

Rethinking Segmental Bridges: External Tendons Only?

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27/09/2023

Agenda

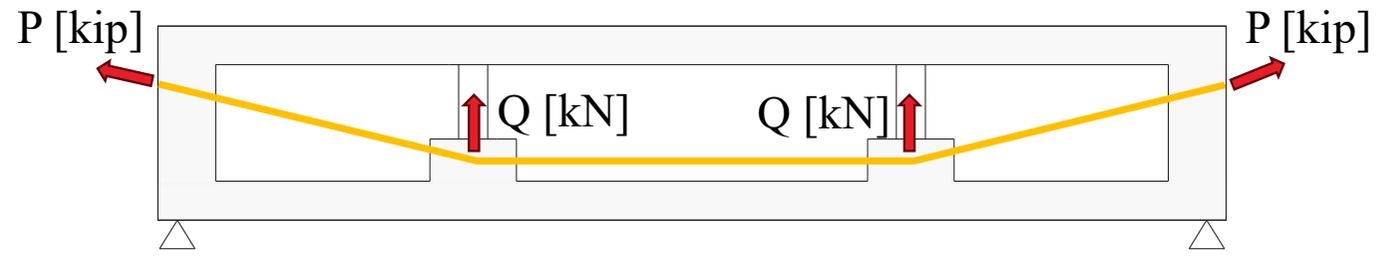
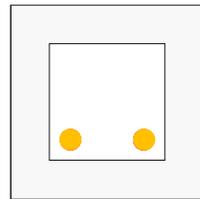
- External tendons: why and why not?
- External tendons overview
- Design and construction – Theemsweg Bridges case study
- Circular economy – Circular Bridge case study
- Summary
- Q&A

External tendons: why and why not?

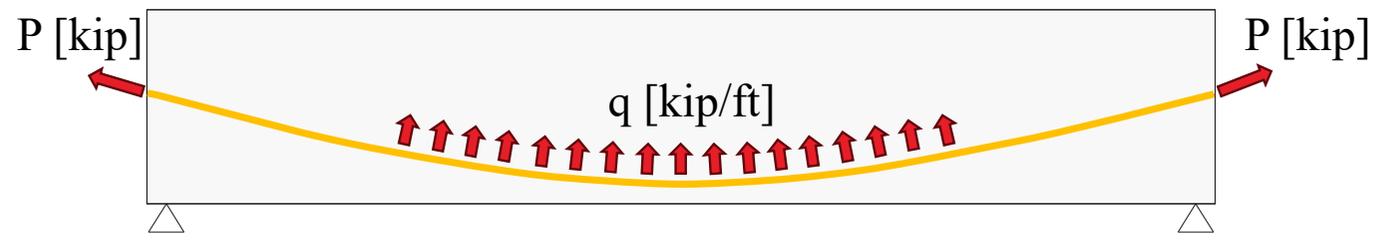
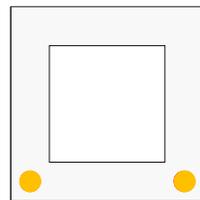
External and internal tendons

Concept

External tendons



Internal tendons



External tendons: why?

- Fully replaceable tendons should they deteriorate in the future.
- Easily inspectable and maintainable compared to internal tendons.
- Smaller prestressing losses compared to internal tendons, which allows to optimise prestressing design.
- Easily achievable draped (inclined) tendon trajectory offers shear enhancement adjacent to the supports, which allows to optimise the section for shear and torsion.

External tendons: why not?

- Require deviators and larger end diaphragms compared to the design with internal tendons; detailing and fabrication complexity.
- Cannot be placed as close to the outermost fibres of the deck cross section as it is possible with the internal tendons and hence penalty on the prestress efficiency.
- Prestressing quantities are higher compared to design with internal tendons only (though hybrid internal + external offers a good balance).
- More prone to accidental damage: mechanical or exposure to fire.

External tendons...



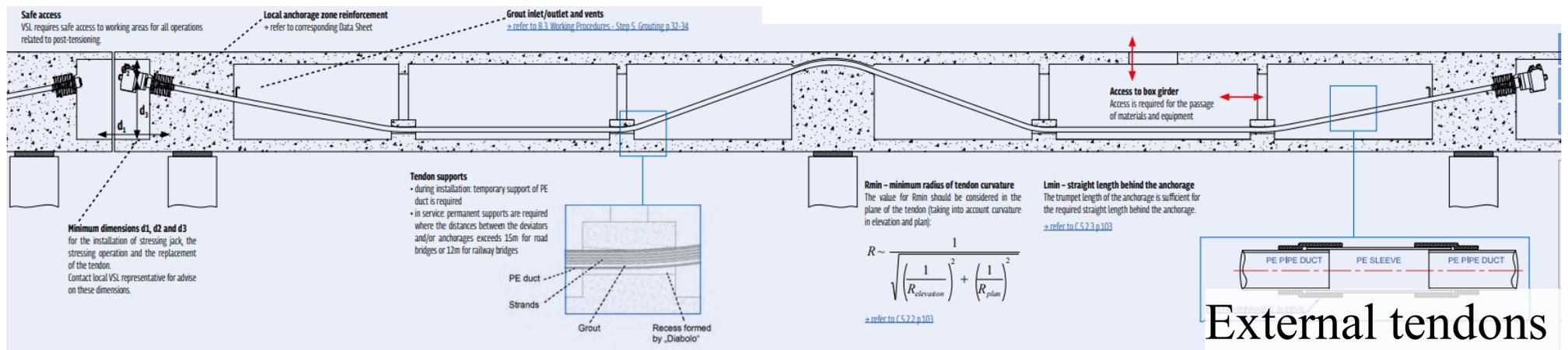
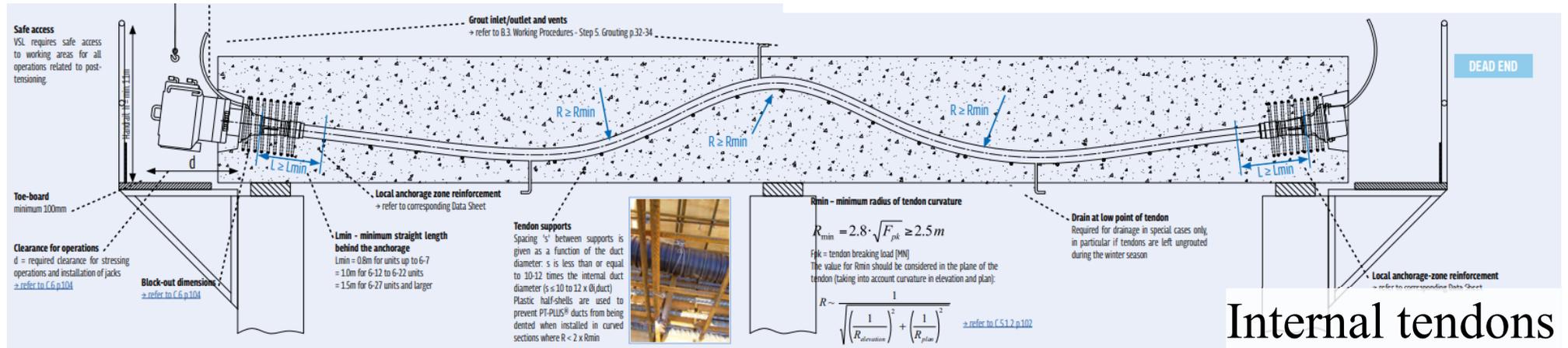
External tendon overview

External tendons overview

- Tendon trajectory.
- Diaphragms and deviators.
- Design opportunities.
- Tendon replacement.
- Inspection and testing.

External tendons overview

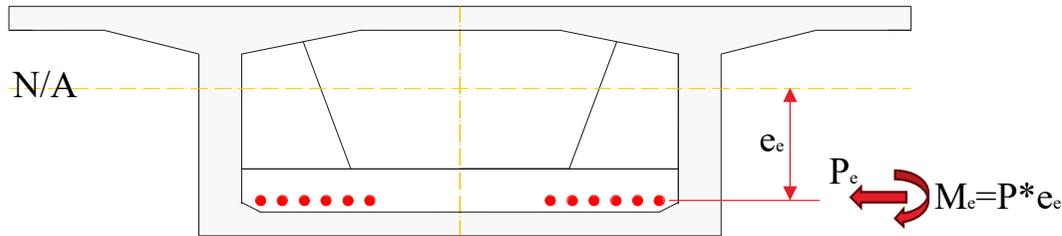
Tendon trajectory : internal vs external tendons



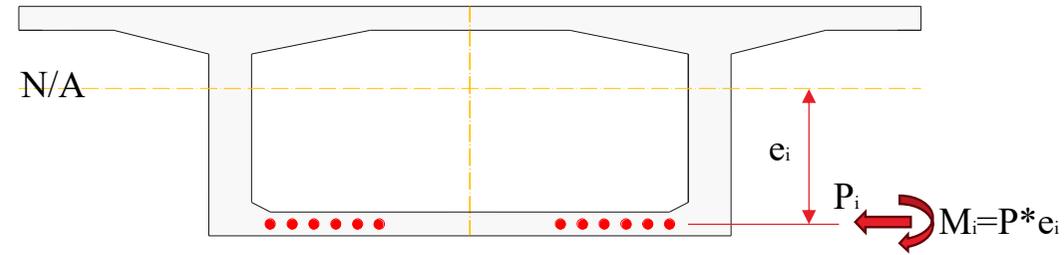
External tendons overview

Tendon trajectory : internal vs external tendons

External tendons



Internal tendons



$$e_e < e_i$$

$$M_e < M_i$$

External tendons overview

Diaphragms and deviators

Deviators and diaphragms are required for external tendons and diaphragms are often larger compared to bridges with internal tendons.



External tendons overview

Design opportunities

- Wobble and friction coefficients are lower for external tendons compared to internal tendons with steel ducts, which translates to efficiency in prestressing design.
- Easily achievable inclined tendon trajectory, which enhance shear and torsion resistance.

Values for coefficients μ and k :

| Type of tendon and duct | Range | Recommended value |
|---|--|--|
| Internal bonded tendon with corrugated steel duct (bare strand) | $\mu = 0.16 - 0.22$ $k = 0.004 - 0.008$ | $\mu = 0.18$ $k = 0.005$ ($k^* = 9 \times 10^{-4}$) |
| Internal bonded tendon with PT-PLUS® polymer duct (bare strand) | $\mu = 0.10 - 0.15$ $k = 0.004 - 0.010$ | $\mu = 0.12$ $k = 0.005$ ($k^* = 6 \times 10^{-4}$) |
| External tendon with PE pipe (bare strand) | $\mu = 0.10 - 0.14$ $k = 0^{(2)}$ | $\mu = 0.12$ $k = 0^{(2)}$ ($k^* = 0$) |
| Internal unbonded tendon with individually greased and sheathed strands | $\mu = 0.04 - 0.07$ $k = 0.004 - 0.006$ | $\mu = 0.05$ $k = 0.005$ ($k^* = 2.5 \times 10^{-4}$) |
| Special application: External tendon with greased and sheathed strands | $\mu = 0.04 - 0.07$ $k = 0^{(2)}$ | $\mu = 0.06$ $k = 0^{(2)}$ ($k^* = 0$) |

External tendons overview

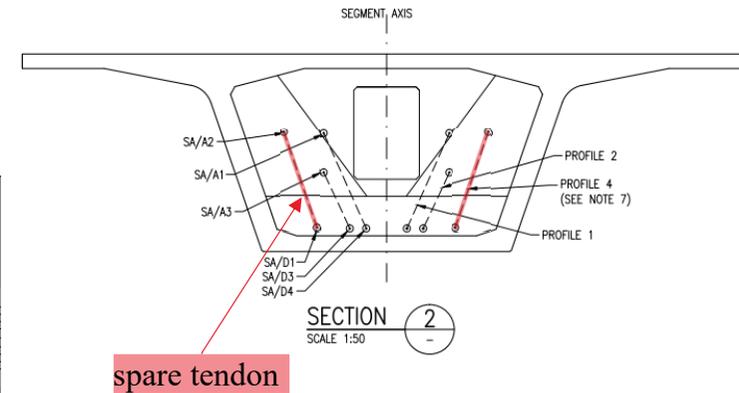
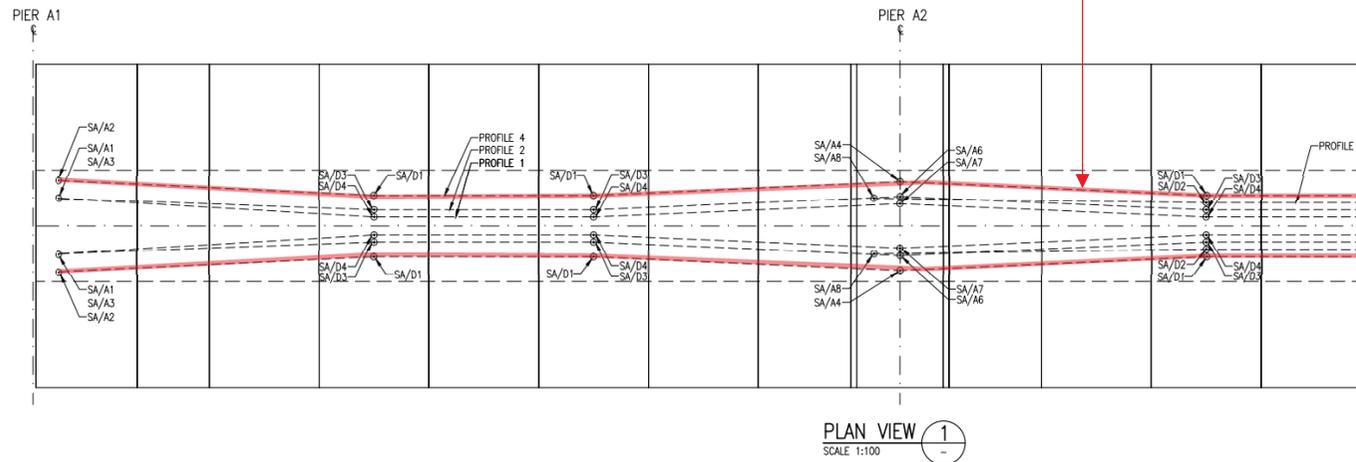
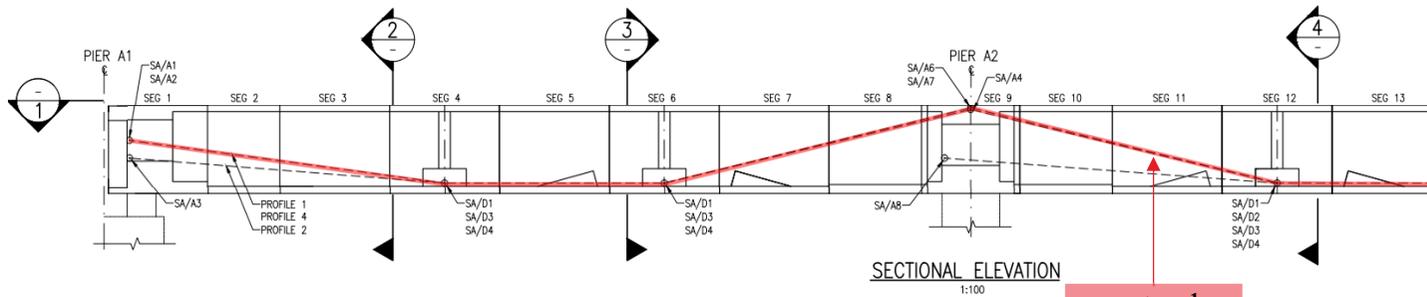
Tendon replacement

Provision for future spare external tendons to accommodate 10% of the total prestressing force in the section (AASHTO LRFD). Although provision for 20% is also common internationally depending on the country and project's specifications.

Utilising spare tendons allow to minimise/avoid disturbance during the possible future tendon replacement works.

External tendons overview

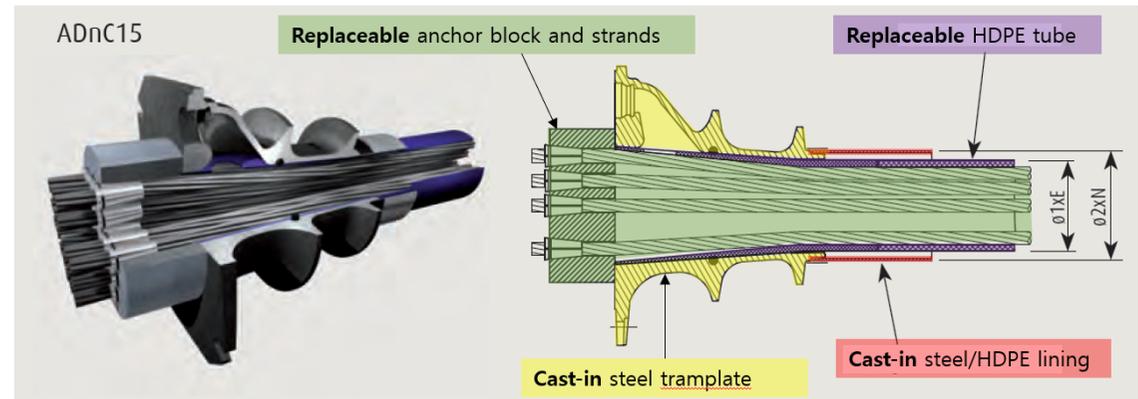
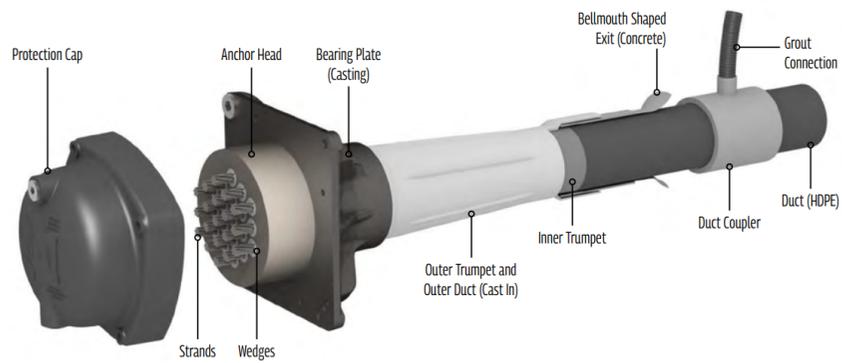
Tendon replacement



Rethinking Segmental Bridges: External Tendons Only ?

External tendons overview

Anchorage details and double sleeve concept



Rethinking Segmental Bridges: External Tendons Only ?

External tendons overview

Diablo tubes and double sleeve concept



Rethinking Segmental Bridges: External Tendons Only ?

External tendons overview

Tendon replacement

Approach to external tendon removal/replacement dependently on type:

1. **Bare strands grouted in ducts:** cutting-off tendons and pulling entire tendons through the “double sleeves”.
2. **Bare strands sealed with flexible fillers** (wax and grease): de-stress strands at the anchorage and pull-out strands.
3. **Greased and sheathed mono-strands in grouted ducts:** extracting individual strands through the dedicated sheaths (greased and sheathed strands).



External tendons overview

Tendon replacement

Cutting-off grouted tendons



External tendons overview

Inspection and testing

Magnetic flux testing:

- Locates areas of steel section loss due to corrosion, wire pitting, or breakage.
- Applies a magnetic field to induce flux paths between the poles.
- Magnetic field “leaks” at points of section loss and the change is detected by sensors.
- Changes are correlated to section loss based on the previous calibrations.



External tendons overview

Inspection and testing

Grout and material testing:

- Visual observations
- Corrosion potential
- Corrosion rate – linear polarization test
- Grout tests
- Tensile strength tests
- Duct material tests



Design and construction – Theemsweg Bridges case study

Theemsweg bridges

Project background

Client:

Port of Rotterdam

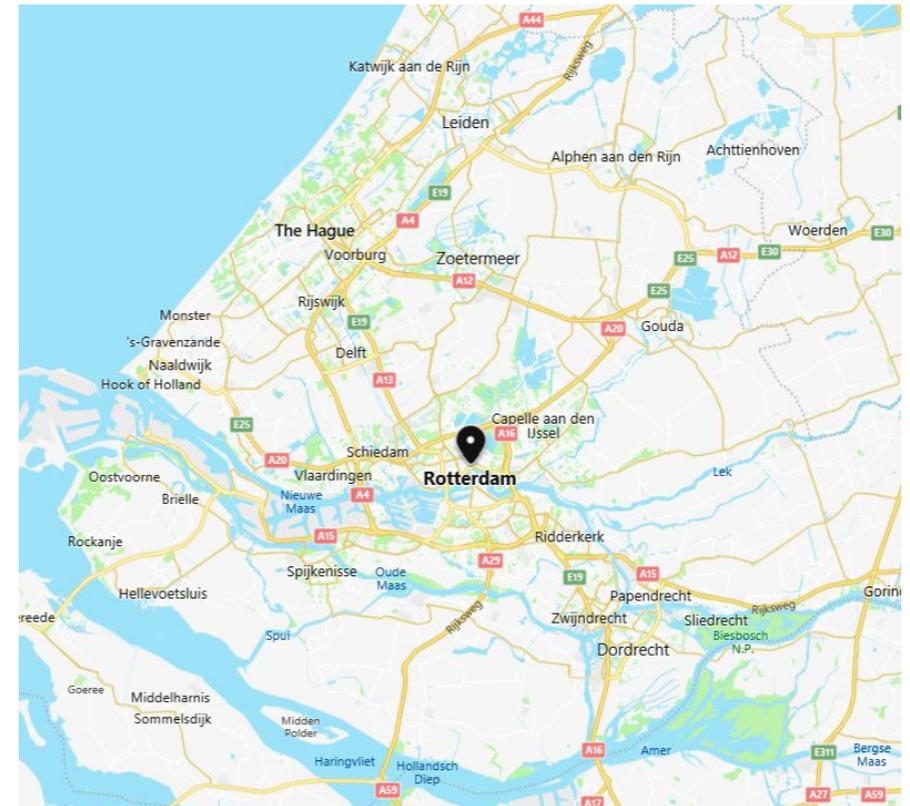
Project:

New Theemsweg Route

Bidding Team:

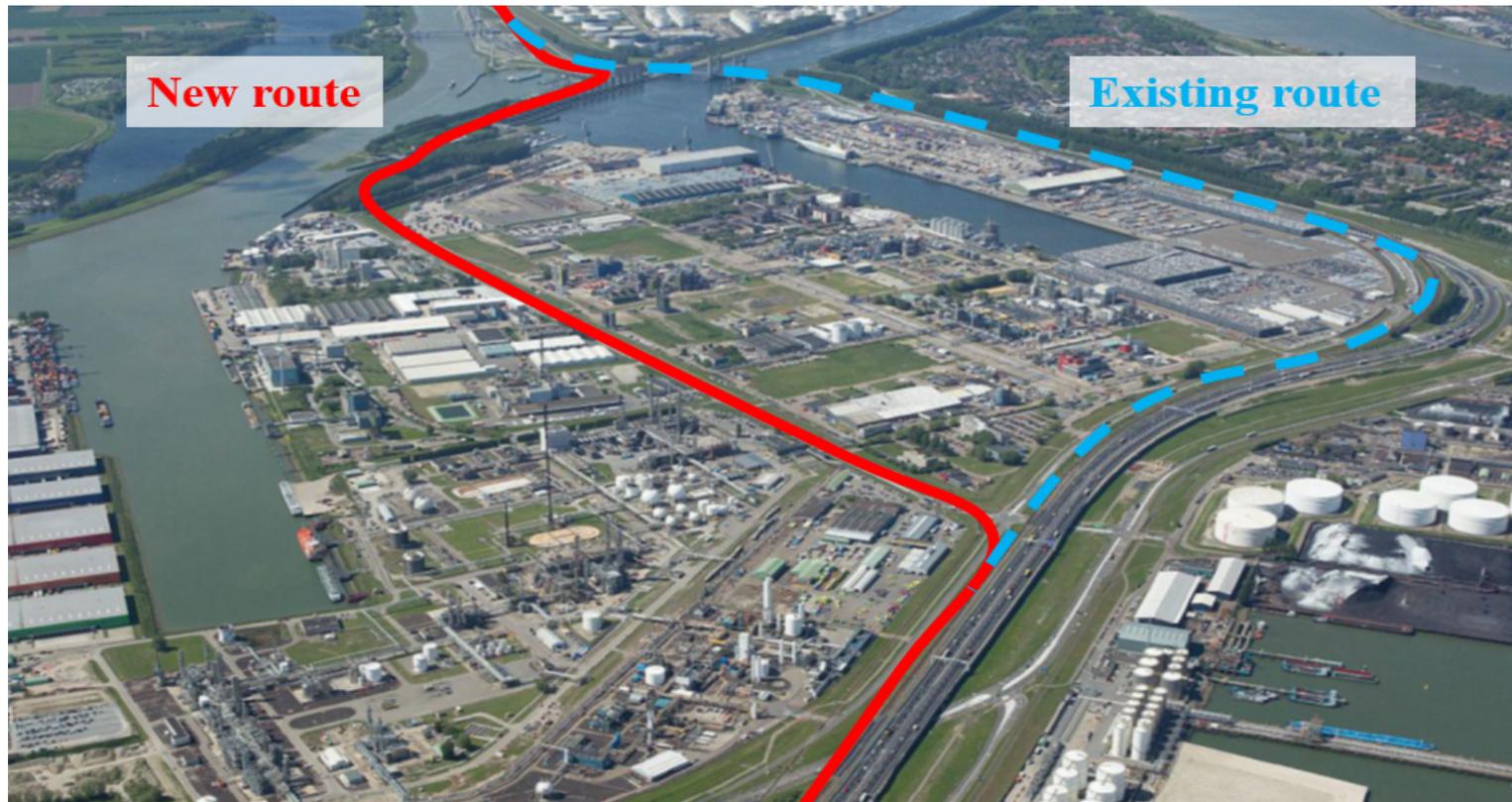
Contractor : JV TPort

Specialist Designer: Arup



Theemsweg bridges

Route

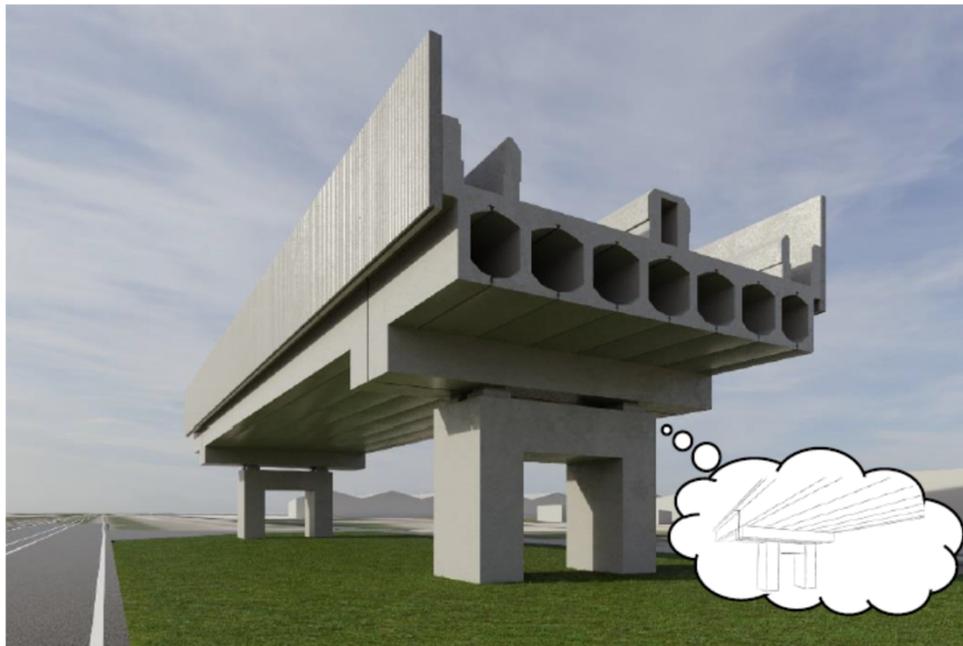


Rethinking Segmental Bridges: External Tendons Only ?

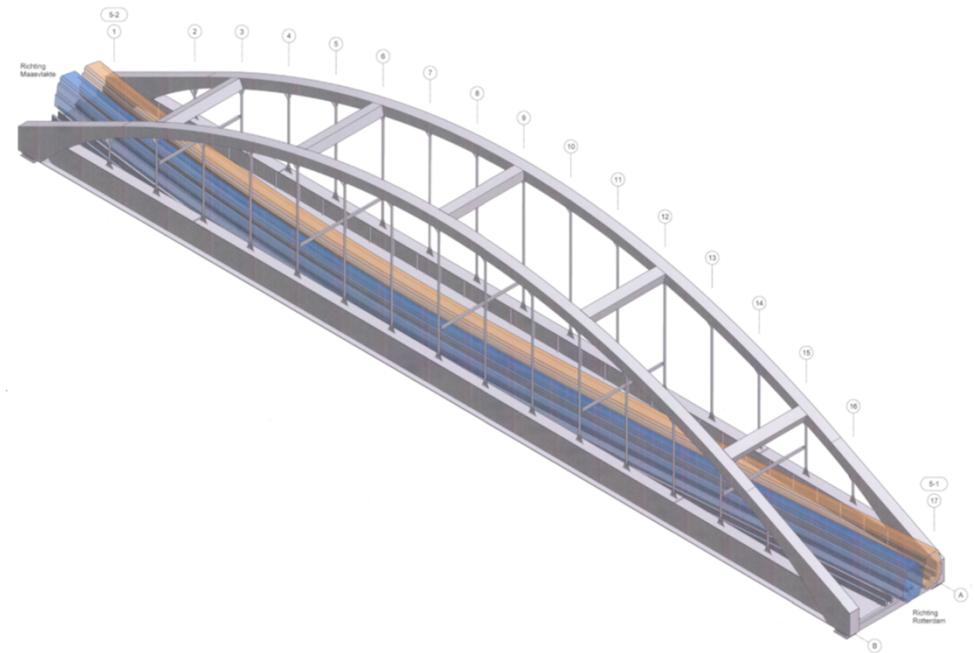
Theemsweg bridges

Reference design

Concrete viaduct



2 x steel arch bridges



Rethinking Segmental Bridges: External Tendons Only ?

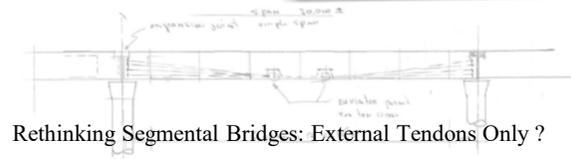
Theemsweg bridges

Alternative viaduct form



Segmental Bridge voor zwaar spoorverkeer, Florida Escambia Bay

- Ontwerp
- 3 dekhoogten, afhankelijk van PVR
 - Veel meer onderdelen in prefab
 - Dwaarsdrager t.b.v. opname horizontale krachten
 - Externe voorspanning in de koker



Rethinking Segmental Bridges: External Tendons Only ?



Onderdoorgaand verkeer tijdens bouw



Werken in de koker is niet optimaal

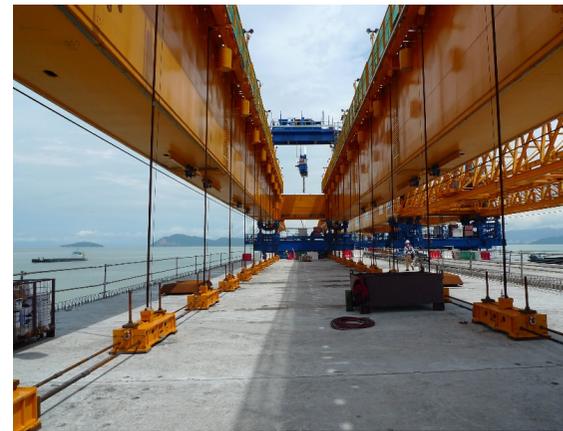
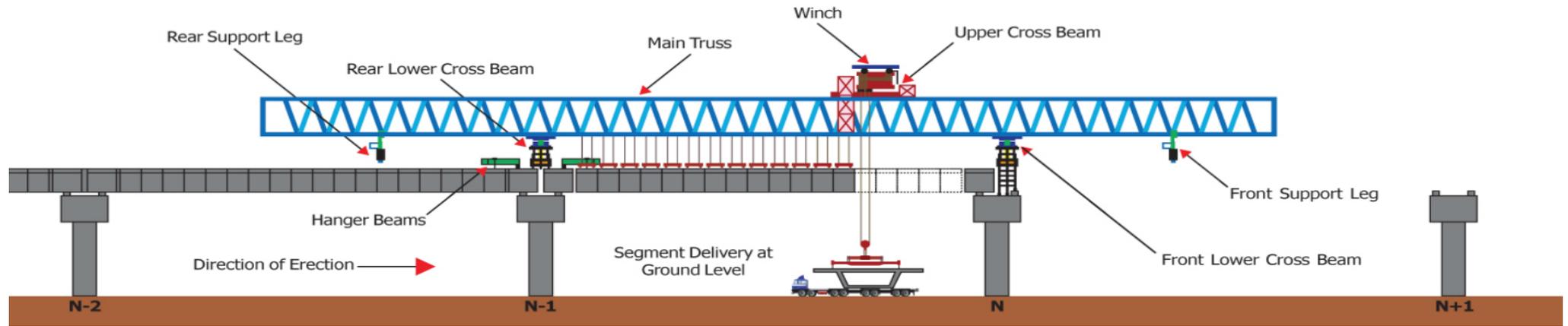


Montage Span-by-Span Segmental bridge

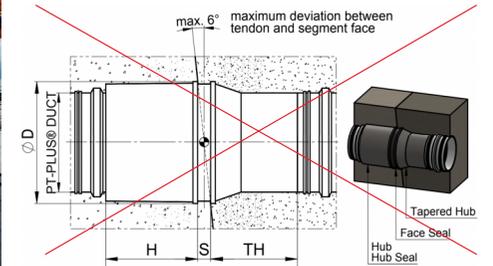
Images courtesy of Florida Center for Macroeconomic Research

Theemsweg bridges

Span-by-span construction



No couplers required for external tendons



Rethinking Segmental Bridges: External Tendons Only ?

Theemsweg bridges

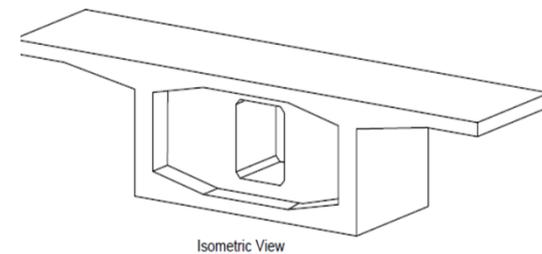
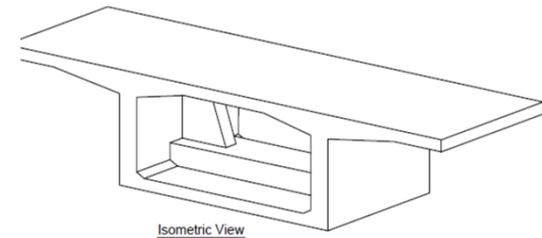
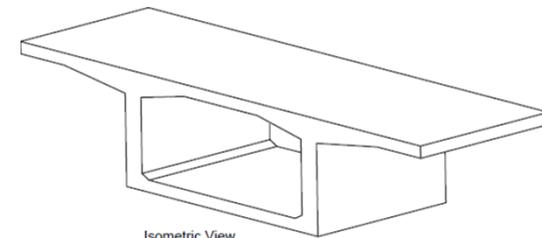
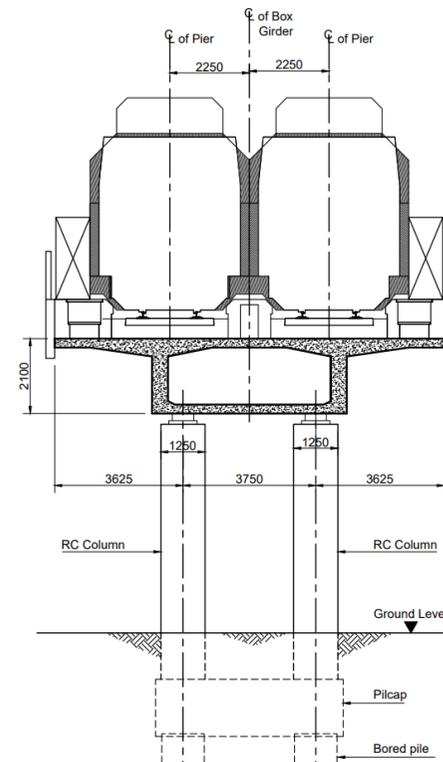
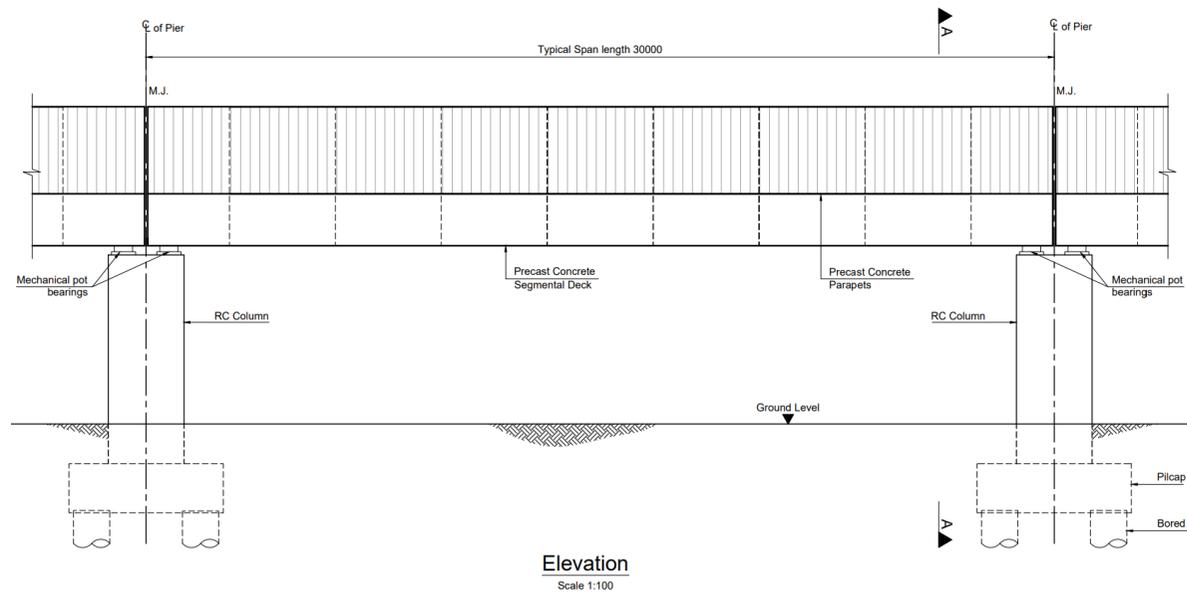
Challenges

- First of this kind in the Netherlands: segmental + external post-tensioning.
- Design of segmental deck for heavy train loading with only external tendons.
- Construction technology new to the Contractor.
- Stringent Client's design requirements; for example 0.3ksi (2MPa) compression at Service (SLS Characteristic).
- High strength concrete 9ksi (C60/75)...or higher.

Theemsweg bridges

General arrangement

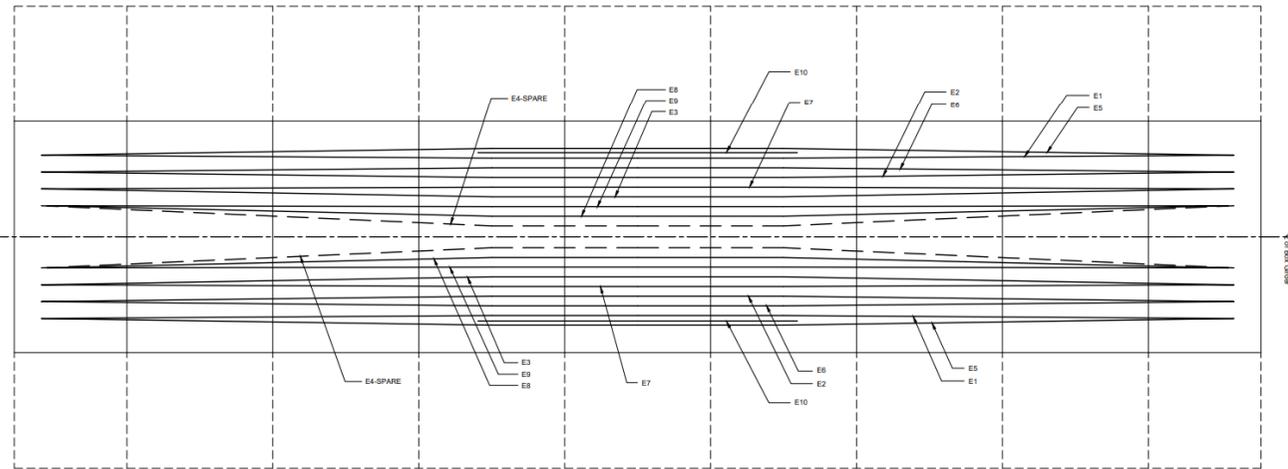
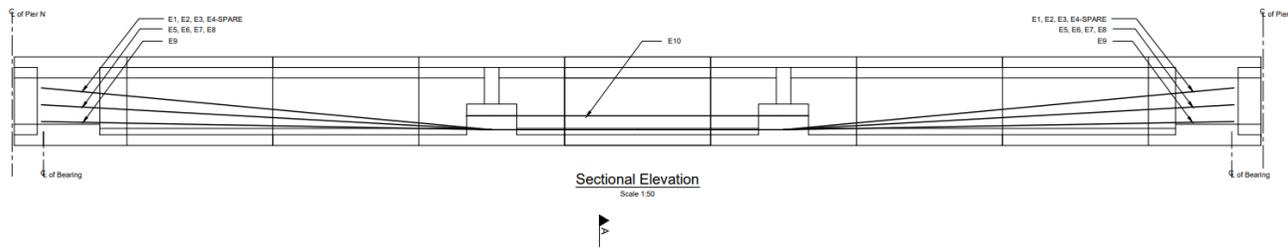
Design of 7 different deck configurations: spans 100' to 155' (30m to 47m), deck 7' to 12' (2.1m to 3.6m) deep.



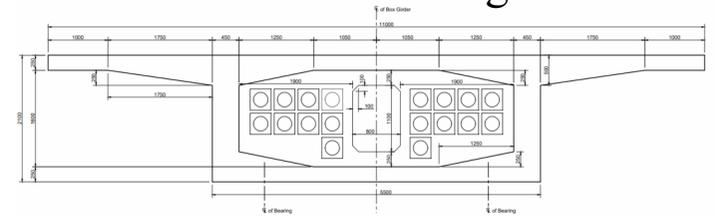
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Theemsweg bridges

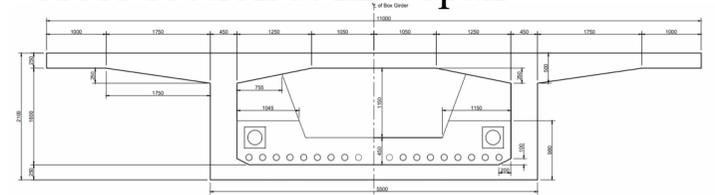
Tendons layout



Cross section at anchorage



Cross section at mid-span



Rethinking Segmental Bridges: External Tendons Only ?

Theemsweg bridges

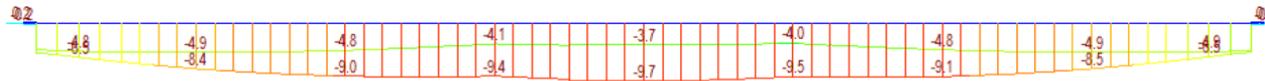
Design considerations

- **Decompression**
 - **Shear and torsion**
 - **Segmental joints**
 - Ultimate moment resistance
 - Fatigue
 - Compressive strength
- } focus considerations

Theemsweg bridges

Design considerations: decompression

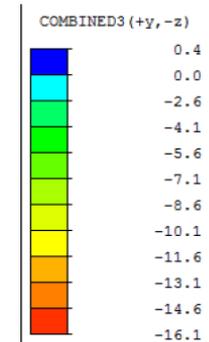
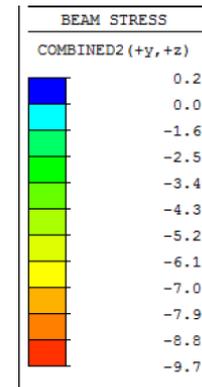
High demand of prestressing steel due to 0.3ksi (2MPa) compression requirement at joints under SLS Characteristic.



SLS Envelope Service stress - Top right fibre (+y, +z)

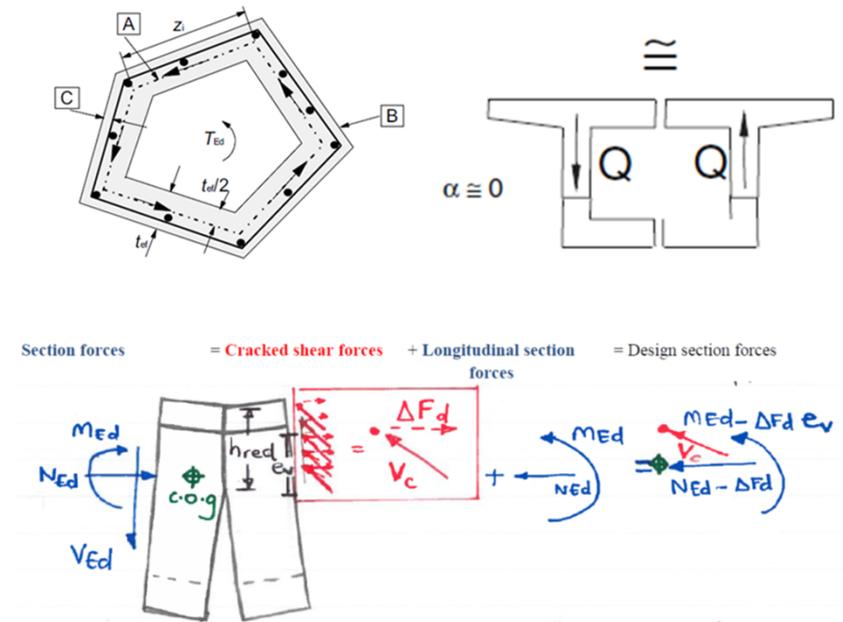
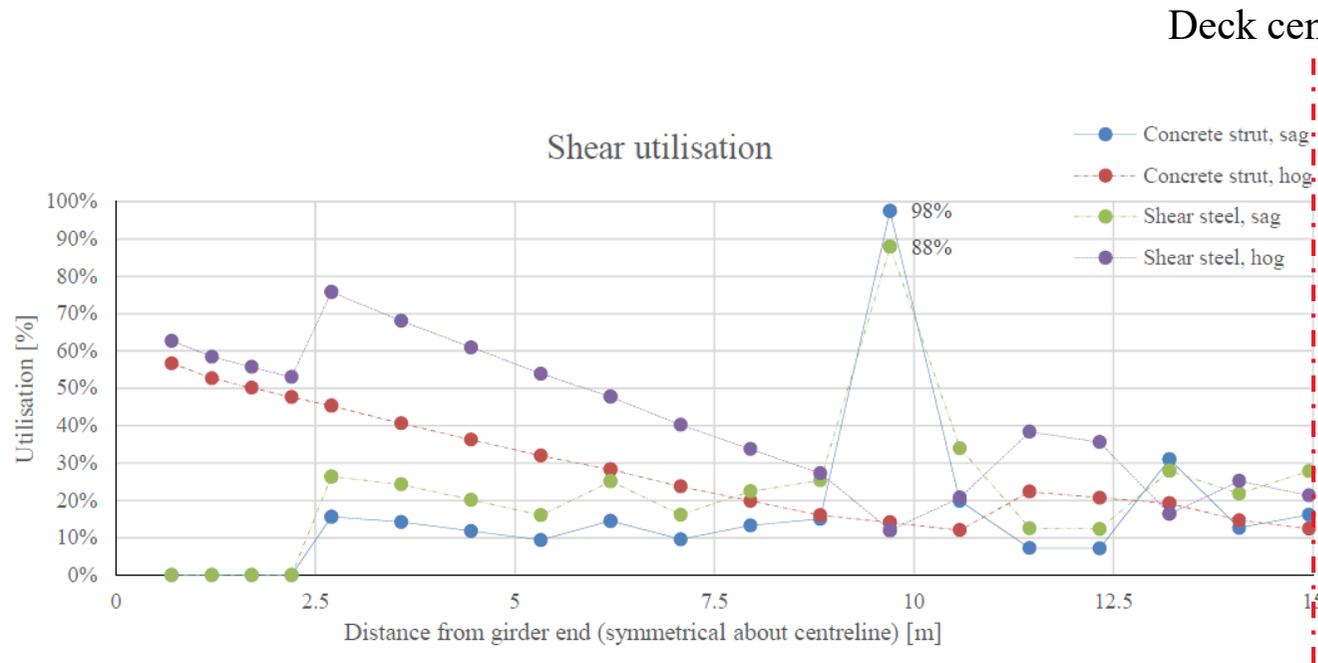


SLS Envelope Service stress - Bottom right (+y, +z)



Theemsweg bridges

Design considerations: shear and torsion



Rethinking Segmental Bridges: External Tendons Only ?

Theemsweg bridges

Design considerations: segmental joints

Segmental joints design

- EN 1992-1-1, Cl. 6.2.5, Equation 6.25 does not cover comprehensively segmental joint design, but AASHTO Guide Specification for Construction and Design of Segmental Bridges provides some principles.
- EN Equation 6.25: $v_{Rdi} = cf_{cta} + \mu\sigma_n \leq 0,5vf_{cd}$
- Author's proposed modification of EN Equation 6.25 for segmental joints:

A_{sk} area of the base of all keys in the failure plane

A_{sm} area of contact between smooth surfaces on the failure plane

c_{sk}, c_{sm} cohesion factors at the base of shear keys and smooth surfaces respectively

μ_{sk}, μ_{sm} friction factors at the base of shear keys and smooth surfaces respectively

$A_{tot} = A_{sk} + A_{sm}$

, and the new proposed equation is given by:

$$v_{Rdi} = \left(c_{sk} \left(\frac{A_{sk}}{A_{tot}} \right) + c_{sm} \left(\frac{A_{sm}}{A_{tot}} \right) \right) f_{cta} + \left(\mu_{sk} \left(\frac{A_{sk}}{A_{tot}} \right) + \mu_{sm} \left(\frac{A_{sm}}{A_{tot}} \right) \right) \sigma_n \leq 0,5vf_{cd}$$

Theemsweg bridges

Parametric design and BIM

- Dense environment
- Lots of potential clashes
- Multiple designers
- Close coordination needed



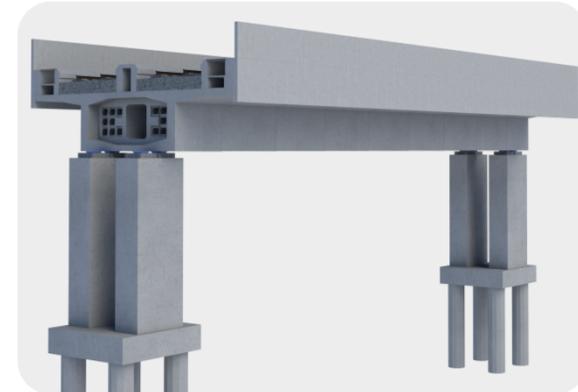
Theemsweg bridges

Parametric design and BIM



Volker Infra Design

- Overall BIM model (LOD 300)
- Alignments
- Surroundings
- Supports
- Weekly BIM coordination meetings



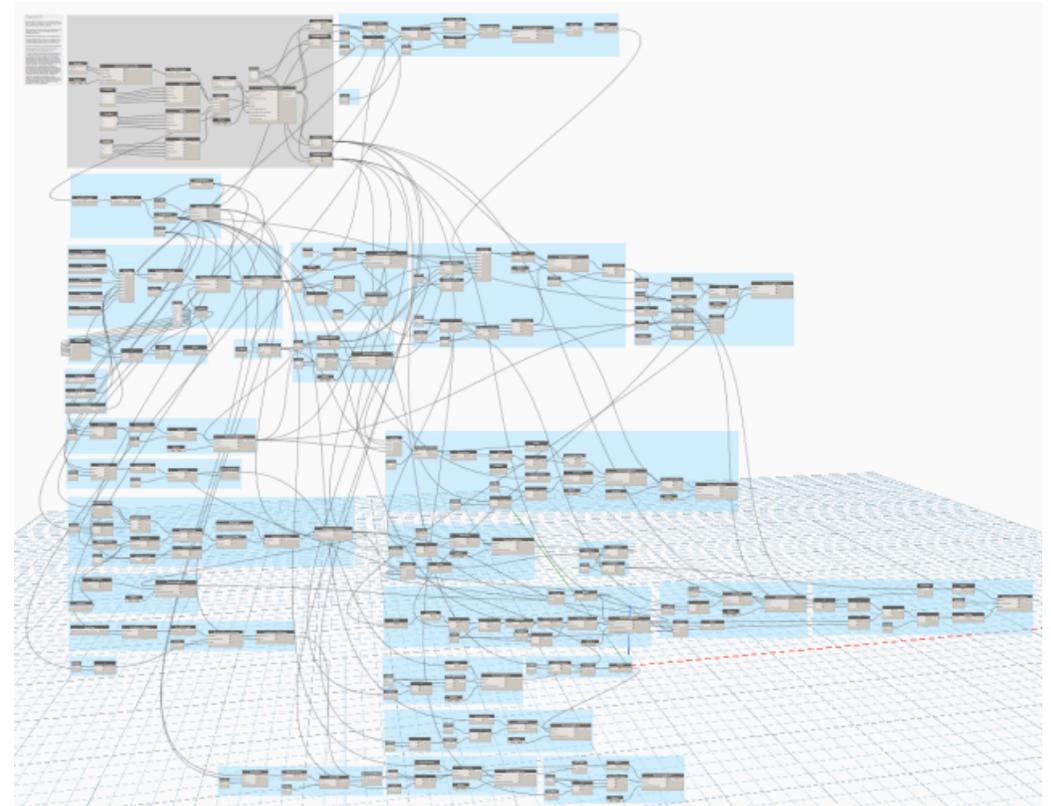
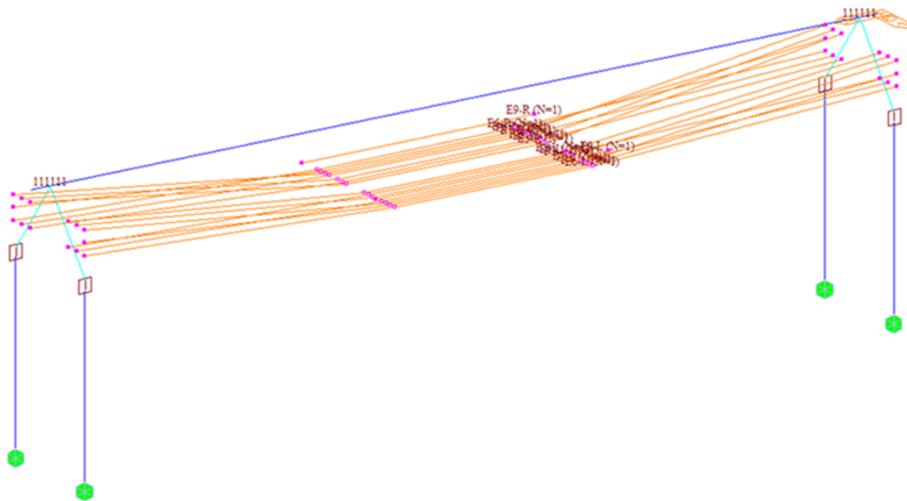
Arup

- Single span LOD 350
- Parametric PT
- Placement in overall BIM model

Theemsweg bridges

Parametric design and BIM

Parametric models; cad and analysis

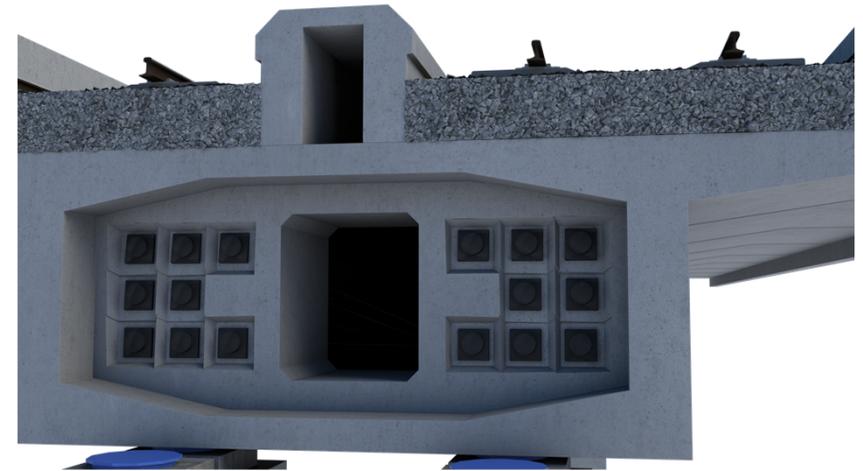
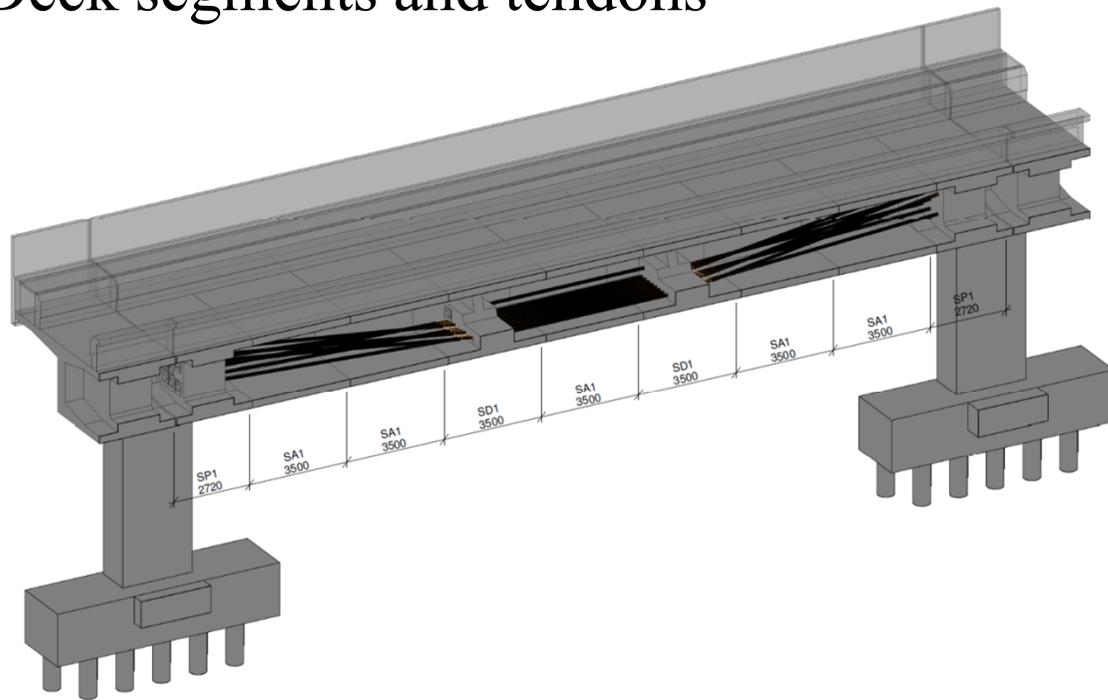


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Theemsweg bridges

Parametric design and BIM

Deck segments and tendons



Sectional Elevation

Rethinking Segmental Bridges: External Tendons Only ?

Theemsweg bridges

Parametric design and BIM

5D (Cost) / tagging

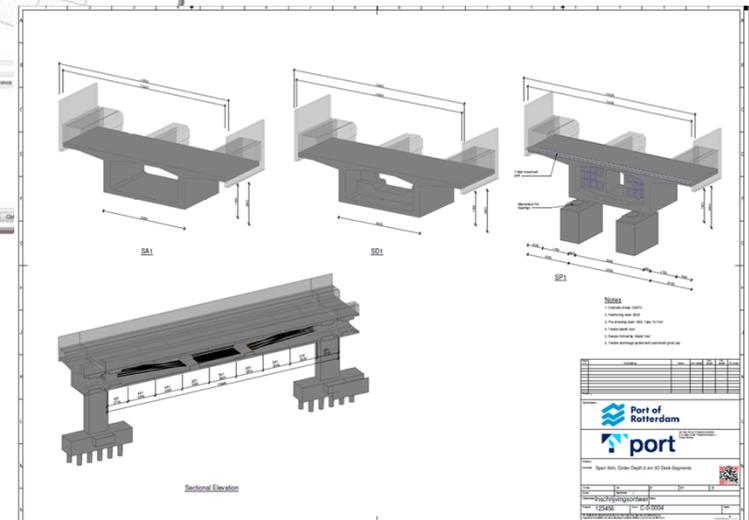
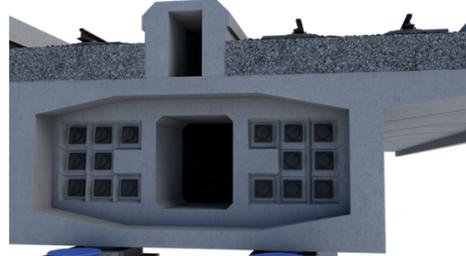
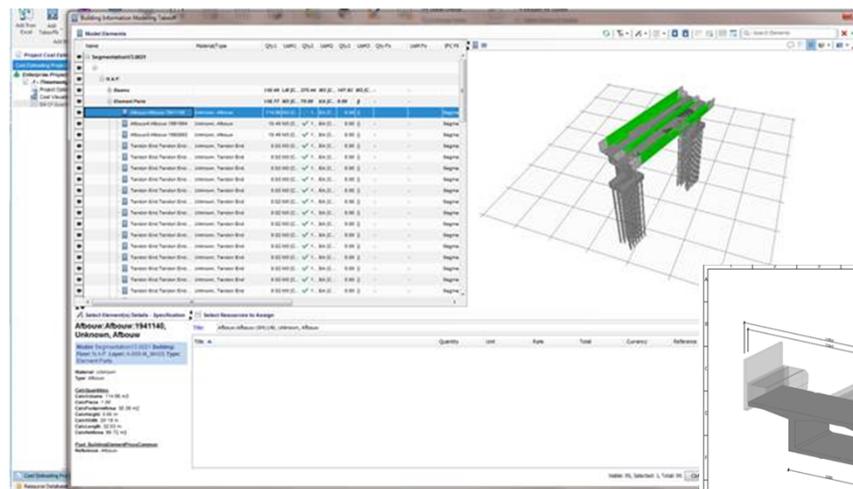
Classification data

Segment name

Segment type

Material data

Etc.



Rethinking Segmental Bridges: External Tendons Only ?

Circular economy – Circular Bridge case study

Circular bridge

Circular bridge in the Netherlands

- Ambition in the circular economy is to close the raw material cycles; from waste to resources.
- There is no waste, reuse requires no new raw materials and used raw materials are put to new use in the most high-value way possible.
- Idea for the circular bridge in the Netherlands: 100% circular bridge that is made up of concrete elements that will stay undamaged after their initial use and are thus suitable for re-use.

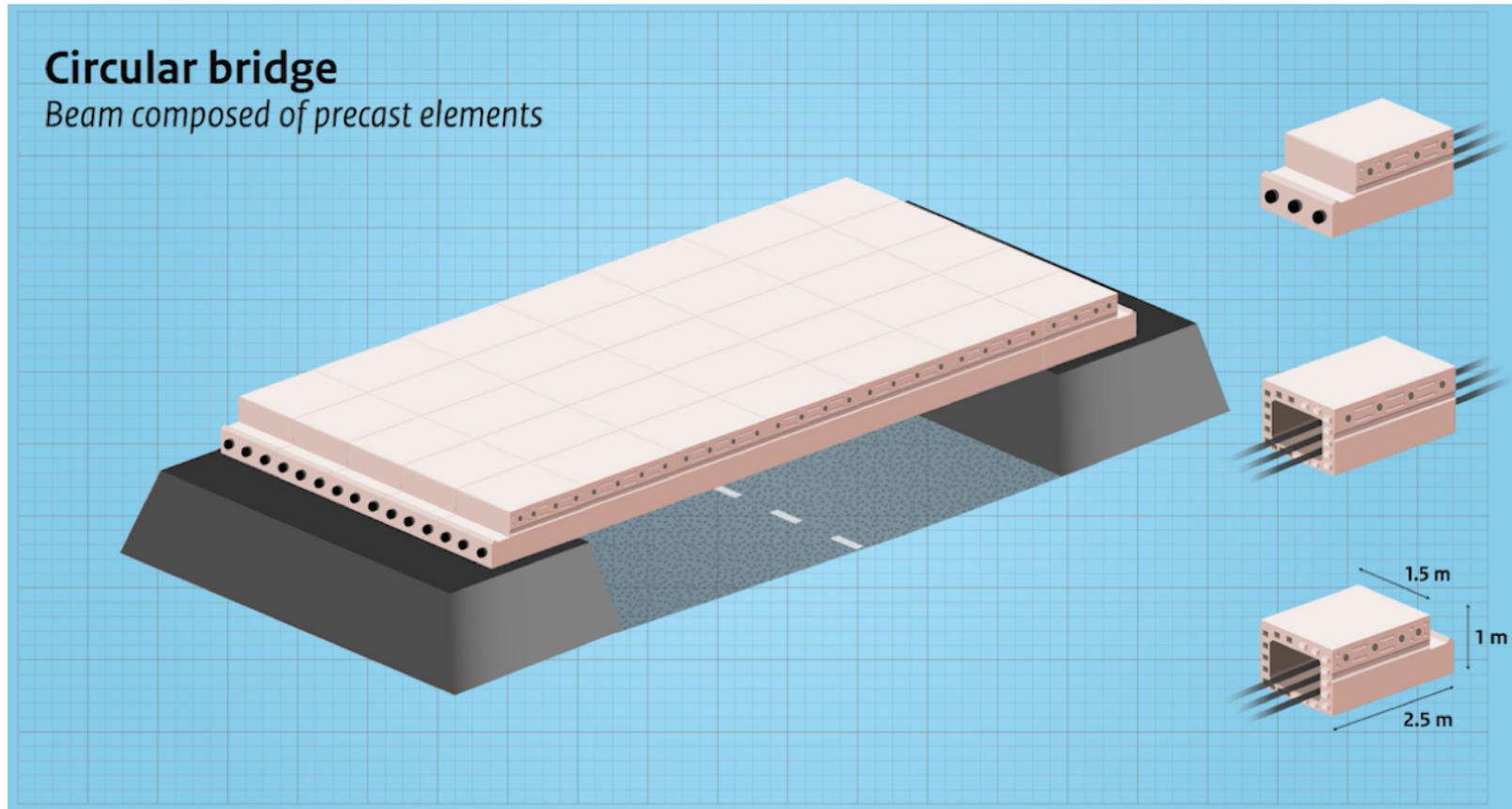
Circular bridge

Circular bridge in the Netherlands

- Rijkswaterstaat, contractor Van Hattum & Blankevoort and precast concrete supplier Consolis Spanbeton, appointed **Arup** to provide expertise in the design of concrete segmental bridge with only external tendons.
- The **prototype** of this first circular bridge was tested at the construction site of the Reevesluis (Reeve Lock) nearby Kampen.

Circular bridge

Circular bridge in the Netherlands



Rethinking Segmental Bridges: External Tendons Only ?

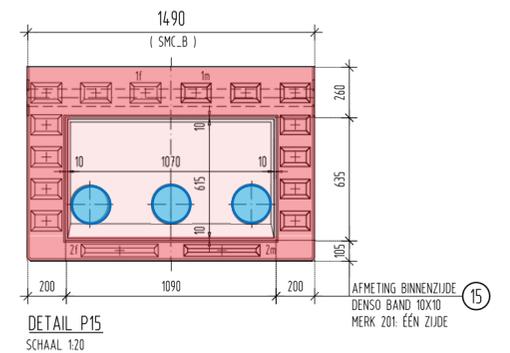
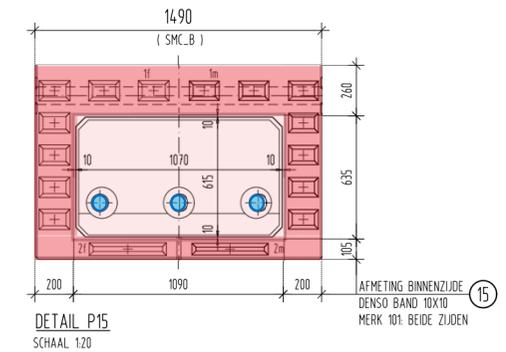
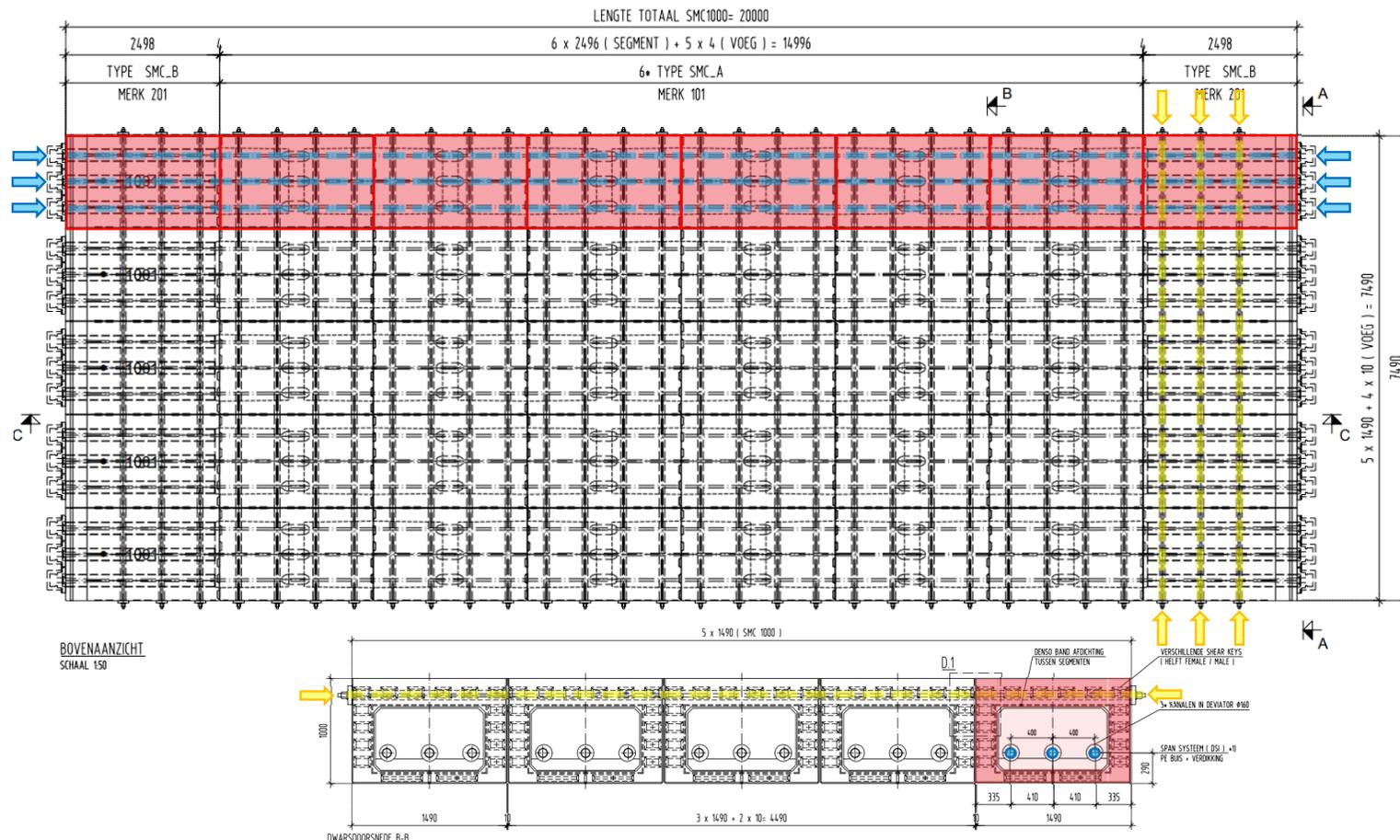
Circular bridge

Circular bridge in the Netherlands

- The bridge comprised of 40 precast concrete elements/segments.
- The segments with shear-keys were constructed in match-cast method.
- The pre-cast concrete segments were connected by means of external prestressing, which were easily disassembled and reused.
- This temporary access bridge, constructed on-site, was later dismantled and moved to another permanent location.
- Cementitious, bonding agent between the segments.

Circular bridge

Circular bridge in the Netherlands



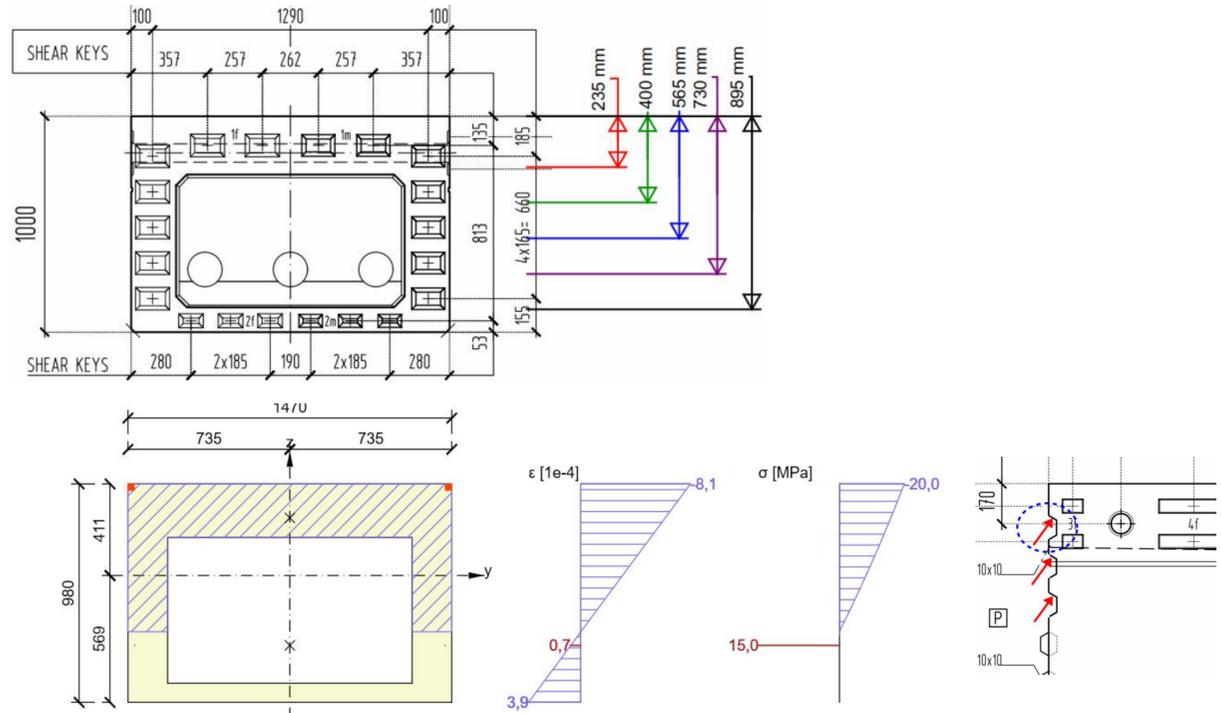
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Circular bridge

Circular bridge in the Netherlands

Shear key design:

- 1) Neutral axis calculation
- 2) Engaged shear keys
- 3) Shear resistance calculation



$$v_{Rdi} = \left(c_{sk} \left(\frac{A_{sk}}{A_{tot}} \right) + c_{sm} \left(\frac{A_{sm}}{A_{tot}} \right) \right) f_{ctd} + \left(\mu_{sk} \left(\frac{A_{sk}}{A_{tot}} \right) + \mu_{sm} \left(\frac{A_{sm}}{A_{tot}} \right) \right) \sigma_n \leq 0,5v f_{cd}$$

Circular bridge

Circular bridge in the Netherlands



Rethinking Segmental Bridges: External Tendons Only ?

Summary

Open-ended questions...

- Could bridges with only external tendons meet our industry's aspirations for increasingly more durable structures?
- To what extent could the maintainability and replaceability of bridges with only external tendons benefit asset owners?
- Could bridges with fully replaceable external tendons be justified despite higher quantities of structural materials compared to the alternatives?
- Could the concept of "Circular Bridge" be employed on a wider scale (material storages/reuse/holistic asset management) to help provide more sustainable assets within the built environment?

Thank you!

Q&A

ARUP