U.S. Department of Transportation
Federal Highway Administration

LIGHTWEIGHT CONCRETE BRIDGE DESIGN PRIMER

A New Resource for Bridge Designers

Source: FHWA

Monthly Webinar Series
ASBI/NCBC

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Structural Lightweight Concrete

- Structural lightweight aggregate (LWA) has been commercially manufactured in USA since 1920
  - Not a new material!
- It was immediately used to produce structural lightweight concrete (LWC)
  - Main benefit was its reduced density
  - Also found to be very durable

San Francisco Oakland Bay Bridge (1936)

Source: FHWA

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LWA is a manufactured product

- Raw material is shale, clay, or slate
- Heated in kiln to over 2,000 degrees Fahrenheit

- Gas bubbles form in softened material
- Gas bubbles remain after cooling
- Clinker is crushed and screened

Source: FHWA

All photos © Stalite Structural Lightweight Aggregates except as noted

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Structural Lightweight Concrete

- When the original patent expired in the 1950s, the use of LWC increased rapidly as other manufacturers entered the market
- Rapid growth continued until the mid 1970s
  - Oil crisis increased energy costs
  - Introduction of pollution controls increased production costs
- Result: Industry production was reduced, then became relatively constant at a lower level; promotion was curtailed

FHWA Efforts Related to LWC

- In the early 2000s, FHWA saw LWC as an underutilized technology that had potential for improving the economy and performance of bridges
  - Information was needed to equip owners and designers to properly evaluate the potential benefits of using LWC
  - Information should include laboratory data and field experience that demonstrate that LWC can be durable and cost effective for bridge designs
  - Additional research was needed to answer some questions, especially about “specified density” concrete in range between LWC and normal-weight concrete (NWC)

FHWA Efforts Related to LWC

- In 2005, the Federal SAFETEA-LU legislation included funds for FHWA to use for research on high performance concrete (HPC)
  - The funds were eventually used to begin work on LWC at FHWA's Turner Fairbank Highway Research Center (TFHRC)
  - Efforts were coordinated with NCHRP Project 18-15 "High-Performance/ High-Strength Lightweight Concrete for Bridge Girders and Decks," which produced NCHRP Report 733 (2013)

FHWA Efforts Related to LWC

- Using the results of the two research efforts and earlier work, the Load and Resistance Factor Design (LRFD) Specifications were revised by AASHTO
  - 2014 – Revised equation for modulus of elasticity, E_c – better correlation for LWC and high strength concrete
  - 2015 – A package of revisions related to LWC was adopted including
    - New definition for LWC
    - Introduction of the concrete density modification factor, λ
    - Insertion of λ into equations where appropriate
  - Changes appear in the binding *AASHTO LRFD Bridge Design Specifications,* 8th ed. (23 CFR 625.4(d)(1)(v))

FHWA Efforts Related to LWC

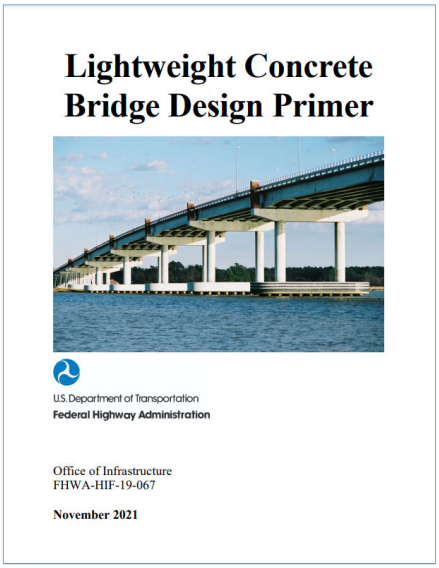
- Even after these changes were made to the LRFD Specifications, LWC was still not being commonly used for bridge design
  - Designers and owners did not see LWC as a reasonable option
  - Perceived higher cost of the material
  - Designers were unsure of how to select properties of LWC for design
- A LWC Primer was identified as a product that would be useful to advance the use of LWC by addressing these concerns
  - Provide basic information for design of LWC bridges
  - Provide information to allow evaluation of potential benefits of using LWC for bridges

Lightweight Concrete Bridge Design Primer

- The LWC Primer was developed to advance the use of LWC by providing
  - Basic information for design of LWC bridges
  - Information to allow evaluation of potential benefits of using LWC for bridges
- The document (FHWA-HIF-19-067) is available for download at:

  https://www.fhwa.dot.gov/bridge/concrete/hif19067_Nov2021.pdf

  or at the Concrete Bridges webpage on the FHWA website



Source: FHWA

Table of Contents

1. Introduction

- Definition of LWC
  - *Concrete containing lightweight aggregate conforming to AASHTO M 195 and having an equilibrium density not exceeding 0.135 kcf, as determined by ASTM C567*. (Note: AASHTO M 195 and ASTM C567 are not Federal requirements.)
- Not a new material
  - LWC has been in the AASHTO design specifications since at least 1969
  - FHWA's *Criteria for Designing LWC Bridges* (1985)
    - LWC has a "*sufficient record of successful applications to make it a suitable construction material … for bridges*" and that "*sufficient information is available on all aspects of its performance for design and construction purposes*."

Introduction

- Benefits of LWC for Bridges
  - Structural
    - Extended span ranges
    - Wider girder spacings
    - Shallower girders
    - Reduced design loads on bearings, substructure elements, foundations
    - Reduced weight of precast elements for handling, hauling, erection

Introduction

- Benefits of LWC for Bridges
  - Durability
    - Internal curing with prewetted LWA reduces shrinkage, cracking, and permeability
    - Similar stiffness of aggregate and paste reduces microcracking and permeability
    - Lower modulus of elasticity reduces cracking
    - Lower coefficient of thermal expansion reduces cracking

Introduction

- Perceived Disadvantages of LWC for Bridges
  - Increased cost of LWA and LWC
  - Reduced durability
  - Reduced structural capacity
  - Availability of lightweight aggregate
  - Lack of familiarity of contractors with lightweight concrete
- The increased cost of LWA and LWC is not insurmountable, as evidenced by the many successful projects completed using LWC
- Other concerns may be based on misconceptions or can be addressed in design

Introduction

- Examples of the Effective Use of LWC for Bridges
  - San Francisco Oakland Bay Bridge, CA – 1936
  - I-5 over Skagit River, WA – 2013
  - Rugsund Bridge, Norway – 2000

San Francisco-Oakland Bay Bridge, CA

- Upper deck of suspension spans was built in 1936 using all-LWC (95 pcf)
  - Saved $3M of original $40M total cost
- Lower deck was reconfigured for highway traffic using LWC in 1958
- Both decks are still in service
  - Have had wearing surfaces

Source: FHWA

I-5 over Skagit River, Mt Vernon, WA

- Emergency replacement of collapsed truss span
  - Total weight of replacement span held to < 915 tons to avoid reanalysis and retrofit of piers
- Sand-LWC used for precast deck girders
  - First LWC girders for Washington State DOT
    - Sand-LWC also used for diaphragms & barriers
  - 162 ft LWC girders weighed 84 tons each
    - Girders were 65” deep with a 6.5-ft-wide top flange
  - Design compressive strength of LWC girders: 9 ksi at 123 pcf
    - Actual design compressive strength = 10,600 psi

Source: Christopher Vanek/WSP

Rugsund Bridge, Norway

- LWC used for center of span for alternate design
  - Increased length of main span from 564 ft to 623 ft (+10%)
  - Used same quantity of post-tensioning even with longer span
  - Moved foundations into shallower water or to edge of water
  - Reduced length of ballast-filled side spans
  - Shortened overall length of structure 33 ft
- Bid for LWC design was 15 percent less than NWC bid
- Pumping of LWC was major issue
  - LWA was shipped from USA to allow pumping of LWC

2. Properties of LWA and LWC

- Provide basic test data on material properties
  - LWA
    - Mechanical and durability properties
  - LWC
    - Types and definitions
    - Fresh and hardened properties; Design parameters
    - Seismic and durability properties; Service life and safety properties
  - Internal curing
    - Modify NWC by replacing a fraction of the fine aggregate in mixture with prewetted LWA to provide curing water from within

Properties of LWA

- Types of LWA
  - Properties vary depending on source and processing

© 2013 NAS

  - LWA can be uncrushed or crushed

© 2016 PCA

Properties of LWA

- Gradations for coarse LWA from AASHTO M 195 (2011)

Nominal Size Designation	25.0 mm (1 in.)	19.0 mm (¾ in.)	12.5 mm (½ in.)	9.5 mm (3/8 in.)	4.75 mm (No. 4)	2.36 mm (No. 8)	1.18 mm (No. 16)	0.075 mm (No. 200)
25.0 to 4.75 mm	95-100	--	25-60	--	0-10	--	--	0-10
19.0 to 4.75 mm	100	90-100	--	10-50	0-15	--	--	0-10
12.5 to 4.75 mm	--	100	90-100	40-80	0-20	0-10	--	0-10
9.5 to 2.36 mm	--	--	100	80-100	5-40	0-20	0-10	0-10

  - Sizes are identified by nominal sizes, typically ¾”, ½”, and 3/8”

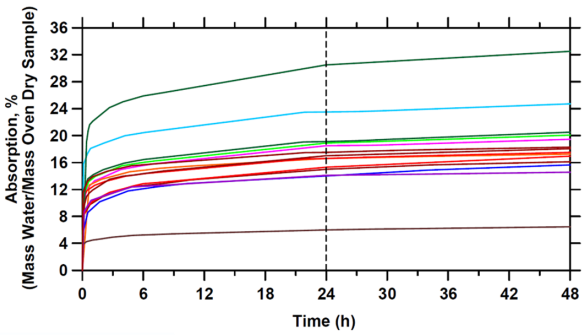
Note: Use of AASHTO M 195 is not a Federal requirement.

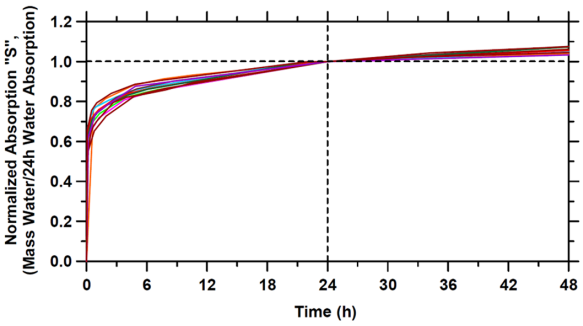
Properties of LWA

- Absorption of LWA
  - May range from 5% to more than 25% by mass of dry aggregate after soaking for 24 hours
    - Significantly higher than typical NWA
    - Depends on LWA source and size
  - Cautions
    - Absorption alone should not be considered as the single determinant of acceptable performance of LWA
    - In past, some agencies have prohibited use of LWA crushed after firing to minimize absorption. May apply to some types of LWA but is not necessary for others.

Properties of LWA

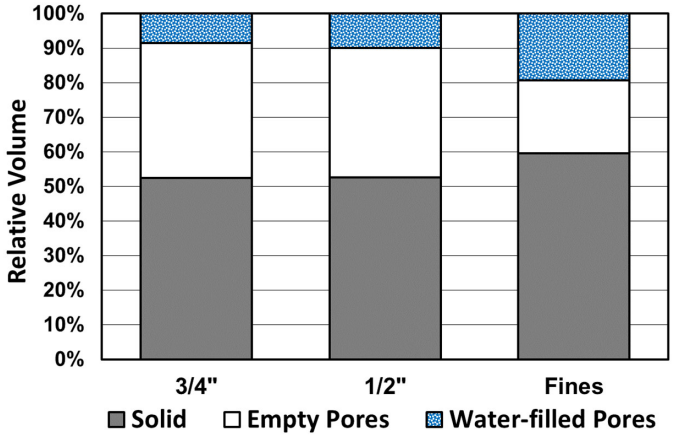
- Absorption of fine LWA from oven dry condition
  - Wide range (5 to 30%) for sources in U.S. (left)
  - Absorption normalized to 24 hr value is very consistent (right)





Properties of LWA

- Condition of LWA with absorbed water
  - Figure represents LWA from one source
  - Varies with size of LWA
  - Less than half of gross volume of LWA is pores
  - Only a fraction of pore volume fills with water
    - Only 20 to 50% of pore volume fills with water



Source: FHWA

Properties of LWA

- Durability of LWA
  - Soundness and Los Angeles abrasion loss data from North Carolina DOT approved coarse aggregate list with NCDOT maximum test limits

Test Results for ¾ in. Gradations (A)	Soundness Test Loss	LA Abrasion Test Loss
Average all sources	0.73%	31.0%
Lightweight Aggregate – Quarry A	0.4%	32%
Lightweight Aggregate – Quarry B	0.1%	31%
Number of sources included in average	*166*	*149*

NCDOT Maximum Test Limit	Soundness Test Loss	LA Abrasion Test Loss
General test limit	15%	55%
For $f'_c > 6$ ksi	8%	40%
For lightweight aggregate	10%	*See Note 2*

Source: NCDOT

  - These LWA sources meet the NCDOT test requirements and are similar to average test results shown which are for all approved aggregates

Properties of LWC

- Types of LWC
  - All-LWC: All aggregate in concrete mixture is LWA
  - Sand-LWC: This mixture uses coarse LWA and NWA fines (sand)
  - Specified-density concrete: any blend of NWA and LWA to obtain a specified density, which can range from all-LWC to NWC
- These definitions were dropped in the LRFD Specifications, 8th edition
  - The density of LWC is specified
  - The supplier determines the blend of aggregates to achieve it

Properties of LWC

- Types of density used to specify LWC
  - Fresh: The density of fresh concrete in its plastic state
    - Used for acceptance at delivery
  - Equilibrium: The density of concrete exposed to a drying environment for sufficient time to reach a constant mass
    - Not typically measured directly with long-term drying
    - Generally based on a density calculated from mix proportions
- The terms “density” and “unit weight” are usually used interchangeably in specifications

Properties of LWC

- Typical range of densities
  - Varies with f'_c
  - For many bridge applications: 0.110 to 0.125 kcf
  - Densities as low as 0.090 kcf may be achieved for lower strength applications, such as decks
  - Specified densities are for plain concrete
    - Add allowance for increase in density with reinforcement
    - Typically 0.005 kcf is used, but this can be inadequate in some cases such as heavily reinforced girders

Properties of LWC

- Hardened mechanical properties
  - Some tests show that LWC has reduced mechanical properties compared to NWC with the same compressive strength
  - However, in some cases, LWC can have properties that are similar to or greater than for a comparable NWC mixture
  - Even when LWC properties may be reduced, designs have been successfully completed and structures have performed well, as illustrated by the limited sample of LWC bridges presented in Chapter 7

Properties of LWC

- Compressive strength
  - For deck concrete, the same compressive strength used for NWC decks can be used for LWC decks
    - If a reduced tensile strength is expected for LWC, some designers have compensated by increasing the specified compressive strength for the LWC deck
    - However, this may not be necessary if tensile properties of LWC are similar to or possibly better than for NWC
  - For girder concrete, a 28-day compressive strength of 8.5 to 10 ksi has been successfully used
    - Some researchers have not achieved high strengths with some LWA. Consult LWA suppliers when considering high compressive strengths

Properties of LWC

- Tensile strength
  - The modulus of rupture, f_r, has often been used as the tensile strength
    - This quantity has limitations but may be used for decks or pavements
    - LRFD Specifications (8th ed.) Equation 5.4.2.6 includes the following expression to define f_r : $0.24\ \lambda\sqrt{f'_c}$
  - The splitting tensile strength of concrete, f_{ct}, is typically used to assess the tensile strength of LWC
    - It is generally accepted that f_{ct} provides a better estimate of the tensile strength in larger bending elements like girders
    - LRFD Specifications (8th ed.) Equation 5.4.2.8-2 can be solved for the splitting tensile strength: $f_{ct} = 0.213\ \lambda\sqrt{f'_c}$

Properties of LWC

- Tensile strength
  - Test data for deck concrete mixtures made using NWA (river gravel) and three sources of LWA for the coarse aggregate and ratios of measured-to-expected splitting tensile strength

Type of Concrete	f_{ct} (ksi)	f'_c (ksi)	$f_{ct} / (0.213 \sqrt{f'_c})$
NWC	0.438	5.505	0.880
LWC with Slate LWA	0.490	5.135	1.02
LWC with Clay LWA	0.520	5.200	1.08
LWC with Shale LWA	0.510	4.980	1.08

Source: Byard and Schindler (2010)

  - In this case, all LWC mixtures exceeded the expected f_{ct} for NWC, while the NWC concrete was below the expected value

Properties of LWC

- Compressive strength
  - Compressive strength gain with time is similar for LWC
  - Stress-strain curve in compression is typically linear to a higher level of stress compared to NWC
    - This behavior reflects a delay in the development of microcracking to higher levels of stress within LWC compared to NWC

Properties of LWC

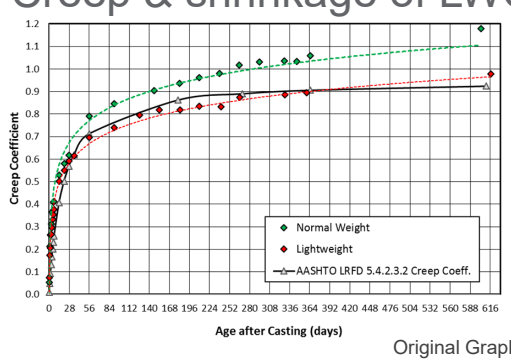
- Modulus of elasticity
  - The modulus of elasticity of LWC is less than most NWC
  - LRFD Equation 5.4.2.4-1 was adopted by AASHTO in 2015 (also in 8th ed.) to better reflect the expected modulus for LWC

$$E_c = 120{,}000\, K_1\, w_c^{2.0}\, f'_c{}^{0.33}$$

  - The effect of LWC is accounted for by including w_c, the unit weight of concrete

Properties of LWC

- Creep & shrinkage of LWC for PS girder (10 ksi)



Original Graphs: © 2016 PCI

  - Values for LWC were less than the NWC mixture
    - Even though the LWC had a higher cement content

Properties of LWC

- Coefficient of thermal expansion
  - Values for LWC are generally less than for NWC
  - Test data for deck concrete mixtures made using NWA (river gravel) and three sources of LWA for the coarse aggregate

Type of Concrete	Control	Internal Curing	Sand-LWC	All-LWC
NWC	6.2	--	--	--
LWC with Slate LWA	--	5.9	5.1	4.3
LWC with Clay LWA	--	5.8	5.1	4.0
LWC with Shale LWA	--	6.0	5.2	4.0

Source: Byard and Schindler (2010)

  - For these mixes, sand-LWC was about 80% and all-LWC was less than 70% of the values for NWC

Properties of LWC – Design Parameters

- The following design parameters are briefly discussed
  - Equivalent rectangular stress block
  - Prestress losses
  - Camber
  - Transfer and development of pretensioned strands
  - Vertical and horizontal shear
  - Resistance factors
- Provisions in LRFD Specifications (8th ed.) can generally be used for these design parameters

Properties of LWC – Durability

- The following aspects of durability are briefly discussed
  - Permeability
  - Cracking tendency
  - Corrosion resistance
  - Freeze and thaw resistance
  - Alkali-aggregate reactivity
  - Abrasion
  - Thermal effects
- Performance of LWC has been shown to be comparable to NWC for these aspects of durability

Internal Curing

- Internal curing (IC) is provided by replacing a portion of NW sand with prewetted LWA fines
  - Absorbed water is released within concrete to cure from inside
  - More effective than externally applied water, especially with less permeable high-performance concretes
  - NYSDOT specification allows the reduction in required duration of wet cure for IC concrete decks
- Any LWC using prewetted LWA provides internal curing

Internal Curing

- Trial placement compares conventional and IC concrete
  - Conditions when concrete was placed near Denver, CO
    - 92°F air temp.
    - 20% RH
  - No conventional curing of any type was applied to either concrete
  - Appearance the next morning – concrete with IC has not dried out

3. Initial Design Considerations

- Reasons to use LWC in bridges
  - Reduced weight or load
  - Enhanced durability and extended service life
  - Other benefits
- Concerns about using LWC in bridges
- Selection of material properties for design
- Estimating the cost of LWC
- Design considerations for elements and structure types

4. LWC Design Using LRFD Specifications

- Review recently adopted changes related to LWC
- Discuss articles in LRFD Specifications that address or could address LWC
  - Example: AASHTO LRFD-8 Design Specifications[1] Article 5.4.2.3 – Creep & Shrinkage: Since LWC is not specifically mentioned, provisions can be used for LWC without modification
  - Comments are given on provisions when appropriate
- Some changes identified during development of the *Primer* have been adopted by AASHTO (not Federal requirements)

[1] *AASHTO 2017, incorporated by reference at 23 CFR 625.4(d)(1)(v).*

5. Construction Considerations

- Topics discussed related to construction using LWC
  - Quality control
  - Proportioning LWC mixtures
  - Prewetting LWA
  - Batching
  - Placing and Finishing
  - Curing
  - Grinding and grooving
  - Heat of hydration

6. Specifying LWC

- Information is provided for selected topics to help designers prepare construction specifications for LWC
  - Density
  - Material properties
  - Test methods
  - Construction specifications
  - Internal curing

7. Project Examples Where LWC Was Used

- A list of bridges for which LWC has been successfully used for the following reasons:
  - Improved structural efficiency
  - Reduced element weight for shipping & handling
  - Allowed reuse of existing structural elements

7. Project Examples Where LWC Was Used

- A wide range of bridge projects is included
  - Large and small; short and long spans; new and old
  - Elements and bridge types include:
    - Decks
    - Pretensioned girders
    - Segmental box girders
    - Suspension bridges
  - Internal curing is mentioned
    - Examples are not provided, but references are given

Project Examples Where LWC Was Used

- **Projects that reused existing structural elements**
  - I-895 Bridge over the Patapsco River Flats – Baltimore, MD
  - Shasta Arch Bridge on Southbound I-5 – Shasta County, CA
  - Route 198 Bridge over Harper Creek – Gloucester County, VA
  - I-5 Bridge over the Skagit River – Skagit County, WA
  - Beach Bridge – North Haven, ME

I-5 over Skagit River, Mt Vernon, WA

- Emergency replacement of collapsed truss span
  - Total weight of replacement span held to < 915 tons to avoid reanalysis and retrofit of piers
- Sand-LWC used for precast deck girders
  - First LWC girders for Washington State DOT
    - Sand-LWC also used for diaphragms & barriers
  - 162 ft LWC girders weighed 84 tons each
    - Girders were 65” deep with a 6.5-ft-wide top flange
  - Design compressive strength of LWC girders: 9 ksi at 123 pcf
    - Actual design compressive strength = 10,600 psi

Source: Christopher Vanek/WSP

Beach Bridge, North Haven, ME

- NEXT D beams used to replace 2 span bridge on island off coast of Maine
  - First use of sand-LWC for a NEXT beam bridge
    - LWC allowed reuse of pier
    - Avoided design and construction of new foundations at difficult site
    - Reduced beam weight for shipping and handling
- Properties of self-consolidating LWC
  - Design compressive strength of 6 ksi
  - Max. plastic density of 120 lb/ft^3

Project Examples Where LWC Was Used

- **Projects that reused existing structural elements** (*cont'd*)
  - Ben Sawyer Bridge – Sullivan's Island, SC
  - Massaponax Church Road over I-95 – Spotsylvania Cty, VA
  - Brooklyn Bridge over the East River – New York City, NY
  - Coleman Bridge over the York River – Yorktown, VA
  - Woodrow Wilson Br over Potomac River – Washington, DC

Ben Sawyer Bridge, Mt Pleasant, SC

- Replace swing span and approaches
  - Swing span constructed off-site and floated in
  - Approach spans constructed off-line and slid in
- LWC used for decks on swing span and approach spans
  - LWC addressed concerns regarding seismic performance and poor soils

Source: FHWA

Coleman Bridge, Yorktown, VA

- Bridge with twin 500 ft swing spans completed in 1952
  - 26 ft wide with 2 lanes
- Superstructure replaced in 1996
  - 74 ft wide with 4 lanes and shoulders
- LWC deck was selected based on cost savings and good experience in VA
- With reduced weight from using LWC deck
  - Pier caps only had to be widened
  - Steel quantity for new trusses was reduced

All photos source: FHWA

Woodrow Wilson Bridge, VA/DC/MD

- Deck replacement in 1983 used full-depth precast post-tensioned deck panels
- Use of LWC for deck panels allowed:
  - Thicker deck for improved durability
    - But lower shipping cost and erection loads
  - Wider roadway with no super- or substructure strengthening
    - Project cost and duration were reduced by avoiding strengthening
- LWC deck performed well until bridge was replaced to improve traffic capacity

Project Examples Where LWC Was Used

- **Projects that improved structural efficiency**
  - Marc Basnight Bridge over Oregon Inlet – Outer Banks, NC
  - Pulaski Skyway Bridge Rehabilitation – Between Newark, NJ
  - Benicia-Martinez Bridge – Benicia, CA
  - Route 33 Bridges – West Point, VA
  - Stolma Bridge – Hordaland, Norway
  - Nordhordland Bridge – Hordaland, Norway
  - Francis Scott Key Bridge – Baltimore, MD
  - San Francisco-Oakland Bay Bridge, CA

Benicia-Martinez Bridge, CA

- I-680 over the Carquinez Strait north of San Francisco
  - Cast-in-place box girder
  - 82 ft (25m) wide deck with 658 ft (201m) max. spans
  - Completed in 2008
- Entire segmental box girder cross-section was LWC
  - LWC used for entire 6500 ft bridge except for pier segments
  - Reduced seismic forces, foundations and cost

VA Route 33 Bridges, West Point, VA

- Bridges across Mattaponi and Pumunkey Rivers were completed in 2006 and 2007
- Approach spans are continuous for LL
- Each bridge has two 200'-240'-240'-200' spliced units with haunched pier segments
- LWC girders and decks reduced foundation loads on poor soils

Source: FHWA

Source: Standard Concrete Products, Inc.

Stolma Bridge, Hordaland, Norway

- World record span when completed in 1998
- Cast-in-place single-cell segmental box
  - Center span is 988 ft (301m)
  - Side spans are 308 ft (94m) and 236 ft (72m)
  - LWC (LC60 ≈ 8.7 ksi) in middle 604 ft (184m) of main span
- LWC was used to achieve better balance between main and side spans

NordHordland Bridge, Hordaland, Norway

- LWC was used for superstructure on the 535 ft cable-stayed main span completed in 1994
  - LWC saved nearly 1% of total contract cost
  - Reduced cost of stay cables and size of hold-down structure
- LWC also used for pontoons on floating bridge
  - Saved 3 to 7% of cost of smaller pontoons
  - Reduced wave forces ⇒ reduced load on structure
- A few other cable-stayed bridges have also used LWC

San Francisco-Oakland Bay Bridge, CA

- Upper deck of suspension spans was built in 1936 using all LWC (95 pcf)
  - Saved $3M of original $40M total cost
- Lower deck was reconfigured for highway traffic using LWC in 1958
- Both decks are still in service
  - Have had wearing surfaces

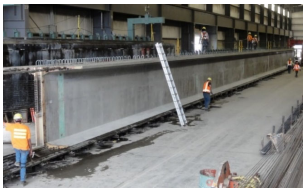
Source: FHWA

Project Examples Where LWC Was Used

- **Projects that reduced weight for shipping & handling**
  - I-5 Portland Avenue to Port of Tacoma Southbound Ramp – Tacoma, WA
  - I-95 Bridge over James River and North – Richmond, VA
  - Route 22 Bridge over the Kentucky River – Gratz, KY
  - I-85 Ramp over State Route 34 – Newnan, GA
  - Automated People Mover (APM) Project – Atlanta, GA

Portland Ave/Puyallup River, Tacoma, WA

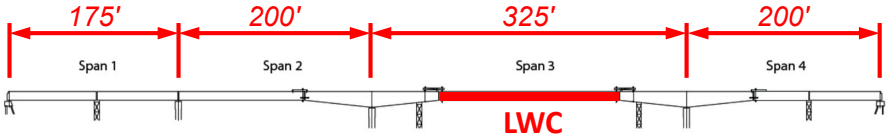
- New US record for longest single piece girder
  - 223 ft long – plus severe skews (add 7 ft)
  - WF100G Mod – 8'-4" tall; 5'-1" wide top flange
  - Same LWC mix as I-5 over the Skagit River
  - Using LWC enabled transporting girder to site



All photos source: Concrete Technology Corp.

Route 22 over the KY River, Gratz, KY

- PS concrete spliced girder proposed by contractor to owner as alternate to original steel girder design
  - 4 spans with 325 ft main span - record for US (2010)
  - LWC used for 185 ft long drop in girders – erected in pairs



Source: Janssen & Spaans Engineering, Inc

All photos source: Haydon Bridge Co.

LIGHTWEIGHT CONCRETE BRIDGE DESIGN PRIMER

A New Resource for Bridge Designers

https://www.fhwa.dot.gov/bridge/concrete/hif19067_Nov2021.pdf

Source: FHWA

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