Prestressed composite box girder bridges with corrugated webs

A critical comparison with flat steel webs

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Some examples of the use of corrugated webs in bridges
(and other civil structures)
• Pont de la Corniche, France
• Himi Yuma Bridge, Japan
• *Ginzan-Miyuki Bridge, Japan*
• Hontani Bridge, Japan
• Long span building structures (by “Zeman & Co”)

![Image of long span building structures](image_url)
Some examples of the use of flat steel webs in composite steel-concrete bridges
Verrieres bridge – France
Roccaprebalza Viaduct: Parma – La Spezia Highway - Italy
Gassino bridge – Torino - Italy
Gassino bridge – Torino - Italy
3

Some theory stuff
Bending behaviour of corrugated webs

As the web is corrugated, it has very little ability to sustain longitudinal stresses. Conventionally, the contribution of the web to the ultimate bending capacity of a beam with corrugated web is assumed negligible, and the ultimate bending capacity is calculated using the plastic modulus of the flanges.

Elgaaly (1997) carried out experimental and analytical studies to verify if the web can contribute to the bending capacity of the whole girder.
Bending behaviour of corrugated webs

In order to verify if the web can contribute to the bending capacity of the whole girder, the failure moment is compared with the bending moment corresponding to the yielding of the flanges. It was found that the web contribution could be neglected.

\[ M_f \simeq M_{yf} \quad \text{versus} \quad M_{y,w} \simeq 0 \]

The bending capacity of the whole girder is affected by many parameters. The following factors were analyzed:

- ratio between the flange and web thickness;
- ratio between the flange and web yield stresses;
- corrugation configurations.

The stresses in the web due to bending are equal to zero except for small regions very close to the flanges where the web is restrained.
Shear behaviour of corrugated webs

FAILURE MODES

- Local buckling
- Zonal buckling
- Global buckling
Shear behaviour of corrugated webs

FAILURE MODES

Local buckling

Zonal buckling

Global buckling
Shear behaviour of corrugated webs

FAILURE MODES

Local buckling

Zonal buckling

Global buckling

θ

60° 45° 30°
Shear behaviour of corrugated webs

FAILURE MODES

Local buckling

Zonal buckling

Global buckling

\[ n = \frac{L_{\text{TOT}}}{a} \]

\[ 1/d \]
Shear behaviour of corrugated webs
Shear behaviour of corrugated webs

Strength of corrugated webs subjected to shear:

- Local buckling (similar expression of the local buckling formula for normal plate girder developed by Timoshenko and Gere)

\[ \tau^{E}_{cr,L} = k_1 \cdot \frac{\pi^2 E}{12(1-\nu^2)} \left( \frac{a}{w} \right)^2 \]

- Global buckling (calculated from the orthotropic-plate buckling theory)

\[ \tau^{E}_{cr,G} = k_g \cdot \frac{D^{1/4}_y \cdot D^{3/4}_x}{w \cdot h^2} \]

- The shear yield stress \( \tau_y \) is defined by the Huber-Von Mises-Hencky yield criterion

\[ \tau_y = \frac{f_y}{\sqrt{3}} \approx 0.58 f_y \]

INTERACTIVE BUCKLING STRENGTH
LIVE LOADS:
ELASTIC ANALYSIS

DEAD LOAD + CREEP + SHRINKAGE + PRESTRESSING + CONSTRUCTION PHASES:
VISCOELASTIC ANALYSIS

• The structure is not homogeneous from the rheological point of view: viscoelasticity theorems CAN NOT be used

• step by step analysis with detailed time history:

\[
\varepsilon_c(t_k) = \int_{t_0}^{t_k} J(t, \tau) d\sigma(\tau) + \varepsilon_{cs}(t_k) \approx \sum_{i=1}^{k} \left[ \sigma_c(t_i) - \sigma_c(t_{i-1}) \right] \cdot \frac{1}{2} \cdot [J(t_k, t_i) + J(t_k, t_{i-1})] + \varepsilon_{cs}(t_k)
\]
Creep and relaxation functions used in phased analysis

\[ \varepsilon(t) = \sigma_0 \cdot J(t, t_0) + \int_{t_0}^{t} J(t, \tau) d\sigma(\tau) \]

\[ \sigma(t) = \varepsilon_0 \cdot R(t, t_0) + \int_{t_0}^{t} R(t, \tau) d\varepsilon(\tau) \]

\[ J(t, t_0) = \frac{1}{E(t_0)} + \frac{\varphi(t, t_0)}{E_{28}} \quad \varphi(t, t_0) \geq 0 \]

\[ R(t, t_0) = E(t_0) + E_{28} \cdot \rho(t, t_0) \quad \rho(t, t_0) \leq 0 \]
Comparison of flat webs solution and corrugated webs solution on the same “testing” bridge
4.1

Construction procedure common to both flat and corrugated webs solutions
Gassino bridge reduced to 3 hammers scheme

- Concrete top slab with bonded prestressing
- Steel webs
- Precast slab used as scaffolding
- Concrete bottom slab
<table>
<thead>
<tr>
<th>Position</th>
<th>Deck depth [m]</th>
<th>Depth/Span length L/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuity support</td>
<td>4</td>
<td>23</td>
</tr>
<tr>
<td>Midspan and abutments</td>
<td>2</td>
<td>46</td>
</tr>
</tbody>
</table>
Single hammer construction phases

Hammers construction phases
Phase 1 - Positioning of steel box pier segment (formwork for concrete diaphragm casting)
Phase 2 - Webs assembling by bolts and adjustment/stiffening by temporary ties

Phase 3 – Slabs concreting
Phase 4 – Internal prestressing

28 tendons: 6 for each segment apart from segment 1 which has 2

<table>
<thead>
<tr>
<th>Nº of strands</th>
<th>Strand cross section</th>
<th>Nominal area</th>
<th>Duct diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>139 mm²</td>
<td>2085 mm²</td>
<td>90 mm</td>
</tr>
</tbody>
</table>
Phase 4 – Internal prestressing

Layout of the connection reinforcement between precast anchorage blocks and upper slab.
Phase 5

Repetition of previous operations working in parallel on several piers

Phase 6 – Alignment of bolted joint on webs between two segments
Phase 7 – External prestressing: 10 tendons with 27 strands in main spans and 22 strands in lateral ones
Phase 7 – External prestressing
Pay attention to the geometrical interferences between external tendons and stiffeners
Transversal truss stiffeners detail.

Longitudinal spacing = 3m

The shape of plenty of them is modified to avoid external tendons geometrical interferences.

(See arrows in the picture beside and in the previous slide)
4.2

Construction time scheduling common to both flat and corrugated webs solutions
**Hammers 1 and 3**

<table>
<thead>
<tr>
<th>Day</th>
<th>Time [d]</th>
<th>Phase</th>
<th>Segment</th>
<th>Side</th>
<th>Set</th>
<th>Segment</th>
<th>side</th>
<th>Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monday</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td></td>
<td>Web+TS+BS</td>
<td>0</td>
<td></td>
<td>Web+TS+BS</td>
</tr>
<tr>
<td>Wednesday</td>
<td>3</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thursday</td>
<td>46</td>
<td>2</td>
<td>1</td>
<td>Right</td>
<td>Web</td>
<td>1</td>
<td>Right</td>
<td>Web</td>
</tr>
<tr>
<td>Friday</td>
<td>47</td>
<td>3</td>
<td>1</td>
<td>Left</td>
<td>Web</td>
<td>1</td>
<td>Left</td>
<td>Web</td>
</tr>
<tr>
<td>Saturday</td>
<td>48</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>Right</td>
<td>BS</td>
</tr>
<tr>
<td>Monday</td>
<td>50</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>Left</td>
<td>BS</td>
</tr>
<tr>
<td>Tuesday</td>
<td>51</td>
<td>4</td>
<td>1</td>
<td>Right</td>
<td>BS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wednesday</td>
<td>52</td>
<td>5</td>
<td>1</td>
<td>Left</td>
<td>BS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thursday</td>
<td>53</td>
<td>5</td>
<td></td>
<td></td>
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<td>1</td>
<td>Right</td>
<td>TS</td>
</tr>
<tr>
<td>Friday</td>
<td>54</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>Left</td>
<td>TS</td>
</tr>
<tr>
<td>Saturday</td>
<td>55</td>
<td>6</td>
<td>1</td>
<td>Right</td>
<td>TS</td>
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<tr>
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<td>57</td>
<td>7</td>
<td>1</td>
<td>Left</td>
<td>TS</td>
<td>1</td>
<td></td>
<td>Prestress</td>
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<tr>
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<td>58</td>
<td>8</td>
<td>2</td>
<td>Right</td>
<td>Web</td>
<td>2</td>
<td>Right</td>
<td>Web</td>
</tr>
<tr>
<td>Wednesday</td>
<td>59</td>
<td>9</td>
<td>2</td>
<td>Left</td>
<td>Web</td>
<td>2</td>
<td>Left</td>
<td>Web</td>
</tr>
<tr>
<td>Thursday</td>
<td>60</td>
<td>9</td>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td>Right</td>
<td>BS</td>
</tr>
<tr>
<td>Friday</td>
<td>61</td>
<td>9</td>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td>Left</td>
<td>BS</td>
</tr>
<tr>
<td>Saturday</td>
<td>62</td>
<td>10</td>
<td>2</td>
<td>Right</td>
<td>BS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Monday</td>
<td>64</td>
<td>11</td>
<td>2</td>
<td>Left</td>
<td>BS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tuesday</td>
<td>65</td>
<td>11</td>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td>Right</td>
<td>TS</td>
</tr>
</tbody>
</table>
4.3

Evolution of internal actions during construction and service life of

FLAT WEB SOLUTION
Bending moment diagrams during hammer construction phases
Bending moment diagrams during hammer construction phases

- End of segment 1
- Prestressing of tendons 1 and 2

Longitudinal axis [m]
Bending moment diagrams during hammer construction phases

-3,00E+07
-2,00E+07
-1,00E+07
0,00E+00
1,00E+07
2,00E+07
3,00E+07

End of segment 1
End of segment 2

Prestressing of tendons 1 and 2

Longitudinal axis [m]
Bending moment diagrams during hammer construction phases
Bending moment diagrams during hammer construction phases

End of segment 3
Bending moment diagrams during hammer construction phases

- Bending moment diagrams show the variation of bending moment [Nm] along the longitudinal axis [m].
- Key phases include:
  - End of segment 3
  - Prestressing of tendons 6, 7, 8
- The diagrams illustrate the impact of construction phases on the bending moment distribution.
Bending moment diagrams during hammer construction phases

- End of segment 3
- End of segment 4
- Prestressing of tendons 6, 7, 8

Longitudinal axis [m]
Bending moment diagrams during hammer construction phases

- End of segment 3
- End of segment 4
- Prestressing of tendons 9, 10, 11
- Prestressing of tendons 6, 7, 8
- Longitudinal axis [m]
Bending moment diagrams during hammer construction phases

End of segment 5

Longitudinal axis [m]
Bending moment diagrams during hammer construction phases

- End of segment 5
- Prestressing of tendons 12, 13, 14

- Coordinate [m]
- Longitudinal axis [m]
Bending moment diagrams during hammer construction phases

Grouting of all internal tendons

Longitudinal axis [m]
Bending moment diagrams: external prestressing introduction on lateral spans

- 50% of lateral spans prestressing
- Grouting of all internal tendons
Bending moment diagrams: end of construction of central hammer

End of construction of hammer 2

Longitudinal axis [m]
Bending moment diagrams: introduction of central spans external prestressing

-50% of central span prestressing

End of construction of hammer 2

50% of central span prestressing

Longitudinal axis [m]
Bending moment diagrams: permanent loads introduction

![Bending moment diagram](image)

**Bending moment [Nm]**

**Longitudinal axis [m]**

**Permanent loads**
Bending moment diagrams: introduction of 2nd 50% of external prestressing
Bending moment diagrams: end of service life (50 years)
4.4 Evolution of stresses during construction and service life of FLAT WEBS SOLUTION
Axial stress in concrete top slab – continuity support section

Axial stress [MPa]

Time [days]

-12.00
-10.00
-8.00
-6.00
-4.00
-2.00
0.00

Internal tendons prestressing
Permanent loads introduction
First 50% of external prestressing on lateral spans
First 50% of external prestressing on central spans
Second 50% of external prestressing everywhere
Axial stress in concrete top slab – continuity support section

Axial stress [MPa]

Time [days]

-11.00
-10.00
-9.00
-8.00
-7.00

50 years: end of service life

377 days: end of construction

50 years: end of service life

377 days: end of construction
Axial stress in concrete bottom slab – continuity support section

- Time [days]
- Axial stress [MPa]

- Internal tendons prestressing
- First 50% of external prestressing on central spans
- First 50% of external prestressing on lateral spans
- Second 50% of external prestressing everywhere
- Permanent loads introduction

- Tiro dei cavi interni
- Tiro dei cavi esterni campate centrali (50%)
- Applicazione carichi permanenti portati
- Ritesatura cavi esterni

- Tensioni Normali [MPa]
Axial stress in concrete bottom slab – continuity support section

50 years: end of service life

377 days: end of construction
Axial stress in steel top flange – continuity support section

- **Internal tendons prestressing**
- **Permanent loads introduction**
- **First 50% of external prestressing on lateral spans**
- **First 50% of external prestressing on central spans**
- **Second 50% of external prestressing everywhere**

**Graph Details:**
- **Axes:**
  - X-axis: Time [days]
  - Y-axis: Axial stress [MPa]
- **Key Points:**
  - Minimum stress values around -100 MPa
  - Maximum stress values around 60 MPa
- **Phases:**
  - Initial internal prestressing
  - Introduction of permanent loads
  - First 50% of external prestressing
  - Second 50% of external prestressing
Axial stress in steel top flange – continuity support section

-80,00  -100,00  -120,00
100 1000 10000 100000

377 days: end of construction

50 years: end of service life

Time [days]
Axial stress in steel bottom flange – continuity support section

- Internal tendons prestressing
- First 50% of external prestressing on central spans
- First 50% of external prestressing on lateral spans
- Second 50% of external prestressing everywhere
- Permanent loads introduction

Time [days]

Axial stress [MPa]

Tensioni Normali [MPa]

Tiro dei cavi interni
Internal tendons prestressing

Tiro dei cavi esterni campate centrali (50%)
First 50% of external prestressing on central spans

Ritesatura cavi esterni

Applicazione carichi permanenti portati

Tiro dei cavi esterni campate laterali (50%)
First 50% of external prestressing on lateral spans

Second 50% of external prestressing everywhere

Tensioni Normali [MPa]
Axial stress in steel top flange – continuity support section

Axial stress [MPa] vs. Time [days]

-180,00
-160,00
-140,00
-120,00
-100,00

377 days: end of construction
50 years: end of service life
Axial stress in concrete top slab – midspan key segment

- First 50% of external prestressing on central spans
- Permanent loads introduction
- Second 50% of external prestressing everywhere
Axial stress in concrete top slab – midspan key segment

- Time [days]

- Axial stress [MPa]

50 years: end of service life

377 days: end of construction

-6.00  -5.50  -5.00  -4.50  -4.00  -3.50  -3.00  -2.50

100  1000  10000  100000
Axial stress in concrete bottom slab – midspan key segment

- First 50% of external prestressing on central spans
- Second 50% of external prestressing everywhere
- Permanent loads introduction

Time [days] vs. Axial stress [MPa]

-0.9, -0.8, -0.7, -0.6, -0.5, -0.4, -0.3, -0.2, -0.1, 0.0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 1.1, 1.2, 1.3, 1.4, 1.5, 1.6, 1.7, 1.8, 1.9, 2.0

0, 50, 100, 150, 200, 250, 300, 350, 400

Tensioni Normali [MPa]
Axial stress in concrete bottom slab – midspan key segment

Time [days]

Axial stress [MPa]

50 years: end of service life

377 days: end of construction

50 years: end of service life
4.5

Modeling of

CORRUGATED WEBS
Overall characteristics

- High longitudinal deformability (accordion effect)
- better U.L.S. shear buckling behaviour;
- Out of the plane inertia (transverse bending/ folded plate).
An analytical method to calculate this ratio is developed through the use of a model that satisfies equilibrium and compatibility conditions.
An analytical method to calculate this ratio is developed through the use of a model that satisfies equilibrium and compatibility conditions.

Hypothesis: the web is under pure bending moment and the axial deformation in each plate element of the corrugated web is negligible.

VIRTUAL WORKS PRINCIPLE

\[
\delta_{3D} = \int_S \frac{M_i \cdot M}{EJ} dS = \int_A^B \frac{F \cdot c \cdot \sin \alpha \cdot c \cdot \sin \alpha}{EJ} dx + \int_B^C \frac{F \cdot c \cdot \sin \alpha \left(1 - \frac{x}{c}\right) \cdot c \cdot \sin \alpha \left(1 - \frac{x}{c}\right)}{EJ} dx
\]

\[
\delta_{3D} = \frac{F \cdot c^2 \cdot \sin^2 \alpha}{EJ} \left(\alpha + \frac{c}{3}\right)
\]
An analytical method to calculate this ratio is developed through the use of a model that satisfies equilibrium and compatibility conditions.

Hypothesis: the web is under pure bending moment and the axial deformation in each plate element of the corrugated web is negligible.

Virtual Work Principle

\[ \delta_{3D} = \int_{S} \frac{M_i \cdot M}{EJ} \, dS = \int_{A}^{B} \frac{F \cdot c \cdot \sin \alpha \cdot c \cdot \sin \alpha}{EJ} \, dx + \int_{B}^{C} \frac{F \cdot c \cdot \sin \alpha}{EJ} \left(1 - \frac{x}{c}\right) \cdot c \cdot \sin \alpha \left(1 - \frac{x}{c}\right) \, dx \]

\[ \Delta_{3D} = 48 \frac{F \cdot c^2 \cdot \sin^2 \alpha}{E \cdot t_w^3 \cdot H} \left(a + \frac{c}{3}\right) \]

\[ \Delta_{FLAT} = \frac{F \cdot L_h}{H \cdot t_w \cdot E} \]

\[ \frac{r_{eq}}{\Delta_{flat}} = \Delta_{3D} = \frac{48 \cdot c^2 \cdot \sin^2 \alpha}{L_h \cdot t_w^2} \left(a + \frac{c}{3}\right) \]
Longitudinal profile

Reduction of modulus of elasticity to take into account longitudinal stiffness

$$\bar{E}_s = \frac{E_s}{350}$$

Web corrugation
4.6

Comparison of results between corrugated and flat webs
Axial stress in concrete top slab – continuity support section

Internal tendons prestressing

First 50% of external prestressing on lateral spans

First 50% of external prestressing on central spans

Second 50% of external prestressing everywhere

Flat webs
Corrugated webs

Permanent loads introduction
Axial stress in concrete top slab – continuity support section

Axial stress [MPa]

Time [days]

-12,00
-11,00
-10,00
-9,00
-8,00
-7,00

-10,00
-9,00
-8,00
-7,00

100
1000
10000
100000

Flat webs
Corrugated webs

377 days: end of construction

50 years: end of service life

University of Patras
Axial stress in concrete bottom slab – continuity support section

- **Flat webs**
- **Corrugated webs**

**Internal tendons prestressing**

- **First 50% of external prestressing on central spans**
- **Second 50% of external prestressing everywhere**
- **Permanent loads introduction**

**Time [days]**

**Axial stress [MPa]**

-0.00
-2.00
-4.00
-6.00
-8.00
-10.00
0.00
50
100
150
200
250
300
350
400
Axial stress in concrete bottom slab – continuity support section

50 years: end of service life

377 days: end of construction

Time [days]
Axial stress in steel top flange – continuity support section

Axial stress [MPa]

Time [days]

Flat webs
Corrugated webs

Internal tendons pretressing
Permanent loads introduction
First 50% of external prestressing on lateral spans
First 50% of external prestressing on central spans
Second 50% of external prestressing everywhere
Axial stress in steel top flange – continuity support section

377 days: end of construction

50 years: end of service life

Flat webs
Corrugated webs
Axial stress in steel bottom flange – continuity support section

- Tensioni Normali [MPa]
- Axial stress [MPa]
- Time [days]

- Flat webs
- Corrugated webs

- Internal tendons prestressing
- First 50% of external prestressing on lateral spans
- First 50% of external prestressing on central spans
- Second 50% of external prestressing everywhere
- Permanent loads introduction

- Anime lisce
- Applicazione carichi permanenti portati
- Tiro dei cavi interni
- Anime corrugate
- Tiro dei cavi esterni campate laterali (50%)
- Tiro dei cavi esterni campate centrali (50%)
Axial stress in steel bottom flange – continuity support section

Axial stress [MPa]

-240.00
-220.00
-200.00
-180.00
-160.00
-140.00
-120.00
-100.00

Time [days]

100
1000
10000
100000

377 days: end of construction

50 years: end of service life

Flat webs
Corrugated webs
5

Cumbering design
Cumbering design

Displacements without cumbering

End of segment one

Longitudinal axis [m]
Cumbering design

Displacements without cumbering

Vert. displacement [m]

Prestressing of tendons 1 and 2

End of segment one

Longitudinal axis [m]
Cumbering design
Displacements without cumbering

Vert. displacement [m]

Longitudinal axis [m]

Prestressing of tendons 1 and 2
End of segment 1
End of segment 2
Cumbering design

Displacements without cumbering
Cumbering design

Displacements without cumbering

End of segment 3
Cumbering design

Displacements without cumbering

-2.00E-02  -1.50E-02  -1.00E-02  -5.00E-03  0.00E+00  5.00E-03

20.00  30.00  40.00  50.00  60.00  70.00  80.00  90.00  100.00  110.00

Vert. displacement [m]

Longitudinal axis [m]

Prestressing of tendons 6, 7, 8
End of segment 3

Fine concio 3
Tiro cavi 6-8
End of segment 3
Prestressing of tendons 6, 7, 8
Cumbering design

Displacements without cumbering

Vert. displacement [m]

Longitudinal axis [m]

End of segment 3

End of segment 4

Prestressing of tendons 6, 7, 8
Cumbering design

Displacements without cumbering
Cumbering design

Displacements without cumbering

Vert. displacement [m]

Longitudinal axis [m]

End of segment 5
Cumbering design

Displacements without cumbering

Vert. displacement [m]

-8,00E-02
-7,00E-02
-6,00E-02
-5,00E-02
-4,00E-02
-3,00E-02
-2,00E-02
-1,00E-02
0,00E+00
1,00E+00

Longitudinal axis [m]

Prestressing of tendons 12, 13, 14

End of segment 5
Cumbering design

Displacements without cumbering

Grouting of internal tendons
Cumbering design

Displacements without cumbering

Vert. displacement [m]

Longitudinal axis [m]

Grouting of internal tendons

First 50% of lateral spans external prestressing
Cumbering design

Displacements without cumbering

Vert. displacement [m]

Closure of key segments

Longitudinal axis [m]
Cumbering design

Displacements without cumbering

Closure of key segments

First 50% of central spans external prestressing

Longitudinal axis [m]

Vert. displacement [m]

Abbassamento [m]

Vert. displacement [m]

Prec. Est. Campate centrali (50%)

Sutura campate
Cumbering design

Displacements without cumbering
Cumbering design

Displacements without cumbering

Vert. displacement [m]

Closure of key segments
First 50% of central spans external prestressing
Introduction of permanent loads
Second 50% of external tendons prestressing

Longitudinal axis [m]
Cumbering design

Displacements without cumbering

1 Year after construction end
Cumbering design
Displacements without cumbering

Vert. displacement [m]
1 Year after construction end
4 years after construction end
Longitudinal axis [m]
Cumbering design

Displacements without cumbering

Vert. displacement [m]

Longitudinal axis [m]

1 Year after construction end

4 years after construction end

16 years after construction end
Cumbering design

Displacements without cumbering
Cumbering design

Displacements WITH cumbering

End of segment 3
Cumbering design

Displacements WITH cumbering

Vert. displacement [m] vs. Longitudinal axis [m]

- Prestressing of tendons 6, 7, 8
- End of segment 3

Fine concio 3
Tiro cavi 6-8
End of segment 3
Prestressing of tendons 6, 7, 8

Abbassamento [m]
Coordinata [m]
Cumbering design

Displacements WITH cumbering

Prestressing of tendons 6, 7, 8
End of segment 3

Fine concio 4

Longitudinal axis [m]

Vert. displacement [m]
Cumbering design

Displacements WITH cumbering

Vert. displacement [m]

Longitudinal axis [m]

Fine concio 4

Tiro cavi 9-11

Prestressing of tendons 6, 7, 8

End of segment 3
Cumbering design

Displacements WITH cumbering

Vert. displacement [m]

Longitudinal axis [m]

End of segment 5
Cumbering design

Displacements WITH cumbering

Prestressing of tendons 12, 13, 14

End of segment 5
Cumbering design
Displacements WITH cumbering

Grouting of internal tendons

Vert. displacement [m]

Longitudinal axis [m]
Cumbering design
Displacements WITH cumbering

Grouting of internal tendons

First 50% of lateral spans external prestressing
Cumbering design

Displacements WITH cumbering

Vert. displacement [m]

Closure of key segments

Longitudinal axis [m]
Cumbering design

Displacements WITH cumbering

Vert. displacement [m]

8.00  108.00  158.00  208.00  258.00

Closure of key segments

First 50% of central spans external prestressing

Longitudinal axis [m]
Cumbering design

Displacements WITH cumbering

Vert. displacement [m]

Closure of key segments

First 50% of central spans external prestressing

Introduction of permanent loads

Second 50% of external tendons prestressing

Longitudinal axis [m]
Cumbering design

Displacements WITH cumbering
Cumbering design

Displacements WITH cumbering

Vert. displacement [m]

Longitudinal axis [m]

1 year after construction
Cumbering design

Displacements WITH cumbering

Vert. displacement [m] vs. Longitudinal axis [m]

-1,50E-02 to 1,00E-02

Y-axis: Vert. displacement [m]
X-axis: Longitudinal axis [m]

1 year after construction
4 years after construction
Cumbering design

Displacements WITH cumbering

Vert. displacement [m]

Longitudinal axis [m]

1 year after construction
4 years after construction
16 years after construction
Cumbering design

Displacements WITH cumbering

Vert. displacement [m]

Longitudinal axis [m]

1 year after construction
4 years after construction
16 years after construction
50 years after construction
Conclusions
Sustainability aspects

Durability ⇒ No tensile stresses in concrete in SLS (Frequent combination)

Economy ⇒ Time saving and elimination of launching girder

Environmental impact ⇒ Elimination of storage areas for segments

Maintenance ⇒ Very easy inspection and control of external tendons

Rehabilitation ⇒ Substitution of external tendons without significant limitation to traffic flow
## Materials amount

<table>
<thead>
<tr>
<th></th>
<th>Flat webs</th>
<th>Corrugated webs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td>0.80 m³/m²</td>
<td>0.80 m³/m²</td>
</tr>
<tr>
<td>Steel</td>
<td>170 kg/m²</td>
<td>155 kg/m²</td>
</tr>
<tr>
<td>Prestressing steel</td>
<td>60 kg/m²</td>
<td>56 kg/m²</td>
</tr>
<tr>
<td>Ordinary reinforcement</td>
<td>170 kg/m²</td>
<td>170 kg/m²</td>
</tr>
</tbody>
</table>
Use of steel

With plane webs

Main girders: 61 kg/m² web weight
34 Kg/m² flanges weight
15 Kg/m² connections, studs, bolts, plates, etc…
16 Kg/m² web stiffeners
15 Kg/m² truss diaphragms

Partial total 141 kg/m² + 29 Kg/m² for pier segments and prestressing deviators
Use of steel

With corrugated webs

Main girders:  
- 74 kg/m² web weight
- 34 Kg/m² flanges weight
- 17 Kg/m² connections, studs, bolts, plates, etc...
- 0 Kg/m² web stiffeners
- 0 Kg/m² truss diaphragms

Partial total: \( 125 \text{ kg/m}^2 + 29 \text{ Kg/m}^2 \) for pier segments and prestressing deviators = \( 154 \text{ Kg/m}^2 \)
Thank u for kind attention!