any safety stickers applied to the equipment should be intact, legible, and understood by the stressing crew.

A comprehensive discussion of safety issues related to stressing post-tensioning tendons is presented in **Section 11.5**.

### Calibration

All calibrations should be performed using specific service gauges and a master gauge. Gauges are often damaged on the job sites as a result of impact or shock, and often two service gauges do not last the typical six-month period between recalibrations. Recalibrating jacking systems is time-consuming and expensive, but avoidable if the service and master gauges are calibrated at a deadweight indicator to read true pressure. The deadweight indicator must be calibrated and traceable through the National Bureau of Standards. The contractor should seek the engineer’s approval to use deadweight-indicated gauges prior to starting operations so damaged gauges can be replaced without recalibrating the ram and gauges as a system.

### Grouting of Tendons

Soon after stressing is completed and the engineer gives approval to cut the stressing tail, all bonded tendons should be grouted with pre-packaged, non-shrink grout. A permanent plastic or stainless-steel grout cap should cover the wedge plate (strand tendons) or anchor nut (bar tendons). A mockup test may be required, depending on the complexity of the tendon profile and as directed by the engineer of record.

### Temporary Tendon Corrosion Protection

Temporary corrosion protection is required for tendons left un-grouted for extended periods due to cold weather or other circumstances using vapor phase corrosion inhibitor (VPCI) powder conforming to the U.S. Department of Defense (DOD) Specification MIL-P-3420F-87 or as otherwise directed by the engineer. If VPCI powder is applied, air circulation should be kept to a minimum.

## 11.2 Temporary Post-Tensioning

With most forms of precast segmental construction, temporary post-tensioning is used to secure the erected segment(s) before the main longitudinal post-tensioning is installed (**Figure 11.1**), for the following reasons:

(a) To provide a rapid means of transferring the weight of the segment from the lifting equipment to the structure within the allowable setting time ("open time") of the epoxy jointing material

(b) To allow application of an even stress over the whole joint face to "bed down" the epoxy and let it set under uniform conditions -- Between 30-50 psi average compression is normally applied. If compression is significantly non-uniform from top to bottom, especially in cantilever construction, epoxy joint thickness may vary, which, after several segments, can affect alignment.

(c) To control a temporary stress condition in the structure -- In this case, the bars can be removed only after construction has reached a stage at which the stress condition no longer exists. If this is necessary due to a design feature, the amount of temporary post-tensioning and sequence of installation and removal will be shown on the contract plans. If the stress arises specifically from the contractor's elected method of operation, equipment, construction loads, or sequence of erection, then the temporary post-tensioning should be designed by the contractor and approved by the engineer within the shop drawing process. In any event, the sequence of installation, stressing, and removal should be clearly shown on the shop drawings and / or erection manual.

Temporary post-tensioning bars may either be overlapped so that individual or coupled bars extend only a few segments, or they may be continuously coupled throughout a cantilever or span. With continuous coupling, the possible cumulative effect of bar extension and concrete shortening should be evaluated, as the point of coupling can "drift" significantly and eat into tolerances of the space within the block-outs (**Figures 11.2** and **11.3**).

The stress in temporary post-tensioning bars is typically limited to 50 percent of the breaking strength of the bars. This typically allows up to 20 re-uses of the bars and the anchors. Bars stressed more than 60 percent of the guaranteed ultimate tensile strength (GUTS) should not be re-used without express permission from the post-tensioning bar manufacturer. Visual inspection of all bars prior to re-use is required; if there is any doubt, they should not be re-used. Internal threads of nuts and couplers of reused systems should also be checked before stressing. If bars are permanent or cannot be removed for re-use, it is acceptable to stress them up to 70 percent of the GUTS.

When using couplers with post-tensioning bars, the couplers must be properly engaged on each bar before stressing. Bars being coupled should be marked at one-half the coupler length from the end of each bar and engaged to the mark prior to stressing. Insufficient engagement may result in failure of the connection during or after stressing and may cause damage to property or injury to personnel.

In cantilever construction, the temporary bars are normally needed only for the last two or three segments of the cantilever, as permanent tendons are installed for most segments. Occasionally, continuously coupled bars cannot be retrieved after closure has been made at the mid-span. In this case, the temporary post-tensioning should be planned so that most of the bars can be recovered before adding the last cantilever segment. Maximum re-use is desirable since temporary bars, and particularly their anchors and couplers, are expensive.

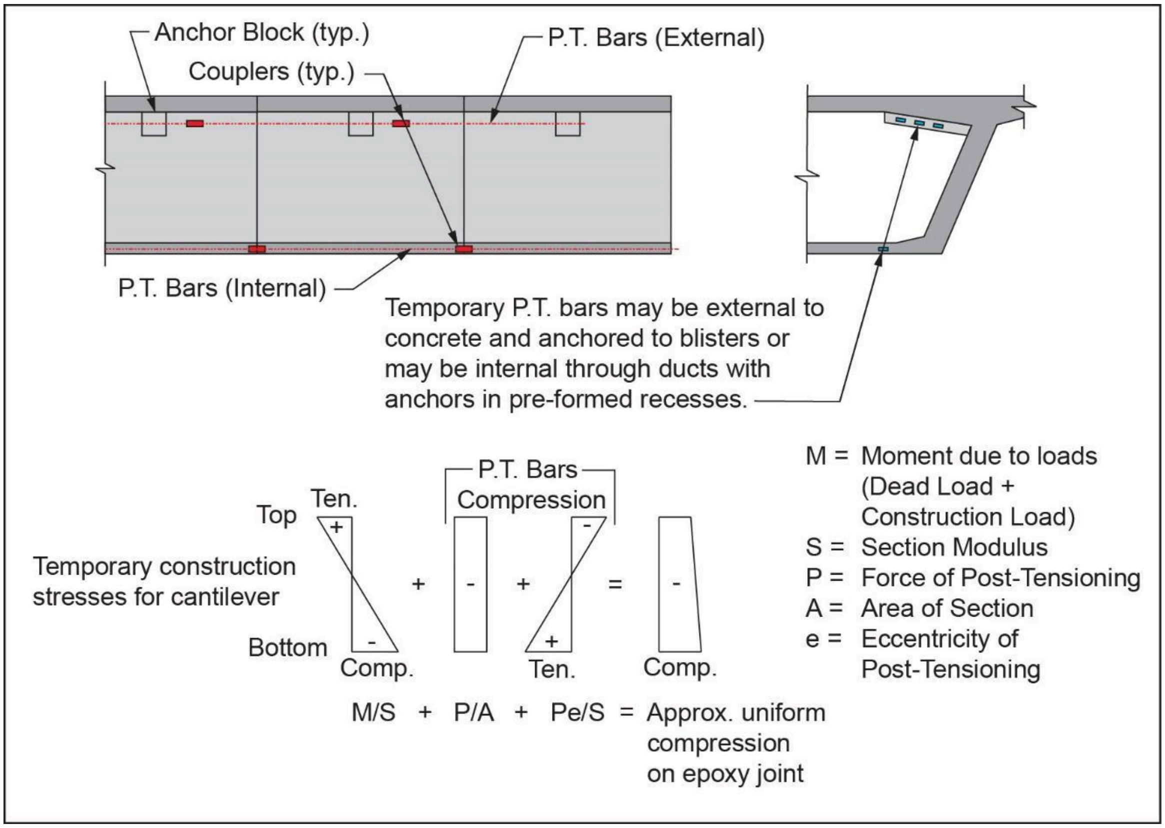


*Figure 11.1 – Use of Temporary Post-Tensioning for Erection*

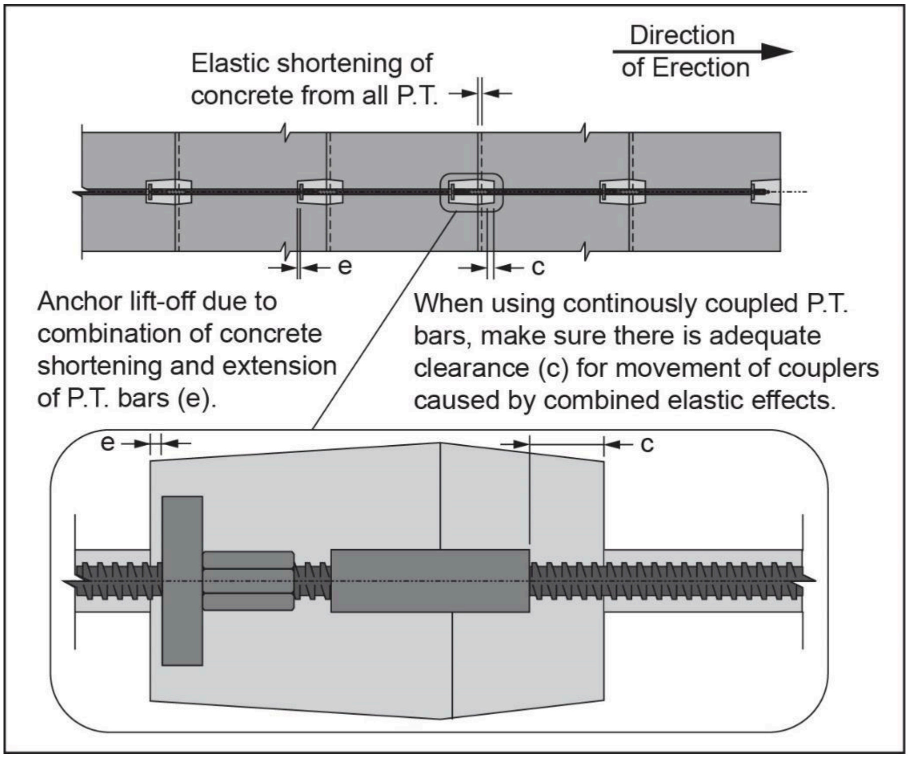


*Figure 11.2 – Use of Continuously Coupled Post-Tensioning Bars*

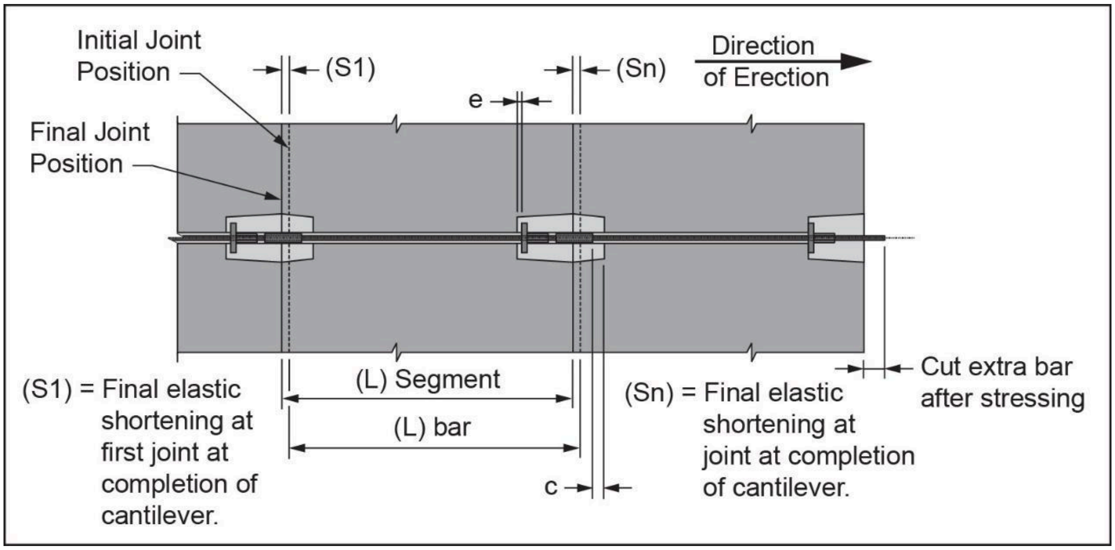


*Figure 11.3 – Coupled Post-Tensioning Bars*

If continuously coupled post-tensioning bars are used, the following should be noted:

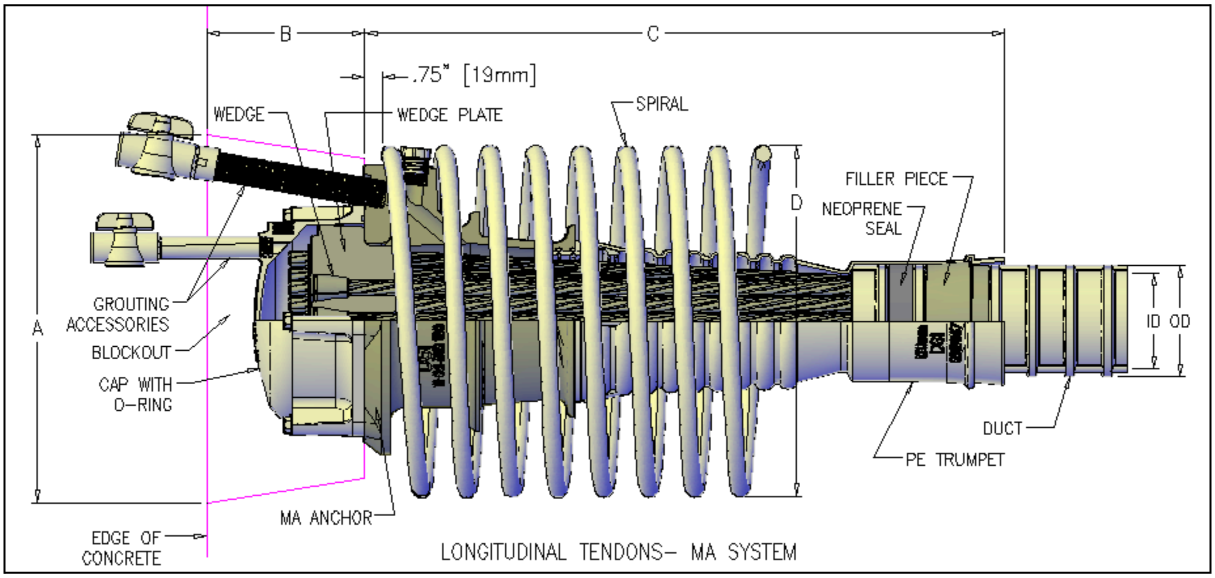
**1.** Each bar extends a small amount (typically 3/8-in. to 1/2-in. per 10 ft segment). If the position of the coupler is critical, bars should be ordered short of a segment length by this amount.

**2.** Particularly in a cantilever, the cumulative effect of adding segments and post-tensioning tendons is an increase in shortening of the earlier segments (S). This can be significant and make the point of coupling in later segments drift in the direction of erection, eating into any tolerance (C). To avoid or minimize loss of tolerance, bars should be ordered to a length shorter than segment length by (S=S1/2).

Variation in segment lengths should be planned for by providing ample tolerance.

## 11.3 Post-Tensioning Systems

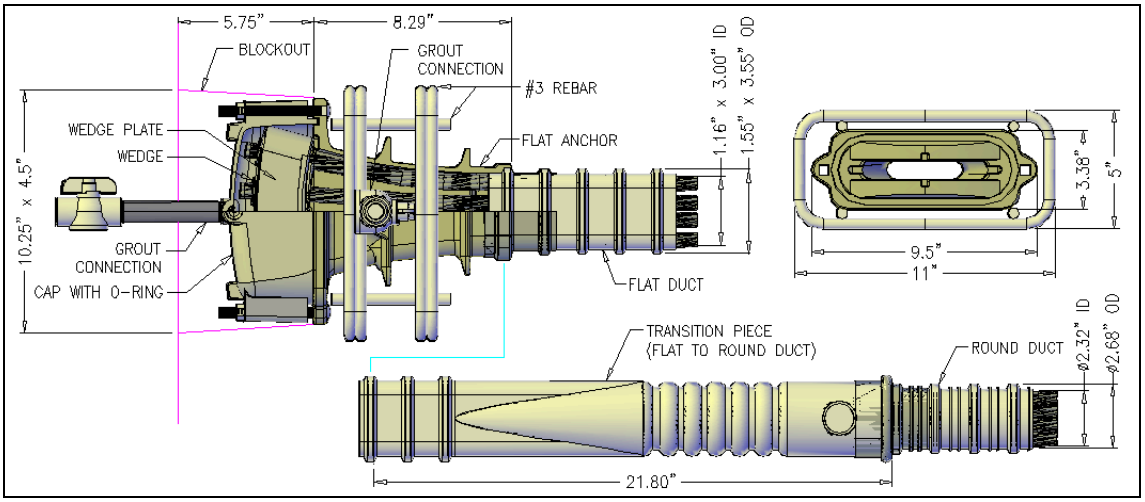
Post-tensioning systems may be used for longitudinal, transverse, or vertical tendons. Both strand and high-strength bar systems exist and, as illustrated by the examples below, each supplier's system is unique. The supplier should be contacted for detailed information pertaining to their system. A list of post-tensioning suppliers follows in **Section 11.4**.



| **Multiplane Anchorage MA**<br>Tendon Size using 0.6" & 0.5" Strands | | **5-0.6"**<br>**7-0.5"** | **7-0.6"**<br>**9-0.5"** | **9-0.6"**<br>**12-0.5"** | **12-0.6"**<br>**15-0.5"** | **15-0.6"**<br>**20-0.5"** | **19-0.6"**<br>**27-0.5"** | **27-0.6"**<br>**37-0.5"** | **31-0.6"** | **37-0.6"** |
|---|---|---|---|---|---|---|---|---|---|---|
| | | **(in)** | **(in)** | **(in)** | **(in)** | **(in)** | **(in)** | **(in)** | **(in)** | **(in)** |
| Block-out (Minimum) | A | 7.50 | 12.00 | 12.50 | 13.50 | 15.00 | 15.00 | 17.00 | 17.00 | 21.00 |
| | B | 5.00 | 6.00 | 6.00 | 6.00 | 6.50 | 6.50 | 7.00 | 8.50 | 9.00 |
| Transition Length | C | 15.75 | 18.01 | 18.10 | 24.15 | 28.15 | 26.18 | 28.97 | 18.00 | 38.31 |
| Rebar Spiral | D | 8.25 | 11.25 | 9.50 | 12.88 | 12.50 | 14.50 | 17.00 | 19.00 | 22.00 |
| Plastic Corrugated Duct | ID | 1.89 | 2.32 | 2.99 | 3.35 | 3.94 | 3.94 | 4.53 | 5.04 | 5.04 |
| | OD | 2.32 | 2.87 | 3.58 | 3.95 | 4.57 | 4.57 | 5.30 | 5.96 | 5.96 |
| Anchor Location | c/c spacing | 9.50 | 12.50 | 10.50 | 14.00 | 13.50 | 15.50 | 18.00 | 20.00 | 23.00 |
| | Min. Edge Dist. | 6.25 | 7.75 | 7.00 | 8.50 | 8.50 | 9.50 | 11.50 | 13.25 | 14.50 |

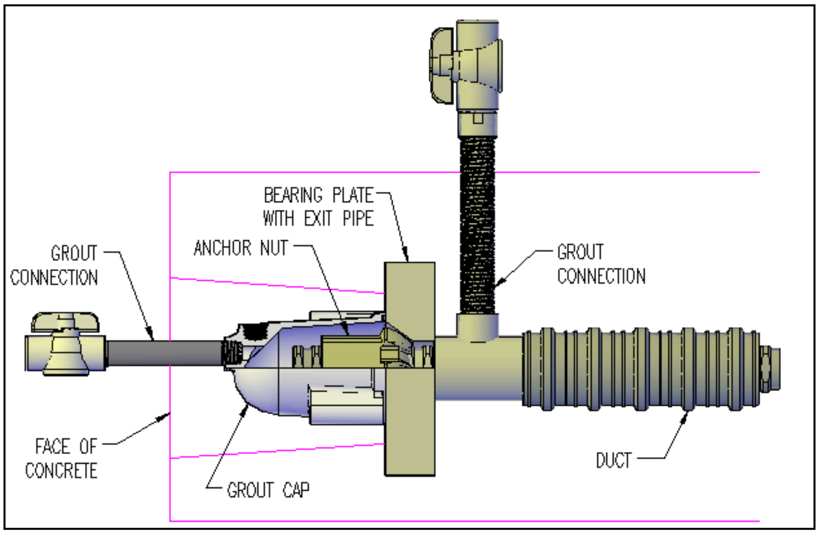
Note: Metal Spiro Ducts are available for all sizes.

***Figure 11. 4 – Longitudinal Post-Tensioning System***
***(Courtesy of DYWIDAG Systems International)***



***Transverse Tendons- FA System (3-06 & 4-06 Strands)***

***Figure 11.5 – Transverse Post-Tensioning System (Courtesy of DYWIDAG Systems International)***



| List of 150 ksi THREADBARS® | 1" | 1-1/4" | 1-3/8" | 1-3/4" | 2-1/2" | 3" |
|---|---|---|---|---|---|---|
| Hot Rolled=HR; Cold Rolled=CR | HR | HR | HR | HR | CR | CR |
| Square Bearing Plate (in.) | 5x5x1.25 | 7x6x1.5 | 7.5x7x1.75 | 9x9x2 | 14x12x2.5 | 15x15x3 |
| Rectangular Bearing Plate (in.) | 6.5x4x1.25 | 8x5x1.5 | 9.5x5x1.75 | – | -- | -- |
| Plastic Corrugated Duct ID (in.) | 2.32 | 2.32 | 2.32 | 2.99 | 3.35 | 3.94 |
| Plastic Corrugated Duct OD (in.) | 2.87 | 2.87 | 2.87 | 3.58 | 3.95 | 4.57 |
| Bar Diameter, Max. (in.) | 1.20 | 1.44 | 1.63 | 2.01 | 2.79 | 3.15 |
| Ultimate Load (kips) | 128 | 188 | 237 | 400 | 774 | 1027 |

Note: Metal Spiro Ducts are available for all sizes.

***Figure 11.6 – THREADBAR® Post-Tensioning System***
***(Courtesy of DYWIDAG Systems International)***

## 11.4 Post-Tensioning Supplier List

A list of Post-Tensioning suppliers can be found on the ASBI website.

## 11.5 Post-Tensioning Safety Issues

### 11.5.1 Introduction

A 0.6-in. diameter strand is stressed to a force of 23 tons, the equivalent of a truckload of steel. Such a force can be dangerous to jack operators or nearby personnel if proper precautions are not taken. Post-tensioning work should only be performed by people with expertise in this field and operators trained under direct supervision of competent PTI-certified instructors. If all potential hazards are understood and carefully considered, and preventive measures taken, work-related injuries can be prevented. The various safety issues involved in handling and stressing post-tensioning tendons are outlined below.

WARNING

Read all safety and operating instructions and warnings before starting any work or operation. **NEVER** stand or allow anyone to stand directly behind, above or below a jack when stressing operations are under way.

### 11.5.2 Safely Handling Post-Tensioning Materials

1. When cutting the steel bands that bind the tendon coils, it is important to remember the coils are under pressure and will want to uncoil like a spring when the bands are released. Strand coils (packs) must always be contained in a proper dispensing unit before cutting the bands. Extreme care must be taken in pulling the loose strand end out of the pack center, as the spring force induced from coiling tends to push the strand out of the pack.

2. Care should be taken in handling tendons; the cut ends of the strands or bars can be extremely sharp and should be deburred.

3. To prevent sparks or hot slag from touching any portion of the strand or bar, which will be under stress, no welding or burning should be performed near post-tensioning materials.

4. No part of strand or bar should be used as a ground connection for welding.

5. Instead of cutting the stressed strand or bar with a torch, an abrasive saw, shear, or plasma cutter should be used.

6. Temporary post-tensioning bars stressed to more than 60 percent of GUTS should never be reused. All bars intended for re-use should be visually inspected and rejected if there is any doubt. The internal threads of nuts and couplers should be checked before stressing. In nearly all cases, re-use is limited to 20 times.

7. Personnel should not stand directly behind stressing operations as any strand failures may result in the strands harpooning out of the jack.

### 11.5.3 Stressing Jack Calibration Requirements

All stressing must have correct and current calibrations, and gauges should be independently calibrated. Generally, specifications require that the jack and the gauge be calibrated as a unit. They cannot be interchanged. The gauge should be labeled and correspond to the jack. Most specifications require use of a master gauge to verify accuracy of the service gauge. In some cases, use of a master gage is allowed in lieu of recalibrating the jack and gauges as a unit. Gauges are typically stored in impact-resistant lock boxes to keep them clean and safe between jacking operations. Boxes should be labeled and stored properly on-site.

### 11.5.4 Jack Use Checklist

1. The jack should be visually inspected for signs of oil leakage or damage.

2. All safety instructions and stickers should be read and understood; any stickers that are not intact must be replaced prior to using the jack.

3. The jack must be free-cycled for operation and all air purged from the jack or seals may be damaged.

4. The pulling head may get twisted during shipping or handling. All internal parts must be properly aligned and any deviations are corrected. The jack cannot be installed unless all tubes are in line. (If a center-hole ram is used, this step is unnecessary.)

5. Jacks arrive with reusable pulling wedges in good condition. The equipment supplier should be consulted about planned and scheduled changes, replacements, or maintenance.

### 11.5.5 Jack Safety Instructions

1. All relevant OSHA standards should be followed regarding, e.g., use of protective clothing and devices, grounding of electrical equipment, control of work area, etc.

2. All system components must be in good working condition prior to use and inspected daily for signs of wear or damage. Jacks should not be used if grippers are worn excessively, hoses are cracked, pressure gauge is inoperable, or other defects are observed.

3. After inspection, a system test should be run (following operating instructions) to ensure all components are in proper working order.
4. The jack must be in the fully closed position when moving from tendon to tendon. While moving the jack, the pump should never be activated.

5. Proper lifting equipment for the jack must be available prior to starting operations. A lifting harness must be used. Never use hydraulic lines for moving or adjusting equipment.

6. Equipment servicing beyond what is described in the operating instructions should be referred to qualified supplier’s service personnel.

7. Proper and complete connection of the hydraulic lines is vital to safe operation. Improper or incomplete coupling of hydraulic hoses may cause injury or death to personnel, or severe damage to equipment. Occasionally checks are needed to verify that the quick couplers are closed.

### 11.5.6 Jack Maintenance Requirements

All equipment should be properly maintained and equipped with manufacturer-recommended safety devices. Disabling or removing safety devices is dangerous and should be avoided. All unsafe or inoperable equipment should be marked as such to prevent further use of the equipment.

### 11.5.7 Installing Stressing Jack

1. To ensure all strands are in the correct holes, the pattern plate should be installed on the tendon, slid to the anchor head while the outer strands are secured, and then slid back. Misalignment of strands will cause damage to both jack and tendon during stressing.

2. The alignment of the anchor head hole pattern (**Figure 11.7**) should be checked against that of the jack. Alignment of the second stressing end should also be verified.

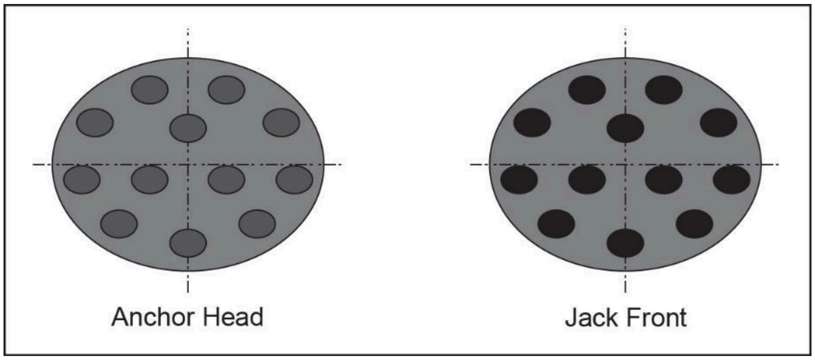


*Figure 11.7 – Anchor Head Hole Pattern*

3. A dead-end keeper plate may be installed, potentially eliminating the need to watch the dead-end during stressing and keeping the anchor plate wedges and strands tight.

4. The jack piston must stay in the full return position, with the automatic stressing head tube protruding and the wedges remaining open. Once this is verified, the jack may be lifted, its axis aligned with the tendons (see **Figure 11.8**) and slid over the strands to the anchor head. Jack support must contact the wedge plate surface before stressing begins.

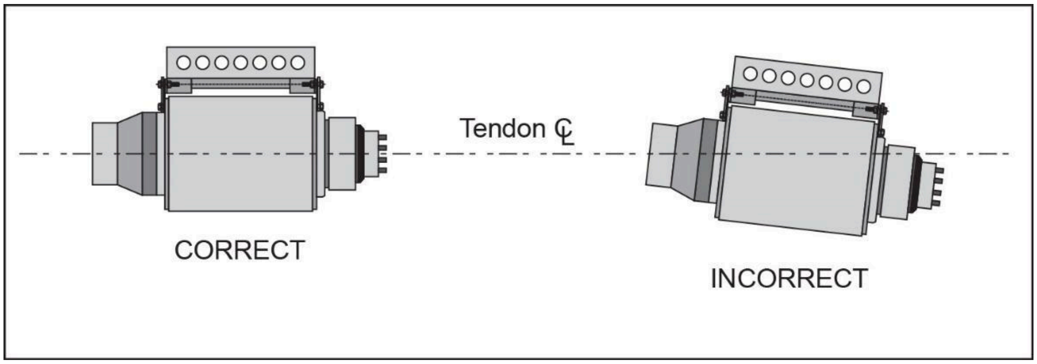


*Figure 11.8 – Jack Alignment with Tendon*

### 11.5.8 Secure Stressing Area

1. Appropriate warning signs should be clearly displayed in the stressing area.
A warning signal (i.e., a horn) must be used to alert personnel that stressing operations are active.

2. Anyone not involved should keep clear and follow any safety instructions from competent operators. Safety rails or barricades should be installed to prevent other personnel from entering.

### 11.5.9 Communications

It is extremely important to establish proper communication among the stressing crew, especially when simultaneous stressing operations take place. Proper communication devices (e.g., radios) should be provided for crew communication.

### 11.5.10 Access with Stressing Jacks Within the Box Girder

Detailing for the segmental box girder should include access dimensions and accommodate access for stressing jacks.

Adequate and safe access to the work area is vital.

### 11.5.11 Precautions in Stressing Operations

1. Before operating any jack, all safety and operation instructions should be thoroughly reviewed and understood.

2. Stressing operations must be under direct control of a superintendent experienced in such operations.

3. Operators must wear proper personal protective equipment (hard hats, safety glasses, steel-toed shoes, gloves, long sleeves, etc.) while operating equipment.

4. The stressing unit should be securely tethered to the structure at all times. In the event a tendon breaks during stressing, this prevents the unit from falling.

5. Operating personnel must keep their feet from becoming entangled in the hydraulic hoses while stressing.

6. Cleaning the wedge cavity is critical. Cement paste or other debris can prevent the wedges from seating and the strand to slip back.

7. When re-stressing a de-tensioned tendon, a new set of wedges should be used. Old wedges should always be discarded.

8. No one should be allowed to stand behind, directly above, or below the jack when stressing operations are underway.

9. All personnel should stay clear of any un-grouted stressed tendons.

### 11.5.12 Chain Falls to Hold Jack on Stands or on Stressing Platform

When stressing tendons on an elevated deck, both the pump and the jack must be tied off.

*Figure 11.9 – Support of Stressing Ram*
*(Photo Courtesy of DYWIDAG Systems International)*

### 11.5.13 Stay Clear of the Jack

The forces at the fixed-end anchorage as nearly as high as at the stressing-end. All personnel should stay clear of the jack.

*Figure 11.10 – Stressing Personnel Located Away from the Stressing Ram*
*(Photo Courtesy of DYWIDAG Systems International)*

### 11.5.14 Overstressing the Tendon

The estimated jacking pressure should never be exceeded. Inspectors should review all pre-determined jacking gauge pressures and associated strand elongations prior to beginning work. In the event a gauge fails mid-stressing operation, the elongation at a given pressure may help the engineer determine the need for restressing. Also, elongation calculations and gauge pressures are calculated well and if one is achieved prior to the other, the engineer should be notified before additional stressing occurs.

### 11.5.15 Fall Hazard

The number one cause of construction-related injuries and fatalities are falls from height. In areas with unprotected sides, where individuals can fall six (6) ft. or more, all personnel must wear safety harnesses and connect to lanyards with a deceleration device. Personnel should be tied off in this manner 100 percent of the time they are subject to a fall hazard.

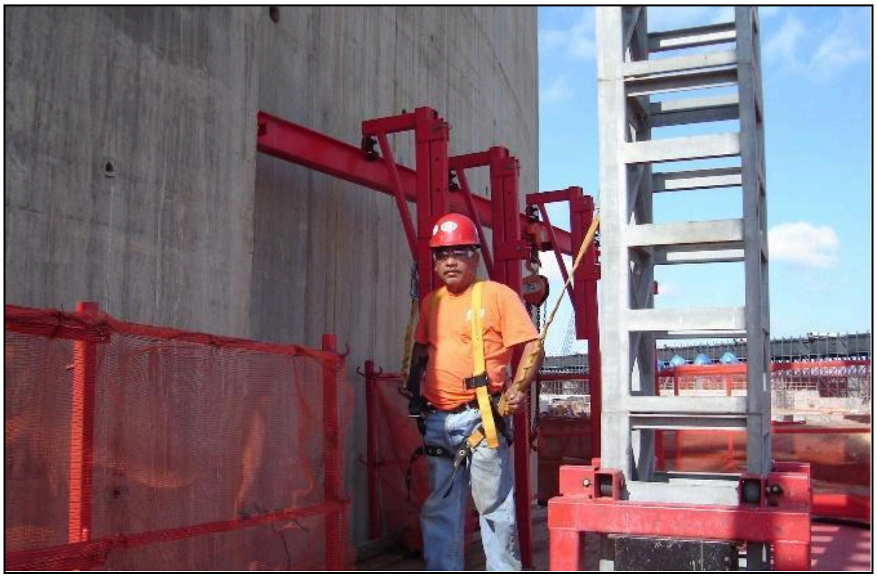


***Figure 11.11 – Safety Harness for Stressing Personnel***
***(Photo Courtesy of DYWIDAG Systems International)***

### 11.5.16 Coupling High-Strength Bars

Extra precautions must be taken in coupling the high-strength bars. Bar ends should be marked at half of the coupler length, as shown below in **Figure 11.12,** and the ends of the bars engaged in the coupler up to the mark. If enough of the thread is not engaged, the bar will fail when stressed. The bar supplier generally provides instructions about the minimum engagement needed.

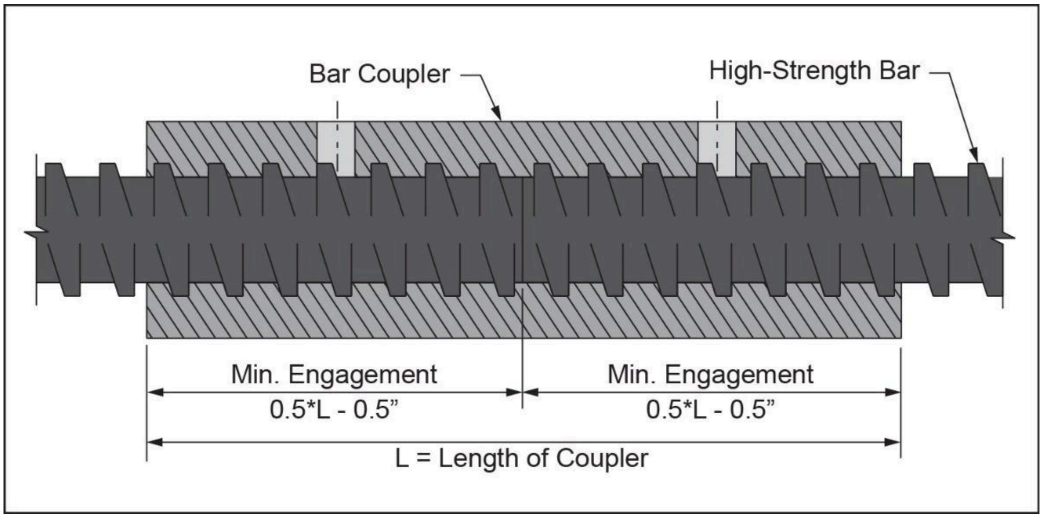


*Figure 11.12 – Coupling of High-Strength Bars*

# TABLE OF CONTENTS

# Chapter 12:
# Epoxy Jointing, Duct Coupler Devices, and Prepackaged Grout

## 12.1 Purposes of Epoxy

The purposes of using an epoxy resin in the joint between the segments are:

- To maintain the structural integrity of the joint and maintain a monolithic concrete segment.
- To completely fill any minor surface imperfections and irregularities between the match cast surfaces.
- To provide a water and grout tight seal, preventing chloride intrusion.
- To act as a lubricant when erecting the segments.
- To ensure a tight fit between the segments so that the compressive and shear stresses are transmitted directly across the joint.

## 12.2 Types and Application of Epoxy

Epoxies are formulated as two-part compounds consisting of a resin and hardener. When mixed together, they begin curing which can take anywhere from a few minutes to a few hours, depending on the formulation, the ambient and storage temperatures, and the mass of the epoxy. The cure time will be shorter when epoxies are mixed in higher temperature conditions and in larger masses. For some applications, such as in span-by-span erection, it is desirable to have a long pot life to allow for the erection and stressing of a complete span, which may take several hours.

***Figure 12.1 – Mixing Segmental Bridge Epoxy***
***(Photos of Courtesy of FIGG)***

Segmental bridge epoxies are specially formulated as either normal or slow setting resins. For segment-by-segment erection, the normal set epoxies are typically used and for span-by-span erection, the slow set epoxies are typically used. In addition, they are formulated for use in different temperature ranges, from 20°F to 115°F. It is important to use the correct pot life and correct temperature range to ensure adequate working time and proper strength gain of the epoxy.

Prior to application, the joint surfaces must be clean and sound. They may be dry or damp, but free of standing water or frost. It is important to remove dust, laitance, grease, oils, curing compounds, and any other contaminants before applying epoxy. Hydraulic oil can leak from stressing operations and must be removed by scrubbing with soap and water. Solvents can leave residues.

Mixing of the epoxy is typically done in the pails. The pre-proportioned units allow for all of Part A (base resin) to be mixed with all of Part B (hardener). The units should never be batched down on site. The epoxy should be mixed per the manufacturer's recommendations or a minimum of 3 minutes with a low-speed (400-600 rpm) rotary drill fitted with an appropriate mixing paddle. The sides of the pail should be scraped down during mixing to ensure there are no streaks of unmixed epoxy in the container. When fully mixed a uniform gray color should be achieved while having a high viscosity similar to peanut butter. Thin epoxy may sag out the joint, not providing the intended water tightness.

Application of the mixed epoxy is typically done by hand, using protective clothing and disposable rubber gloves as shown in **Figure 12.2**. Since the available working time of the epoxy may be short, sufficient labor should be utilized to coat the joint well within the open time specified by the epoxy manufacturer. Epoxy is applied to both faces of the segments to a thickness of approximately 1/16 in. on each face to sufficiently lubricate the segments and prevent potential joint leakage in the finished structure. The epoxy should be applied approximately 1 in. clear of any tendon ducts to guard against excess epoxy intrusion into the duct and approximately ½ in. shy of the outside edges. Specific application requirements are included within the manufacturer’s specifications and project documents.

***Figure 12.2 – Applying Epoxy onto Face of Segments***
***(Photo Courtesy of FIGG)***

Once the adjoining segments are aligned, a post-tensioning force is applied using bars to squeeze the epoxy. For span-by-span construction, this post-tensioning force is generally temporary in nature comparison to cantilever construction where the post-tensioning becomes a part of the final structure. The post-tensioning force shall be adequate to restore the as-cast joint geometry, achieve a uniform epoxy thickness, and in a specific sequence to minimize differential stresses through the joint.

When the segments are brought together and stressed, excess epoxy is squeezed out as shown in **Figure 12.3**. For joints over traffic, procedures must be implemented to avoid dropping epoxy on cars equipment and into the environment by using diapers, as shown in **Figure 12.4**, or other means. Once the segments have been joined and stressed, all excess epoxy should be cleaned from the concrete. Hardened epoxy is more difficult to remove if allowed to remain. It is essential to swab all the ducts before the epoxy cures to ensure any epoxy which entered the duct does not create an obstruction for the tendons. The use of segmental duct coupler devices simplifies the placement of the epoxy and ensures the squeezed epoxy will not enter the duct when the segments are stressed together.

***Figure 12.3 – Epoxy Squeeze Out After Application of Post-Tensioning Force***
***(Photo Courtesy of RS&H)***

*Figure 12.4 – Using an Epoxy Jointing Diaper*
*(Photo Courtesy of FIGG)*

When bridge piers columns are constructed using pre-cast concrete boxes, epoxy should also be used between the segments for the same reasons described above. The epoxy is applied in a horizontal and overhead orientation, rather than in a vertical orientation as on the spans.

## 12.3 Post-Tensioning Duct Types and Application

Post-tensioning ducts serve to both fully enclose the prestressing steel stand and provide a conduit for the strand. Post-tensioning tendons are comprised of multiple prestressing strands within each duct. Ducts are sized larger than the tendon to create additional space for the injection of grout into the tendon. Post-tensioning tendons can either be external or internal to the concrete.

Internal tendons are those tendons which are fully encapsulated by the duct and concrete. Examples of internal tendons are top slab cantilever tendons, as seen in **Figure 12.5** and bottom slab continuity tendons. Internal tendon ducts are typically corrugated polypropylene or polyethylene plastic and designed specifically for use with a given post-tensioning system provider. Because the tendons are protected by the surrounding concrete, the thickness of the corrugated plastic duct is less than that of an external tendon duct. The reduction of duct thickness provides the flexibility needed to properly obtain the vertical and horizontal tendon deviations required by the project documents. In non-aggressive environments the use of galvanized corrugated metal ducts is sometimes permitted for use in lieu of plastic. Internal ducts for tendons greater than four strands are round with diameters ranging from 2 in. to 5 in. Four strand tendons, generally installed transversely in the top or bottom slabs of segments, commonly utilize an oval or "flat" duct. Guidance on the requirements for internal post-tensioning ducts are provided in PTI/ASBI M50 Guide Specification on Grouted Post-Tensioning.

External tendons are those tendons which are external to the concrete and installed within the interior of a concrete box girder as seen in **Figure 12.6**. External post-tensioning ducts consist primarily of smooth, high-density polyethylene (HDPE) pipe. These ducts typically have a greater wall thickness than ducts used for internal post-tensioning tendons. Sections of HDPE ducts can be joined by heat-welding, ethylene propylene diene monomer (EPDM) sleeves with stainless steel bands or electrofusion couplers. At areas of deviation, the HDPE pipes are either connected to pre-bent steel pipes placed in the concrete or passed through bell shaped voids created by void-formers called diabolos. The specifications for external post-tensioning HDPE duct are also provided in PTI/ASBI M50 Guide Specification on Grouted Post-Tensioning.

*Figure 12.5 – Top Slab Internal Tendon Ducts*

*Figure 12.6 – External Post-Tensioning Tendons*

*(Photos Courtesy of FIGG)*

Galvanized rigid steel pipes are also used in combination with internal corrugated plastic duct and external smooth HDPE duct. Steel pipes may be used for internal tendons along areas with tight bending radii or for external tendons locally in areas of deviation such as pier segments and deviators. The steel pipes are pre-bent in a fabrication shop using the specifications provided in the project documents for a given tendon profile. Proper installation of the pipe is important to avoid kinks within the tendon.

## 12.4 Precast Segmental Duct Coupler Devices

Precast segmental duct couplers have been introduced in conjunction with the industry's overall effort to extend the lifespan of segmental bridges. Coupler assemblies ensure water and air tightness of the tendon duct across the segment-to-segment interface and prevents grout from crossing over into nearby adjacent ducts. Current post-tensioning suppliers use either specifically designed compressible gaskets in conjunction with mating hubs or positive connection mechanisms which extend across the segment joint to achieve the required seal. Segmental duct couplers should not be confused from other slip-on style couplers typically used to lengthen ducts or couple ducts extending through cast-in-place closure joints.

Specific details should be considered when designing for and selecting a precast duct coupler device. Because the coupler device is typically 1 in. larger in diameter than the duct to which it connects to, consideration must be given to the tendon layout to ensure adequate clear space is provided between the duct coupler assemblies to allow proper concrete consolidation and reinforcing steel placement within the coupler zone. Additionally, the coupler shall have the ability to accommodate the angle where ducts pass the joint at a skew angle. Current specifications limit the skew angle to 6 degrees for duct coupling devices. Further specification requirements can be found in PTI/ASBI M50 Guide Specification on Grouted Post-Tensioning.

## 12.5 Purpose for Grouting Post-Tensioning Tendons

The cement grout injected into a post-tensioning duct is vital for the defense against corrosion of the prestressing steel strand. The steel strands are susceptible to corrosion damage because of the high post-tensioning stresses and the small wire diameter. If the prestressing steel corrodes, danger of potential future tendon failure can occur. As seen in **Figure 12.7**, a grouted post-tensioning tendon provides multiple layers of corrosion protection to the prestressing steel. Protective measures include surface treatment of the concrete, the concrete itself or the interior of the box girder, the duct, the grout, and in some instances, strand or bar coating such as epoxy or galvanizing.

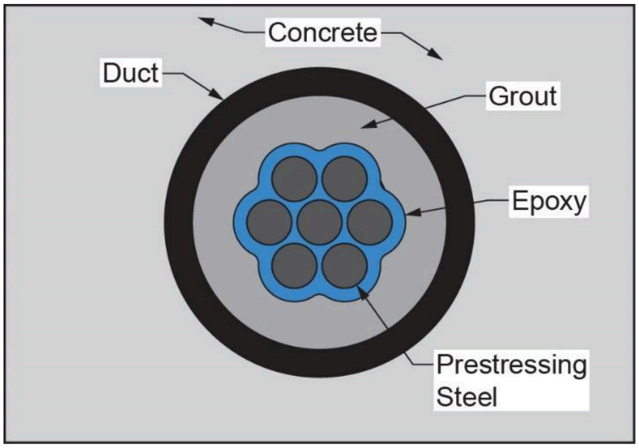


*Figure 12.7 – Multilevel Corrosion Protection for Grouted Post-Tensioning Tendons*

The cementitious grout provides corrosion protection by passivating the steel strands using the high alkalinity inherent to hydrated cement. Complete filling of the ducts with a non-bleed grout ensures damage due to freezing and expansion of trapped water/moisture within the tendon and the external concrete does not occur. This can only be consistently achieved with the use of prepackaged grouts formulated to have zero bleed. The low permeable nature of prepackaged grout ensures corrosive chemicals such as deicing chlorides do not penetrate the enclosed prestressing steel. Chloride ions destroy the passivating iron-oxide layer on the steel surface therefore exacerbating steel corrosion. In addition, carbon dioxide from the atmosphere, if allowed to penetrate through the cement grout, can reduce the grout pH leading to a loss of passivity, and ultimately, corrosion. Therefore, it is important that the prepackaged grout have a low permeability. Discussion of prepackaged grouts can be found in **Section 12.6**.

## 12.6 Prepackaged Grout

Prepackaged cementitious grouts were developed to increase quality control reliability compared to the variability seen with site blended grouts and to eliminate bleed water voids. Prior to the implementation of prepackaged grouts, site blended grouts would often have bleed water within the ducts once the grouting was complete resulting from a lack of quality control. The bleed water would migrate and accumulate towards the upper end of the duct and subsequently either absorb into the grout matrix leaving a soft, overhydrated and non-protective grout or leave a column of water near the anchorage. Once the bleed water evaporated, large voids were created within the tendon duct making the tendon more vulnerable to chemical attack and corrosion. In addition, other deleterious chemicals, admixed with the grout, could migrate with the bleed water and accelerate strand corrosion. For these reasons, site blended grouts are not recommended for use on segmental bridges. Prepackaged grouts are recommended for use on **all** segmental bridge projects and shall be in accordance with Class C grout requirements provided in the current PTI M55 Specifications for the Grouting of Post- Tensioning.

The use of approved, quality prepackaged cement grouts, employment of certified personnel experienced with grouting of post-tensioning, and the implementation of a strict grouting operations plan including quality control testing is paramount to ensure a correct and successful grouting operation is achieved. Specifics on personnel certification, grout mixing equipment, grouting operation plan requirements, quality control testing of prepackaged and mixed grouts, and other operational requirements can be found in the current PTI M55 Specifications for Grouting of Post-Tensioning. Furthermore, for segmental bridge construction, post-tensioning systems must complete testing required by ASBI/PTI M50 to ensure constructible, robust systems are used while meeting, at minimum, Protection Level 2 (PL2) requirements.

Even when prepackaged grouts are used, it is necessary to inspect all anchorage zones and high-point grout vents to detect the presence of bleed water and voids within 24 to 48 hours after grouting. Without proper post-grout inspection protocols, severe corrosion may go undetected potentially leading to future tendon failure. Specific details to facilitate post-grout inspection should be provided by both the project documents and post-tensioning supplier. Post-grout inspections are performed using borescopes as shown in **Figure 12.8**. All post-grout inspection observations should be fully documented and continue until the inspection agency is assured the chosen grout material and grout methods will provide a properly grouted tendon without voids or bleed water accumulation. If specified by project documents, a reduced frequency for post-grouting inspection may be implemented after a required number of tendons are verified to have no voids. It is recommended, at minimum, to inspect 50 percent of the tendons per span. Any change to the procedures and materials defined within the approved grouting operations is cause for the return of increased post-grout inspection frequency. Voids discovered during post-grout inspections must be repaired using a submitted and approved procedure. Void repairs are preferably performed using volumetric (vacuum) grouting methods with trained personnel experienced in vacuum grouting equipment and procedures. An example of a fully grouted tendon is shown in **Figure 12.9**.

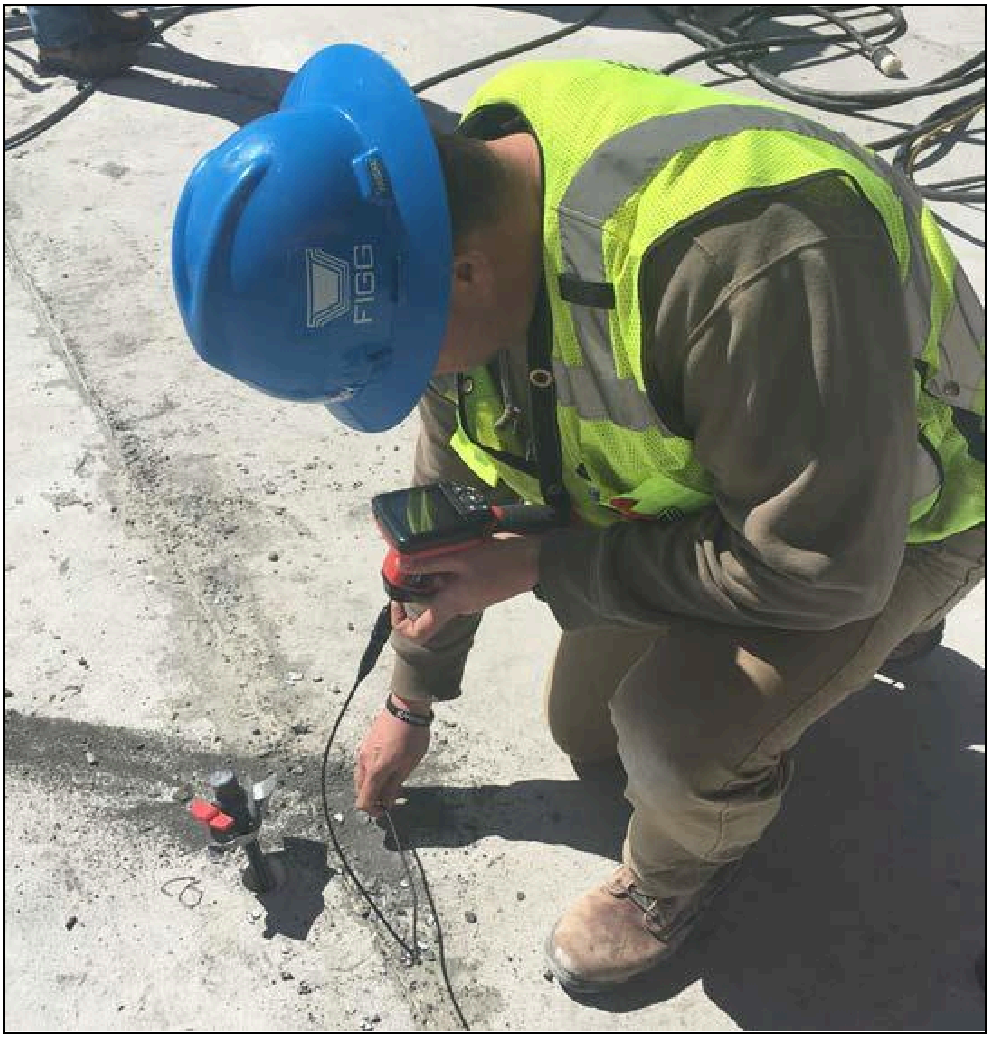


***Figure 12.8 – Post-Grout Inspection Using Borescope***
***(Photo Courtesy of FIGG)***

***Figure 12.9 – Completely Filled Duct with Prepackaged Grout***
***(Photo Courtesy of FIGG)***

## 12.7 Prepackaged Epoxy Grouts for Anchorage Protection

Prepackaged epoxy grouts are designed to provide an additional layer of protection to anchorages of post-tensioned tendons on segmental bridges. Although all post-tensioned anchorages are encapsulated with grout-filled caps, some locations require additional protection based on environmental conditions and exposure potential. Anchorage zone pourbacks are to be provided at locations identified within the contract documents and in accordance with PTI/ASBI M50 specifications. Epoxy grout pourbacks are generally constructed for each individual tendon anchorage, as seen in **Figure 12.10**, or combined to encapsulate multiple anchorages in locations such as expansion joints.

***Figure 12.10 – Epoxy Grout Pourbacks for Anchorage Protection***
***(Photo Courtesy of FIGG)***

Prepackaged epoxy grouts offer the following benefits:

- Pre-measured kits (no mixing errors).
- High bond strength.
- Non-shrink.
- Low exotherm.
- Impermeable to moisture, chlorides and chemicals.
- Resistant to impact, vibration and stress.

## TABLE OF CONTENTS

# Chapter 13:
# Geometry Control

## 13.1 General

Geometry control of precast segmental bridges is achieved in the casting yard. The short-line system of casting, where each segment is cast next to the previous one in an adjustable machine, is based on making very fine adjustments to each match-cast segment in the casting cell. The long-line casting system, on the other hand, erects formwork on the ground in the shape of the soffit, and uses a traveling form that moves along the soffit form to cast each segment. The long-line method, as well as some other erection methods such as cast-in-place cantilever, achieve geometry control mainly when building or positioning the soffit forms. This chapter concentrates on the short-line system, since it is more commonly used, although many of the principles discussed apply to the others.

Precise geometry control has nothing to do with the size, thickness variations, or tolerances of the component pieces of the segments, although these are important to the overall quality of the finished product. Instead, precision in geometry control depends on exactly measuring the as-cast position of the new segment relative to its match-cast neighbor.

The casting yard setup is shown below in **Figure 13.1**. Note that the segment being cast in the forms is the "west cast" segment, also referenced as the "new" segment. The segment previously cast and cast against is the "match-cast" segment or "old" segment. Alignment is controlled by an instrument on a permanent base and a permanent target. Neither instrument nor target should be disturbed, or control must be re-established. Adequate benchmarks should be maintained in case that need arises.

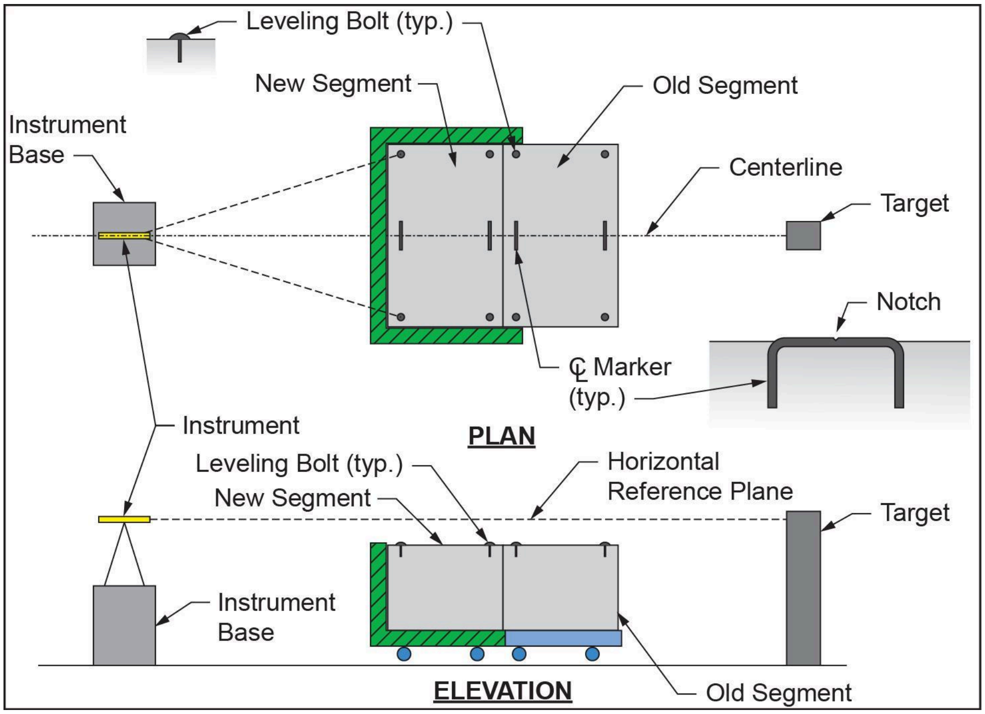


*Figure 13.1 – Alignment Control Setup*

The casting cell must be plumb, level, and is usually square so that geometry control is established mainly by positioning the old segment as prescribed by the casting curve and as shown in **Figure 13.2** below.

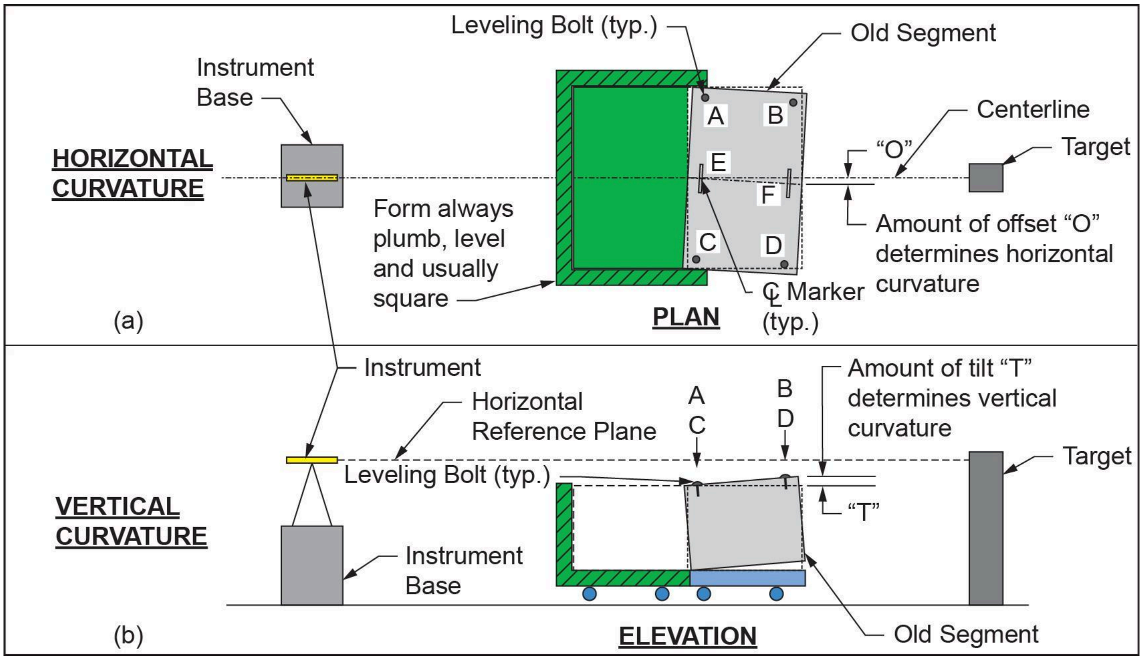


*Figure 13.2 – Alignment Control Setup (continued)*

As the first segment is cast and the top slab finished, four (4) elevation bolts (A, B, C, and D) typically positioned over the webs, as well as two centerline markers (E and F), are installed. The following morning, when the concrete has achieved the required strength, the elevations of the tops of the bolts are recorded and the centerline is scribed onto the markers. At that point, the segment is rolled forward for match casting.

After the first segment is moved to the match casting position, alignment control setup is reset based on the instructions provided by the casting curve. The centerline remains unchanged, unless the bridge is curved, in which case an offset "0" is used as shown in **Figure 13.2(a)**. Vertical curvature is handled similarly. Even if the bridge is flat, it is necessary to adjust for the deflections occurring during construction and from material time effects. As mentioned, the amount of adjustment to be made is determined by the casting curve, which is typically part of the shop drawings. If the segment is positioned such that both centerline markers are in line with both the instrument and the target, and the bolt elevations are the same as those measured before the segment was moved, the segment will line up exactly with the next segment to be poured.

Geometry control also requires an excellent surveyor. He or she should be on the job daily and keep accurate records. Their work should be meticulously double-checked by an inspector since even small errors are expensive and time-consuming to correct.

After each segment is properly reset and setup for the new one is complete, the new segment is cast. As with the previous segment, the following morning after casting when the concrete has achieved the required strength, the surveyor marks the center line and records the bolt elevations of the new segment. Before the old segment is moved the elevations of its bolts and its centerline position are checked to determine if the old segment moved during casting the new one. Position changes often occur due to: settlement of the soffit rails caused by the segment weight, vibrations made by the fresh concrete, or forces applied during form closure.

When constructing a bridge using girders or whole spans cast in place, it is normal practice to set forms to within 1/100 ft (1/8 in.) of the desired position, corrected for anticipated deflection. Each new segment should be cast to stay within this tolerance based on as-cast surveys of the previous segments. Accuracy depends on consistency; the same individuals should make the as-cast observations at the same time each day, prior to stripping the forms of the new and old match-cast segments. Usually, as-cast observations are performed first thing each morning before the daily crews arrive and when weather conditions are most stable from day to day.

All the critical readings are taken after casting. While it is important to have an accurate setup before casting, some movement, however slight, will occur -- so the true achieved geometry is recorded after casting. Casting errors are compensated for by adjusting the position of the next setup and so on. In fact, the major challenge in geometry control is tracking these errors and correcting for them.

Precision within the geometry control system is essential. One potential source of error is making incorrect assumptions about the deformation characteristics of the concrete. These deformations are difficult to predict and most attempts are, at best, sophisticated judgments. In segmental construction, actual deflection can differ from the theoretical, just as identical girders can differ in camber by a few inches in precast girder production. In precast segmental construction, however, most shrinkage has usually already occurred during storage, and the concrete has matured substantially by the time of erection. This helps eliminate the significant variations likely with young concrete.

## 13.2 Casting Cell Geometry Control System

Geometry control is achieved in the casting cell using the system discussed in **Section 13.1** and illustrated in **Figures 13.1 and 13.2**.

As shown in **Figure 13.2**, the elevation control bolts (A, B, C, D) are set over the webs, where no vertical deflection occurs from transverse flexure or post-tensioning. (As an example, wing tips may deflect upward by 3/4 in. from transverse post-tensioning.) Horizontal control is established by setting the match-cast segment at the necessary skew, at offsets measured at centerline hairpins (E and F). Vertical alignment is set by adjusting jacks on the soffit carriage of the match-cast segment until the elevation bolts are above or below the plane of the top of the bulkhead by the desired amount.

As shown in **Figure 13.3**, the geometry of a segmental bridge surface is typically defined by establishing 3D global coordinates (easting (E), northing (N), and elevation (Z)) at the centerline and equidistant from the left and right over each web at each joint. These coordinates are directly calculated from the stationing, instantaneous radius of curvature, longitudinal profile grade, and superelevation at each joint. Global elevations are adjusted for camber. Global structural torsional twist rarely requires camber adjustments, but they are incorporated when necessary.

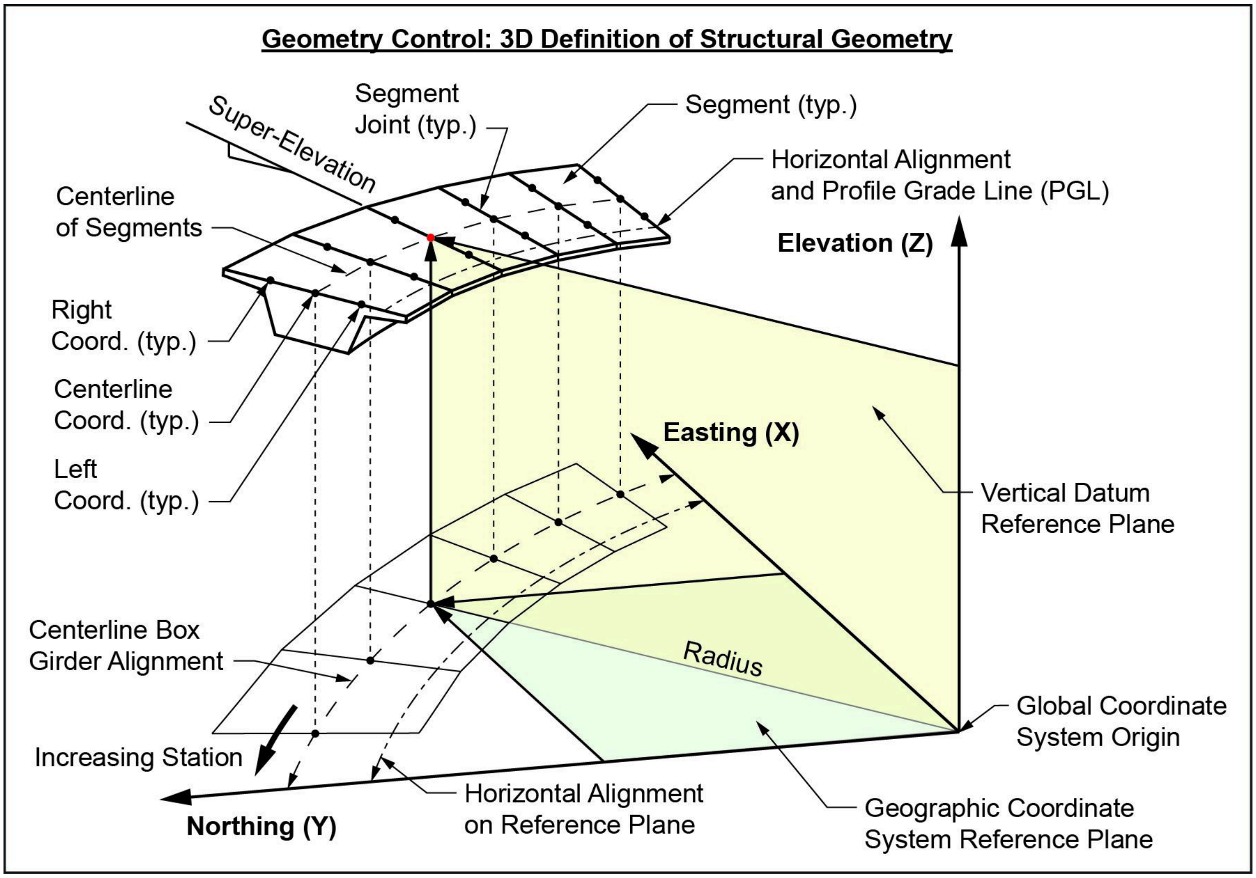


*Figure 13.3 – Definition of Global Geometry*

As shown in **Figure 13.3** and **Figure 13.4**, three consecutive joints define the intrinsic geometric surface shape of two consecutive segments: the previously made match-cast segment joint, the new match-cast segment joint, and the bulkhead joint with the next-to-be-cast segment.

Assuming the after-cast coordinates of the match-cast segment are known from previous observations and calculations, it is tedious but relatively straightforward to conceptually set the cell-bulkhead at the desired position of the next (new-cast) joint in global space (**Figure 13.4**) and transform the global coordinates of the two known joints and the new desired (bulkhead) joint from 3-D global space to the local coordinates of the casting cell.

The remaining coordinates are defined by the bulkhead and cell centerline (**Figure 13.5**). This transformation provides the setup of the match-cast segment relative to the desired bulkhead location for the new-cast segment.

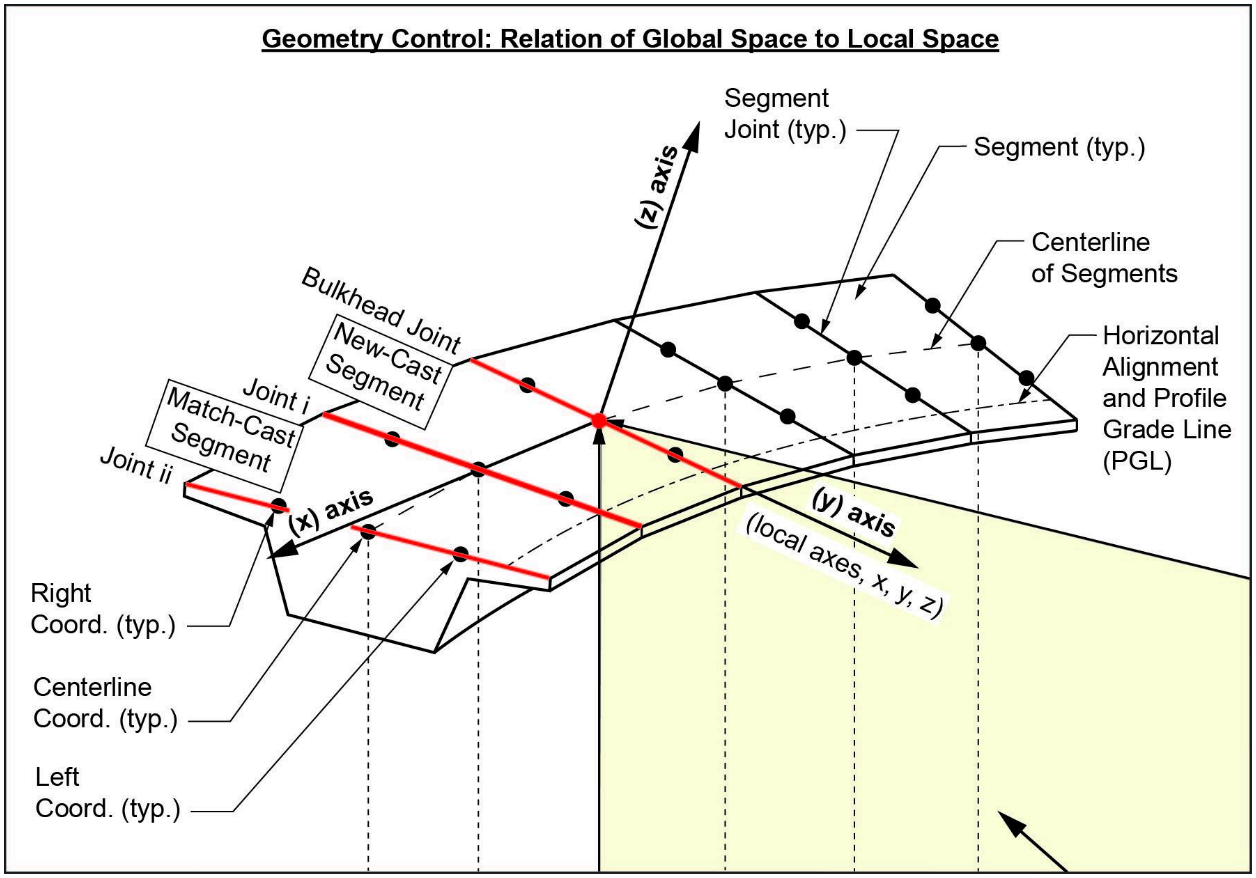


*Figure 13.4 – Match-Cast, New-Cast and Bulkhead Joints in Global Structure*

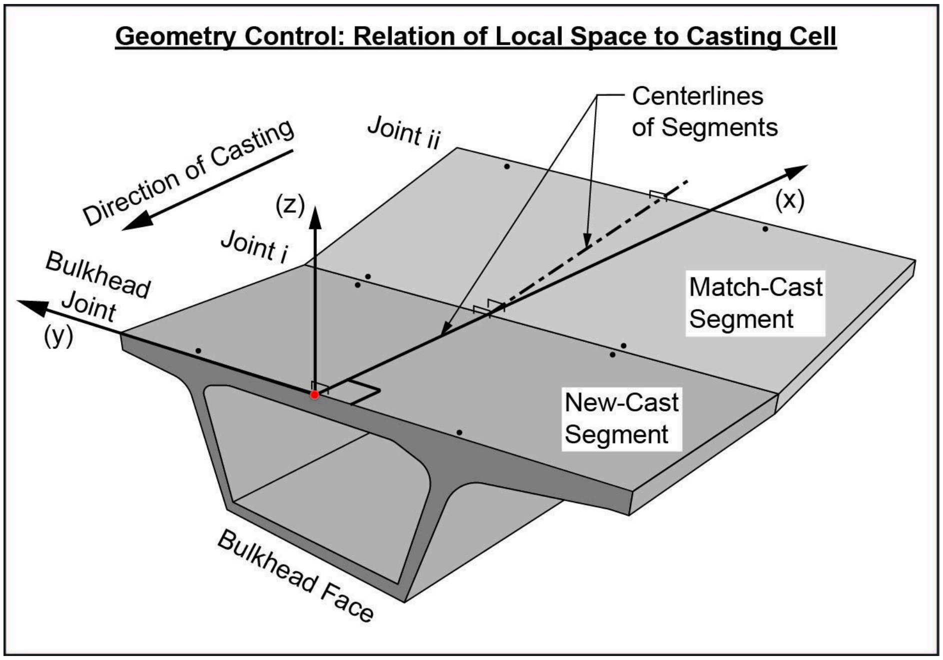


*Figure 13.5 – Segments in Local Casting Cell Coordinates*

To reference the new segment to the cell and facilitate after-cast observations, four new elevation bolts and two new centerline hairpins are placed in the top of the new-cast segment, close to match-cast joint and bulkhead. This is illustrated in **Figure 13.6**. The bolts and pin closest to the bulkhead (bolts $A_c$ and $C_c$ and centerline pin $E_c$) define the position of the bulkhead joint. Those closest to the match-cast face (bolts $B_c$ and $D_c$ and centerline pin $F_c$) relate directly to those next to them on the match-cast segment ($A_m$, $C_m$ and $E_m$) and, thus, to the previous bulkhead joint. Likewise, the bolts and pin at the far end of the match-cast segment ($B_m$, $D_m$ and $F_m$) relate to the previous ones (A, C, and E - not shown) and the previous bulkhead joint.

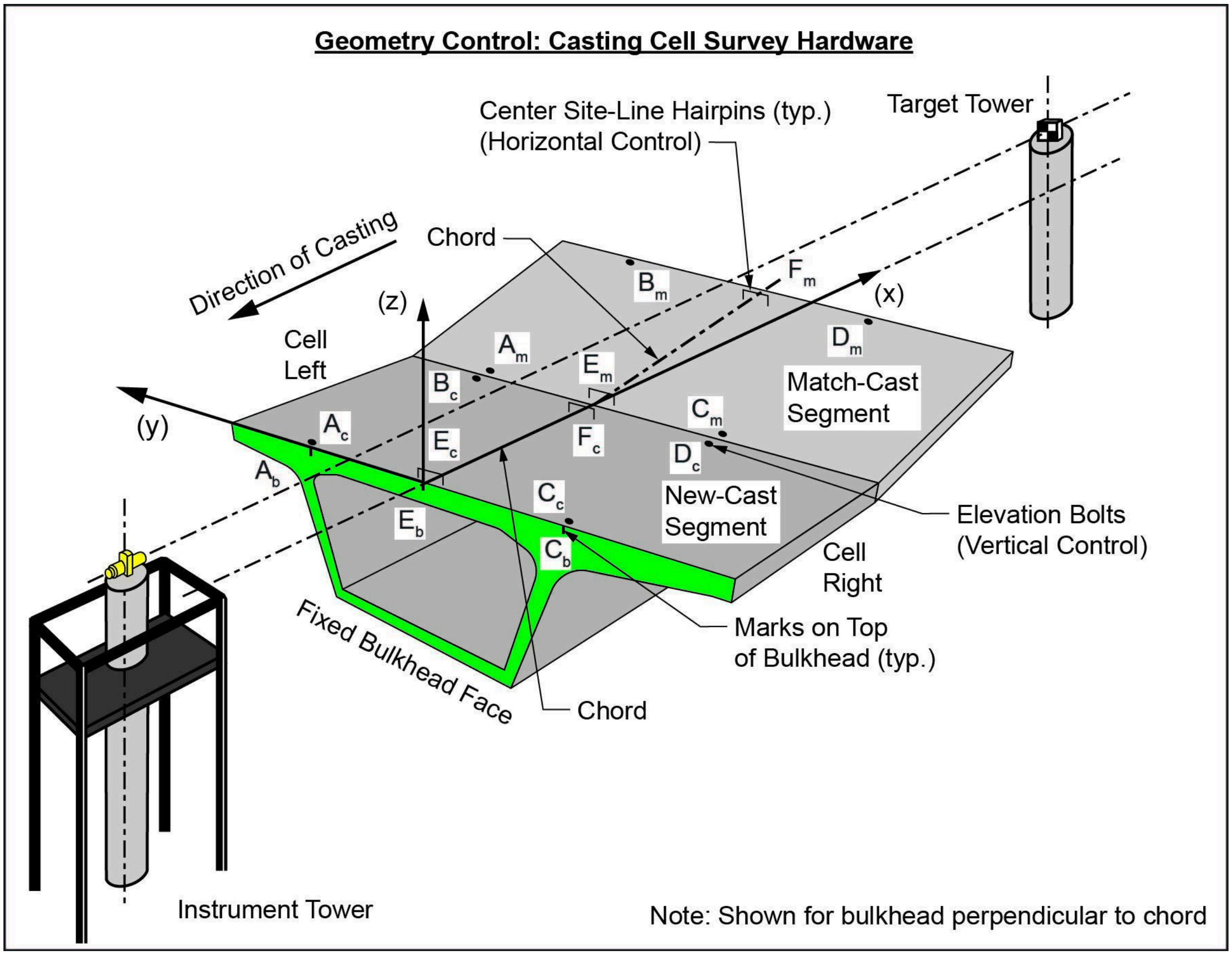


*Figure 13.6 – Cell Hardware and Survey Observations*

No setup is perfect and match-cast segments move a little during casting. After casting, all bolt elevations are carefully surveyed relative to the elevations at the top of the bulkhead. The centerline of the casting cell is punch-marked into the centerline hairpins on the new-cast segment. As **Figure 13.6** illustrates, these marks have an offset of zero, providing there is no mistake in punching.

All four centerline hairpin offsets are measured from the casting cell centerline. The length of the new-cast segment is measured along the webs, between like-bolts (i.e., $A_c$ to $A_m$ and $C_c$ to $C_m$), and the average is used for centerline length. This measurement requires setting all bolts and hairpins a constant, short distance from the joints. Elevation bolts should be a constant distance ("W/2") from the centerline. The same center-punch marks in the elevation bolts are used in length measurement as for setting the point of the survey leveling rod.

**Figure 13.7** summarizes a theoretical set of after-cast observations and includes the general condition of a deliberate -- or accidental -- non-zero center offset at the match-cast joint.

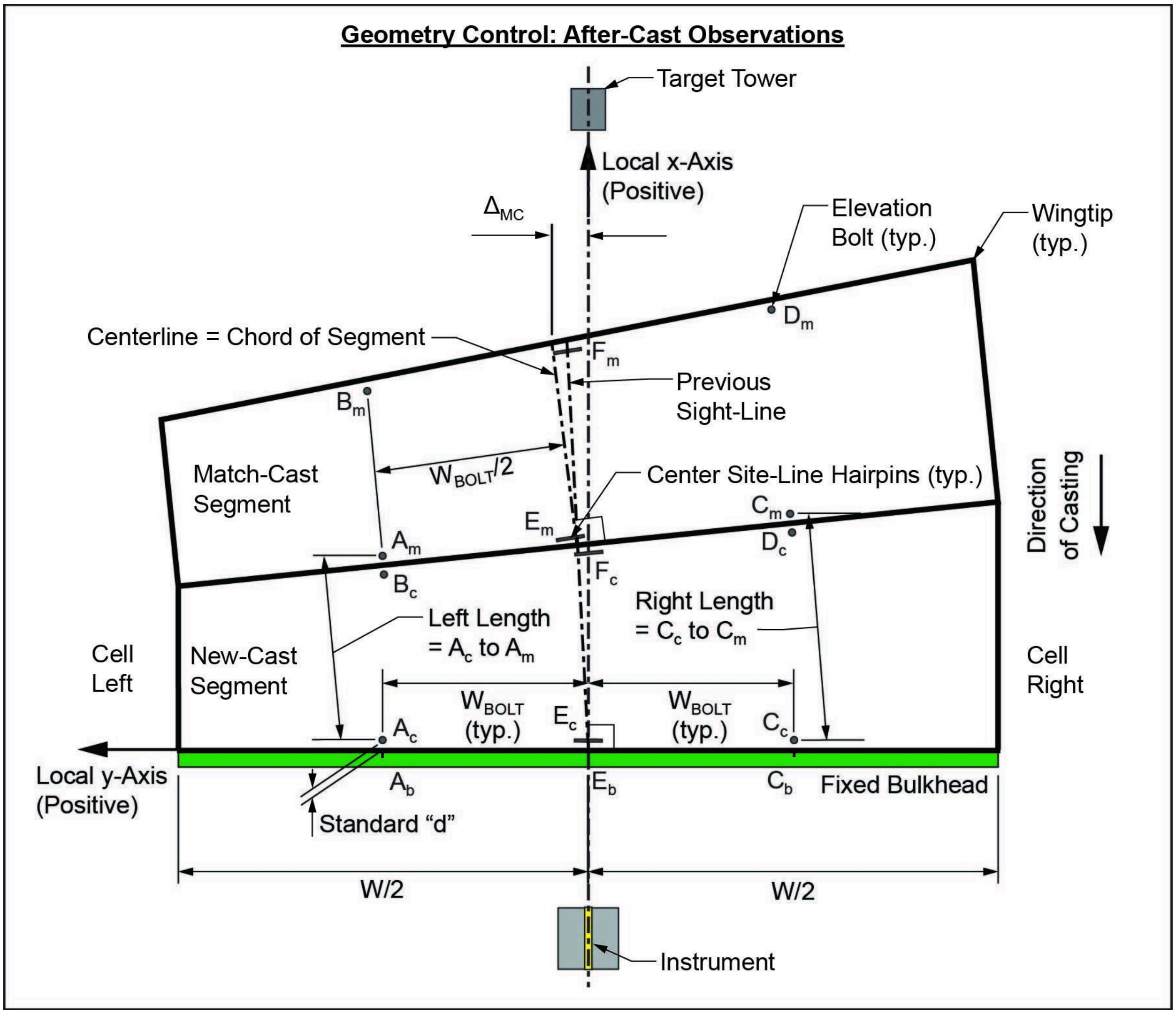


*Figure 13.7–After-Cast Survey Observations with General Condition of Non-Zero Offset*

As shown in the **Figure 13.7**, survey results are first converted into coordinates local to the cell itself and then local to the cell-axes of the match-cast segment when it was newly cast. By using these match-cast cell-axes as a reference, the coordinates are transformed from the cell to global space to provide the "as-cast" location of the new bulkhead joint. The entire process – formally known as the 3-D Coordinate Geometry Transformation Technique – is repeated for each segment. (Note that this specific technique was developed in 1979 for the Linn Cove Viaduct. Other techniques have been developed since then, but the intent of this chapter is to provide instruction on geometry control using a historically successful technique.)

For simplicity of construction and ease of operation, casting cells are almost always fabricated so that the bulkhead is perpendicular to the cell centerline. The soffit form is generally rectangular, and the web and wing forms operate parallel to the cell centerline – as was shown in **Figure 13.6**. Horizontal alignment is attained by slewing the match-cast segment in plan – holding the centerline offset of the match-cast face at zero - while offsetting the far-end face (most remote from the bulkhead) by the desired amount. This places the bulkhead joint face perpendicular to the chord connecting the centerline points of the new-cast segment. The resulting joints in the segment bridge are not radial – that is, they are not on a radial line. Rather, they are perpendicular to the chord - i.e. slewed off-radial one way or the other depending upon the direction of casting. Such joints are often referred to as "chord-perpendicular joints."

Calculating the global 3-D coordinate geometry for any curvature is relatively simple when joints are truly radial (see **Figure 13.3**). However, to keep casting cells simple, coordinates generated on radial coordinates must the modified to chord-perpendicular coordinates before performing transformations from global space to the cell or vice-versa. The mathematics involves interpolating (in 3D) along the longitudinal lines of the left and right elevation control points, with some iteration, until the global coordinates of the joint lines are mutually perpendicular to the centerline chords. Since the direction to skew the joint depends upon the necessary or contractor's elected direction of casting, this step may wait on the actual casting. However, it is useful in the meantime to include 3D coordinates for radial joints on the design plans – as the first step in a process.

Observations are made to an accuracy of ±0.001 ft and should involve separate readings by two different teams or lead surveyors. The alignment of the cell and elevation and the attitude of the bulkhead should be checked regularly against remote benchmarks or survey points to guard against errors due to possible equipment drift.

Geometry control calculations are tedious and best performed by a computer, with numbers processed either graphically or numerically. A graphical plot at an exaggerated scale is recommended as a check against computations and to provide a visually recognizable warning in advance of error.

The information presented above is a basic introduction to geometry control needs and techniques. Variations on the basic process accommodate situations where, for example, occasional elevation bolts and centerline hairpins cannot be placed in their desired locations due to construction details such as block-outs; or to accommodate breaks in superelevation across the width of the segment or an offset profile grade line. In all cases, the key is respecting that the elevation bolts over the webs define vertical control and the centerline hairpins define horizontal control. Finally, it is important that little or no twist be inadvertently introduced when moving a new-cast segment into the match-cast position. A simple check is illustrated in **Figure 13.8**.

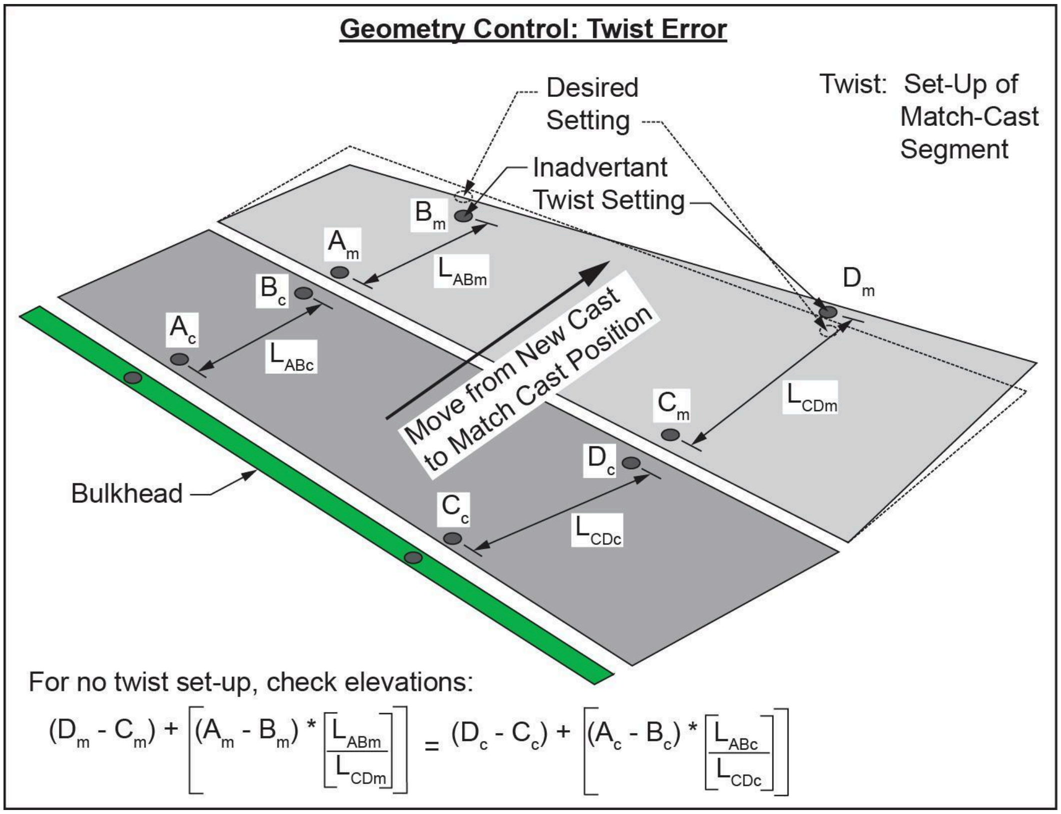


*Figure 13.8 – A Check for Twist of the Match-Cast Segment*

## 13.3 Geometry Control Measuring Equipment

Geometry control requires four precise types of measurements, as follows:

(1) **Offsets:** Centerline offsets are measured from the casting cell centerline by using a metal scale fitted with a center point which sits in a punch-mark on the hairpins. A spirit level should be attached to the scale to verify it is horizontal, and the scale held at a right angle to the centerline of sight in the cell (see **Figure 13.9**).

(2) **Elevations:** Elevation readings on the bolts are made by placing a precision level on top of the fixed mounting and reading a leveling rod fitted with a scale for measurement down to.005 ft. To ensure readings are taken at exactly the same point each time, the leveling rod should be fitted with a center point which sits in a punch-mark in the top of the bolt.

(3) **Lengths:** A steel tape is used for length measurement. It is advantageous to measure lengths between the center point marks on the hairpins, the distance between adjacent hairpins, and along the bolt lines between the leveling punch-marks. Readings should be estimated to at least .002 ft (see **Figure 13.7**).

(4) **Lateral offsets** to the level bolts should be measured from the centerline hairpins. Bolt positions should be accurately marked on the bulkhead so the level bolts are always at the exact required offset from the centerline (**Figure 13.7**).

With care and precision, the readings obtained will allow precise processing using 3D coordinate geometry computations, which most accurately define curved surfaces in space. Good recordkeeping is essential.

Occasionally, one or more of the geometry control hairpins or bolts is lost. This is not irretrievable; construction can typically continue construction by using known relative positions of adjacent undamaged markers. It will result in slightly less predictable control over the erection alignment.

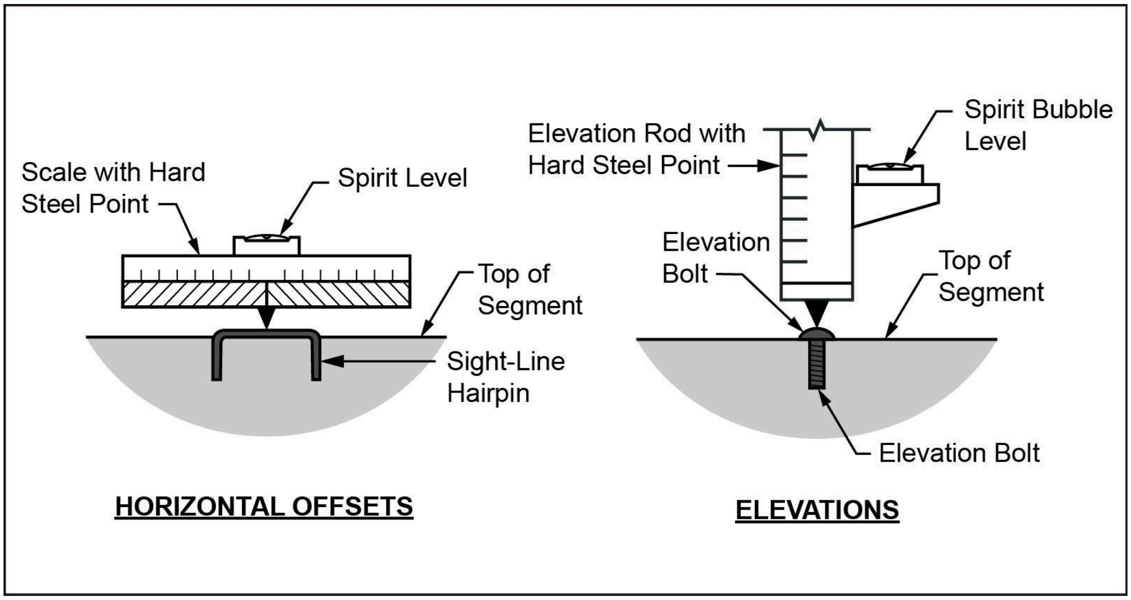


*Figure 13.9 – Geometry Control Measuring Equipment*

## 13.4 Geometry Control of the First Pier Segment

The first segment or starter segment of a span or a cantilever has no match-cast segment against which its geometric position can be referenced, because the first or starter segment is typically cast between the fixed bulkhead and a temporary starter bulkhead. When moving this first segment from temporary storage into the match-casting position, it is set to the same position it had after casting by reading the same elevation on the bolts and the same offsets on the markers. If any casting curve adjustments need to be made, they are incorporated at this time. This provides a starting point from which all other segments can be subsequently referenced. The bolt and centerline marker readings are also used for setting the first segment in its required attitude in the erected structure.

If the first segment is a pier or abutment segment, it is usually shorter than typical segments. It is important to establish a transverse horizontal control line on the segment's surface while in the casting cell. This ultimately provides a greater baseline length for aligning segments in the field.

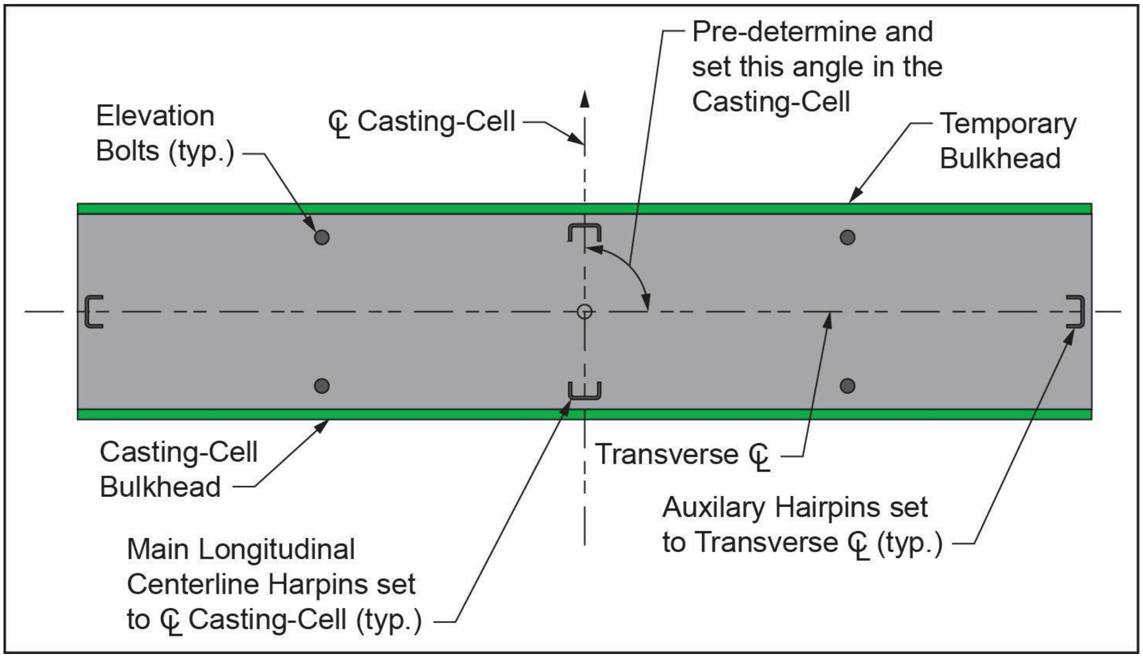


*Figure 13.10 – Geometry Control for Starting (Pier) Segment*

As illustrated in **Figure 13.10**, a standard procedure is to determine either a radial line or a line parallel to the bulkhead and establish this on the center of the segment, with horizontal alignment hairpins set as far out on the segment wings as possible. This line must be observable on the completed bridge, either from above or from the ground below. In the latter case, the line has to be scribed onto the end faces of the wings, and two observation stations must be established on the ground, one on either side of the pier.

Cast-in insert locations and orientations for bearings should be checked and re-checked. Piers are often built along the radial alignment, resulting in different bearing offsets and positions versus a line perpendicular to the bulkhead of a pier segment. Typically, the bearing seats on a pier are radially offset from the alignment and aligned with the horizontal surface of the global alignment. A pier segment is generally cast along the local bridge alignment, resulting in the bearings being offset by different distances from the transverse horizontal control line and centerline of the casting cell, as well as being set non-level in the casting cell.

After casting, precise setting and checking of the first erected segment position is essential; any error is magnified in proportion to the ratio of the length of the cantilever or continuous run of segments to the transverse baseline width.

Erection of the first segment is critical and should be done to an accuracy of .001 ft.

It is vital that all information from the casting operations and the calculated as-cast actual and relative positions of the segments be carried into the field erection process.

It is admittedly much harder to achieve the same accuracy in the field as in the casting yard – using a crane to place a large chunk of concrete with an accuracy of a few thousandths of a foot is difficult – but there are tools and practices that can help. As depicted in **Figure 13.11**, installing supplementary transverse alignment markers while the segment is in the casting cell allows the horizontal adjustment of the pier segment to be set in the field. This has the added advantage of using the baseline of the full segment width instead of relying on the shorter, front-to-back longitudinal centerline marks.

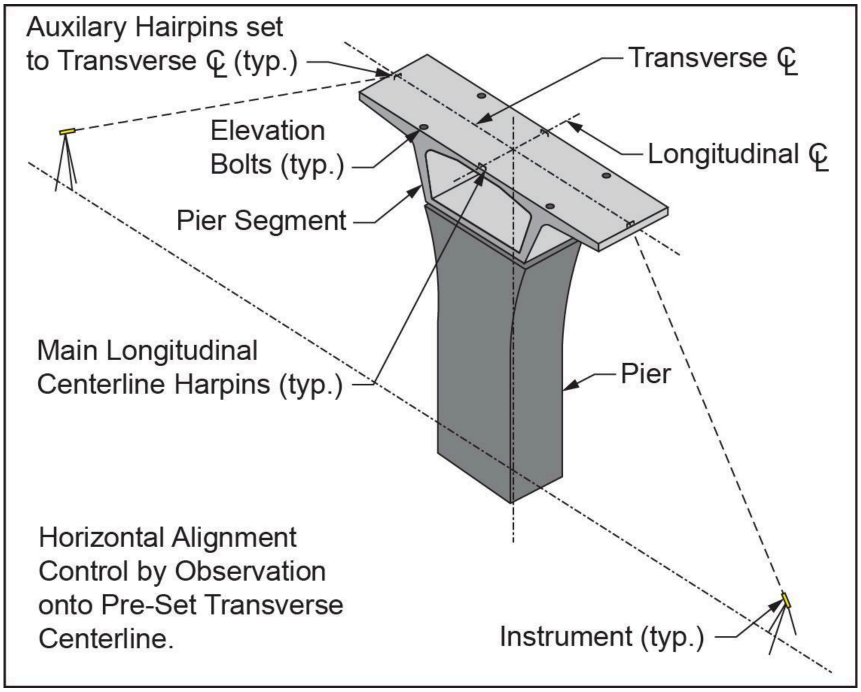


*Figure 13.11 – Setting Pier Segment from the Ground*

During erection, elevations and horizontal alignment should be checked to verify they are in agreement with the calculated as-cast positions. If not, then adjustments may be necessary including re-orienting or rotating the cantilever after erection, calculating a compensatory setting for the next cantilever, or shimming the joints. Shims, packs, and wedges should only be used as a last resort, as this practice may lead to endless "corrections of corrections." Shimming is not effective for short cantilevers or deep girders.

## 13.5 Field Survey Checking During Erection

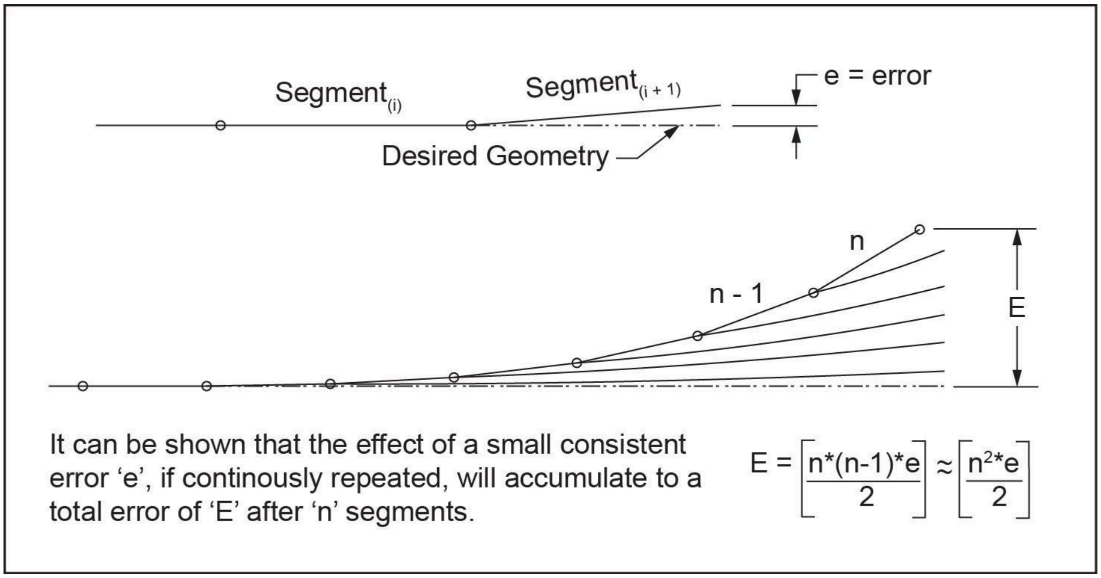
After the pier segment has been set and checked, the horizontal and vertical alignment of successive segments must be checked as well. Calculating and measuring elevations each time each segment has been erected is standard practice. The horizontal alignment is also checked and should match the theoretical horizontal geometry. The only errors should be slight deviations due to casting errors and corrections. The overall line should closely track the desired line.

An acceptable tolerance should be allowed for the vertical alignment, since this is subject to all kinds of variations due to construction loads, creep, shrinkage, temperature, post-tensioning variations, etc. Still, the alignment at erection should closely agree with the required alignment when duly corrected for variations. It is difficult to put a precise figure on this tolerance, as it depends on the type of construction.

Any substantial variations from line and level, or trends noticed early in construction, should be closely studied and corrected. Corrective actions might include checking procedures for errors, especially systematic errors; amending casting curves for future segments; or if absolutely necessary, shimming the joints with glass fiber matting or high density polyethylene (HDPE) sheets to adjust alignments. Again, the use of shims is a last resort since it causes stress concentrations on the segments and prevents the joints from closing properly, which may cause problems during tendon grouting.

## 13.6 Systematic Errors

A systematic error made in each casting operation -- resulting from either a computational error or as a physical defect of the equipment – will be repeated in each segment of a run. **Figure 13.12** shows the cumulative effect, where the final systematic error (e) after "n" segments equals n(n-1)e/2. In other words, a systematic error of .002 ft in each segment becomes an offline error of .09 ft after 10 segments and an error of .38 ft after 20 segments. Clearly, systematic errors must be avoided, and proven techniques should be used.



It can be shown that the effect of a small consistent error 'e', if continously repeated, will accumulate to a total error of 'E' after 'n' segments.

$$E = \left[\frac{n^*(n-1)^*e}{2}\right] \approx \left[\frac{n^{2*}e}{2}\right]$$

*Figure 13.12 – Effect of Accumulation of Systematic Errors*

Systematic errors can also occur after casting, during segment storage. These errors often result from a combination of: concrete creep and shrinkage effects of the concrete while the segment cures; any applied loads on the concrete at support points; and applied post-tensioning (typically transverse post-tensioning). Consequently, it is important to monitor the geometry control points of each segment in storage. If any changes are noted in the geometry control points, the cause(s) should be identified to determine if changes are needed to the segment storage methodologies before the effect of the error accumulates.

## 13.7 Achieved Profiles

**Figures 13.13** and **13.14** below illustrate variations in cantilever and span-by-span profiles. Cantilever structures, when compared to span-by-span structures, are more susceptible to variations in the actual profile at the time of construction; however, adjustments can be made during construction to achieve an acceptable final grade.

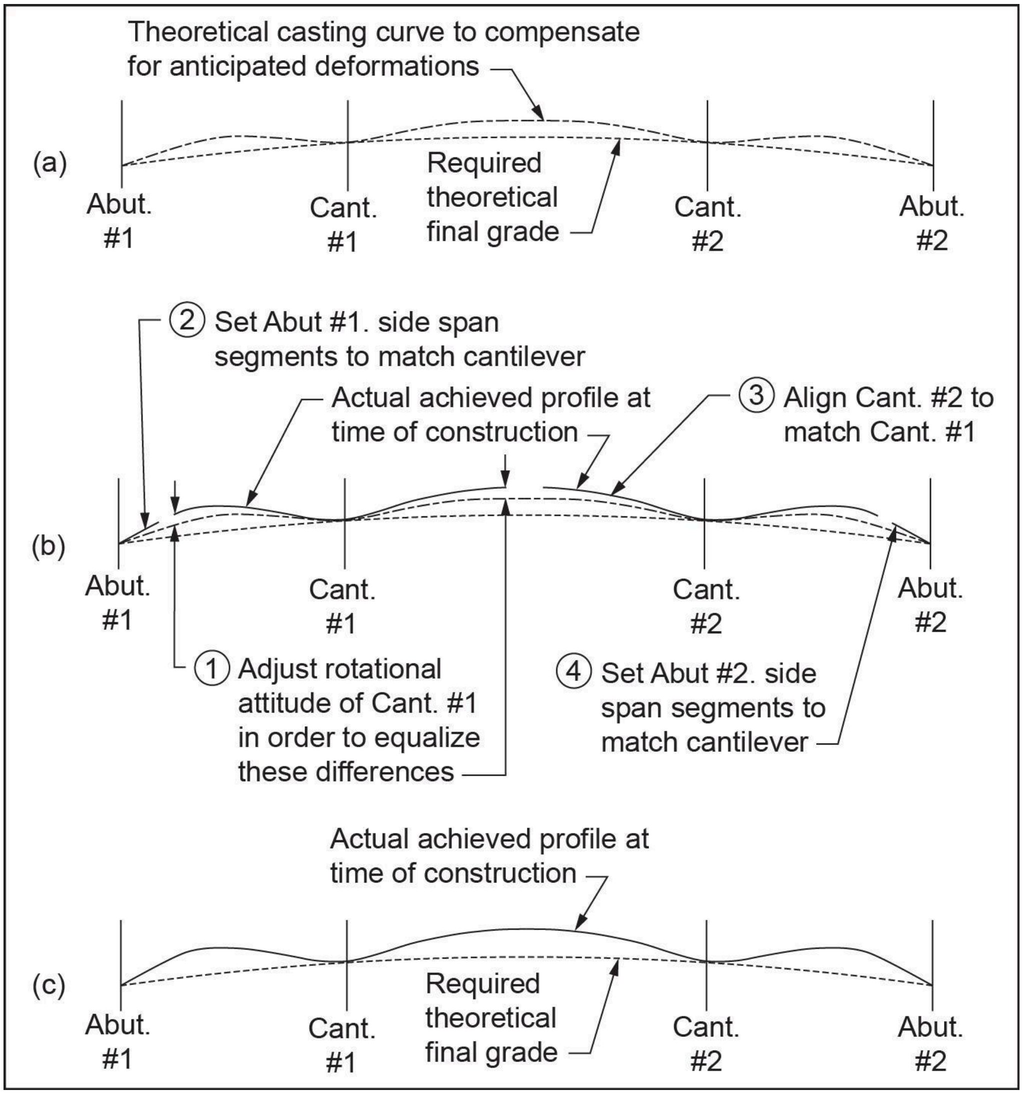
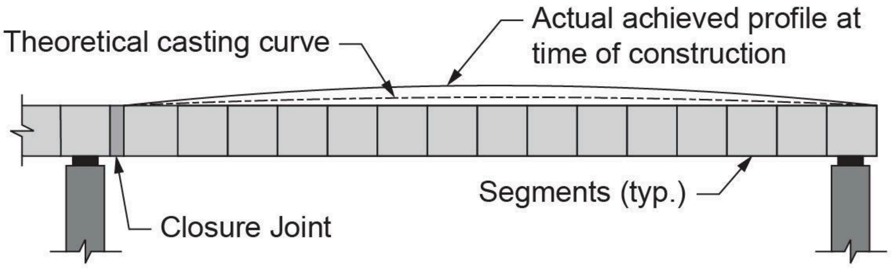


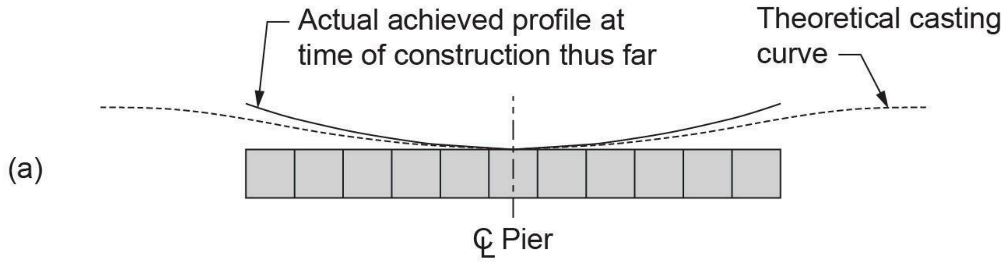
*Figure 13.13 – Alignment of a Cantilever Structure (Three-Span)*



Span-by-span construction is less susceptible to casting curve and casting geometry discrepancies than cantilever construction. This is because there are typically fewer segments per span, the spans are usually shorter, the segments are sometimes longer, and there is usually a closure joint in each span that permits some field adjustments. Also, span-by-span constructed spans are generally stiffer than cantilever construction spans.

*Figure 13.14 – Alignment of a Span-by-Span Structure*

**Figures 13.15** and **13.16** illustrate correction of a profile by joint shimming – though it must be emphasized that this should only be done if absolutely necessary, as it can lead to complications and is not entirely predictable.



If the observed profiles do not match casting curve and if it is clear that they will continue to diverge, then some corrective action is possible by shimming the joints with woven glass fiber matting embedded in the epoxy between the joints. Usually the remaining cantilever segments have already been cast according to the original casting curve by this time, making corrections by casting compensations impossible. Shimming should be done only if absolutely necessary, and then it should be kept to a minimum because the effects on geometry are not easily predictable, which can lead to continuously correcting over corrections in the remaining cantilever segments. Additionally, thicker epoxy between the match-cast faces can lead to more epoxy intrusions into the cantilever and/or continuity ducts because the match-cast faces are not erected and joined in the same position that they were original match-cast in.

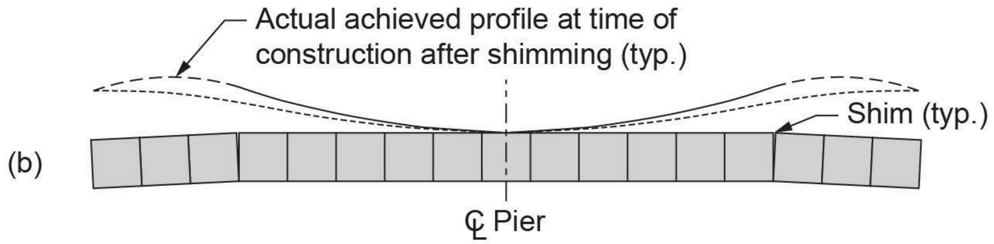
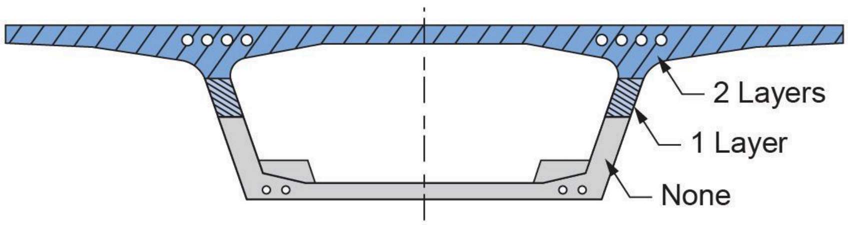


*Figure 13.15 – Shimming Joints to Correct a Profile*



Shimming joints with woven glass fiber matting to provide a wedge shaped joint to correct alignment. It is recommended that no more than 2 layers maximum be used at any joint. Layering as shown would tip the next segments downward. To tip the next segments upwards, shim from the bottom. Shimming joints may occasionally be necessary in cantilever construction. It is unlikely to be used in other precast segmental types of construction (i.e. span-by-span).

*Figure 13.16 – Shimming Joints to Correct a Profile (continued)*

## 13.8 Shimming Methodology using HDPE Sheets

Shims provide rotations at the joints between segments, known as angle breaks. These angle breaks are intended to correct the alignment of the subsequent segments in a span during erection procedures and are most commonly used in balanced cantilever construction. The locations of shims are first determined based on non-conflicting areas with post-tensioning ducts and shear keys. Shims can provide both vertical and horizontal corrections to guide the segments back to their target coordinates according to the chosen configuration and thickness of the shims. Based on previous research and recent industry practice, the material of choice for the shims is high-density polyethylene (HDPE). HDPE provides strong compression resistance while minimizing the risks of hardpoints at the contact surface interface between segments, also known as the joint. The size of the shims will be based on the required and allowable correction that does not negatively affect the grouting of post-tensioning ducts and sealing of the joint between the two segments. A shim thickness larger than 3/16” is not advised. It is advised that corrections requiring shims larger than 3/16” be distributed to more than one joint. It is imperative to note that all shim work plans must be approved by the Engineer-of-Record (EOR) before implementation during erection procedures and are only intended to take place as a last resort to correct the alignment of the bridge.

The corrective angle breaks provided by shims are determined from the results of the projection differences between the most recently erected segment and the span closure. “Projection differences” are defined as the error between the erection target coordinates at the closure joint and the projection to that closure joint based on the achieved (as-built) coordinates of the most recently erected segment. Calculating the required size and configuration of the shims is based on this calculated projection difference and analyzing the amount of correction that can be safely achieved. The amount of correction that can be safely achieved is determined by several factors such as shim stress concentration analysis at the faces of the segments and the required shim size. The required shim size is limited by the allowable shim size, the depth of the segment, the width of the segment, and the remaining length of the bridge to be erected. The amount of correction achieved with the shims is calculated by selecting a “driver shim” with a predetermined location on the face of the segment and using small angle theory as shown in **Figure 13.17**.

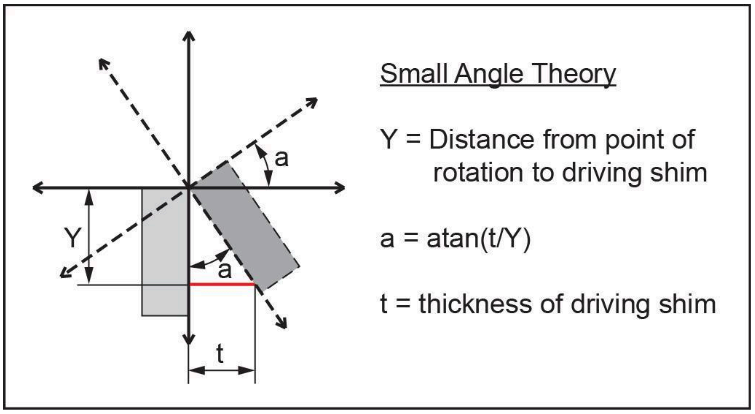


*Figure 13.17 – Shimming Small Angle Theory Concept*

The driver shim is used to determine the amount of angle break and hence the amount of correction that will take place at the leading joint of the last erected segment. It is crucial not to rely solely on the driver shim to correct all the projection differences. Based on the thickness of the driver shim, the locations of the shims that are plus and minus 1/16” must be determined to assist the driver shim; these additional shims are referred to as “assist shims”. Without the locations of the assist shims, the stresses required to erect the segments will likely compress a single driver shim, and the anticipated results and trust in the effectiveness of shimming will almost surely elude the erection team. The implementation of assist shims will also help distribute the overall stresses at the faces of the segments and reduce the potential for stress concentrations. Refer to **Figure 13.18**, which shows a graphic representation of the location of the driver and assist shims; multiple shims at each location may be installed to assist with the distribution of stress at the face of the segments. The location of the shims must also be mirrored about the vertical or horizontal centerline of the segment face for even load distribution and to achieve the required corrective action. As shown in **Figures 13.18** and **13.19**, shims installed for vertical alignment corrections must be mirrored about the vertical centerline of the segment, and shims installed for horizontal alignment corrections must be mirrored about the horizontal centerline of the segment. Analyzing the angle break created in the joint will provide insight into the different zones with limits to where the different sizes of shims can be installed to maintain the correct angle break at the joint and distribute the stress at the faces of the segments. The epoxy used to seal the joints between the two segments must be carefully applied on the face of each segment before installing the shims and ensure any epoxy that has entered the ducts is removed. Again, a detailed work plan showing the locations of the shims and step-by-step installation instructions to be followed by the crews should be provided for review and approval by the EOR.

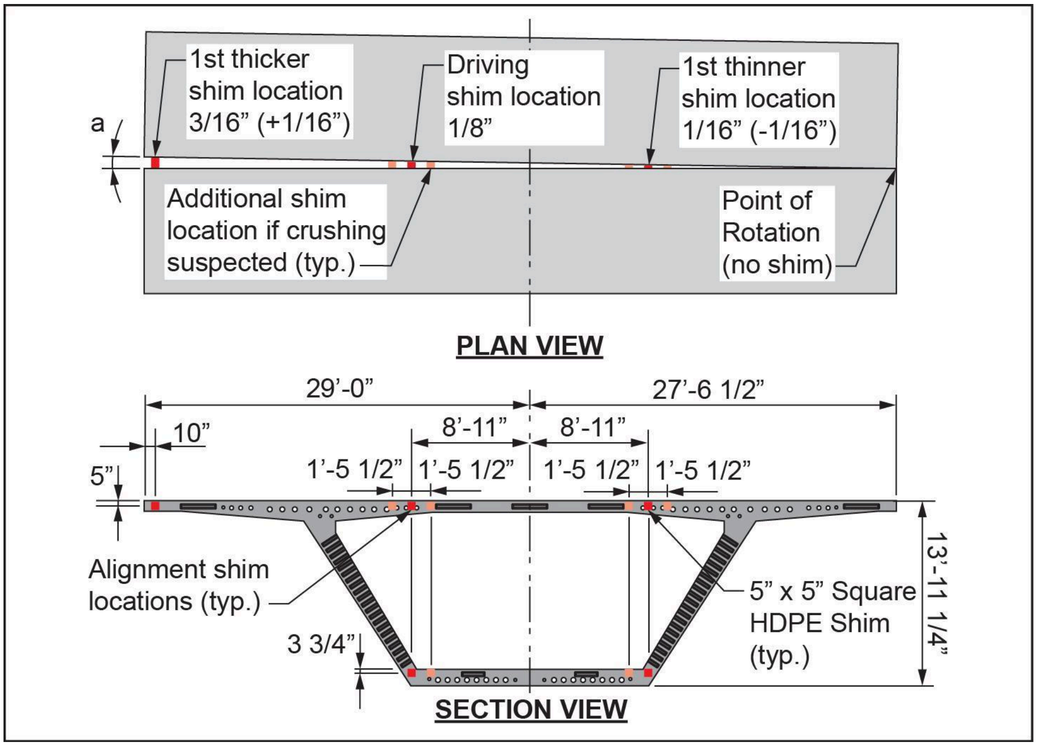


*Figure 13.18 – Horizontal Shim Layout*

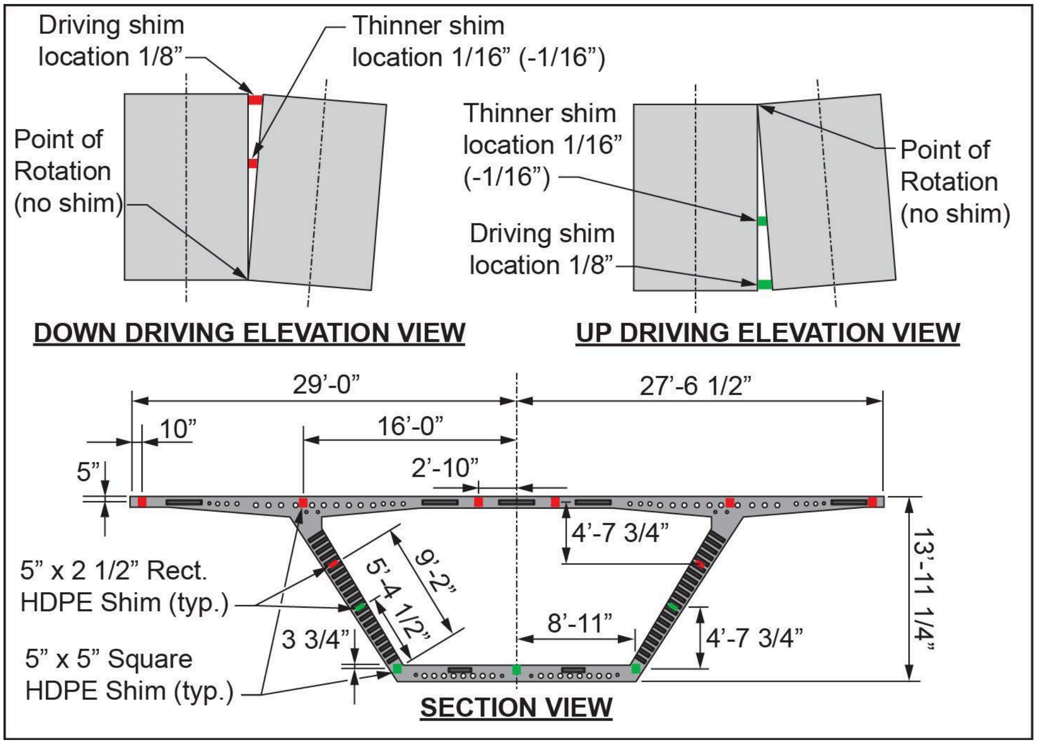


*Figure 13.19 – Vertical Shim Layout*

## 13.9 Geometry Control of Cast-in-Place Cantilever Segments

As mentioned at the start of this chapter, geometry control of a cast-in-place cantilever casting system is mainly achieved when building or positioning the soffit forms. This system presents some important considerations not common to the short-line casting system focused on previously.

Instead of four (4) elevation bolts and two (2) centerline hairpins per segment, a cast-in-place cantilever segment has only two elevation bolts close to the bulkhead. These elevation bolts are placed near, but typically not over, the webs. This is because most cast-in-place form travelers secure their traveler beams over the webs. The precise location of the elevation bolts should take into account the specific form traveler system, placing the bolts such that an extended survey rod will not conflict with the traveler beams, bogies, bracing, or enclosure hardware.

When setting the position of the soffit forms for the bottom slab, top slab, and cantilever wings, it is important to calculate the point positions at all bulkhead form break points, survey control points, and the segment centerline. Traveler deflection due to all reinforcement, any precast elements, and concrete are typically added to the initial setup values. Control points (typically located along the tops of the cantilever wings and top slab) are used to calibrate the traveler deflections resulting from casting the next cantilever segment. Traveler deflections are initially estimated based on the assumed weight and stiffness of each form traveler element, then adjusted for the next segment based on the field measurements taken at final setup and after casting. The deflections will not necessarily be the same across all control points (i.e., cantilever wing control points will deflect differently from the top slab control points).

Monitoring the two elevation bolts and select survey control points throughout cantilever construction is generally more important in cast-in-place versus precast cantilever construction, due to the former method's greater variability. For example, actual segment weights are not precisely known since segments cannot be weighed separate from the structure. As such, estimates need to be very accurate regarding the actual weight of the concrete, reinforcing steel, prestressing steel (bars and strands), and imbeds; reduction of the gross concrete volume taking into account the volume of reinforcing steel, post-tensioning ducts, and imbeds; and the allowance for the swelling of formwork during concrete placement.

Similarly, the stiffness of the concrete when loaded is subject to greater variability. Precast segments are typically erected and carrying load 28 days or more after casting. By then, the concrete modulus is fairly stable and predictable, as are creep and shrinkage effects within the concrete. In cast-in-place construction, on the other hand, segments are carrying load as soon as one day after casting. Although the concrete of the segment has sufficient strength to carry the construction loads, stiffness gain, creep, and shrinkage are subject to the curing conditions. A segment cast on a warm, sunny fall day will have different concrete modulus, creep, and shrinkage curves than a segment in the same cantilever cast on a cold, snowy winter day. It is very important to monitor the two elevation bolts and select survey control points throughout cantilever construction and update the casting curves appropriately using actual field measurements.

With these additional considerations, the original casting curve developed from the profile and camber will inevitably need to be updated and / or revised due to changes in the initial assumptions. It is important to check phase deflections daily to ensure they are in alignment with the predicted phase deflections so as to minimize such "chasing" of the casting curve.

## 13.10 Pier Shaft Segments

**Figure 13.20** shows one observation technique used for alignment control while casting precast pier shaft or column segments. Other methods use inserts, plumb lines, leveling bolts, etc.

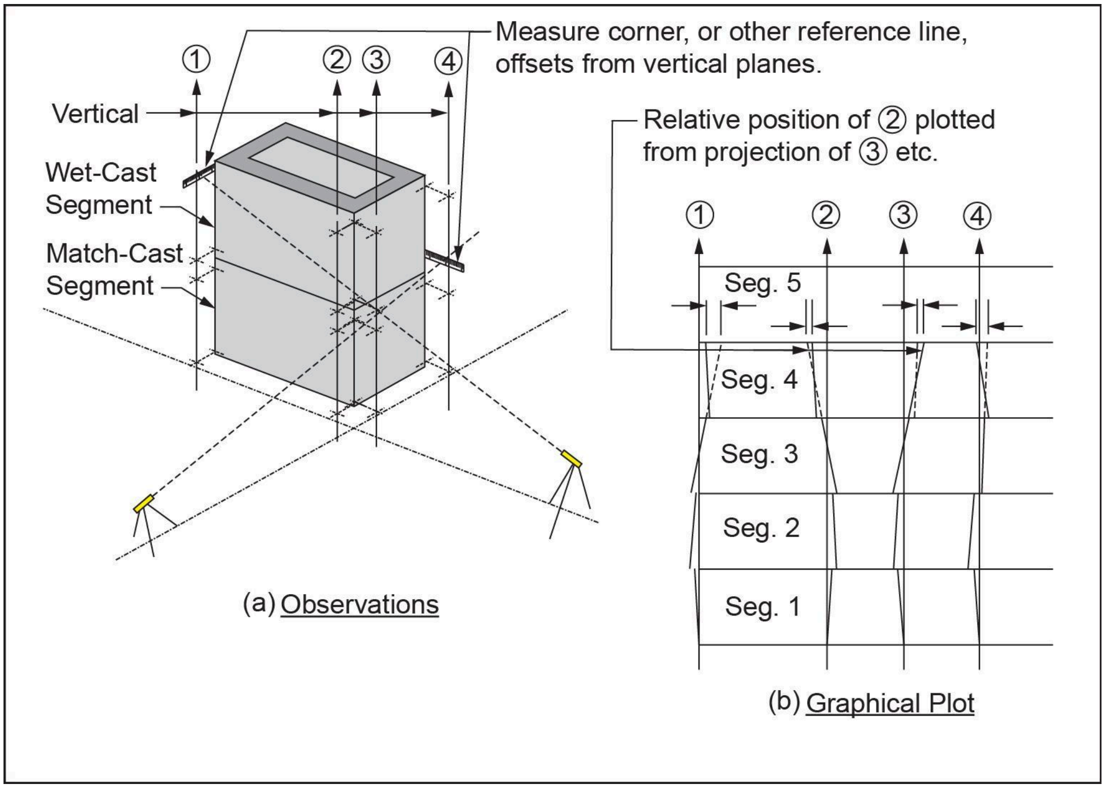


*Figure 13.20 - Geometry Control for Precast Pier Shaft Segments*

Pier shaft segments are generally simpler to precast than superstructure segments since their alignment is usually vertical (straight), requiring no manipulation of the match-cast segment. Alignment about two axes and segment lengths are monitored and recorded with each segment cast. Pier arch segments are an exception; their curved alignment necessitates manipulating the match-cast segment.

Preventing systematic errors is critical to pier shaft segment precasting and erection. Since the superstructure weight is typically supported at the top of the piers, any change in the verticality of the pier can increase P-delta effects and impact the pier's capacity. Additionally, the cross-section must be aligned from the bottom pier shaft segment to the top one. Torsional deformations in the column may cause different and / or unanticipated bearing locations at the top of the precast pier shaft, resulting in reduced capacity and / or difficulty in meeting geometric requirements.

## 13.11 Temperature Effects

### 13. 10.1 Temperature Expansion and Contraction

A rise or fall in temperature causes a structure to shrink or expand. Bearings and road joints are designed to accommodate this movement. This temperature effect may cause problems during construction of some types of precast segmental bridges. **Figure 13.21(a)** shows one example: a structure with a fixed pier in the center. After the cantilever on the fixed pier is erected, a connection is made to the remainder of the structure (**Figure 13.21(b)**). This connection must be strong enough to pull the erected part of the structure over its bearings in compensation for temperature movements. If the connection is too weak, the cast-in-place splice will crack.

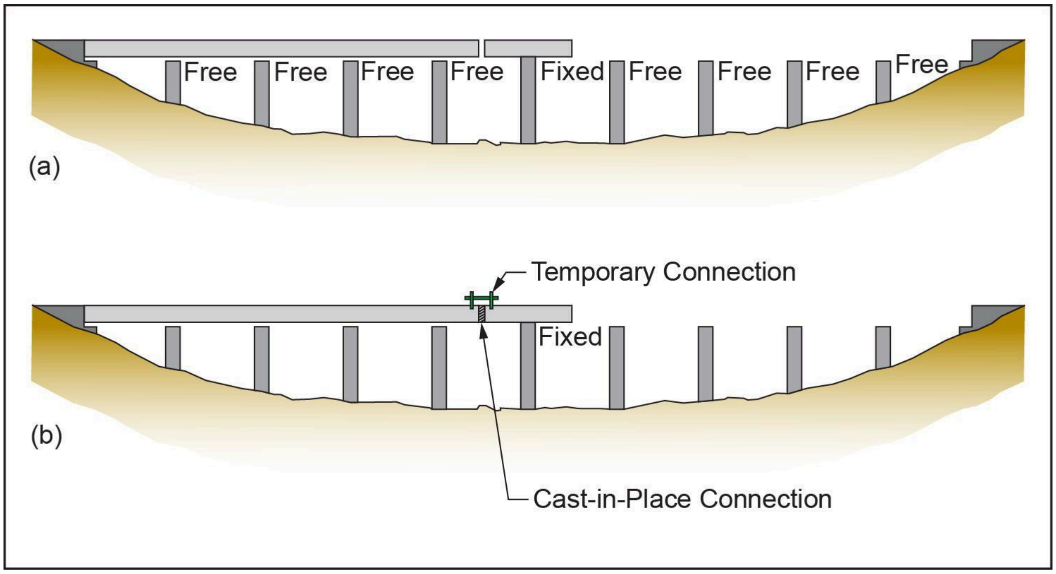


*Figure 13.21 – Temperature Expansion and Contraction Effects*

### 13.11.2 Temperature Gradient

A temperature gradient, or differential, exists when one part of the structure has a different temperature from another part. This commonly occurs when the top slab of the box girder, which is directly exposed to the sun, heats up faster than the webs and the bottom, which are not directly exposed. Temperature differences of 30 to 40 degrees Fahrenheit can easily occur.

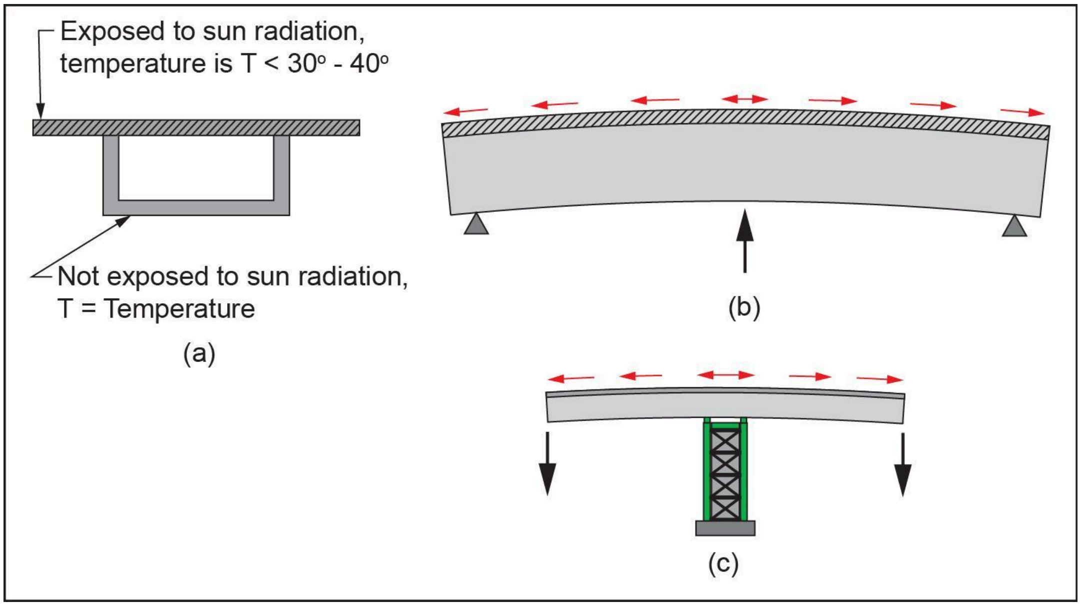


*Figure 13.22 – Temperature Gradient Effect*

As illustrated in **Figure 13.22**, the top slab wants to expand, but the bottom slab does not **(a)**. A girder supported at the ends cambers due to this temperature effect **(b)**, while the tips of a free cantilever **(c)** will deflect downward.

Though the amount of movement increases with the length of the cantilever, a 1 in. deflection is common. Because of this, the only suitable time for measuring elevations during erection is at sunrise, before the structure has been exposed to sun radiation.

The movement of the cantilever tips likewise impacts the timing of casting the mid-span splices. **Figure 13.23** shows the recommended procedure, which avoids the effects of sun exposure and temperature by following these steps:

a. Connect the cantilevers at the tip by means of a strongback
b. Cast the splice when the deflections at the cantilever ends are returning to a neutral position and movement is minimal (around 9 p.m.)
c. Early the next day, before temperature gradient effects occur, stress as many tendons as allowed by the strength of the still-green concrete (usually 2-4 tendons, enough to compress the splice so subsequent temperature deflections do not crack the bottom slab at the splice)

If the splice is cast in the morning, the temperature gradient effect may crack the bottom of the closure joint before the day is over. The specific timing of casting concrete and stressing tendons should be carefully evaluated for each project. Variables such as concrete strength gain, external temperatures (i.e., summer versus winter), size of cantilevers, and relative thermal movements must be considered with determining when and how to cast the splice and stress the tendons.

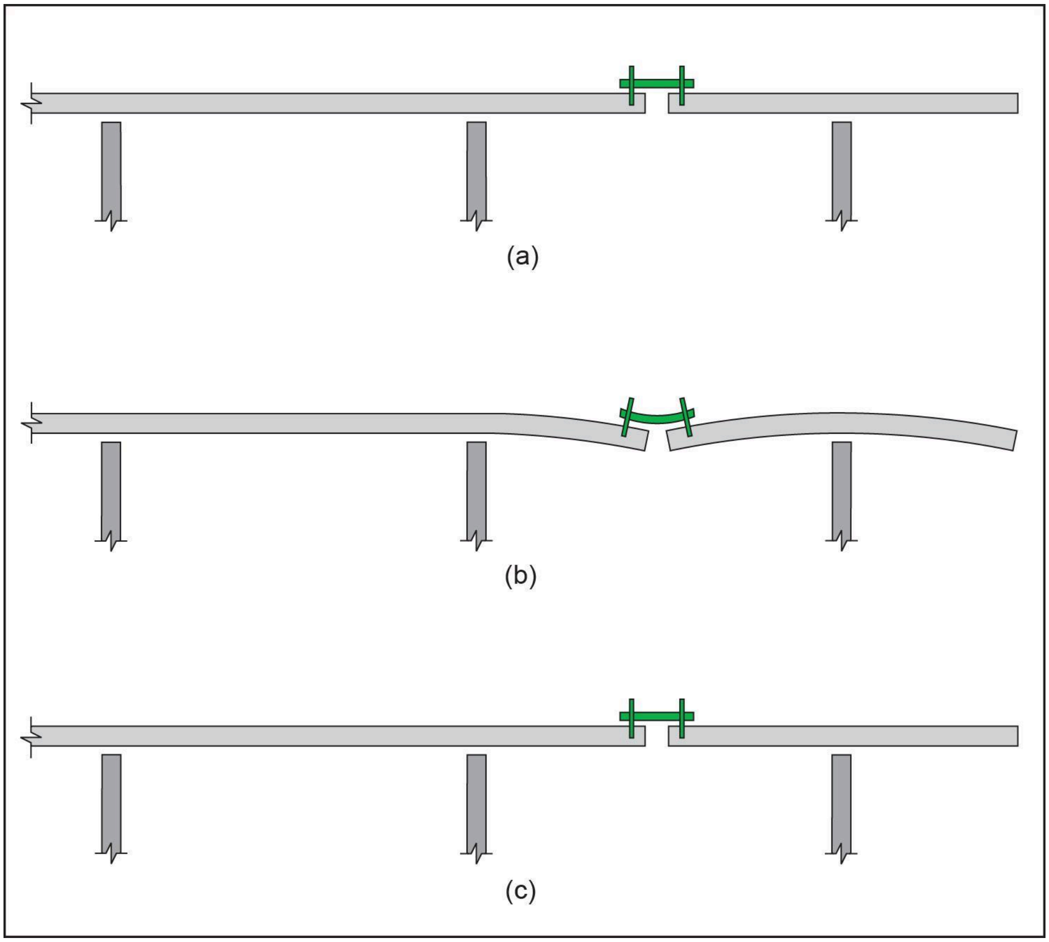


*Figure 13.23 – Deflection Caused by Temperature Gradient*

# TABLE OF CONTENTS

# Chapter 14:
# Bearings and Expansion Joints

As vulnerable parts of a bridge structure, bearings and expansion joints allow it to expand, contract, and accommodate eccentric and seismic movements while maintaining structural integrity and protecting the substructure. The bearings also transfer loads from the superstructure to the substructure. Expansion joints are subject to much wear and tear by traffic and impact loading; if not properly designed, tested, manufactured, and installed, they often incur future maintenance costs.

The specific type of bearings and expansion joints to be used are specified in the project plans. Usually a drawing is included, with notes identifying design standards, project-specific requirements, dimensioning, and most importantly, manufacturing quality standards and installation guidelines. Special provisions shall include a detailed description of materials, tolerances, blockout geometry, shipping, and handling.

The selected product must meet detailed quality standards, including third-party independent performance test validation, which are lined out in an accompanying performance-based specification. Subcontracted manufacturing of joint assemblies should not be permitted, since the required test validation and warranty must be provided by the primary supplier.

Following project-specific protocol, the contractor submits shop drawings supported by design calculations, in accordance with current AASHTO design standards, and the required third-party performance testing. The reviewing engineer then verifies that the submittal complies with the project's specification requirements.

When the product is delivered on site, an inspector must verify that it conforms to the shop drawings and is properly installed in accordance with manufacturer requirements under the initial direct supervision of a factory-trained technician.

## 14.1 Bearings

Three types of standard movement bearing systems are most commonly used on segmental bridge projects: laminated neoprene bearings (with or without sliding plates), High Load Multi-Rotational (HLMR) bearings, and disc bearings.

**Neoprene bearings** are often selected for simple load and movement needs due to their ease of installation and essentially low-maintenance performance. Their limited load-bearing and movement capacity, however, limit application to simple span structures, approach spans, and short distances between expansion joints. Neoprene bearings with sliding plates (**Figure 14.1**) have more movement capability and can accommodate greater distances between expansion joints.

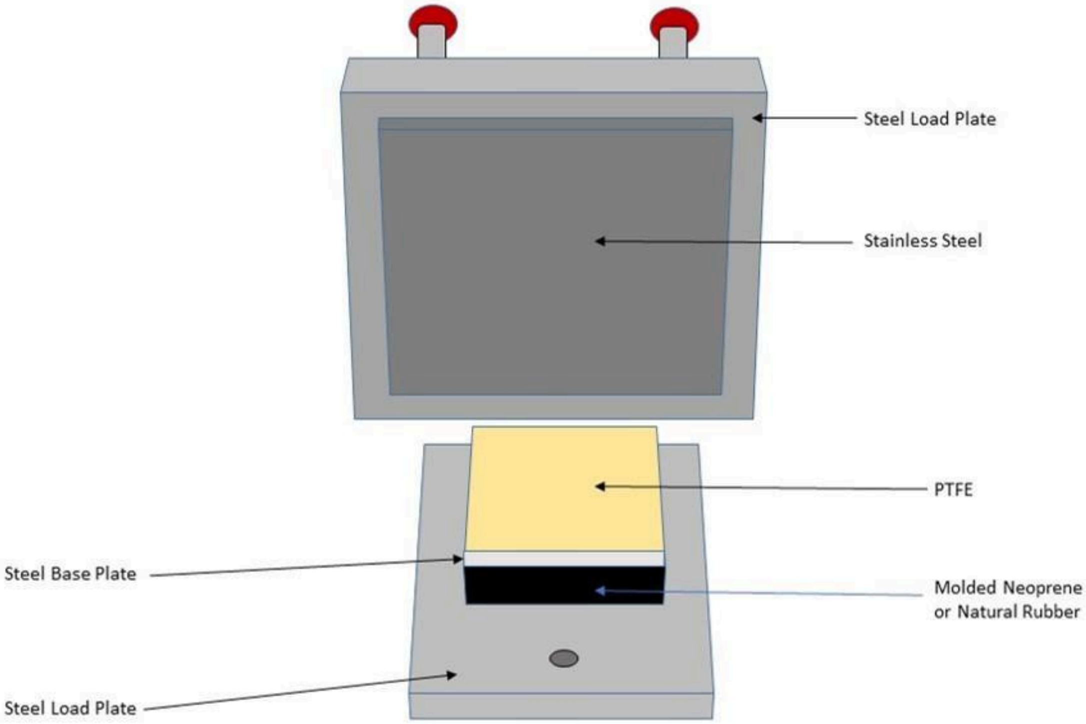


*Figure 14.1 - Rendering of Sliding Neoprene Bearing*

**HLMR bearings**, such as Pot and Disc bearings, are capable of handling larger loads and movements, making them suitable for longer span structures with rotation capability and thermal movement requirements. Pot bearings consist of a base plate containing a rubber cushion inside a low cylinder or ring that allows modest rotation. The name derives from the system design, which includes a confined elastomer, in conjunction with a top plate, located on a piston designed to fit precisely within a rubber cushion “donut hole” inside the cylinder. This elastomer disc is under high pressure, requiring a seal to prevent the rubber from squeezing out of the “pot.” The top plate may have one of three arrangements: fixed, free, or guided.

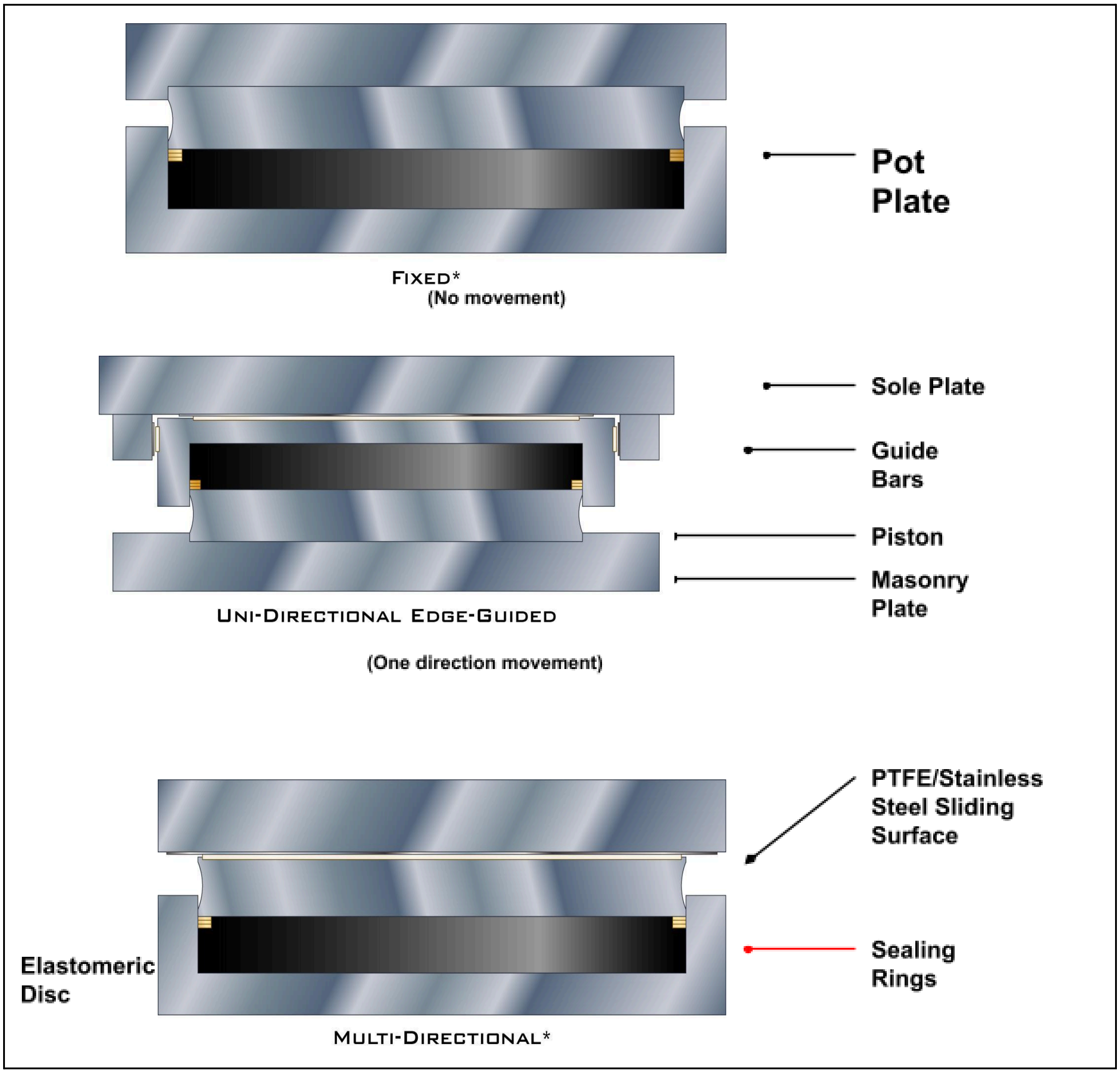


*Figure 14.2 - Examples of Pot Bearings*
*(Graphic Courtesy of D.S. Brown Company)*

**Disc bearings** provide greater rotational capacity than traditional pot bearings by using a molded urethane disc that is unconfined. The disc is unconfined at the sides, with a pin securing the urethane element. Thermal and multi-directional movements are facilitated through sliding top plates. The disc's specific geometry and dimensions are calculated taking load, rotation, and movement requirements into consideration. Concerns about elastomer leakage may be alleviated by selecting a disc made of solid polyether urethane.

To provide horizontal fixity to the structure, bearings are typically bolted or welded to a steel load plate with embedded anchors or dowels in the pier/abutment and in the concrete segment above.

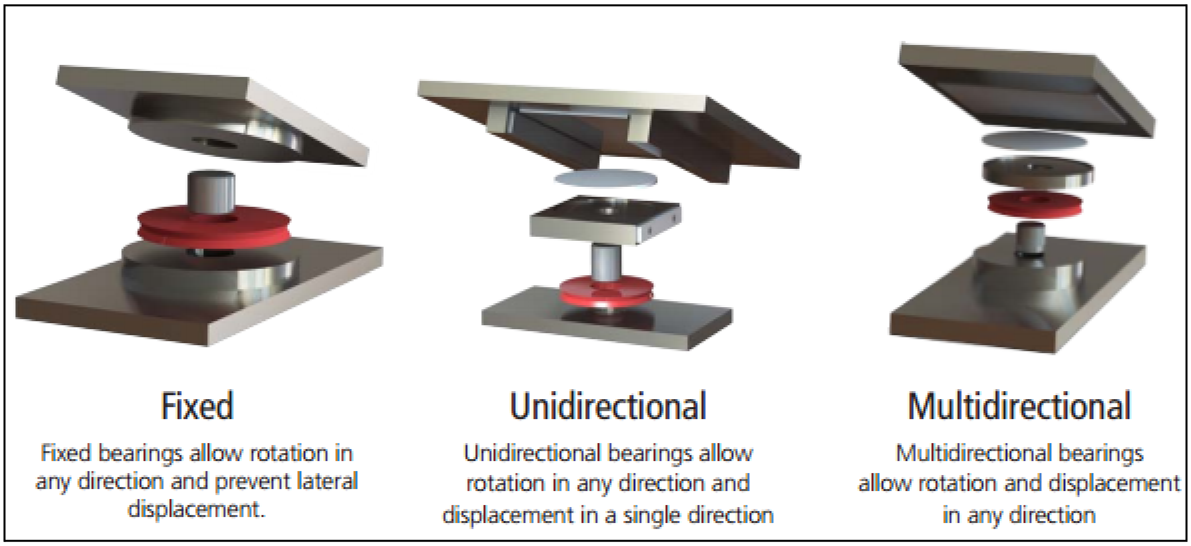


***Figure 14.3 - Disc Bearings***
***(Graphic Courtesy of R.J. Watson Inc.)***

### 14.1.1 Seismic Bearings

Several types of bearings designed for seismic conditions are commercially available and in use, including seismic pendulum, lead rubber, and disc sliding systems. The Structural Engineer shall determine an appropriate Seismic Bearing System based upon form, fit and design criteria.

***Figure 14.4 – Example of Disc Sliding Seismic Isolation Bearing***
***(Graphic Courtesy of R.J. Watson Inc.)***

### 14.1.2 Bearing Installation

Proper bearing installation demands attention to the following aspects.

#### 14.1.2.1 Mortar Pads

The heavy loads transmitted by the bearings from the superstructure to the substructure make the substructure and superstructure concrete on both sides highly stressed. Using a flowable material or dry pack to ensure uniform load distribution is critical. Mortar pads are recommended to facilitate appropriate installation and bearing functionality.

During bearing placement steel shims are often used between the pier and the bottom anchorage studs. To avoid anchor deformation and subsequent mortar pad cracking, a compressible shim, such as wood, may be used in lieu of all steel to prevent anchor deformation.

Both neoprene and HLMR bearings require use of mortar pads above and below the bearing, since neither the top of the pier nor the bottom of the structure can be built with a small enough tolerance. The pads are typically comprised of specialty mixes with high early strength and low shrinkage properties; the specific material selected shall meet established industry standards and be approved by the Owner, Specifier, or Project Engineer. Neoprene bearings require a mortar strength of 3,000 - 4,000 psi; HLMR bearings commonly need 6,000 psi. Most critically, to provide completely uniform support to the bearing, the mortar pad must be free of all voids. This demands both a quality product and thorough inspection.

For poured or grouted joints especially, a full-scale test of the grout-placing procedures is also recommended.

#### 14.1.2.2 Horizontal Orientation and Performance Assurance

Bearings are nearly always installed horizontally to assure stability and functionality; Bearing Manufacturers must provide calculations and performance test data to validate movement capabilities in accordance with those established for a given structure.

#### 14.1.2.3 Temperature Adjustment

Bearings with sliding surfaces should be adjusted based on the ambient temperature at the time of installation. The designer uses the site’s average ambient temperature to calculate how much the bridge will expand or contract and, therefore, how much the bearing will need to be able to move either way. If, however, the bearing is installed during the coldest time of year, the bridge will expand when the temperature rises. In this case, the bearing’s top plate needs to be shifted so full temperature movement is available for expansion. Temperature adjustments must be shown on the approved shop drawings.

#### 14.1.2.4 Direction of Movement

Guided HLMR bearings, which allow movement in one direction only, need to be installed so that the bearing’s direction of movement is the same as that of the bridge. For straight bridges, this is the bridge axis. For curved bridges, instruction should be provided on the plans regarding the direction of movement. There is often some tolerance since the space between the guide bars is about 1/8 in. larger than the top plate of the bearing sliding in. This amount of tolerance for bar spacing shall be outlined in Material Specifications.

This 1/8 in. space should be carefully divided into two equal amounts on either side of the top plate and kept constant with temporary inserts until the bearing is placed. This provides the guide bars with some movement capability in both directions, as well as tolerance for turning.

## 14.2 Expansion Joints

The four types of expansion joints used on segmental bridges, along with identified movement capabilities, are:

- Strip seal joint systems – movements up to three (3) in.
- Molded, steel-reinforced rubber cushion bolt-down system – movements up to 13 in.
- Modular Joint Systems (Standard and Seismic Systems) – movements up to 52+ in.
- Finger joints – movements up to 12 in. Sliding type finger joints can accommodate even larger movements.

The same adjustments necessary for bearings (discussed above) apply to expansion joints.

### 14.2.1 Strip Seal Joint Systems

Strip seal expansion joint systems are an effective and versatile option for movements up to 4 in ~~3 in~~. A neoprene sealing element (gland) is mechanically locked within a machined edge rail cavity, with an anchoring arrangement designed in accordance with current industry standards or special provision code requirements.

The steel extrusion assemblies are A-588 or A-36 grade steel with a galvanized finish. The edge rail cavity that accepts the locking lug is machined to fully engage the sealing element and prevent leakage. The sealing element is further secured using a single-component moisture curing adhesive.

During joint-setting, grade and temperature adjustments are made in accordance with the manufacturer's recommendations as outlined in the shop drawings. Strip seal systems typically come in 22’ 6” sections bolted together with a 2” opening. If the system is not adjusted for temperature and installed with the 2” standard gap, bolts must be removed prior to header concrete hardening.

The main advantages of a strip seal system are its simple design, movement versatility, armored edge protection, and mechanically locked-in-place neoprene sealing element.

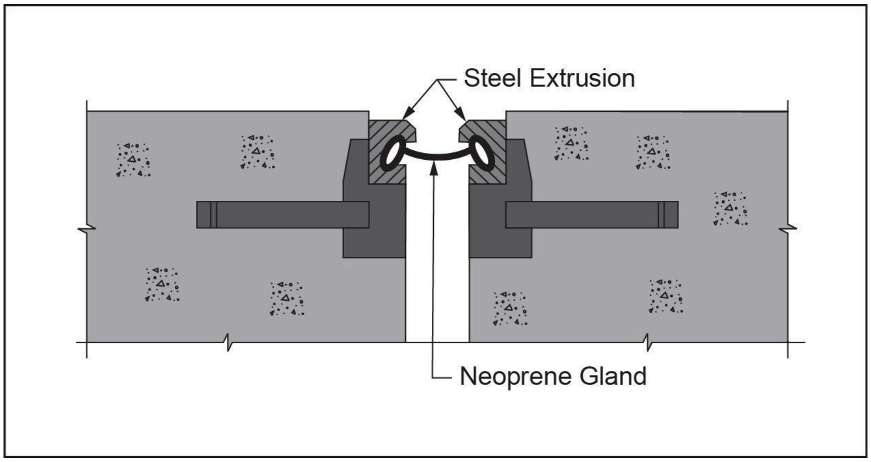


*Figure 14.5 - Typical Strip Seal Expansion Joint System*

### 14.2.2 Preformed Silicone Joint Sealing System

The Preformed Silicone Joint Seal System is comprised of a continuous extruded preformed inorganic silicone seal, a single component silicone locking adhesive, and a two-component primer. The gland is formed in an inverted “V” design which reduces stress on both the seal and adhesive as it is not in tension during normal cyclic movement. The inverted “V” design helps to minimize accumulation of debris but also provides a means to evacuate debris during normal operating conditions. The silicone locking adhesive, coupled with a two-part primer, creates a strong bond to concrete, elastomeric concrete, and steel armoring.

It is highly resistant to the damaging effects of ultraviolet radiation and ozone attack. It will also remain flexible in almost any environment as it offers material stability in a temperature range from -60°F to +350°F. Preformed Silicone Joint Seals can be used with or without armoring covering joint movements from 0-5”.

Should there ever be a puncture, the preformed silicone joint seal can be repaired using the silicone-based locking adhesive. Splicing, intersections, upturns, and directional changes can also be performed in the field by using the silicone locking adhesive. Maintenance with this type of seal is minimal with periodic flushing of the joint to remove accumulated debris. The system shall meet the requirements of ASTM D8138.

### 14.2.3 Molded, Steel-Reinforced Rubber Cushion Bolt-Down Joint Systems

Molded, steel-reinforced rubber cushion bolt-down systems have numerous applications thanks to a low-profile design, large movement capacity, and cartridge anchor technology that enhances durability in an aggressive traffic environment. The system’s minimal blockout recessing, even for larger movement requirements, and lack of moving or mechanical accessories, satisfies designers looking for product simplicity.

An additional advantage is the ability to perform sectional, as opposed to full-length, joint removal and replacement.

As with all mechanical joint systems, temperature adjustments are necessary during construction. The force required to open and close the molded system is arranged with and accommodated by the manufacturer prior to installation.

### 14.2.4 Modular Joint Systems

#### Standard Movement Systems

A modular expansion joint system divides large movements into a series of smaller movements equally distributed among modules, or cells. As shown in **Figure 14.6**, the overall system design involves a matrix of surface beams connected to below-grade support bars, which ride back and forth within support boxes during thermal movement variances. Between each beam, a mechanically locked sealing element seals the joint during thermal movement differentials.

These systems must meet industry recommended design criteria and life-cycle performance fatigue standards. Reputable manufacturers perform a battery of tests developed in conjunction with researchers and transportation officials and document the results to verify quality.

Additionally, the project engineer, the contractor, or the specifier should also verify the manufacturer follows a formalized quality control program that complies with American Institute of Steel Construction (AISC) requirements. For quality control reasons, devices made by a subcontracted manufacturer are not acceptable.

For new construction, the contractor should confirm that the manufacturer is producing modular expansion joint systems at full length, with factory-installed seals, and that all lifting, shipping, and temperature adjustment hardware are included in the per-foot price. Field welding on modular joints should meet AWS D1.5 Bridge Welding Code specifications.

**Figure 14.7** shows a large capacity modular expansion joint system being prepared for installation.

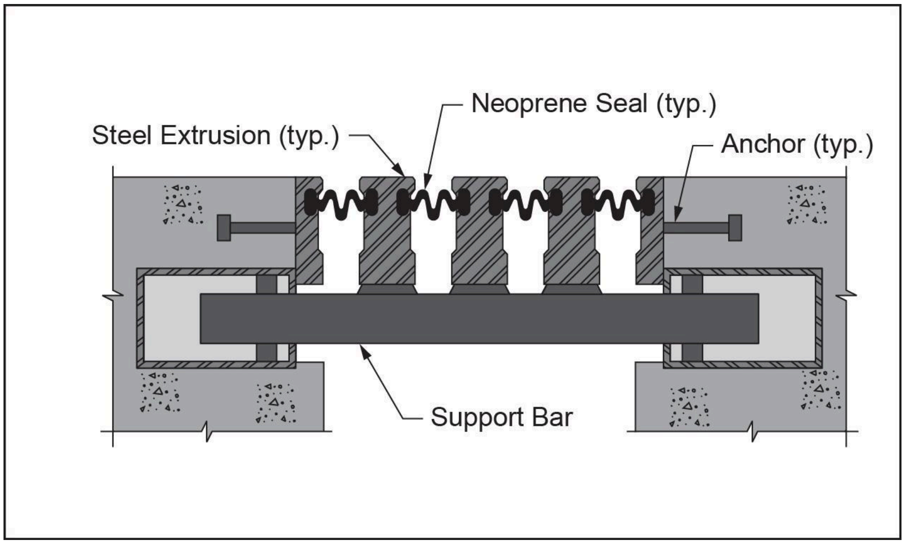


*Figure 14.6 –Typical Modular Expansion Joint System*

***Figure 14.7 –Installation of a Modular Expansion Joint System, Veterans' Glass City Skyway, OH (Photo Courtesy of FIGG)***

### Multi-Directional Movement and Seismic Modular Joint Systems

The non-linear or seismic movement requirements presented by long-span or curved structures can be satisfied by using multi-directional and/or seismically designed modular expansion devices.

Any product design being considered should be tested for individual and simultaneous multi-directional and accelerated movement capabilities and life-cycle fatigue to verify performance meets current design and industry standards.

Installation should be performed in accordance with manufacturer requirements, with documented procedures provided to the contractor as part of the shop drawings submittal. A qualified factory-authorized representative should be on site during initial joint placement, adjustment, and setting operations.

## 14.2.5 Finger Joint Systems

A finger joint consists of two steel plates, either burned or machined to accommodate thermal movement requirements, which are attached to a bridge's structure and its end bent. The "fingers" of the joint traverse the joint opening and are shaped to minimize the opening between the two plates.

All finger joint systems should incorporate a mechanically locked-in-place sealing device to prevent the intrusion of corrosive chemicals. Larger finger joint designs should also incorporate a fabric-reinforced trough to prevent the intrusion of water or chlorides.

Finger joints tend to be relatively generic in design, but unique elements and features may be incorporated into a project-specific application. Contractors should look for features that minimize installation labor and cost and provide flexibility in future maintenance.

Careful placement and installation is required to ensure appropriate structural support beneath the finger plates. Care should be taken to align the fingers for adequate linear movement and prevent misalignment and possible damage.

The principal disadvantage of finger joint systems is the difficulty of effectively maintaining and cleaning the below-grade troughs.

A sealed finger joint system incorporates a simple extruded neoprene sealing element and a machined steel retainer below the bolt-down finger assemblies. Smaller movement systems use a standard neoprene strip seal system, while large-movement systems implement a hybrid fabric-reinforced and molded sealing element with strip seal locking lugs within the machined steel seal retainer. This results in a simply sealed design that also meets low-profile requirements.

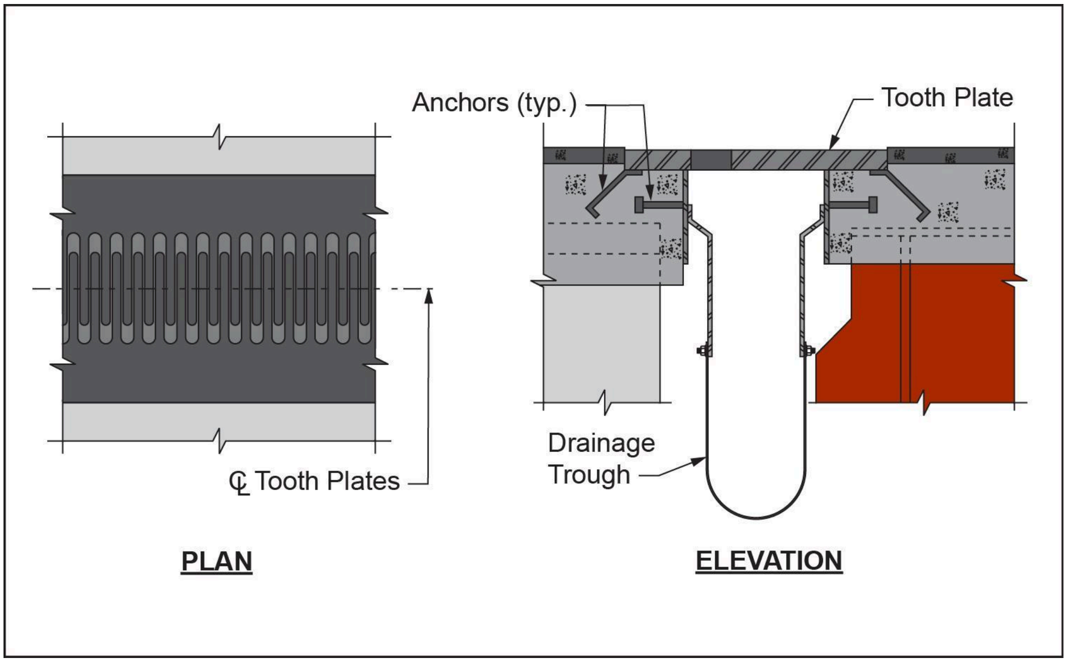


*Figure 14.8 - Typical Finger Joint System*

***Figure 14.9 - Typical Finger Joint System in Place, Sailboat Bridge, OK***
***(Photo Courtesy of FIGG)***

# TABLE OF CONTENTS

# Chapter 15:
# Lessons Learned

## 15.1 Overview

This chapter outlines common problems related specifically to the construction of concrete segmental and cable-supported bridges. All construction problems are the ultimate responsibility of the contractor. Even when accountability for certain aspects is delegated to the contractor's Construction Engineer, it is incumbent on the contractor to resolve all construction-related issues that arise throughout the project within the boundaries of the contract documents and owner's requirements. Additional resources from The Owner, the on-site inspection staff, the designer, or other entities can provide input on issue resolution and be valuable in ensuring quality and functionality of the final product is not affected.

## 15.2 Equipment Considerations

Developing a construction bid is complex and depends on multiple factors. For example, determining an achievable overall rate of production for erection or casting segments that is compatible with the project timeframe requires factoring in the availability of compatible equipment based on the complexity and variability of the structure. These factors can have a significant influence on the cycle times for casting and erection of segments.

The cost of necessary construction resources must be balanced with the impacts to the construction time. In order to achieve contract completion within the designated time constraints, production rates, equipment availability, equipment durability, and other factors will need to be carefully evaluated. The impacts to cost and time for procuring unanticipated additional resources to complete a project can be catastrophic and should be avoided by proper project resource planning.

### 15.2.1 Construction Loads

AASHTO LRFD Bridge Design Specification outlines detailed requirements for construction loads on segmental bridges. This reveals the critical impact construction loads can have on segmental bridge design.

Some notable construction failures have been due to overloads. It is essential the contractor determine precisely the weight of the erection equipment (particularly the erection gantries) and other loads, versus the assumed loadings included in the contract documents.

### 15.2.2 Truss Stability

Structures erected with an erection gantry often experience the greatest demand during the erection phase. It is essential to strictly follow all procedures outlined in the gantry supplier's user manual. The loads imparted by an erection gantry can be significant, and the details of its support are critical to the performance of the gantry/structure system.

One aspect to note is the stability of the columns when loaded by the gantry. This is of particular importance when the gantry includes a pendular leg, a support that is pinned at top and bottom and carries no moment. This type of connection can lead to a highly unstable system for tall or flexible columns. Difficulties occur when the loading from the gantry causes a longitudinal displacement in the column, inclining the pinned leg as shown in **Figure 15.1,** and applying an additional shear to the column. This secondary shear can create increasingly large deflections, until the entire system becomes unstable.

The failure risk related to this type of support requires the full attention of the contractor's engineer. Full consideration should be given to potential sources of flexibility, including foundation stiffness, and potential cracking of the column. This should be done even when initial loading is anticipated to cause no displacement (i.e., loading at the center of the column), as small placement tolerances can lead to significant displacements in flexible columns.

Mitigation measures include altering the support conditions of the truss or bracing the columns against longitudinal movement by mobilizing adjacent structures.

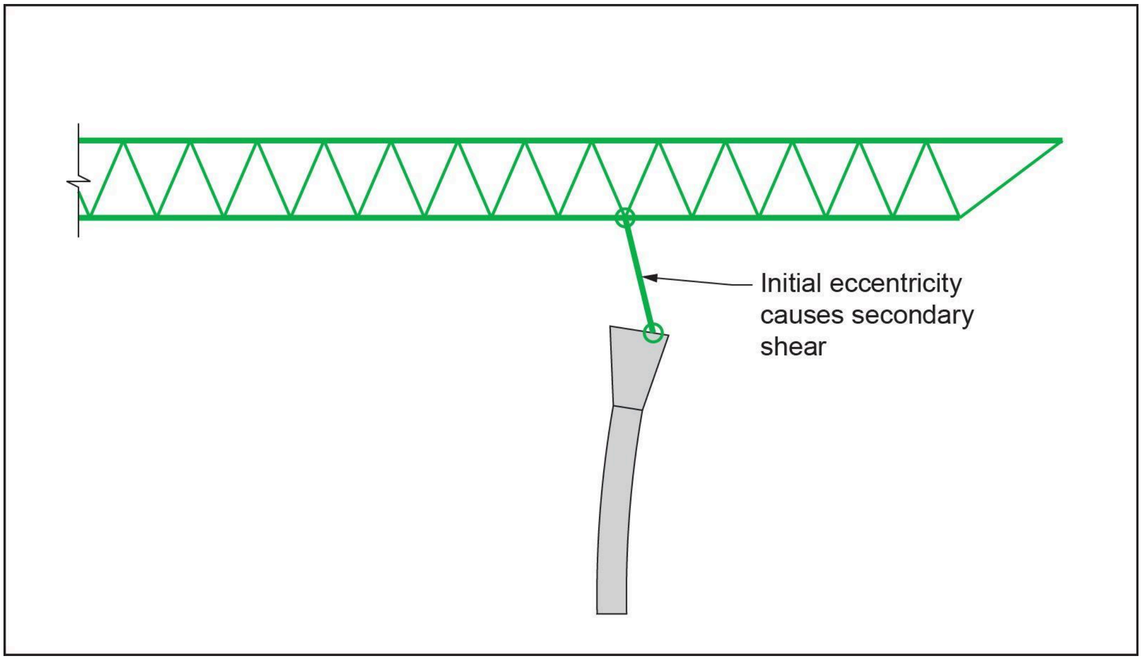


*Figure 15.1 – Gantry Support Instability*

### 15.2.3 Bearing Capacity of Truss Supports

When erecting segments with a gantry, the space available on the pier cap for the truss supports may be limited. In fact, it is not uncommon for the truss supports to be forced to, or even hooked over, the edge of the cap. In these situations, the bearing capacity of the region surrounding the supports must be verified, as a local shear failure can lead to loss of support for the truss. Less catastrophic, but still of concern, significant spalling of the cap may require costly repairs. These problems can be mitigated by post-tensioning the supports against the pier cap through temporary sleeves, or by increasing the local reinforcement above that specified in the design plans.

### 15.2.4 Warping Under Concentrated Loads

Erection equipment often places concentrated loads high on the structure. While it is good practice to locate these loads above a rigid point, such as directly above a web, secondary effects must be accounted for. For example, high local loads can warp a box girder section, creating bending moments in the flanges. This should be calculated and accounted for whenever concentrated loads are applied asymmetrically to a box section.

### 15.2.5 Gantry & Truss Cost Evaluations

Erection gantries and trusses are complex pieces of machinery that need a very detailed analysis of total cost associated with the piece of equipment. This equipment is often manufactured overseas, and it is best practice is to visit and inspect these pieces of equipment prior to shipping. Make sure shipping terms are fully understood and proper costs and insurance are accounted for in the pricing. Considerable room required for the assembly/disassembly of the equipment along with storage of all the shipping containers. With equipment being manufactured overseas, make sure spare parts package for major components are included in pricing considerations. Make sure that lighting, not only light placement but also wire routing is considered in the design of the equipment, equipment to be worked in non-daylight hours. Fall protection for workers during all operations of the equipment needs to be considered so proper tie off points or protective measures can be incorporated in the design. Having manufacturer personnel on site during assembly and operation for training also needs to be considered in pricing analysis, these personnel can be expensive and have limited work windows if they come in from overseas. The line speed of hoisting equipment needs to be considered to determine speed of operation and opening of roadways. Also if a full load test is required after the equipment is assembled or moved, make sure that it is included in your budget and also your schedule. Make sure electrical and hydraulic components are compatible with the supply chain of the country where work is being performed.

## 15.3 Out-of-Balance Moments

When erecting or casting in balanced cantilever, often times the out-of-balance moment (OBM) during construction is the controlling load case for the superstructure and/or pier. Applying the correct equipment weights and dynamic loading, such as the drop segment condition for precast erection, is critical to bridge design. The pier must be designed to support the OBM during cantilever construction when the moment is carried into the pier either through a monolithic connection between pier and pier segment or external brackets mounted to the pier. Designers usually don't consider this load case in their pier design.

Although maybe not the most cost-effective falsework solution, supporting the OBM with ground bearing falsework eliminates the construction live load demand on the pier.

Furthermore - the AASHTO prescribed segment drop load (2A) will generally control. This must be dealt with during design - so that the Contractor can properly make provisions for this load. If columns are not designed for Segment drop, then this must be clearly stated it the design assumptions.

## 15.4 Alignment and Geometry Problems

Alignment and geometry during construction deserve close attention, as errors and oversights can lead to major issues. Even with the powerful computer programs now used to calculate alignment and geometry control, significant and costly errors occur. Global graphical plots of alignment and elevation control computer output should always be performed to reveal any numerical errors. In addition, the following quality control measures should be taken during segment production and erection activities:

- Meticulous review and double-checking of all casting curves and geometry control procedures.
- Independent check of all geometry control readings and set-up calculations.
- Frequent verification, using independent benchmarks, that the instrument, target, and form bulkhead all remain at fixed positions.
- Use of erection elevations and horizontal alignment controls during erection to ensure correct alignment.

A plan for how to deal with problems should be required before beginning erection. Allowable geometry tolerances should be included in the special provisions. Allowable forces at closure to bring the structure back into alignment should be included in the design and shown on the Contract Documents

### 15.4.1 Geometry Control in Gore Regions

Gore regions occur where roadway width varies significantly, such as between a throughway and an approach ramp. Sometimes, this is accommodated by varying the length of the overhang, but that is not always sufficient. In these situations, the distance between the webs may vary within a given span or casting set. To keep the webs at a vertically rigid point, it is good practice to alter the positions of the survey markers to stay near the webs. Note that this can lead to a confusing set of casting coordinates, which are more typically set to accommodate a fixed offset. Communication and coordination between the contractor’s engineer and the casting yard survey team is critical to avoid casting errors in these cases.

### 15.4.2 Fit of Match-Cast Segments

In general, match-cast segments should fit perfectly during erection, but if the match-cast surfaces are changed after being taken apart, they will not. Changes to the surface may result from:

- Excessive sandblasting.

- Repair of surface defects after match-casting (for example, a broken shear key).
- Epoxy injection of cracks.

Repairing surface defects should generally be delayed until after segment erection to avoid further damage to the joint.

## 15.5 Steam Curing and Warping

Steam curing in the casting yard can be an effective method for gaining high early strength – but improperly done, it can lead to fit-up problems during erection. Applying steam only to the wet-cast segment creates a temperature differential with the match-cast segment. During curing, the match-cast segment will curve, transferring the curvature to the wet-cast segment. When steam is removed, however, the match-cast segment will revert to its original shape, while the wet-cast segment retains the curvature.

## 15.6 Post-Tensioning

Careful planning and execution of post-tensioning (PT) is essential in successful project completion. Most segmental structures will have many varying types, sizes, lengths, and configurations of post-tensioning. It is important for the field engineering staff to understand the PT requirements in the project design, along with any changes made by the construction engineer. It is the responsibility of the contractor, the quality control and quality assurance, the inspection staff, and the owner to be in agreement with PT procedures and requirements. Prior to commencement of activities formal meetings, and field discussions should be held to determine intended forces, theoretical elongations, intended elongation measuring methods, documentation procedures, material tracking, field issue escalation procedures, conditions for acceptance, and safety protocols.

### 15.6.1 Short Tendon Elongations

Segmental construction, particularly balanced cantilever construction, often involves stressing tendons that are significantly shorter than typical; tendons as short as 30 ft. are not uncommon. In these cases, elongation readings can be strongly affected by the stressing procedure.

Typically, tendons are stressed and re-seated at a relatively low level before being stressed to their final values. For tendons whose final elongation is low, this can account for a measurable loss of stress. This must be accounted for in the secondary pull, or the elongation readings will consistently indicate the tendons have been overstressed. Often, project specifications require the measured elongations to be within a tolerance of the theoretical value, typically ±7 percent. For short tendons, the measured elongation may be only a fraction of an inch, and seven percent of that can be less than the tolerance of measurement. Applying a ±7 percent tolerance specification is not practical, therefore, and alternate methods of force verification (e.g., a dead-end lift-off) should be discussed with the EOR prior to performing the work.

### 15.6.2 Tendon Blockages

To avoid blockages prior to or during tendon installation, the following procedures are recommended:

- Use mandrels during casting to ensure alignment of all ducts at joints.
- Temporarily seal empty ducts (esp. vertical ducts) to prevent debris from entering prior to tendon installation.
- Swab ducts immediately following segment erection to eliminate blockages due to epoxy squeezed into the joint or use duct couplers to eliminate this issue.
- If plastic ducts in footings collapse due to hydrostatic pressure from the concrete, use concrete coring equipment to create new openings for tendon placement.
- As a last resort, locate the blockage, then remove it by carefully chipping into the duct.

If the one or more tendons cannot be installed, alternative provisional ducts should be used as required by the specifications for tendon installation.

### 15.6.3 Tendon Pop-Out

Prestressing tendons exert outward pressure in areas where the tendons are curved or kinked. When this curvature is intentional, the design provides reinforcing to contain the tendon. Sometimes though, mistakes made during construction cause this tendon to pop-out. **Figure 15.2** illustrates this, showing a slab containing a tendon that is intended to be straight. Insufficient support has made the tendon sag between the joints, thus creating a possibility for tendon pop-out, delamination, or bending cracks. The cost of repairing tendon delamination can be significant, especially in the bottom slab where access can be very difficult. **Figure 15.3** shows two curved tendons at a diaphragm, one over the other. When there is adequate distance between tendons, a large radius of curvature, and properly compacted concrete between the ducts, problems very rarely develop. But at times both the distance between tendons and the concrete quality between ducts may be less than intended. As a consequence, as illustrated in **Figure 15.3**, duct "b" may be pressed into duct "a," spalling the concrete and causing a problem with stressing the tendon in duct "a."

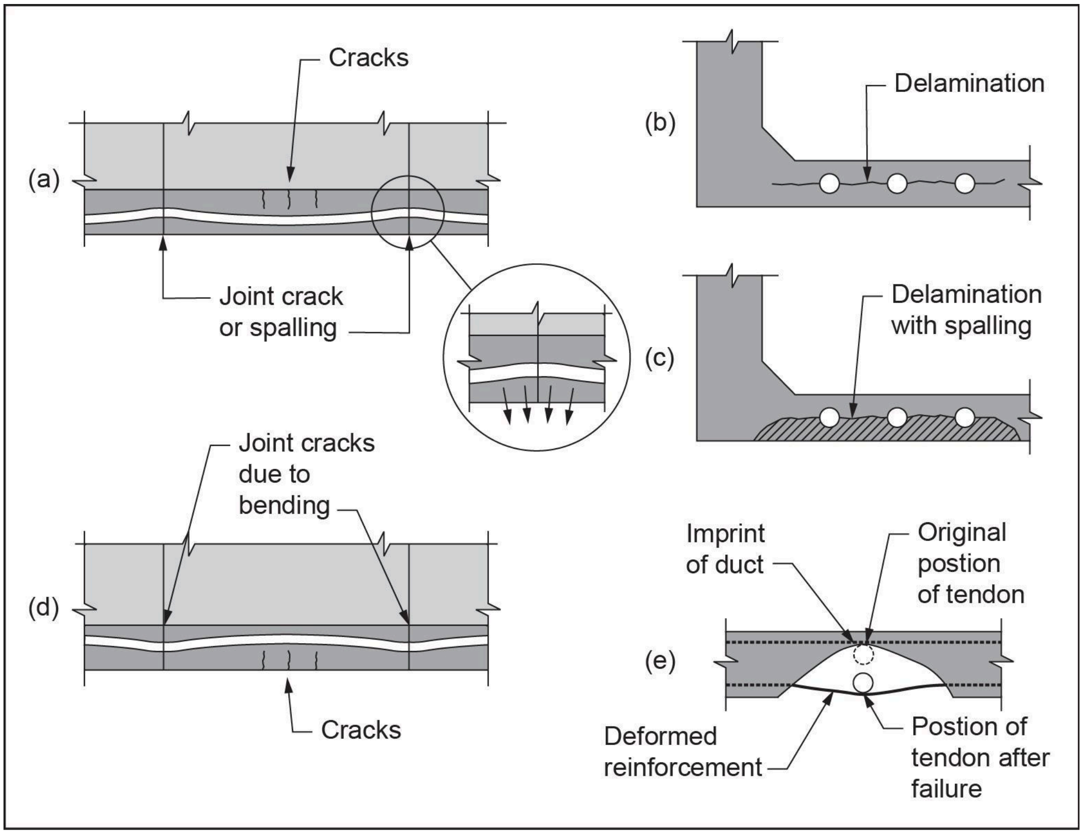


*Figure 15.2 – Effects of Tendon Duct Misalignment*

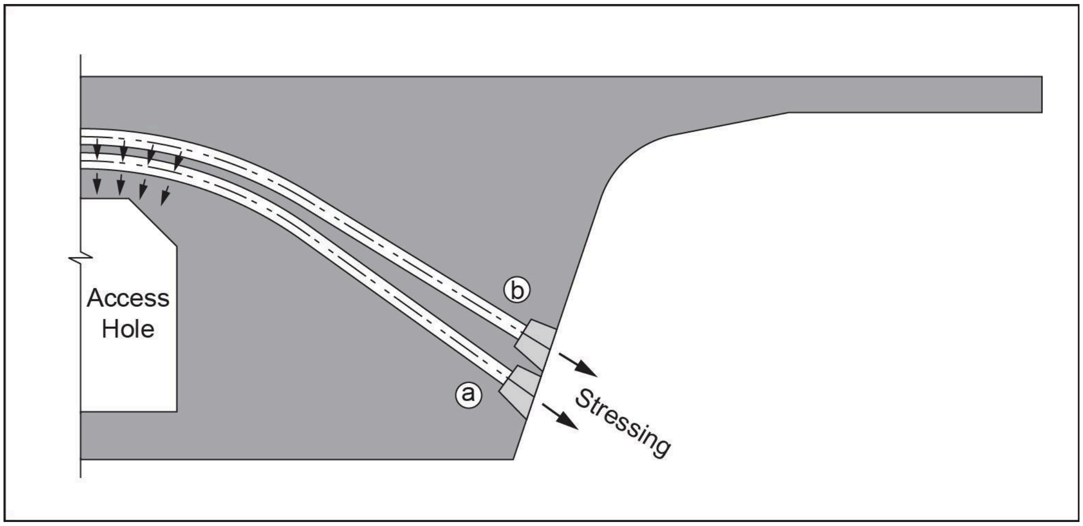


*Figure 15.3 – Curvature Pressure Exerted by Tendons*

## 15.7 Epoxy Not Setting

When epoxy fails to properly set, the usual cause is careless mixing of the resin and hardener. Soft epoxy means the shear keys must transfer the entire design shear from one segment to the next – something the keys are not designed to do. When soft epoxy is first noted, an engineering check must be performed to verify shear key capacity.

To mitigate this issue, the following are good practices:

1. Good quality control should be established for epoxy mixing. It helps to color the hardener differently from the resin so proper mixing can be visually checked.

2. Once soft epoxy is noted and the cause established, if an engineering review indicates the keys across the joint are adequate, no further structural repair is required.

3. If there are issues with epoxy setting, the material in the joint should be tested for any problems with durability.

4. Always check epoxy expiration dates prior to use on the job.

## 15.8 Freezing of Water in Ducts and Recess Pockets

Great care should be taken to prevent any outside moisture or water from entering into empty ducts or recess pockets. This water, if left in place, can negatively affect grout quality and can cause unforeseen damage to the structure through freeze-thaw cycles. The following steps should be considered to prevent potential negative effects:

1. Grouting tendons and recess pockets before the onset of frost whenever possible, noting that grout itself can freeze and that grouting at freezing or low temperatures.

2. Empty water from any tendons or anchor pockets that cannot be grouted by:

a. Providing drains and ensuring that they function.
b. Displacing the water with compressed air, noting that excessively high air pressure can also be a problem.

3. Providing temporary corrosion protection for the tendon if ducts must be left ungrouted for a long period of time (if contract allows).

## 15.9 Construction Access for Each Phase

Access during each phase of construction must be carefully reviewed and planned by the contractor. Often, not giving enough consideration to access during estimating leads to cost overruns during construction. Attention must be paid to leading edge access and platforms for the top and bottom decks and the completed bridge (**Figure 15.4**). During planning, thought should be given to how the bridge exterior surface will be finished. Then, perhaps most critically, the exterior surface must be finished while construction progresses to avoid the need for expensive access equipment after the structure is completed.

Additional temporary access into segments during construction may be needed if permanent access locations are too far away and would require moving of materials from the inside of the segments a great distance. Consider how materials like conduits, formwork, shoring, jacks, etc. need to be moved around inside the segments.

*Figure 15.4 – Construction Access at the Leading Edges*
*(Photo courtesy of Brayman Construction.)*

# TABLE OF CONTENTS

# Chapter 16:
# Construction Engineering and Inspection (CEI) of Segmental Construction

## 16.1 Project Site Roles

To appreciate the responsibility of the construction engineering and inspection (CEI) consultant, it is important to identify the role of each of the stakeholders involved during the construction phase. Some owners and agencies may refer to this consultant as Construction Administration, Construction Management, or other similar terms. Clearly defining each role helps avoid the risks associated with assuming the responsibilities of another party and the resulting miscommunication.

The primary roles defined here are:

- Owner
- Contractor
- Contractor's engineer
- CEI team

**The Owner** – The owner is the entity for which the project is constructed and will be responsible for the future evaluation and maintenance of the structure. In concrete segmental bridge projects, this is most often a state or local governmental agency, or other transportation authority or agency. The owner may or may not have a daily presence on the project and may have limited involvement unless an issue escalates to a level requiring their attention. Regardless, the owner relies on the CEI team to administer the project and keep them informed of construction progress and issues that arise. The owner also relies on sound technical advice from the CEI team, as well as from other sources including the FHWA, the engineer of record (EOR), or specialized consultants.

Ultimately, the owner's appointed decision–maker weighs and evaluates the technical merits of all advice and input received, along with the experience and expertise of the owner's team, to arrive at a decision that is in the entity's best interest. This process may consider non–technical factors as well. It is critical that the CEI team provide the most accurate and timely information on project issues and assist the owner in this decision–making process.

**The Contractor** – The contractor is responsible for constructing the project. Their challenge is to plan and schedule a means of executing all the work required to fulfill the contract. The contractor's goal is to build the project in reasonably close conformity with the plans, specifications, and special provisions provided by the owner while maximizing the potential for reasonable profit. This role bears very high risk. While most engineers and inspectors recognize this fact, relatively few fully appreciate its extent. With one bad decision, the contractor can put the project behind schedule and reduce or eliminate any profit. To help offset as–yet–unknown issues that inevitably arise, contractors typically try to maintain a contingency, or cushion. The contractor is also responsible for purchasing all materials, managing site workers and subcontractors, and dealing with suppliers, in addition to interfacing with the CEI team and the owner. The CEI team should recognize that the contractor must weigh the technical aspects of an issue against many other factors.

**The Contractor's Engineer** – The role of the contractor's engineer is defined by the contractual agreement with the contractor, which outlines the specific tasks to be performed. The contractor's engineer bases all submittals and decisions on engineering judgment, knowledge, and experience and provides the contractor with specific engineering and technical advice. When this advice does not agree with the EOR's or owner's engineering opinion, it falls to the contractor's engineer to demonstrate and justify all of his (or her) assumptions and calculations.

**The CEI Team** – The CEI team is responsible for administering, monitoring, and inspecting the work to verify that the project is constructed in reasonably close conformance with the plans and specification – backed up by detailed documentation that demonstrates this fact. The CEI team's ultimate objective is to ensure the owner receives what is indicated in the contract documents. This means all regulations and permits are obtained; all operations adhere to the terms of the contract; the quality of work meets or exceeds industry standards; contractor payments are processed timely; and any changes are promptly and equitably addressed. The CEI team must coordinate and balance the interests of the owner, the requirements of the designer, the work of the contractor and the contractor's engineer, as well as the issues and concerns of multiple jurisdictions, utility owners, and stakeholders. The CEI team also must be able to make decisions and facilitate the construction process rather than simply escalating issues up the ladder to the owner for resolution. Though some issues may require escalation, most can be resolved at a lower level. The CEI team may also be responsible for surveying, material sampling and testing, material collection, and product certifications.

## 16.2 CEI Early Involvement

The CEI team can provide critical support early in the project, playing a proactive role in all construction planning and execution activities and weighing the benefits and risks for all stakeholders. Experienced CEI teams can contribute by performing constructability or biddability reviews of the contract documents, providing input and advice regarding contractor pre–qualification, assist with pre–bid Q & A, participation in the preconstruction conference or other meeting(s), or assist with bid review and analysis.

## 16.3 Preconstruction Conference

The preconstruction conference is generally the first formal project meeting attended by all contracted parties. Sometimes chaired by the CEI team leader, it is usually associated with the *Notice to Proceed* and structured to follow specific state and/or federal guidelines. The primary purpose of the preconstruction conference is to formally introduce the parties and to review some early action items that must be completed before work can begin. Involving the CEI team in pre–bid activities allows them to lay the groundwork for successfully engaging each party. At the preconstruction conference, the CEI team should understand the motivations and concerns of each stakeholder and develop strategies to address these concerns before construction starts. This project–wide meeting is also an excellent time to discuss early action items and activities that must be completed before work can begin, including any associated submittals, and to establish a program for technical workshops needed to get the engineering work underway.

## 16.4 Weekly Progress Meetings

Weekly or bi–weekly progress meetings are an important ingredient of successful project management. While not a substitute for daily interface and communication between the CEI and contractor teams on all levels, formal progress meetings allow discussion of specific, timely issues pertinent to project execution. Often, general topics for discussion include:

- Safety
- Work Progress
- Two–Week Look Ahead Schedule for Major or New Activities
- Status of Submittals, Requests for Information (RFIs), Nonconformance Reports (NCRs), and RFCs (Requests for Change)
- Environmental Issues
- Outstanding Issues
- New Issues

A formal agenda should be agreed on by all parties and distributed well before the meeting so attendees can familiarize themselves with the issues to be discussed.

It is not necessary to resolve all outstanding issues in these meetings, but to provide a forum for open discussion where parties express their positions and work collaboratively on possible paths to a resolution. Each meeting should be kept to one hour, which requires a strong chairperson to run it efficiently and keep everyone focused on the agenda. If meetings consistently run long, one or more general topics may need to be handled at a separate meeting. Attendees should not be allowed to use the meeting as a soapbox to impose their position.

The CEI team should submit formal minutes of these meetings. The minutes should be distributed before the next scheduled meeting and formally agreed upon by all parties at the start of the following meeting. The minutes provide a snapshot of the project for that date and a contemporaneous record that is valuable for all parties.

## 16.5 Document Control: Engineering Submittals, Shop Drawings, Project Communications, RFIs, NCRs and RFCs

A key component of the CEI team's role is document control. Contract documents may consist of several hundred design drawings, standard specifications, special provisions, and permits. By project completion, the final documentation package may exceed thousands of pages and may include as–built drawings; shop drawings; material warranties; project correspondence including change orders, supplemental agreements, RFIs (request for information), NCRs (non–conformance report), and RFCs (request for change); daily inspection reports; and material testing reports. These enormous packages must be organized and presented in a clear and accessible manner, in the event of an audit and to provide information for future project maintenance, repair, addition, or demolition work. Owners may have specific guidelines and may also require the use of specific software for tracking and storing documents electronically and/or hard copy. Long-term retainage of contract documents must be considered for any document control plan.

Segmental bridge projects will generate specific contract documents. These will include a high volume of project specific shop drawings, work plans for erection, casting, post–tensioning, grouting and reinforcing.

It is the responsibility of the CEI team to ensure RFIs are addressed and answered in a timely manner. Contractual requirements should be established for RFI response times. NCRs, issued by the CEI team for work not meeting project specifications or quality standards, should be acted upon timely by the contractor and tracked by the CEI team to ensure compliance with any recommended corrective measures.

## 16.6 Technical Workshops / Submittals / Format

Since the construction engineering and submittals required for a typical segmental project are considerable, contractors usually hire a specialized engineering firm to perform as the contractor's engineer and prepare erection details, staged construction calculations, and shop drawings. (Refer to **Section 16.1** for further description of this role.) To maintain schedule, it is important that these submittals get underway soon after Notice to Proceed. One approach is for the CEI team to organize a series of workshops for the owner, EOR, contractor, and contractor's engineer to review expectations for submittal content, format, PE stamp requirements, submittal schedule, and processing procedures. Some owners accept a completely paperless system; others are open to using digital technology for expediting submittals and reviews but require hard copies for permanent records. Discussing and agreeing on these items early gets everyone on the same page and into an efficient production mode.

## 16.7 Concrete Mix Designs

Concrete mix designs are another critical detail to address early, particularly if trial mixes must be established, tested, and approved prior to precast operations. Often necessary, trial mix testing can be very time–consuming and may quickly become critical path if one or more mixes fail to meet all requirements. The CEI team should work closely with the precaster, the contractor, the testing lab, and the owner to coordinate the testing and acceptance process for trial mixes. Any contract–required concrete mix testing and approval must be considered in the contract schedule and the contractor's casting and erection schedule program.

## 16.8 Casting Yard Quality Control / Geometry Control

The CEI team overseeing casting yard operations should be involved early in reviewing precast forms and yard set–up issues including quality control, concrete supply, rebar jig and cage assembly, geometry control, and segment handling, storage, and transport. Once these major items are underway, the CEI team can work with the contractor on the details of segment casting with the objective of quickly achieving a desired production rate while meeting all contract requirements and tolerances. This last aspect is critical, as it is normal and often essential to have a significant inventory of cast segments already in storage before erection starts. Additionally, working with the contractor, the CEI should establish detailed checklists for reinforcement verification, post–tensioning duct layout, location of all embedded items such as erection sleeves/anchor bolts, utility ducts, and other miscellaneous items. These checklists then become part of the contractor's quality control program, which should be based on specific contractual obligations.

Once segment casting begins, the CEI team typically works closely with contractor personnel on geometry control. As detailed in Chapter 13, it is strongly recommended that two independent survey checks be made for as–cast geometry setups and that each one be checked by at least two independent methods, preferably including one graphical method. This vastly improves the likelihood of catching a survey error, sign reversal, or transposing problem.

In addition to performing the traditional geometry control survey, personnel should thoroughly check each match–cast segment for dimensional tolerances and any casting defects. Repairs identified in the casting yard and corrected before shipment are far less costly than those identified during or just prior to erection, when erection of that segment is on the critical path. Specific items to review include duct positions at the match–cast joints, exit orientation angles for embedded post–tensioning ducts, broken shear keys, crushed or out–of–position post–tensioning ducts, bearing surfaces, embedded items, etc.

It is important that information on any repairs or corrections needed after erection (e.g., repairs to a match–cast face) be communicated clearly and timely from the casting yard to the erection site.

If there are elements at the interface of substructure and superstructure that are dimensionally very tight, as–builts should be taken for coordination with the subsequent segment casting. For further information, refer to **Chapters 9** and **13** of this handbook.

## 16.9 Review of Erection Procedures

Regardless of the construction method, erection procedures are typically a required submittal. An erection schematic is included as part of the contract drawings, noting that complete details of the procedures, sequence, and associated staged calculations will be developed by the contractor. Most often, the contractor will engage a specialty engineer to perform this work. Some owners contractually may require the CEI team to review the erection procedures from an engineering perspective, paying special attention to stability, equipment capacities, safety, schedule, and any other requirements of the contract. Other owners delegate this task to the EOR, who takes the perspective of loading, reviewing the submittal to ensure the partially constructed, permanent structure can support the erection loads and that the loads are consistent with those assumed in design. Several reviews and iterations of the erection procedures and sequence may be required to obtain approval. Load testing of the specialized equipment is typically specified in the contract and is witnessed and approved by the CEI team.

## 16.10 Confirmation of Erection Procedures

It is imperative that crews strictly follow the approved erection procedures and sequence and that any suggested changes are thoroughly developed and subjected to the full approval process. Once erection commences, the contractor's engineer and a member of the CEI team should sign off on each step. This dual sign–off is especially important for erection gantries, where failures are most often related to critical steps being missed or improperly carried out during launching. The consequences of a gantry failure – serious injury or fatality, property damage, schedule impacts, and all associated costs – can be crippling to a project. Paying attention to details, following the approved sequence, and maintaining competent supervision are critical. The minimum qualifications for personnel operating the erection gantries should be specified in the contract and strictly enforced.

An example of a dual sign–off on an erection launching procedure is included at the end of this chapter.

## 16.11 Post–Tensioning and Grouting

As the primary reinforcing element in a precast segmental bridge, the structural significance of post–tensioning cannot be overstated and warrants special attention to installation, tensioning, and corrosion protection via grouting. CEI staff must include trained, certified personnel to oversee the operations. CEI field crews should have personnel with PTI Level 2 certifications and ASBI Grouting Certification. The CEI team should ensure applied forces are per design requirements by confirming jack calibrations and gauge pressures and reconciling elongations. Any inconsistencies must be satisfactorily explained and/or corrected.

Post–tensioning and grouting should be performed by trained personnel who understand the importance and the quality required. Both the contractor and the CEI team should keep detailed records of these operations and reconcile them routinely so that complete sets of data are turned over to the owner at project completion.

Examples of a stressing record and a grouting record are included at the end of this chapter.

## 16.12 Bearings, Expansion Joints and Seismic Devices

Likewise, bearings and expansion joints must be correctly installed to ensure the bridge moves as intended without distress. Bearings can be fixed or provide for movement in one or both directions; if the latter, they must be oriented based on the direction(s) of motion desired. Both expansion joints and bearings are typically set to specific dimensions based on the temperature at the time of installation.

If the bearings and expansion joints are intended to work in harmony with seismic restrainers or shock transmission devices (STDs), each element must be installed correctly and within specified tolerance. A thorough review of all related tolerances is recommended prior to precasting and substructure construction to verify all elements can be installed as required. The CEI team and the contractor should agree early on specific procedures and checks for these elements to include as part of the project's quality control program. For further information refer to **Chapter 14** of this manual.

## 16.13 Safety

The contractor is responsible for overall site safety and the safety of all persons and property on the site. As such, the contractor normally has one or more full–time on–site safety representatives assigned to oversee the work and ensure compliance with all local and federal safety requirements. Any party that has been involved in post–accident investigations and the lengthy and costly litigation that can result will fully appreciate the importance of a detailed and comprehensive accident prevention program.

Having the CEI team attend contractor toolbox meetings is strongly recommended, particularly just prior to the start of any new operation. A construction work plan reviewed by the construction manager addresses how the physical operation will be performed, along with any associated job hazard analyses (JHAs) that need to be fully understood by the workforce. The owner may provide, or request the CEI team to include, trained safety personnel specifically assigned to conduct daily site inspections and be the go–to for the owner/CEI team regarding safety issues.

It is good practice to make safety the first agenda item at all formal progress meetings, as these weekly or bi–weekly forums provide an excellent way to address safety planning and/or corrective actions. On a daily basis, the entire team must understand that safety is everyone's responsibility. Many teams achieve excellent safety records by adopting the practice that no one should walk by an unsafe act or condition without taking corrective action or bringing to the attention of the appropriate individuals who can correct it.

## 16.14 Environmental Issues

As with safety, environmental compliance involves everyone. The CEI team and the contractor should work together to identify environmentally sensitive issues, particularly when working over water or adjacent to streams and wetlands. Together, they should develop appropriate responses, as regulatory agencies impose significant fines for non–compliance and owners suffer doubly when they seek permits for future work. In addition to construction site stewardship, measures such as waste reduction and minimizing water use may be implemented. Other measures might include best management practices (BMPs) for sediment collection, water treatment systems for high pH (alkalinity), or specified disposal methods for grout, concrete epoxy, Styrofoam, or other construction byproducts.

For segmental bridge construction, specific attention needs to be paid to activities that can have environmental effects. Pressure grouting of tendons can produce spills and will necessitate carefully planned actions and responses to ensure containment of the material. Additionally, segment epoxy for pre-cast construction must be contained at all times and prevented from dripping or intruding into the surrounding areas.

## 16.15 Claims and Changes

Another key facet of the CEI team's role is handling claims and changes. Precast structures can be complex and, often, the related claims and changes are equally complicated. CEI teams must have personnel with expertise and experience in the construction technique and the contractors means, methods, and scope to properly represent the owner's interests.

## 16.16 Summary

Quite simply, the CEI team must be a part of the solution and not part of the problem. The CEI team impacts project success by choosing to be either proactive or inactive. The role demands an active, engaged team, as inaction never represents the best interest of the owner.

There is no place on a successful project for an adversarial attitude. The CEI team must lead by example with a cooperative, collaborative attitude. When the contractor's personnel know the CEI team and the owner are working with them toward a common goal, productive relationships flourish and everyone wins.

Many projects start with a bit of trepidation, as the staff often do not know each other well. If the CEI team shows a positive, can–do mindset every day, the contractor and the rest of the team reciprocates. Someone has to be the first to cooperate; for the good of the project, it must be the CEI team.

Below are a few reminders to help CEI teams lay the foundation for project success.

- **Be Consistently Fair** – It is much harder to tighten requirements once they have been relaxed. Project requirements should not vary day to day or inspector to inspector. The CEI team manager needs to ensure uniform inspection, decision–making, discipline, and overall treatment.

- **Explain Priorities** – If something is particularly important from an inspection point of view, the CEI team manager should explain why to all parties including the contractor. This helps educate and engage the work force and improves quality.

- **Resolve Different Interpretations of Plans and Specifications** – Often a contractor interprets an item in the plans or specs differently from the CEI team or the owner. It is up to the CEI team to resolve this, with the recognition that the contractor's interpretation may be equally valid. By being open–minded and careful listeners, the CEI team can resolve such differences amicably and in the best interest of the project.

- **Do Not Expect Perfection but Insist on Quality and Conformance** – The CEI team should focus on specification tolerances and ensure the project is constructed in reasonably close conformance with the plans and specifications.

- **Wipe the Slate Clean Every Day** – The CEI team cannot let their judgment remain clouded by the past. If the contractor or another team member is not being cooperative, the CEI team must judge each issue on its merits alone. This is very difficult but extremely important.

- **Share Ideas** – The CEI team should share ideas with the contractor that might help the project. This can be anything from alerting the contractor of required submittals to an alternate way a challenging operation was performed on another project.

- **Keep the Team Informed** – The CEI team should hold meetings well in advance of any major submittals to develop clear consensus of requirements and acceptance criteria. This minimizes resubmittals.

- **Be Proactive** – Similarly, the CEI team should hold meetings in advance of every operation to ensure all parties have the same understanding of the requirements. The earlier these meetings are held the better, to allow more time to resolve any concerns that arise. The CEI team should identify any issues before they have a negative impact the schedule.

- **Show Respect to All Project Personnel** – One big mistake a CEI team can make is thinking the contractor does not care about quality work. This is not true, though it may be helpful to explain to the workforce why certain aspects of the work are more critical. When personnel understand the importance of, for example, accurate positioning of confinement or bursting force reinforcing behind post–tensioning, the quality of their work can improve. When they think the inspector is merely berating them with the specifications, quality and morale may suffer.

- **Provide Sound Technical Advice to the Owner** – The CEI team should always meet with the owner before meeting with the contractor. At these pre–meetings, the CEI team and others can openly share information with the owner so they can make the best–informed decisions for the project on technical issues. The CEI consultant should ensure the owner benefits from the experience and expertise of the CEI team, the contractor, the contractor's engineer, and any other relevant specialists. It can be easy to simply agree with the owner, but it is in the owner's best interest for the CEI and all technical advisers to give an honest opinion and, on occasion, to play devil's advocate. Opinions must be backed up with facts, reason, and whenever possible, examples from similar situations. Few owners will go outside the norm of industry practice without clear and sufficient reasons. No owner can or should make a decision based on incomplete information.

- **Present a Consistent Message** – Once the owner has made his decision, the CEI team should present it to the contractor and maintain a consistent message. An owner makes a decision based on many factors and, in the best interest of the project, the CEI team must support the final decision.

- **Add to the Contractor's Motivation** – All parties have motivators and with contractors, like everyone else, the carrot gets better results than the stick. If the CEI team can show the contractor that certain actions are costing the contractor money, they will likely respond in a beneficial manner. On the other hand, if early mistakes are treated too leniently, there is little incentive to avoid them later. Established processes and behaviors – good or bad – are difficult to alter. For this reason, it is important to incorporate quality standards into the work early. A very true adage states, "It is always cheaper to do it right the first time."

- **No Surprises** – The CEI team should always avoid surprising the owner or the contractor. If a strong letter to the contractor is required, the CEI team should have already had meetings with the contractor about the issue. If a letter is necessitated by a problem that has come up suddenly, the CEI team needs to have a face–to–face meeting with the contractor to go over it together. When someone gets a strongly worded letter "out of the blue," relations can degrade quickly and the project suffers. Similarly, any news that must be delivered to the owner, especially regarding budget, schedule, changes or personnel, or safety issues, should be presented as early and honestly as possible.

The owner has engaged the CEI team specifically to facilitate the construction process through coordination, communication, and documentation. It is important to maintain a professional distance from the contractor, while fostering a relationship of mutual respect and trust. Likewise, the relationship with the owner must be respectful, professional, and built on trust. With this approach, the CEI team occupies the unique position of helping both the owner and the contractor achieve success with a quality project delivered on time, within budget, and meeting all project goals.

# TABLE OF CONTENTS

# Chapter 17:
# Construction Inspection Guidelines for Concrete Segmental Bridges

## 17.1 Recommended Practice for Initial Inspection of Forms

The purpose of the initial form inspection is to verify that the form was manufactured and can be assembled in accordance with the approved form shop drawings, as well as inspection of the operation and maintenance of the form during the first few castings. During this process, it is imperative that inspections be made to verify the suitability of the forms in reference to the points discussed in the following sections. All inspections must be carried out with the corresponding set of shop drawings and project specifications readily available while adhering to a systematic approach for documenting that all dimensions are thoroughly verified.

### 17.1.1 Form Dimensions and Tolerances

Check the dimensions of the segment the form will produce (see **Figure 17.1**) to confirm that the dimensions are within the tolerances given in the project documents. Commonly specified tolerances and their interpretation are shown in **Figure 17.2**.

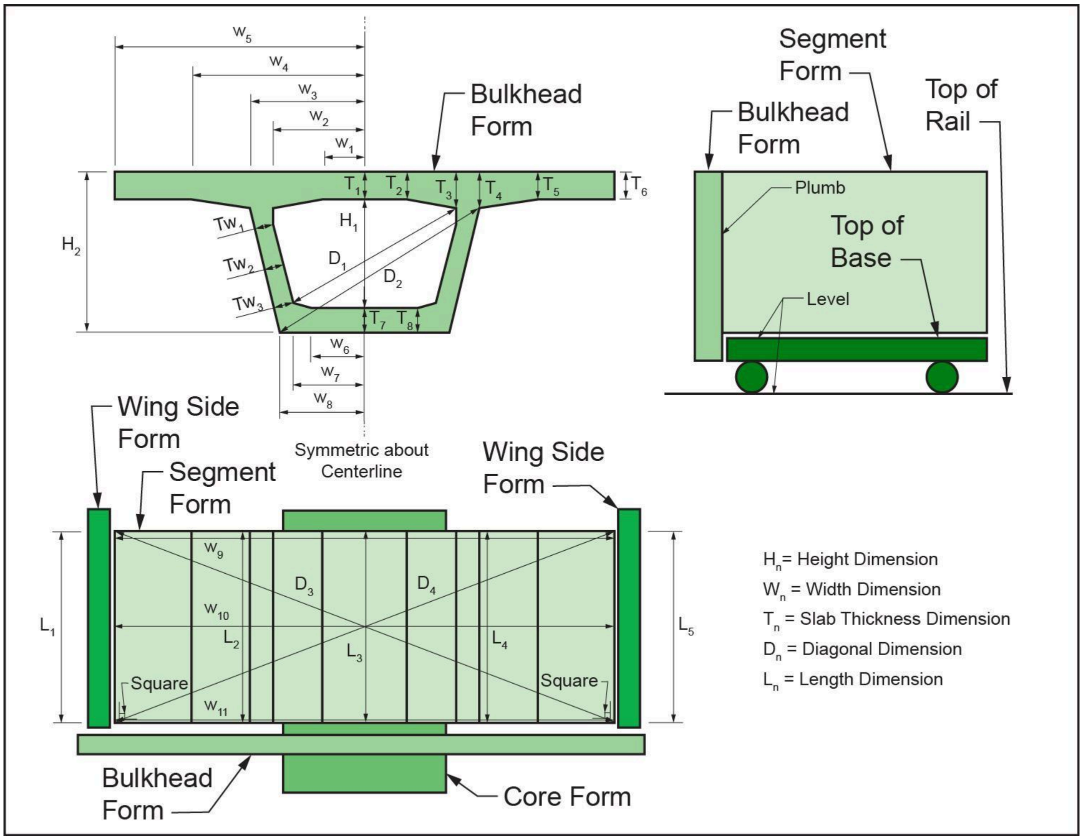


*Figure 17.1 – Measurement of Form*

(To correlate tolerances, see sketches below.)
Overall Depth of Segment
Length of Match-Cast Segment (Not Cumulative)
Length of Cast-in-Place Segment
Web Thickness
Depth of Bottom Slab
Depth of Top Slab
Overall Top Slab Width
Diaphragm Thickness
Grade of Form Edge and Soffit
Tendon Hole Location
Position of Shear Keys
Deviation of Segment Ends from a Plane in Width or Depth
Deviation of Surface from a Plane at Any Location Measured with a 10 ft Straight Edge

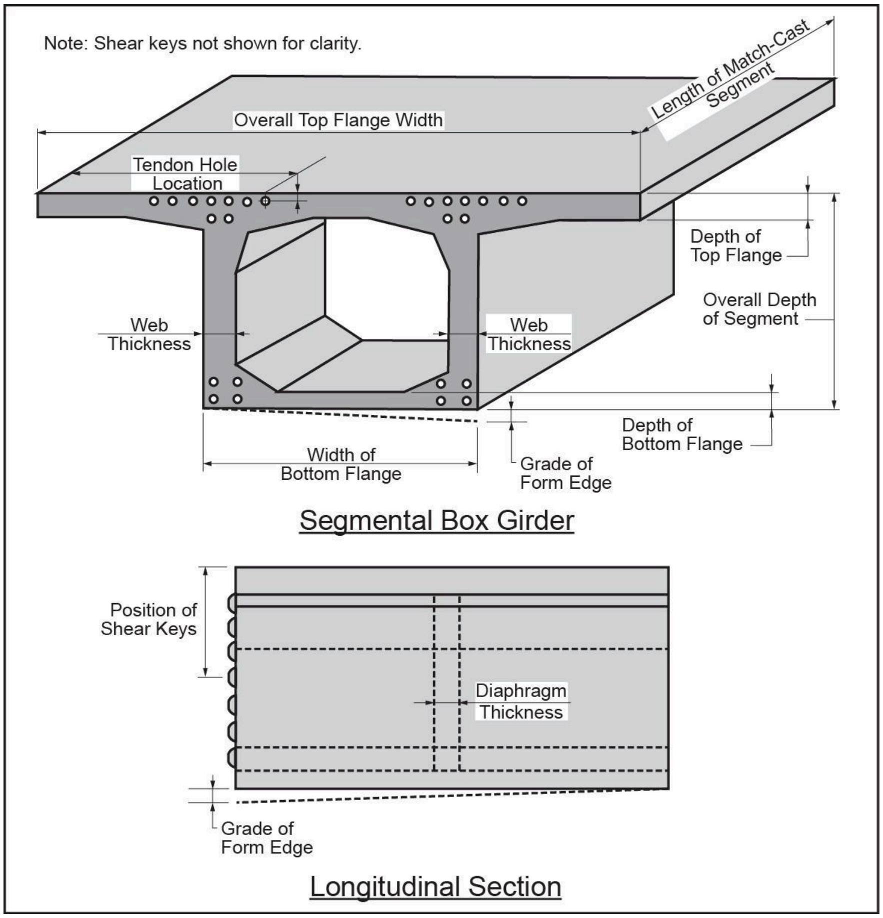


*Figure 17.2 – Commonly Specified Tolerances for Segmental Box Girder Bridge Construction*

Dimensional checks are necessary at the bulkhead side and the match-cast side, as well as in between. Dimensions of the match-cast and bulkhead sides should be identical. Variations in dimensions at the two ends may result in mortar leakage or require large forces on the match-cast segment to close the form which may move the segment out of alignment.

The form should be reassembled as required to revise and verify dimensions of the section for all variations in web and bottom slab dimensions (see **Figure 17.3**). Most balanced cantilever bridges require thickening of the bottom slab and sometimes thickening of the webs near the pier. For this reason, forms may have to accommodate several section changes.

Dimensional location of any items attached to the form to secure their position during casting of concrete and requiring removal before shipping the forms should be noted.

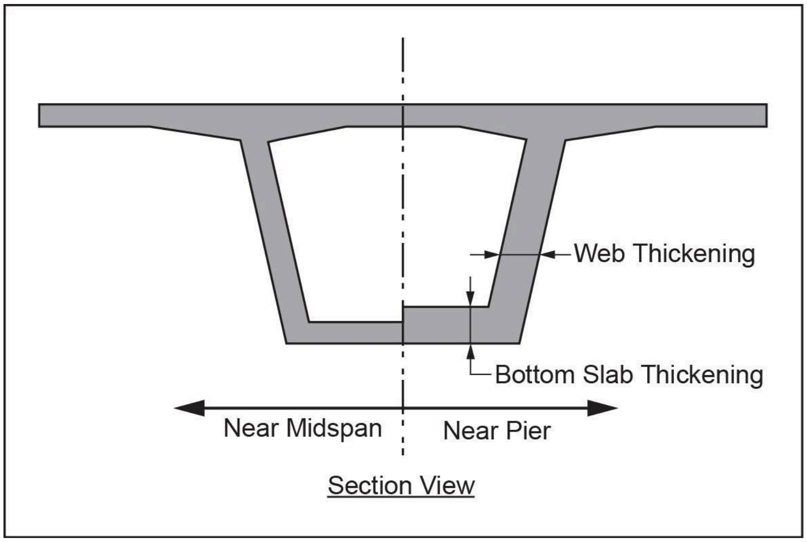


*Figure 17.3 – Accommodation of Form to Section Changes*

### 17.1.2 Form Operation

The geometry control of precast segmental bridges is based on the assumptions that the soffit of the new segment is level, and the bulkhead face of the new segment is plumb or perpendicular to the soffit (see **Figure 17.1**). This should be carefully checked using the appropriate instrument and, since the bulkhead could potentially move each time a segment is cast, it should be checked for each new segment set up.

The match-cast segment needs to be placed in a certain position with respect to the form (see **Figure 17.4**). After the appropriate setting of the match-cast segment, the position should be finetuned to be within the specified tolerance. Mechanisms such as hydraulic jacks or screw jacks are used to accomplish this adjustment. The position changes to be controlled by such mechanisms are rotation in the horizontal plane, rotation in the vertical plane through the bridge centerline, and rotation in the vertical plane perpendicular to the bridge centerline. In addition, the match-cast segment should be able to move parallel, and perpendicular to the direction of the bridge centerline.

The seals between individual form panels and the match-cast segment must prevent mortar leakage from the fresh concrete. Such leakage affects both quality and appearance of the segments. The seals are a major feature of form design and, since they are usually flexible rubber or neoprene gaskets, they require regular cleaning and maintenance. Checking of seals is a continuous task during production. Of particular importance is the seal between match-cast segment and form panels, because the position of the old segment is not fixed and the seal and form must adapt to the old segment's rotated position. Any movement of the match-cast segment during closing of the form will cause errors in the bridge alignment.

The use of form oil is necessary to reduce adherence between the form and the segment, particularly in top slab overhangs. Bond between the vertical faces of the new and old segments is reduced by generous application of the specified bond-breaker, (usually a mixture of soap and talcum powder). A procedure for bond breaking should be shown on the segment shop drawings or described in the *Construction Special Provisions* to ensure that shear keys and the segment faces are not damaged during the process of breaking the bond between segments.

Inspection of the forms during casting of the initial segments should verify that the form allows for inspection of rebar, post tensioning ducts and anchorages as well as other embedded items in the form. Such inspections mainly relate to clearances, post-tensioning anchor-duct alignment, and embedded item locations. The inspector should be able to enter the form for this inspection prior to closing the inner form.

For placement of concrete, it is important that the concrete can be brought to its final location without dropping from a great height and without having to move it with a vibrator. Refer to the American Concrete Institute (ACI) guidelines for proper concrete placement procedures. Special chutes, slides or openings in the top slab form are usually required to place the bottom slab concrete. For finishing of the deck, it is important that the top surface be leveled by screeding over the match-cast segment and the fixed bulkhead. The form design should minimize obstructions that interfere with the use of the screed.

The initial inspection of form operation should verify that the form is provided with access ladders and safe working platforms with railings all around.

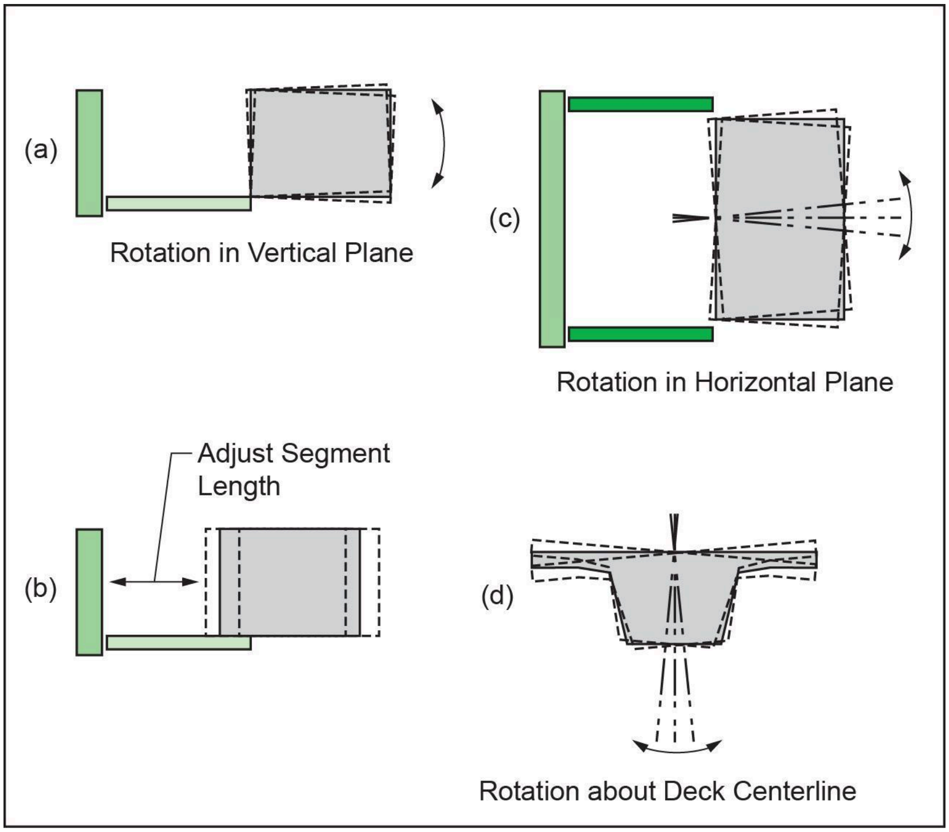


*Figure 17.4 – Typical Requirements for Form Adjustments*

## 17.2 Recommended Practice for Daily Inspection of Forms

The following daily inspections of forms are recommended:

- Verify that the form is clean and that movable parts are oiled and greased as required. Because of the many mechanical parts used in the form, such as those used for collapsing the inner form and adjusting the position of the match-cast segment, hardened concrete spills not properly and regularly cleaned will render the form inoperable.

- Verify that seals are clean and flexible. Proper functioning of seals in preventing loss of mortar is essential to the production of segments of acceptable quality. It is essential that seals be cleaned daily, and that any hardened concrete is removed. Seals are usually made of neoprene and are easily damaged. They should be repaired or replaced as necessary.

- Verify that the form oil approved for use on the project is applied in accordance with the manufacturer's instructions.

- Check to ensure that the form is adjusted correctly for the segment to be cast. This is particularly important whenever there is a change in bottom slab or web thickness or other section variation.

- Inspect to ensure that recesses, attachments for embedded items, and holes in the bulkhead are set up properly for casting the next segment. One item that is sure to vary from segment to segment is the post-tensioning. This variation occurs in both cantilever post-tensioning and continuity post-tensioning. For this, anchor recesses may have to be removed or added. Holes for tendon ducts in the bulkhead must be closed or opened. It is very demanding and important that the contractor and inspector independently check the post-tensioning in each segment. If an error is made here, the consequences are very serious.

- Check the closure of the form around the bulkhead, between the bottom slab form and side form, and around the match-cast segment. Closing the form at bulkhead and at bottom slab form usually does not present great problems since bolts through the form can exert enough clamping force to achieve the seal. Closure around the match-cast segment where clamping through the form is not possible is more problematic and this is where the effort should be concentrated.

- Check the temperature of the form immediately before casting concrete. The combination of low-slump concrete and forms heated by the sun to high temperatures may cause a condition where the water in the concrete evaporates as soon as the concrete contacts the form. This leads to an unsatisfactory surface condition. Forms should preferably be placed under cover that is protected from the weather. Alternatively, the form can be cooled with water prior to casting. If this is done, excess water must be removed prior to concrete placement, e.g. with compressed oil-free air. Care must be taken in removing excess water not to remove the form oil.

## 17.3 Recommended Practice for Inspection of Cut and Bent Rebar

Detailing of the reinforcement should adhere to the project specifications. A commonly specified reference is "*Reinforcing Bar Detailing*", published by the Concrete Reinforcing Steel Institute. Topics of primary importance on this subject for segmental bridge construction are discussed below.

- Ensure that the steel has passed all required tests and has been approved for use on the project. This indicates that the quality and mill tolerances of the rebar are acceptable.
- Verify that the steel has been properly tagged and that the tags show bar diameter, bar number and the segment it is intended for. This is the responsibility of the contractor but should be checked occasionally by the inspector.
- Check reinforcement for cutting and bending tolerances, and either correct or reject any reinforcement not within tolerance.

Unless specified to the contrary, steel will typically be cut and bent in accordance with standard tolerances set by CRSI (Concrete Reinforcement Steel Institute). These tolerances are as shown in **Figure 17.5**. For straight bars, only cutting tolerances apply. If required, a higher tolerance can be specified, or alternatively, a lap splice provided.

Bends are made around pins which are designed in such a way that the steel is bent to the correct radius. Proper bar bends are important for the function and fit of bars in the segment. A badly bent bar may not function properly as demonstrated in **Figure 17.6**. Bars that are bent with a pin radius lower than recommended run the risk of yielding the rebar and decreasing its structural effectiveness as designed by the Engineer. The location of bends is also very important as shown in **Figure 17.7**. The bars shown extend from cover to cover on each end, and the tolerance on cover may be less than the standard tolerance on the bar length. In any case, where a single bar extends from cover to cover, a tighter tolerance should be indicated on the shop drawings, or the bar may be re-detailed with a lap splice with the approval of the Engineer.

- Check epoxy coating in accordance with special provisions. Epoxy coating can be damaged during handling or by field cuttings. Corrosion will concentrate on uncoated areas. For this reason, damaged areas of the coating must be repaired per the project-specific approved repair procedures.

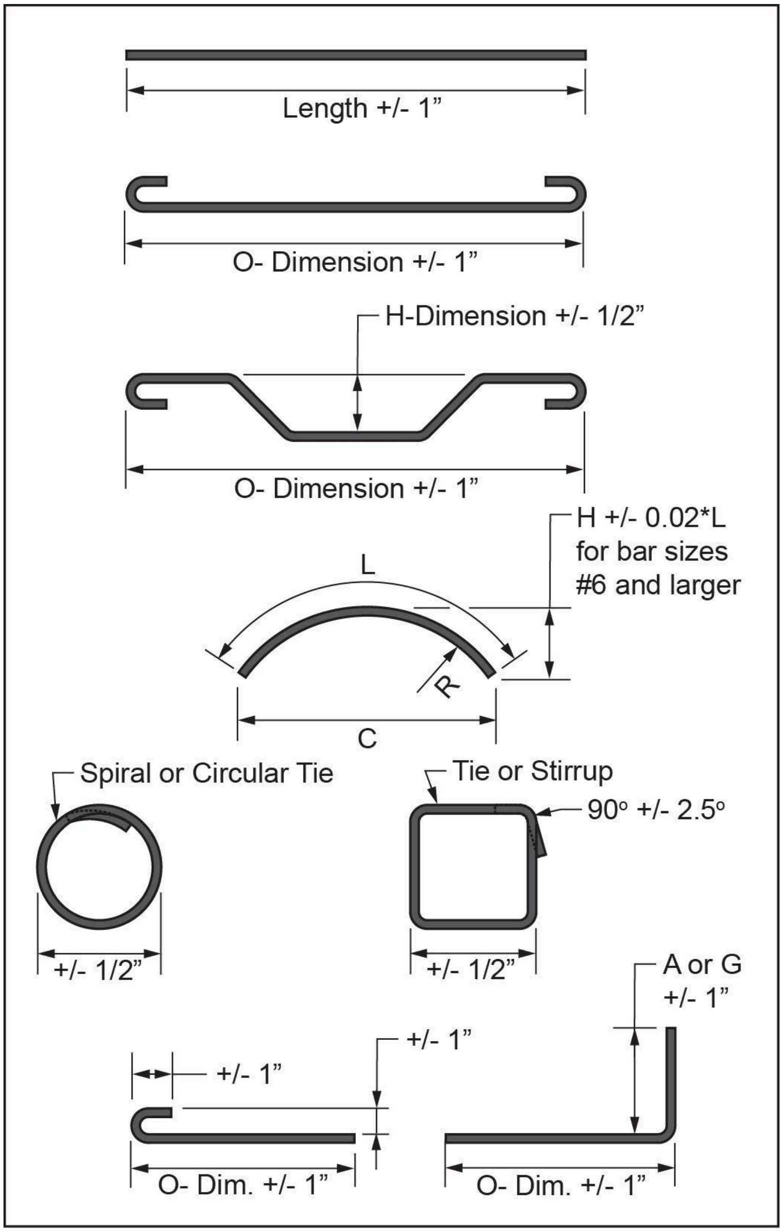


*Figure 17.5 – Standard Fabrication Cutting and Bending Tolerances*

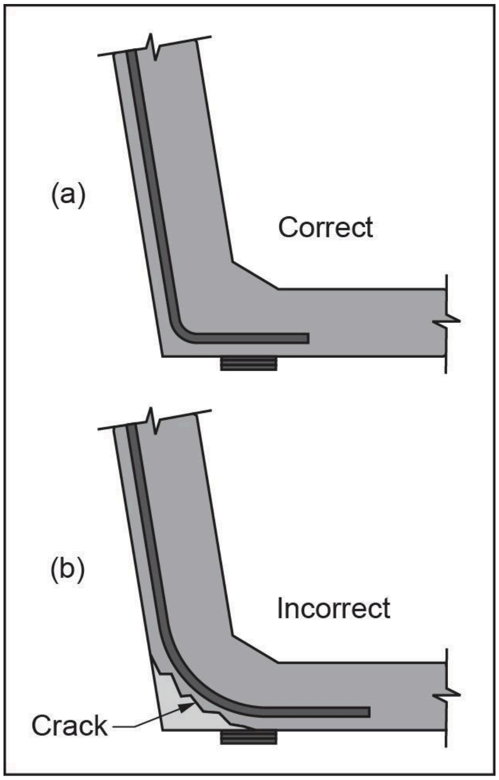


*Figure 17.6 – Example of Poorly Bent Rebar*

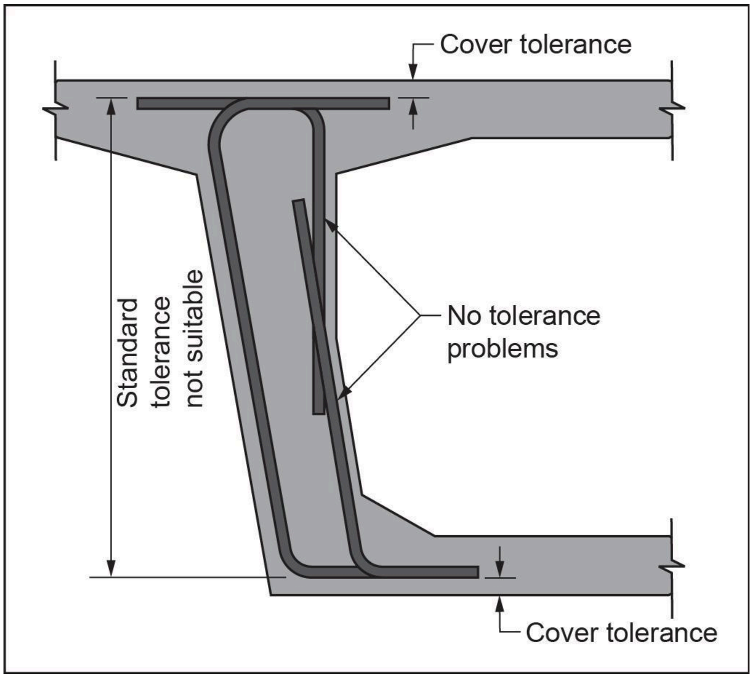


*Figure 17.7 – Requirement for Tight Tolerances*

## 17.4 Recommended Practice for Inspection of Rebar Cages

With the goal of a production rate of one (1) segment per form per day, the rebar cage assembly is critical and most of the inspection should occur while the cage is on the template waiting to be placed in the form. The template, also known as a jig, is a temporary structure (see **Figure 17.8**) which simulates the size and dimensions of the segment form and is used by steel workers to pre-assemble the reinforcing steel cage and ensure that the cage will fit the form.

On some projects, there may be many different segment types, each of which will have a different rebar cage. In order to match each cage and segment correctly, the contractor will have to design a good identification system. All cages should be tagged in accordance with this system. The inspector should identify the cage, verify the identification tag, and check to ensure that an approved shop drawing was used for making the cage.

The rebar cage should be inspected with the corresponding set of shop drawings readily available while adhering to a systematic approach for documenting that all the following items below are verified:

1. Segment dimensions. Inspection for segment dimensions, day to day, will be required on projects where segments have a lot of variation on the bottom slab, web thicknesses and length of the overhang. In this case, the template for making rebar cages must allow variable dimensions and these dimensions should be verified.

2. Bar diameters. There is no tolerance on the use of bar diameters. For example, #4 bars cannot be used instead of #5's and conversely. Any deviation in bar diameters should be checked with the Owner's Engineer

3. Number and spacing of bars. The spacing of bars (center to center distance of bars in the same mat) shown on the shop drawings should be within the specified tolerance. In some cases, larger tolerances could be allowed; for example, when openings or embedded items prevent placement of a bar. Any exception to the specified tolerances should be approved by the Engineer. The contractor may elect to have frequently occurring variations pre-approved. Whatever the case, the total number of bars shown in the shop drawings to be placed in a mat should always be present. Additional bars can usually be accepted, at no additional cost, for the convenience of the contractor.

4. Number of ties. Ties should generally be steel wire ties. The number of wire ties is specified in the standard specifications. No welding should be performed unless reviewed and approved by the Engineer.

5. Length of lap splices. The minimum length of lap splices is shown on the shop drawings. The minimum length should be verified in the cage. L-splices may be longer than required. In case field splices are required, dimensions of minimum lap splices should be approved by the Engineer.

6. Number and type of distance keepers; also known as rebar support chairs. Requirements for the number of support chairs between the top and bottom reinforcing are usually provided in the standard specifications.

7. Size of distance keepers. Size of distance keepers is most important since it determines the cover and therefore the durability of the concrete segment. In addition, it determines the intended

location of most structural reinforcement. In general, reinforcement is more effective as it is placed closer to the faces of beams and slabs, and the position is determined by the clear cover. The tolerance on cover is the tolerance for the location of the rebar mat in respect of the outside and inside faces of the segment. This tolerance is not typically required for the joint face of the segment. Once the structure is erected, the joint faces will not come into contact with the atmosphere and cover on the joint faces will not have durability consequences. The cover of reinforcement from the joint faces should be shown on the shop drawings.

Special reinforcement may be required at locations where segments need to be strengthened; for example, at pickup points, strutting supports, near openings (temporary or permanent manholes). Post-tensioning anchors also call for special reinforcement, such as spirals and hair pins (see **Figure 17.9**). Locations where tendons are strongly curved may also require special reinforcement. These should be depicted in the contractor's shop drawings.

The dimensional integrity of a rebar cage must be maintained during transportation of the cage. For this purpose, the cage can be stiffened with a frame (see **Figure 17.10**).

The rebar cage should be inspected for obstructions to the location of tendon ducts. The tolerances on duct placement and support should be given in the project documents. A commonly referenced guide is the "Post Tensioning Tendon Installation and Grouting Manual" published by the FHWA. Tendon ducts should be placed at their designated locations without cutting any rebar. Ducts should preferably be placed in the cage before it is placed into the form, so that modifications to the reinforcement cage required to let ducts pass through can be made without loss of segment production. For instructions regarding field cutting and bending of reinforcement, *see* ***Section 17.7*** *"Recommended Practice for Solving Rebar Conflicts."*

The cage should be checked for damage to epoxy coating, and damage to the coating should be repaired.

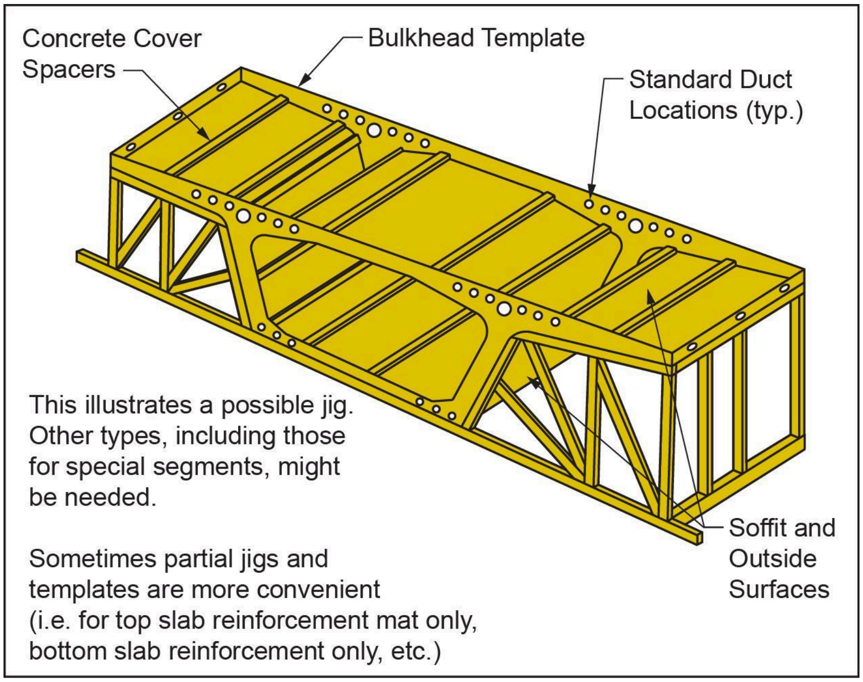


*Figure 17.8—Jig for Fabrication of Rebar Cage*

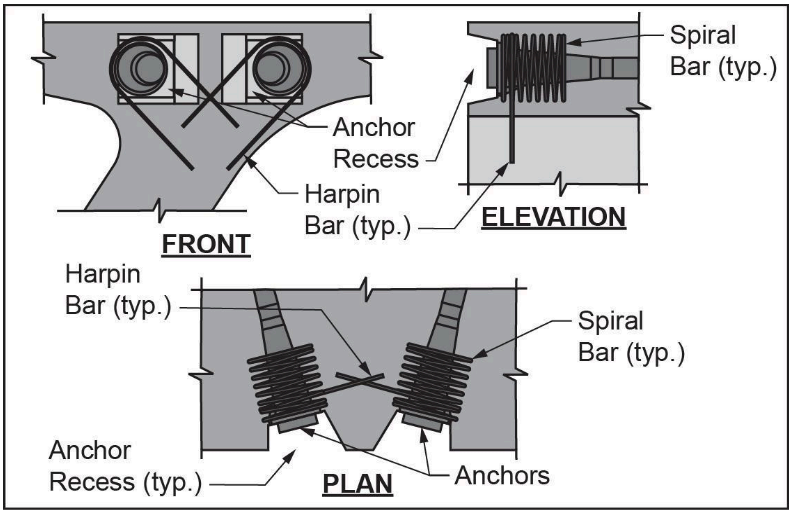


*Figure 17.9 – Reinforcing Steel at Post-Tensioning Anchors*

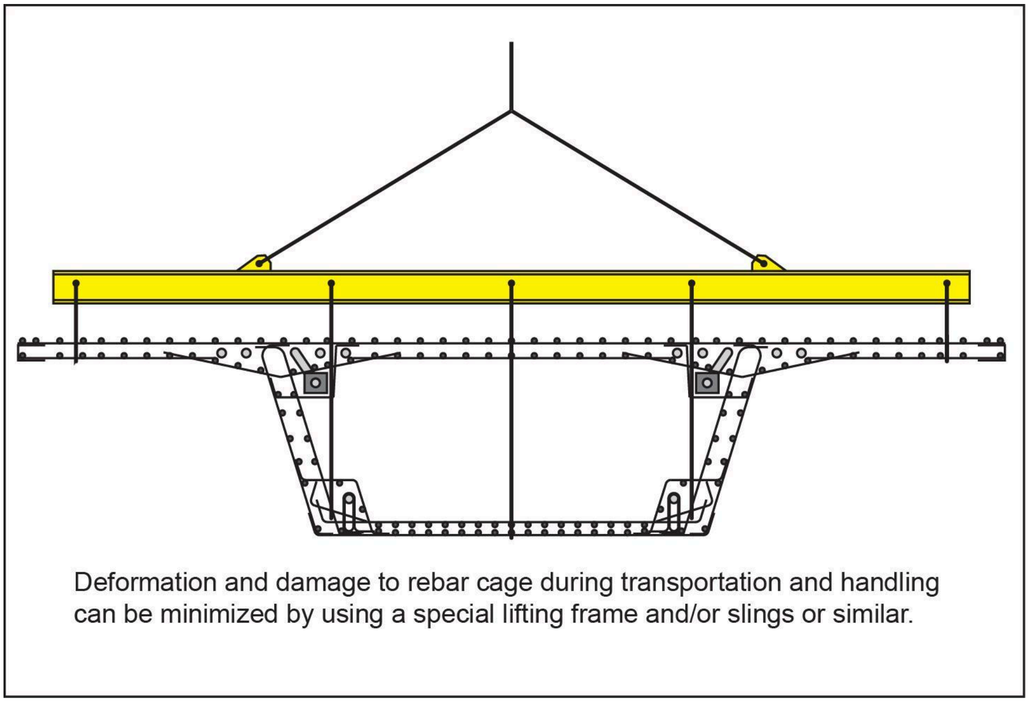


***Figure 17.10 – Handling of Prefabricated Rebar Cage***

## 17.5 Recommended Practice for the Initial Inspection and Storage of Post-Tensioning Hardware

Initial inspection of the post-tensioning hardware on the project is necessary to verify that the hardware conforms to the approved shop drawings. All post-tensioning inspections must be carried out with the corresponding set of shop drawings and project specifications readily available while adhering to a systematic approach for documenting that all details are thoroughly verified. Initial inspection should consider the issues discussed below.

The hardware covered by the shop drawings consists of:

| | |
|---|---|
| **Anchors**: | Anchor Plates, Anchor Heads or Wedge Plates, Wedges |
| **Ducts**: | Duct, Duct Couplers |
| **Miscellaneous**: | Grout Caps, Grout Inlets, Grout Vents |

*(See **Figures 17.11** and **17.12**.)*

The shop drawings show the dimensions of the individual pieces and how these pieces should be assembled. All hardware sizes should be shown in the shop drawings and be checked, including longitudinal, transverse, and vertical post-tensioning, as applicable. Sampling and testing requirements for the post-tensioning hardware should be given in either the General Specifications or Special Provisions of the contract documents.

Wedges and wedge seats for post-tensioning hardware are subject to machine tolerances which are extremely small. These tolerances are the responsibility of the post-tensioning materials supplier.

The inspector should limit inspection to obvious details such as length and number of pieces used to make up the wedge or any damage apparent to the naked eye.

Most anchors are forgings or castings, which may have gone through a number of machine operations. The inspector is concerned only with a visual inspection of the surfaces. Casting errors are normally not visible. The conical surfaces for wedges in the anchor head should be smooth. The wedge should be able to easily slide into it. The anchor head, if any, should bear flush against the bearing plate. The outside surface of wedges should be smooth and clean, and the inside surfaces serrated over their whole length. At the tip of the wedge, the teeth are usually filed down for a short distance to ensure that the strand force is distributed over the length of the wedge. Where the shop drawings indicate that the components should have drilled holes for attachments of any kind, their presence should be checked.

All post-tensioning hardware and duct material should be stored in a manner so that it will be protected from corrosion and entrance of foreign material. Materials should be protected from weather (including direct sunlight) until installed into the rebar cage or forms. Wedges should be stored inside. Duct material and anchorages should be stored on wooden platforms and protected from the weather. Ends of ducts should be capped to prevent entrance of foreign material during storage.

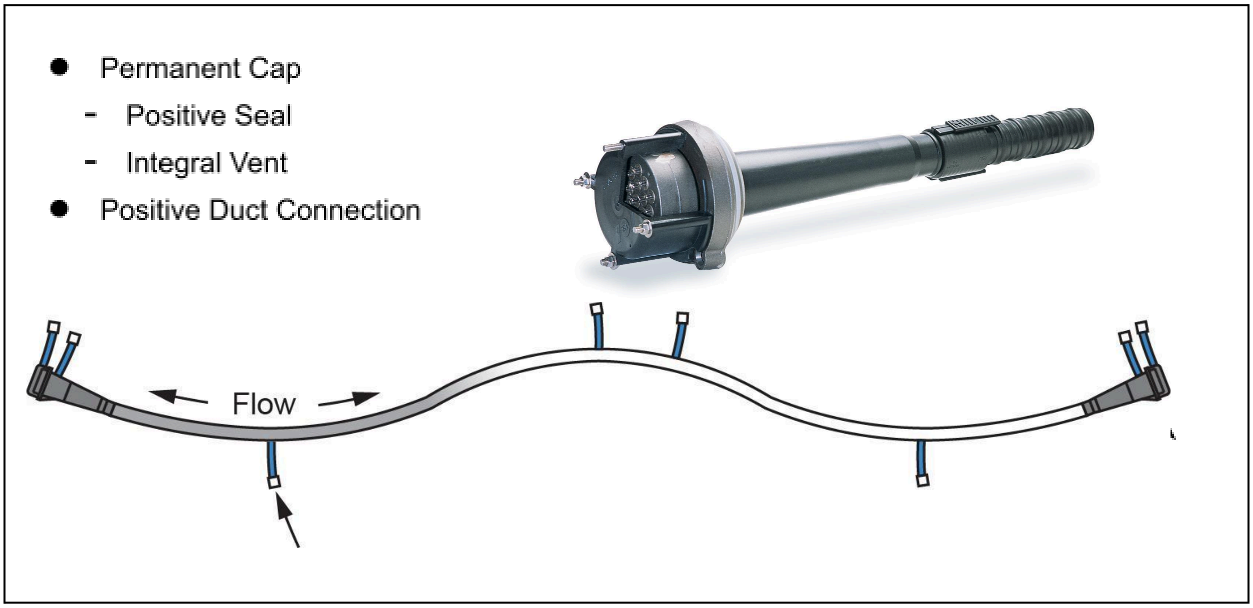


*Figure 17.11 – Typical Post-Tensioning Anchorages (Strand Systems)*

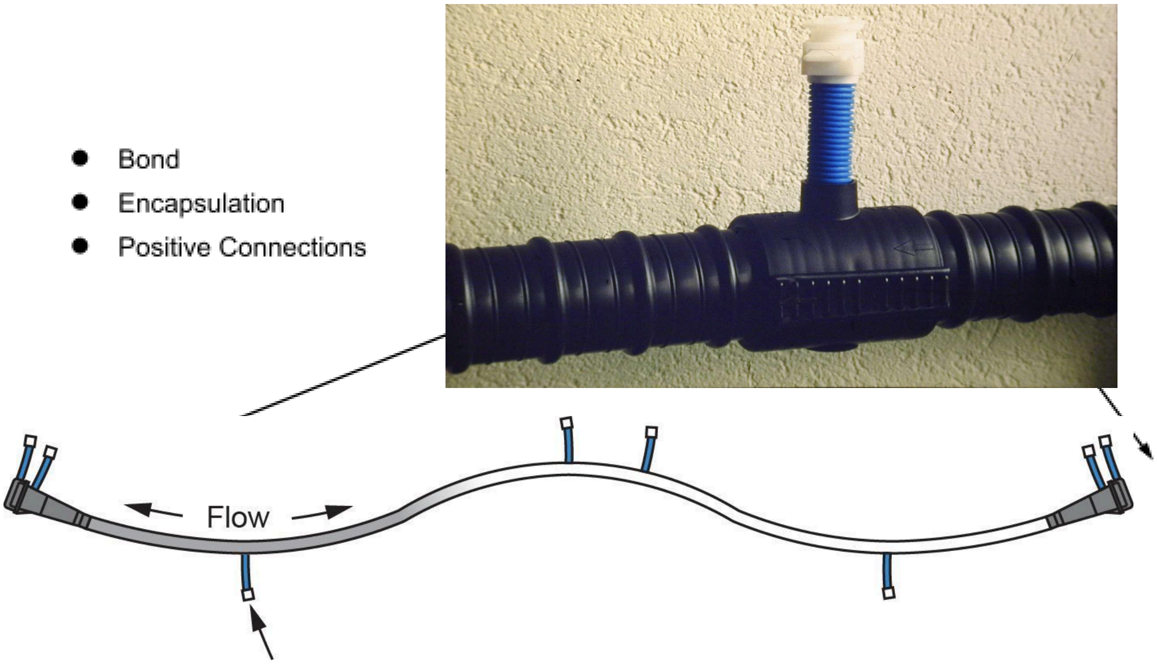


*Figure 17.12 – Plastic Duct and Grout Vent Connection*

## 17.6 Recommended Practice for Inspection of Post-Tensioning Hardware in the Reinforcement Cage

Inspection of post-tensioning ducts and other embedded items in the rebar cage is based on approved shop drawings showing the location of ducts, rebar, and any other embedded items. In areas where there is congestion of rebar, ducts or other embedded items, two dimensional or three-dimensional drawings illustrating the location of all embedded items should be included in the contract drawings.

The inspector should confirm the proper size and material of the duct that is being used for each location. The contract documents should include procedures for coupling of duct to achieve the proper lengths needed. This should include material information for "heat shrink" wrapping material for duct joints. For welding of HDPE duct, proper procedures must be submitted for approval and should include listing of experienced certified personnel that will be performing the welding. The inspector should verify that post-tensioning ducts can be placed in their correct locations in the cage without major relocation or cutting of rebar.

One item that can be placed effectively into the rebar cage is the tendon duct. The advantage of placing the ducts into the cage before the cage is placed into the form is that interference problems can be solved at this time without loss of production. Also, the number and approximate locations of the ducts can be verified, saving on inspection time at the form. Usually, the ducts are placed in their approximate location since they cannot be tied before connection with the previous segment and the anchor, which must be made in the form. For resolution of interference problems, *see* ***Section 17.7****, "Recommended Practices for Solving Rebar Conflicts."* When the shop drawing calls for grout vents, the vents can be placed in the rebar cage. Anchor reinforcement such as spirals and hair pins should be placed in the cage. However, their final position can only be adjusted after placement of the cage in the form and after the anchor has been installed.

Ducts must be properly secured inside the rebar cage to ensure it will not move during concrete placement. It must be secured to withstand workers stepping on it, concrete being dropped on it, and concrete "floating" the duct. Duct location and alignment must be maintained during concrete operations to ensure proper post-tensioning geometry. Often this can be achieved through the use of mandrels that secure the position and location of duct during concrete placement.

Duct must also be protected from any damage during final rebar placement and concrete operations. This shall include protection from bending, kinking, scraping or abrading, and puncture. Any damage to the duct will negatively affect future grouting operations.

## 17.7 Recommended Practice for Resolution of Rebar Conflicts

Resolution of conflicts between locations of embedded items is primarily the responsibility of the Engineer of Record and should be resolved during the design phase. When the Contractor makes significant modifications to the post-tensioning details or the length of segments, responsibility for resolution of conflicts between locations of embedded items and revised details shifts to the Contractor and the Contractor's Specialty Engineer.

Conflicts in placement of rebar may be resolved by moving, bending or cutting rebar. Cutting of rebar generally requires approval of the Owner's Engineer (Construction Engineering Inspector). Moving rebar is generally allowed. Bending rebar is generally allowed but sometimes requires use of hairpins to secure the pipe bend. As shown in **Figure 17.13a**, bar 1 will tend to straighten, and a hairpin is needed to prevent spalling. Geometry of bar 2 under tension is maintained by the concrete. Pre-approved tolerances and methods for cutting and moving reinforcement should be established with the Engineer. Typical bar locations as shown in **Figure 17.13b** can serve as a template for differentiating rules for each family of bar.

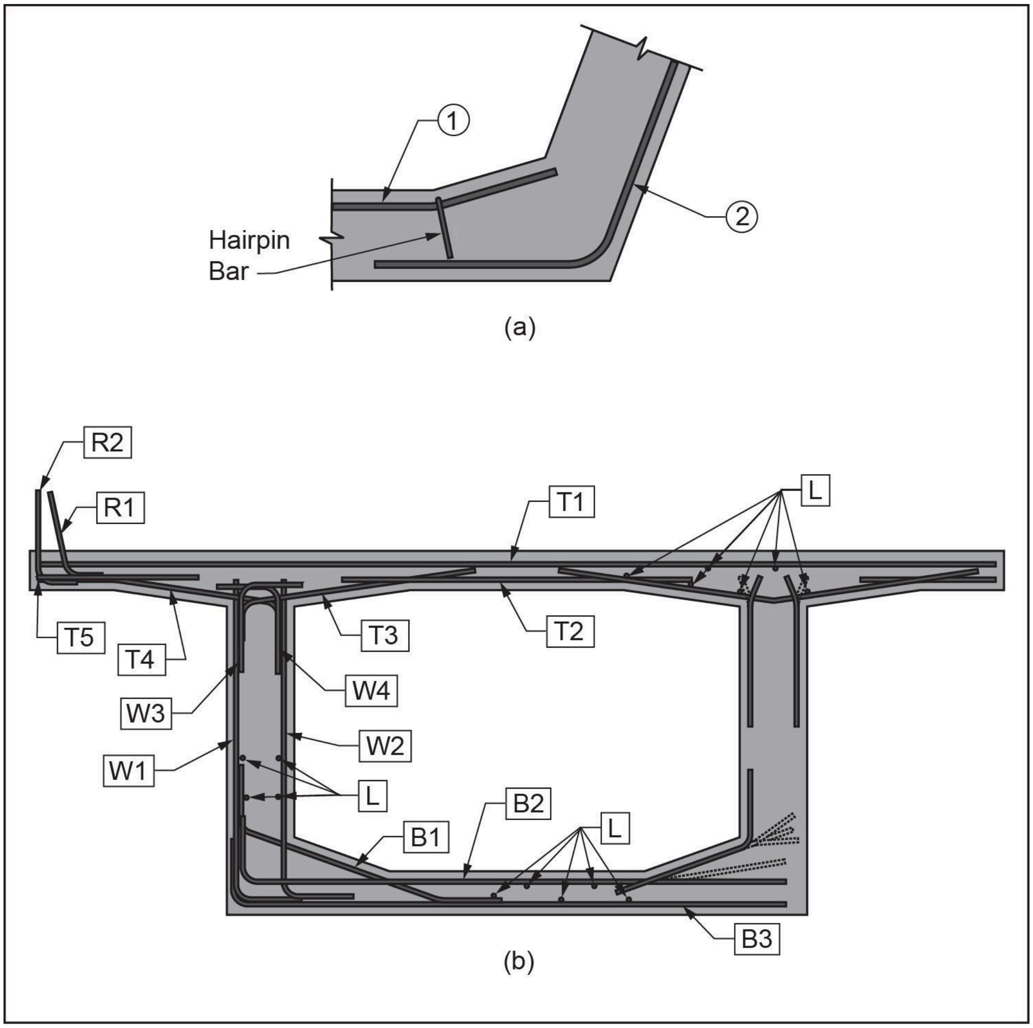


*Figure 17.13 – Aid for Solving Rebar Conflict*

## 17.8 Recommended Practice for Inspecting Post-Tensioning Hardware in the Form

All post-tensioning hardware should be inclusive of the chosen system that has been submitted by the contractor and approved for use. Each system should be provided by the manufacturer with shop drawings identifying all the necessary components. These systems are pre-tested and there should be no substitution or variance from any aspect of the system. All post-tensioning inspections must be carried out with the corresponding set of shop drawings and project specifications readily available while adhering to a systematic approach for documenting that all details are thoroughly verified.

As noted in **Section 17.7**, the number of ducts and anchors should be checked before the cage is in the form. However, final location can only be achieved and inspected after the cage is in the form. Anchors and ducts are both subject to placement tolerances. The tolerance on the location of tendon ducts at the face of a segment is typically smaller than the tolerances on reinforcement. This tolerance also applies to the location of anchors.

Duct should be rigidly supported at the proper location in the forms by ties to reinforcing steel. The requirements for support spacing should be in the project specifications, and may vary by duct type, location and material. During concrete placement for precast segments, mandrels should be used as stiffeners in each duct, shall extend throughout the length of the segment being cast and at least 2 ft into the corresponding duct of the previously cast segment. The mandrels should be of sufficient rigidity to maintain the duct geometry at the segment joints, including the angle of the duct relative to the segment axis, when applicable. Other means for stiffening post-tensioning ducts for concrete placement may be implemented as approved by the EOR.

The recess pocket (see **Figure 17.14**) determines the angle of the anchor plate and the distance from the face of the segment. The connection between the anchor and the recess must be strong enough to hold the anchor firmly in place during concrete placement, and it must also be mortar tight. The recess pocket should be constructed within the tolerances given in the project documents. To minimize friction losses and wire breaks when stressing tendons, ducts and anchors should be closely aligned.

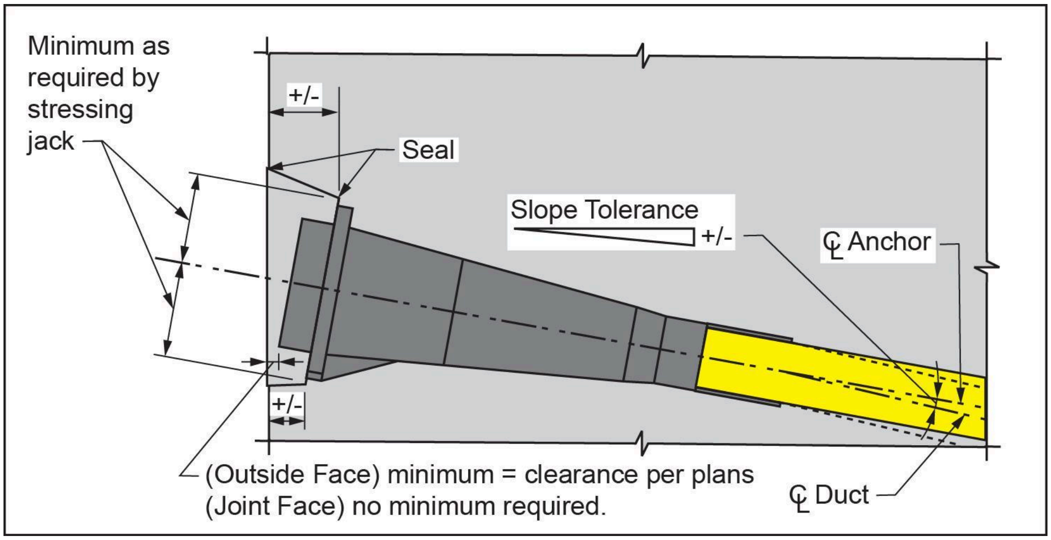


*Figure 17.14 – Tolerances on Anchor Placement*

## 17.9 Recommended Practice for Concreting Segments

The sequence of concrete placement in the segment forms will vary dependent on several factors. These include, but are not limited to, the following:

The Dimensions of Segment
The Depth of the Box
The Thickness of the Webs
The Number of Webs
The Slope of the Webs
The Presence of Internal or External Tendons
The Size and Spacing of Reinforcement Bars
Location of Anchorages and Ducts
Slump of Concrete
Concrete Additives Such as Accelerators, Water Reducers or Retarders
Temperature and Humidity at Time of Placement

Generally, concrete placement should be performed in one continuous operation to prevent cold joints. While some projects have allowed diaphragms to be cast separately to reduce the overall weight of the segments during erection, construction joints are generally not allowed.

One difficulty with placing concrete in segments is due to the bottom slab not having a top form. The concrete that is placed in the web will flow into the bottom slab if vibrated strongly. The pouring sequence shown allows proper consolidation of concrete in the bottom of the web and finishing the surface of the bottom slab. The most important issue for finishing the bottom slab is to make sure that the slab thickness meets the tolerances.

Generally, concrete is placed first in the bottom slab. Placing this concrete often needs to be done through a chute or from an opening in the top slab of the core form. Then, concrete will be placed through the web in the bottom corners. Upon vibrating the web, concrete tends to flow into the bottom slab. Care must be taken to minimize the flow and yet obtain good consolidation.

The concrete should be vibrated following acceptable vibrating practices. Care should be taken in vibrating the webs since the concrete will keep flowing out of the webs and into the bottom slab as long as vibrating continues or the concrete achieves its initial set. Post-tensioning anchors should receive special care during vibrating. The close windings of the spiral sometimes prevent the concrete from filling the space behind the anchor and inside the spiral.

The deck slab is poured last. Placement usually starts from one side of the segment and proceeds transversely across the segment to the opposite side.

Ducts for post-tensioning tendons can be moved or damaged by concrete. This may occur during placing of concrete or during vibrating. If tendons are located at the intersection of web and bottom slab, the pressure caused by vibrating can easily move the ducts if not properly secured. If a duct becomes dislodged at a location that is difficult to access, the segment may be lost.

In some cases, the top slab is the riding surface. The finishing operation is therefore important and should be carefully inspected. The top of the slab should be first struck off either by hand or mechanically. A vibrating, rolling, or standard concrete screed works well for an initial pass for leveling. A light application of bull floats may be used to provide a smooth, even, uniform dense finish.

It is the contractor's responsibility to verify which cylinder strength breaks are required by the project specifications. Typically, cylinders are prepared and broken to check the strength of the segments for these major events:

Stripping Forms
Segment Transport
Transverse Post-Tensioning
Completion of Curing
28 and Day Strength
Spares

For initial curing, store test specimens with the segment where the temperature of the test specimens will be approximately that of the concrete in the structure. Again, be sure to verify with the specific contract documents for the project requirements related to concrete cylinder production and testing.

Match-cured cylinder mold or maturity measuring devices may also be used for measuring early strength. See **Figure 7.15** for a typical casting sequence.

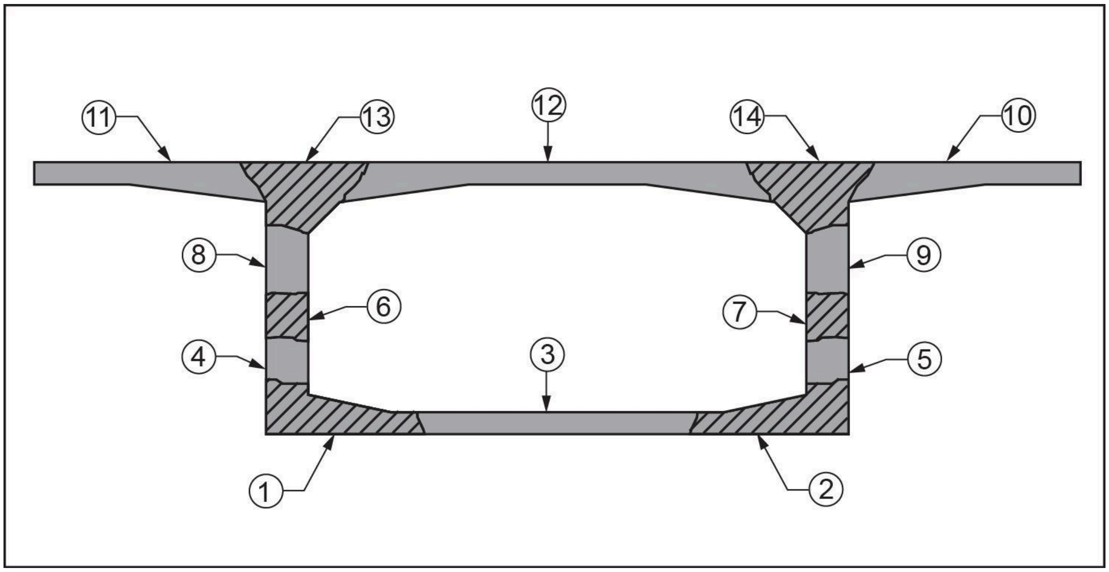


*Figure 17.15 – Casting Sequence for Regular Precast Segments*

## 17.10 Recommended Practice for Inspection of Curing of Segments

The Contractor should use the curing method set out in the Special Provisions or may propose an alternate curing method for review and approval by the Engineer. Requirements for curing may be affected by needs for early strength, local climate conditions, segment size, and other factors.

## 17.11 Recommended Practice for Inspection of Stripping Forms and Bond Breaking

The following steps are recommended relative to the stripping of forms and breaking the bond between segments:

**1. Check strength of segment prior to giving permission to strip forms.**
The strength required for stripping forms has been provided on the plans or in the special provisions. Also, shop drawings should be checked for an indication of whether or not transverse post-tensioning must be stressed before forms can be stripped off.

**2. Upon removal of inner form and outer form, check webs for casting defects.**
If casting defects are present (honeycombing near anchors for example), this is the most suitable time to determine whether or not the segment will be accepted. If not accepted, it can be removed and a new one made. If it is likely that the segment can be repaired, it should be accepted provisionally subject to acceptable repair.

3. **After removal of forms, break bond between “old” and “new” segments.**
Breaking bond is accomplished by the method or process shown on the shop drawings. This process must ensure separation of the segment without damage to the keys or the face of the segment.

**4. Inspect joint between the match-cast and wet-cast segment for key breakage.**
The keys ensure that the weight of the last segment of a cantilever will be carried by the cantilever. Generally, the margin of safety allows a small percentage of the keys to be broken. Guidelines for the extent of the damage permissible to keys should be submitted by the contractor and approved for use. It is not recommended to repair the keys prior to erection. Any repair made to the match-cast surfaces will lead to fitting problems and usually to severe spalling upon erection. The better practice is therefore to establish a guideline for acceptable key breakage and make the repair after erection.

**5. Ensure that the correct number is painted on the segment.**
The numbering system of segments is part of the contractor's shop drawing submittal. The number indicates where the segment will be stored and erected. It is very important that the segment be numbered correctly with the direction of stationing. It is also recommended that segment designation be etched into the concrete in the bottom slab.

**6. Ensure all segment deficiencies are properly documented.**
All inspections of segments for defects must be carried out with the corresponding set of shop drawings and project specifications readily available while adhering to a systematic approach for documenting all defects.

## 17.12 Recommended Practice for Inspection of Segment Handling in the Casting Yard

1. **Segment handling in the casting yard should be in accordance with an approved segment handling procedure.** Segment handling in the yard consists of lifting the match-cast segment off the soffit form, traveling with the suspended segment to storage, and placing it on a prepared foundation. The procedure to be submitted and approved describes:

a. The crane, movement, boom, safe working loads.
b. The lifting frame is a device that distributes the lifting force to generally four pickup points (see **Figure 17.16**).
c. The attachment of the lifting frame to the segment.

2. **The inspector must verify that the required concrete strength for handling is achieved.** The concrete strength required for lifting the segments is provided in the special provisions. If not, it should be proposed by the contractor and approved by the Engineer for use. The chosen method must be able to handle the segments without causing structural or cosmetic damage to the segments.

3. These attachments are generally post-tensioning bars (**Figure 17.16**) that go through the top slab. For lighter segments, lifting loops may be used. C-hooks can also be used and should be carefully positioned with the lifting line in the center of gravity of the segment. If C-hooks are used, the contractor shall submit this location for each different segment type and the inspector should verify that it is placed properly.

4. The inspector shall verify that the approved handling procedures are being followed and that no damage to the segments is occurring. Any deviation from approved procedures shall be identified and the Engineer should be notified.

5. If any damage is identified while handling the segments, inspectors shall adhere to a systematic approach for documenting any defects.

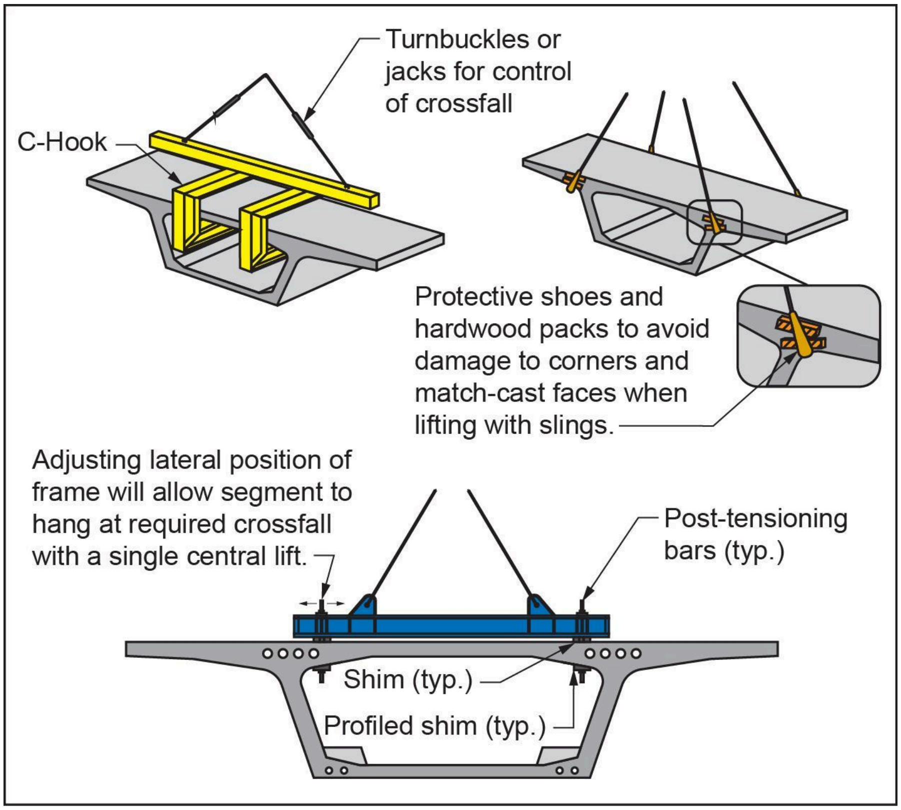


*Figure 17.16 – Handling Segments*

## 17.13 Recommended Practice for Inspection of Repairs Made to Segments

The inspector should verify that there is an approved repair procedure and that this procedure is being followed. There may be multiple repair procedures provided for review and approval. The inspector shall verify that the proper procedures are being followed for each repair. All inspections of segments for repairs must be carried out with the corresponding set of shop drawings and project specifications readily available while adhering to a systematic approach for documenting all defects.

The repair procedure should address the following:

1. **Repair of Voids** (honeycombing) involves considerations related to the appearance of the repair, the durability of the repair, and the structural adequacy of the repair as discussed below.

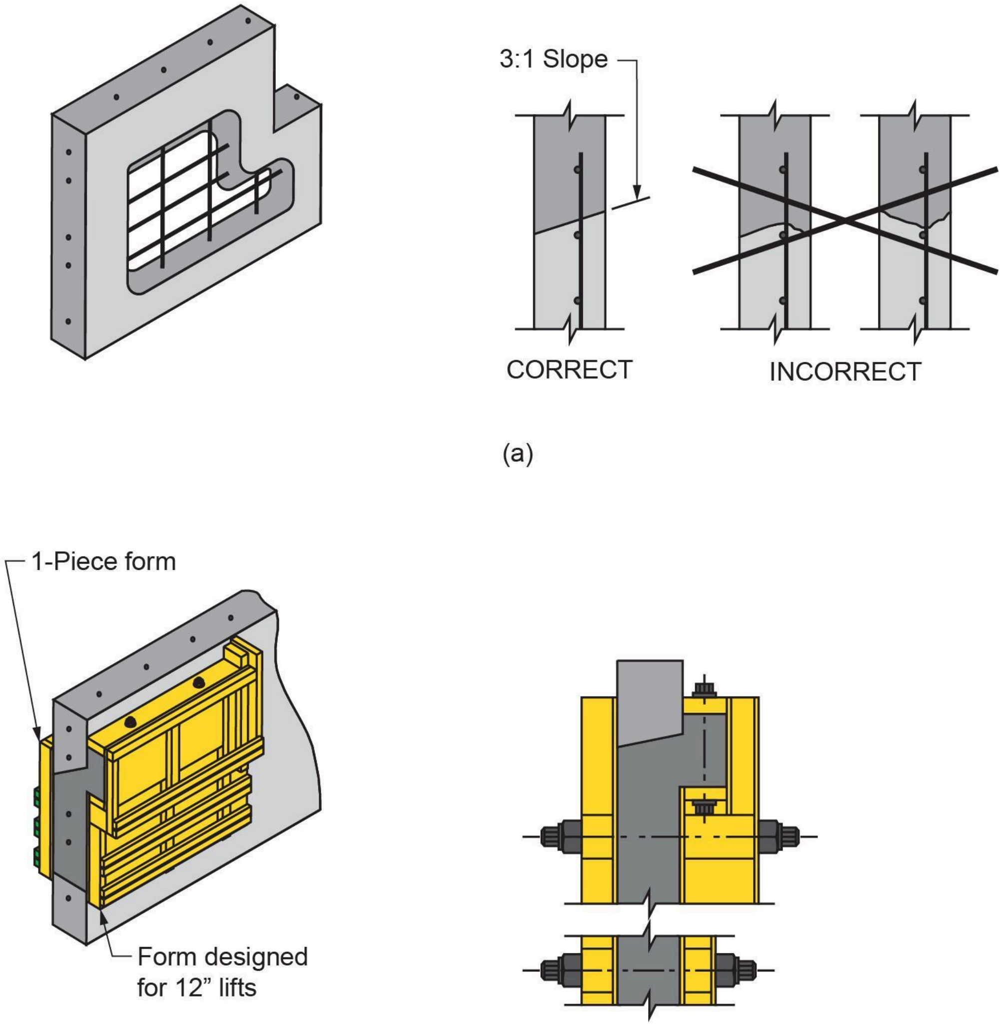
The appearance of the repair concerns color and surface finishing. Since most repairs are darker than the surrounding concrete, it is best to make trial mixes of the mortars proposed for repairs at the time of approval so that color differences can be judged. These trial mixes should be made **before** they are needed. Part of the procedure submitted by the contractor should be the names and qualifications of the person(s) making the repairs.

The durability of repairs is determined by the quality of the repair material and the bond of the repair material to the old concrete. Bond is determined by surface preparation, type of binding agent, and method of filling the void. The different types of voids require treatment. **Figure 17.17** shows the repair of a hole in the web which can be effectively repaired, more easily than surface damage. Other issues to be addressed are curing and shrinkage of the repair.

Careful attention must be taken when repairs are required at the face of the segments to ensure that the match-cast properties are not affected. These repair procedures must be approved by the Engineer.

Structural repairs pose a significant concern for the structural integrity of the segments and should be done following strict project-specific guidelines and methods approved by the Engineer.

**Repair of Cracks.** The assessments and repair of cracks shall be verified with the project-specific guidelines and approved by the Engineer. The contractor must verify that all repair procedures and materials follow the manufacturer's recommendations.



(a)

(b)

*Figure 17.17 – Repair of Honeycombed Area*

## 17.14 Recommended Practice for Inspection of Segment Storage

The inspector should verify that there is an approved procedure for storage of segments. The procedure indicates how, where and on what material the segments are supported and whether or not double stacking is allowed. It also indicates the layout of the storage area and the order of placing and removing segments. In addition, the contractor usually performs work in the storage area, such as curing, transverse post-tensioning, finishing recesses, repairs of cracks, honeycombing, and surface finishing. Some of these tasks, such as transverse post-tensioning and repairs, require the presence of an inspector.

The inspector should ensure that the approved material is used to support the segments which will cushion the load evenly. Oak blocks are often used. Supports are placed under the webs because the load bearing capacity there is much higher than at any other location. The bottom slab could not handle the load without cracking. Three (3) supports are provided per segment – two under one web near the ends and a third in the middle of the opposite web (see **Figure 17.18**). This method provides predictable bearing forces and will support the segment evenly.

In case of double stacking, the support blocks should be placed correctly on the lower segment (see **Figure 17.18**). If webs are not vertical, the second segment is supported on the top slab of the lower segment. This will bend the slab. The contractor will take this bending effect into account when he proposes double stacking, but it is important to realize that this proposal is based on placing the supports correctly. The shop drawing should provide size of supports and exact location and tolerances.

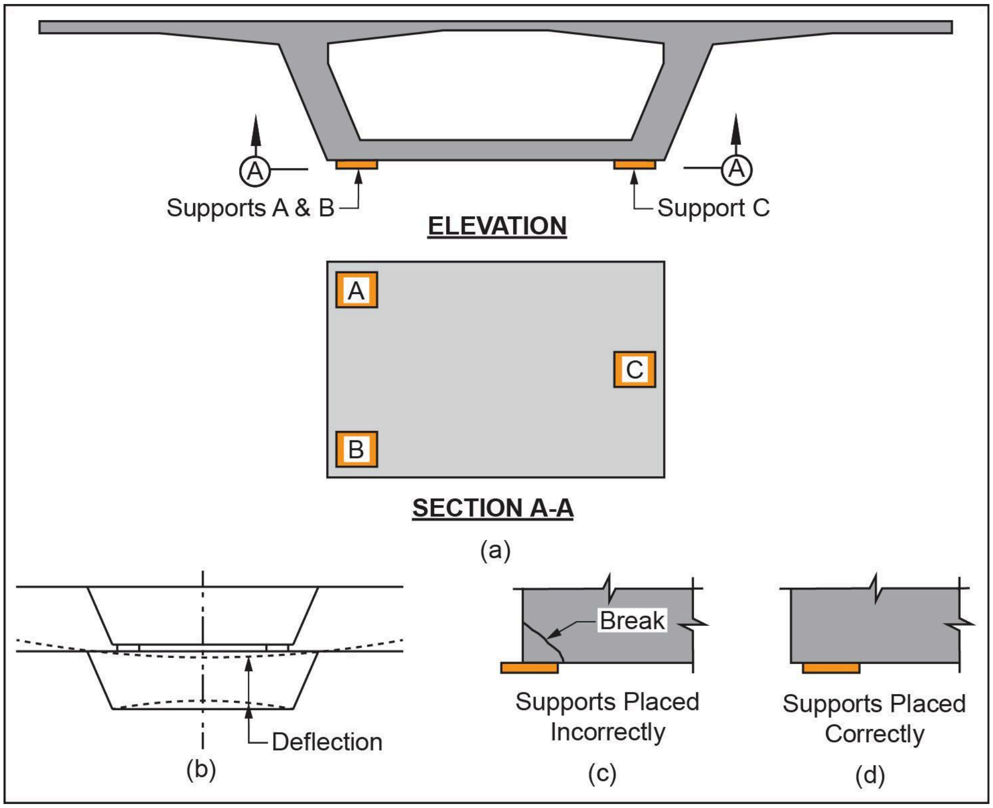


*Figure 17.18 – Stacking Segments*

## 17.15 Recommended Practice for Inspection of Segments for Payment

In reviewing segments for payment, the following details or criteria should be reviewed by the inspector and found to be acceptable:

- Segments should have a uniform appearance. This means even color and few or minor surface defects. The most common surface defect is caused by air bubbles. This occurs when plywood or steel forms are used but seems to be somewhat controllable. If size and number are such that the quality of the segment is clearly affected, the bubbles have to be sealed in accordance with an approved repair procedure.

- Generally, the bond breaker will adhere to the joint faces and will have to be removed by very light sandblasting or wire brushing. The operation should also remove the laitance to ensure the epoxy will be applied to solid material and will provide an excellent bonded joint with high tensile strength. The sandblasting should be as light as possible to achieve this. Strong sandblasting can remove too much material which would reduce the fit obtained with the match-casting procedure.

- Ducts should be checked for alignment and cleanliness, and anchors and recesses for the presence of mortar. Recesses should be cleaned out so far that the jack will fit into it. Anchors should be entirely free from mortar.

- Segment dimensions should be within the prescribed tolerances set forth in the contract.

- The segment should be checked for cracks, spalls, damage to keys and repairs including repairs on match-cast faces.

- Any defect should be repaired in accordance with the approved repair procedure, and the repair should be approved before full payment for the segment is made.

- The 28-day strength of the segment should be checked. If the 28-day strength is not achieved, it should be decided whether or not to accept the segment.

## 17.16 Recommended Practice for Inspection of Segment Transportation

Segments handling normally consists of removing segments from storage, placing the segment on a vehicle, moving the segment to the job site, unloading and storing the segment on-site, reloading the segment on-site, and lifting the segment for erection. Ideally, the contractor should use the same method of suspending the segment for all handling operations. However, this is not always the case. For example, during transportation in the casting yard, a sling may be used, while during erection on site, the contractor may opt for a lifting frame or C-hook. The different handling methods should be covered by calculations of the suspended segment. These calculations should differentiate between the stage where transverse post-tensioning is stressed or unstressed.

Segments are usually handled and stored strictly according to the approved procedure in the casting yard. The same arrangements also are required on site. The support conditions on vehicles are the same as in the yard. Calculations of loading during transport by vehicle should include an appropriate impact factor.

The inspector should verify that the contractor has obtained all the required permits for roadway transportation and that the contractor has the means to honor the requirements of these permits. Since this concerns heavy transports, permits are usually required for overloads and illegal widths. These need to be obtained by the contractor.

If the transport involves maintenance of traffic problems, the inspector should ensure that there is an approved maintenance of traffic plan. It is also necessary for the inspector to ensure that the contractor has informed all the parties involved and enforces the maintenance of traffic plan. Maintenance of traffic problems often occur in case of heavy transports such as cranes and segments. Usually these have been anticipated by the designer and are covered by special provisions.

## 17.17 Recommended Practice for the Inspection of Epoxy Joints

1. **Ensure that the epoxy resin is approved for use on the project**. The Special Provisions require completion of several tests on the epoxy resin. The approved epoxy will have passed these tests.

2. **Review all manufacturer’s recommendations for storage, preparation, mixing, and use of the product**.

3. **Ensure that the contractor is implementing the safety recommendations from the supplier.** Containers with epoxy resin carry warnings regarding toxicity of the materials and instructions in cases of emergency. The contractor should point out the hazards to the workers and should have the required supplies available on site in case of an emergency.

4. **Ensure that a supplier's representative is present at the time of first use on the project**. The consequences of errors made in mixing, application and/or removal of epoxies are costly and generally unnecessary. The presence of a manufacturer's representative thoroughly familiar with the product pays off, and the inspector should insist on it. For maximum benefit, all persons working with the material should be present at this first application.

5. **If there are several types of epoxies on the project, ensure that labeling is such that they cannot be interchanged**. Epoxy resins must be formulated specially for a variety of conditions. The ambient temperature is most important. An epoxy resin formulated for use in cold weather would set almost immediately if used in warm weather. Conversely, an epoxy resin formulated for hot weather would cure only after a long time if used in cold weather. Since weather conditions vary, epoxy resin suppliers formulate their product for a particular weather condition and if erection over several seasons is anticipated, there will be several formulations supplied. These should be kept apart.

6. **Ensure that the two components of the epoxy are properly mixed. Epoxy consists of a resin and a hardener, often referred to as components A and B**. As long as these are kept separated, the resin will not set. In order to function as designed, the two components A and B must be very thoroughly mixed. If not, the resin will not set. Improper mixing has been the cause of high repair costs. Good mixing is generally ensured by:

a. Using manufacturer's recommended equipment in accordance with manufacturer's instructions.

b. In addition to the above, using different colors for components A and B. If the color of the mix is uniform, the resin and hardener are properly mixed.

7. **Ensure that pot life and open time requirements are adhered to**. Although there is a certain safety range, one should understand that epoxy will bind and cure only if used within these specified time limits.

8. **Ensure that joint faces are properly prepared**. A good bond of the epoxy to the concrete is only achieved if the joints are dry and clean.

Dry is usually defined as "absence of surface water". This means that epoxy cannot be used when it rains. Also, after a rain, the joints should be dried off (preferably with a moderately hot torch).

9. Clean means that the joint has been lightly sandblasted to remove cement paste and bond breaker, and that subsequent soiling is removed by wire brush.

10. Be aware of surface temperature requirements as well. Some manufacturers require a minimum surface temperature prior to the application of epoxy. Concrete surface can be heated to achieve these requirements. Any heating procedures shall be submitted and approved by the Engineer prior to use.

11. Verify all necessary hardware is in place for any duct coupling devices required for use. This could include gaskets, additional coupler pieces, or any other proprietary materials from the manufacturer. Review the shop drawings to ensure that couplers are properly installed.

12. **Ensure that conditions for use of epoxy are met**. The conditions for use of epoxy are humidity and ambient temperature range as prescribed by the manufacturer and/or specifications (see also item 7).

13. Prior to initial epoxy application, the inspector should determine the proper amount of epoxy needed to achieve the requirements of the contract documents. The required thickness of epoxy and the surface area of each face that epoxy is to be applied should be used to calculate the needed volume of epoxy for each operation.

**Ensure that the epoxy is properly applied to the joint faces**. Epoxy should be applied to each adjoining face to ensure proper coverage and seal. Review contract documents and manufactures recommendations for application of epoxy near or around duct coupling devices. Usually, workers apply epoxy with a gloved hand. Though primitive, this is the most effective method. Ensure complete coverage of segment faces with a specific focus at the top of the segment.

14. **Ensure that excess epoxy is removed from exterior joint faces**. Since epoxy is applied to the joint in a much greater quantity than required for filling the joint, much of it will be squeezed out upon applying the temporary prestress. This excess epoxy forms a bead at the joint faces, on both the inside and outside of the box girder. On the inside, this bead is usually left in place. On the outside, this is unsightly and is usually removed. This often requires access to the outside of the segment for work and inspection.

The treatment can consist of removing the epoxy with a tool as long as it is soft. This will leave a mark accentuating the joint. In case the box will receive a surface treatment, this is the simplest way to remove the epoxy bead. Alternatively, the epoxy can be removed without leaving marks by chiseling it off after it hardens. This, however, is more time-consuming.

15. **Ensure that excess epoxy is cleaned from tendon ducts**. As epoxy beads form on the outside, the same occurs at the tendon ducts. Squeezed out epoxy will enter the ducts. Duct coupling devices should eliminate any epoxy from entering the duct. However, if couplers are not used, ensure ducts are free from any epoxy intrusion. This epoxy is removed by inserting a brush with a long handle into each duct. This is done immediately after applying the temporary post-tensioning and releasing the segment from the crane.

16. **Ensure that the curing process is being monitored**. Epoxy will perform its function, which is to provide tensile strength at the joint and seal the joint from moisture penetration, only if it is cured. Normally the epoxy will cure, but on occasion, a bad batch or badly mixed batch will not set. To monitor this, simple field tests have been devised such as gluing a small concrete test cube against the inside of the box with the epoxy used for the joint. The next day a firm blow with a sledgehammer will either fail the epoxy or the concrete. Although not very scientific, this "test" surely indicates whether or not something is obviously wrong.

The special provisions may prescribe tests to be performed on the epoxy during erection. Such tests usually apply to the strength of the epoxy.

17. **Ensure that tests prescribed by the Special Provisions to be performed during erection are made**.

**18. Ensure that there is an approved procedure for removal of epoxy from joint faces.**

If, for some reason, a segment cannot be erected and epoxy has been applied to the joint faces, the epoxy must be removed. In order to avoid delays, the contractor should submit a procedure for this for approval. The usual procedure consists of:

a. Scraping off as much of the epoxy as possible while it is still soft.
b. Burn off the remainder with a low heat torch.
Sandblast the joint to thoroughly clean the joint.

## 17.18 Recommended Practice for Tendon Stressing

All aspects of tendon stressing should be in accordance with The Project Specifications. A commonly referenced document is the FHWA *“Post-Tensioning Tendon Installation and Grouting Manual.”* ***Special care should be given to observation of the safety guidelines for stressing of post-tensioning tendons presented in Chapter 11.***

## 17.19 Recommended Practice for Inspection of Grouting

Inspection of grouting should confirm conformance with the recommendations of **Chapter 12**, *and the project specifications. Frequently referenced documents are the PTI / ASBI Guide Specifications.*

## 17.20 Recommended Practice for Inspection of Cast-in-Place Segmental Structures

The recommended practice for inspection of precast segmental structures is, with few exceptions, also valid for cast-in-place segmental work.

Exceptions are those operations strictly related to the techniques such as geometry control, segment handling, etc. which obviously do not apply.

Form tolerances for cast-in-place segmental bridges should be adhered to with great care. A form which produces heavier segments on one of the cantilever arms will have a large effect on the unbalanced moment. The geometry control for cast-in-place segmental bridges is less demanding since it is almost "self-correcting." Curing on the other hand is more critical since the progress of the work depends on the concrete achieving early strength. Post-tensioning generally occurs long before the concrete achieves design strength and post-tensioning anchor sizes may have to be adapted for use with lower strength concrete. The sequence of segment concreting has to be adapted to the flexibility of the form carrier.