LONG-TERM BEHAVIOUR OF BALANCED CANTILEVER BRIDGES

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Long-term behaviour of balanced cantilever bridges

ACES Workshop, Corfu, 2010
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Koror-Babbelao Bridge, Palau, Micronesia

- Construction: 1977 – span of 241m (WR)
- Depth above support 14.2 m
- Excessive deflection
- Reconstruction: 1996 – external tendons
- Collapse several months after the reconstruction

Long-term behaviour of balanced cantilever bridges

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Supposed reasons for excessive deflection

1. Actual prestressing of the superstructure is lower than it was assumed in the design due to the losses namely greater relaxation of prestressing steel.

   This effect might be increased by very high level of initial prestressing, which was allowed by some previous national design codes.

   In the Czech Republic the permissible limit of $0.935 \, f_{p_{0.2}}$ was allowed and even its "improving" by 5% overstressing was possible.
**Effect of the steel relaxation**

**Long-term behaviour of balanced cantilever bridges**

Strands 1500/1770 MPa EN 10138

\[ \sigma_{0.1} = f_{p0.1k} = 1500 \text{ MPa} \]
\[ \sigma_{0.2} = 1570 \text{ MPa} \]
\[ R_m = f_{pk} = 1770 \text{ MPa} \]

Permissible stress at jacking (ČSN):

93.5% of \( \sigma_{0.2} \) or 80% \( f_{pk} \)
i.e. 1416 MPa for 1500/1770 MPa
i.e. 1546 MPa overstress (87% \( f_{pk} \))

Permissible stress at jacking (EC):

90% \( f_{p0.1k} \)
i.e. 1368 MPa for 1500/1770 MPa
(77% \( f_{pk} \))

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**Diagram:**

- **Lana s normální relaxací (popouštěná)**
- **Srovnání průběhu relaxace v čase při sigma/Rm = 0.7**
- **Norma:**
  - ČSN 736207
  - AASHTO ASBI
  - Cerifikáty SRN

- **Lana s normální relaxací (popouštěná)**
- **Srovnání průběhu relaxace v čase při sigma/Rm = 0.8**
- **Norma:**
  - ČSN 736207
  - AASHTO ASBI
Supposed reasons for excessive deflection

2. Actual friction of tendons was probably greater than calculated due to sheath splicing at the contact joints, insufficient tightness of sheaths, delayed grouting etc.

3. Effective modulus of elasticity of concrete may be lower due to the loading of a very young concrete in context of the balanced cantilever method of construction.

4. Deflection may be affected by the shear lag which formerly was not considered.
Modulus of elasticity according to EN 1992-1-1

\[ E_{cm} = 22 \times \left( \frac{f_{cm}}{10} \right)^{0.3} \]

- secant modulus \( E_{cm} \) is derived from the working diagram at the stress level of 40% \( f_{cm} \)
- It depends also on concrete composition:
  - tables are for quartz aggregate
  - limestone aggregate -10%
  - sandstone aggregate -30%
  - basalt aggregate +20%
- Table values should be used when more precise values are not available or no precise analysis is not required!
- Testing of concrete properties is required for FCM!

<table>
<thead>
<tr>
<th>Třída betonu</th>
<th>C12/15</th>
<th>C16/20</th>
<th>C20/25</th>
<th>C25/30</th>
<th>C30/37</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E_{cm} ) (MPa)</td>
<td>20</td>
<td>24</td>
<td>28</td>
<td>33</td>
<td>38</td>
</tr>
<tr>
<td>( E_{cm} ) (GPa)</td>
<td>27</td>
<td>29</td>
<td>30</td>
<td>31</td>
<td>33</td>
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</table>

<table>
<thead>
<tr>
<th>Třída betonu</th>
<th>C35/45</th>
<th>C40/50</th>
<th>C45/55</th>
<th>C50/60</th>
<th>C55/67</th>
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</thead>
<tbody>
<tr>
<td>( E_{cm} ) (MPa)</td>
<td>43</td>
<td>43</td>
<td>53</td>
<td>58</td>
<td>63</td>
</tr>
<tr>
<td>( E_{cm} ) (GPa)</td>
<td>34</td>
<td>35</td>
<td>36</td>
<td>37</td>
<td>38</td>
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</table>

<table>
<thead>
<tr>
<th>Třída betonu</th>
<th>C60/75</th>
<th>C70/85</th>
<th>C80/95</th>
<th>C90/105</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E_{cm} ) (MPa)</td>
<td>68</td>
<td>78</td>
<td>88</td>
<td>98</td>
</tr>
<tr>
<td>( E_{cm} ) (GPa)</td>
<td>39</td>
<td>41</td>
<td>42</td>
<td>44</td>
</tr>
</tbody>
</table>
Modulus of elasticity according to EN 1992-1-1, ČSN, etc.

Long-term behaviour of balanced cantilever bridges

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Modulus of elasticity of C30/37 as tested according to ČSN ISO 6784:1993, Z1:2003

**Betocent C30/37 in 28 days from Beton Berger and Holcim Pardubice**

- **Modul pružnosti [MPa]**
  - **Berger**
  - **Holcim**
  - **Lineární (Holcim)**
  - **Lineární (Berger)**

**Concrete C35/45, 28 days old**
- Distribution up to 25% from average
- Samples from TBG Chomutov others

**Long-term behaviour of balanced cantilever bridges**

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Modulus of elasticity with respect to time course

EN 1992-1-1 Formula for estimation:

\[ E_{cm}(t) = \left( \frac{f_{cm}(t)}{f_{cm}} \right)^{0.3} \cdot E_{cm} \]

- where:

\[ f_{cm}(t) = \beta_{cc}(t) \cdot f_{cm} \]

\[ \beta_{cc}(t) = \exp \{ s \cdot [1 - (28/t)^{1/2}] \} \]

- \( s = 0.2 - 0.38 \) due to cement class
Modulus of elasticity with respect to time course as tested

Concrete C35/45, age of 3, 7 and 28 days,
Composition with CEM 52.5N – class R

Long-term behaviour of balanced cantilever bridges

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5. Theoretic values of deflection are affected by the creep function. In the analysis the Moersch' function was often utilized. Application of currently recommended function (EC2) may lead to increase of calculated deflection by up to +100%.

6. There may be influence of differential creep and shrinkage of concrete in box section (the bottom slab and the walls are at supports much thicker than the top slab). Delayed shrinkage should be taken also into account.
Supposed reasons for excessive deflection

7. There may be fatigue influence of repeated live load and thermal effects.

8. Load of the main span was greater due to increased thickness of the pavement layers (blinding concrete).

9. Finally the prestressing tendon's area might be reduced or even lost by corrosion.
### Basic data of some bridges erected by the free cantilever method

<table>
<thead>
<tr>
<th>Bridge</th>
<th>River or Valley</th>
<th>Completion time</th>
<th>Main span [m]</th>
<th>Depth at support [m]</th>
<th>Depth at midspan [m]</th>
<th>Deflection [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Děčín</td>
<td>Labe</td>
<td>1990</td>
<td>104</td>
<td>5,8</td>
<td>3,0</td>
<td>~ 20</td>
</tr>
<tr>
<td>Mělník</td>
<td>Labe</td>
<td>1993</td>
<td>146</td>
<td>9,0</td>
<td>2,65</td>
<td>11</td>
</tr>
<tr>
<td>Vepřek</td>
<td>Vltava</td>
<td>1996</td>
<td>125</td>
<td>6,9</td>
<td>2,5</td>
<td>n.a.</td>
</tr>
<tr>
<td>Úhlavka</td>
<td>valley</td>
<td>1997</td>
<td>130</td>
<td>7,5</td>
<td>2,8</td>
<td>4</td>
</tr>
<tr>
<td>Doksany</td>
<td>Ohře</td>
<td>1998</td>
<td>137</td>
<td>7,0</td>
<td>3,0</td>
<td>1</td>
</tr>
<tr>
<td>Hačka</td>
<td>valley</td>
<td>2007</td>
<td>106</td>
<td>6,25</td>
<td>2,65</td>
<td>-</td>
</tr>
<tr>
<td>Litoměřice</td>
<td>Labe</td>
<td>2009</td>
<td>151</td>
<td>7,5</td>
<td>3,5</td>
<td>-</td>
</tr>
<tr>
<td>Lahovice</td>
<td>Vltava</td>
<td>2010</td>
<td>104</td>
<td>5,2</td>
<td>2,6</td>
<td>-</td>
</tr>
</tbody>
</table>
Monitoring of the main span deflections [cm] against time [years]
Zvíkov Bridge rehabilitation

Zvíkov Bridge over the Vltava
- max. span of 84m
- Completed in 1963
- Rehabilitation in 1996
- Midspan hinges were fixed
- External prestressing

Long-term behaviour of balanced cantilever bridges

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Bridges on I/13 road over the Labe River
- Main span of 104m
- Completed in 1985
  - Both bridges with excessive deflection of 20-25 cm with progressive increase of 1 cm/year without any stabilization
  - In 2004 - 2005 rehabilitation and strengthening by external tendons

Long-term behaviour of balanced cantilever bridges

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Děčín Bridge Rehabilitation

Long-term behaviour of balanced cantilever bridges

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Monitoring of the main span deflections [cm] against time [years]
Litoměřice Bridge

Spans 43+64+72+90+151+102+60
Spans 1-3, 7 casted on fixed scaffolding
Spans 4, 5, 6 balanced cantilevering
(Doka form-travellers)
Depth of superstructure 3.5 / 7.5 m
DSI bonded prestressing
Week construction cycle

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Long-term behaviour of balanced cantilever bridges

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Lahovice Bridge across the Vltava

Spans 68+104+62.7
Depth 2.6 m / 5.2 m
Ramps joined to the midspan
Construction cycle 9-13 days

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Lahovice Bridge across the Vltava

Long-term behaviour of balanced cantilever bridges

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Long-term behaviour of balanced cantilever bridges

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Oparno Bridge – processing of surveying measurement

- Measurement A, FT setting
- Reinforcement, segment casting
- Measurement B
- Stressing of stays
- Measurement C
- Form-traveller move
- Measurement D

Numbering of points for outline setting and surveying

1. T1, T2, T3, T4 – Telemétry v Lamelách 2, 7, 11 (CCA v polovině délky lámely)
2. Kontrolní měřící body B1, B2, B3 budou umístěny v čele běžné lámely
3. BOD B1 resp. B3 je vždy vlevo resp. vpravo od osy oblohu při pohledu ve směru stanicení
Deflections after casting of the 13L segment

Deflection of – 4 cm
Deflections after stressing of stays of the 13L segment

Deflection of + 14 cm

Influence of temperature ± 8 cm

Long-term behaviour of balanced cantilever bridges
Conclusions from the testing of modulus of elasticity

- Values of modulus of elasticity of concrete received from comparable samples are very variable, influence of the real aggregate is a principle one.

- Statistic distribution of samples from one concrete plant is high, however the basic trend is clearly visible.

- Indicative values given in the EN 1992-1-1 are basically correct and usable in standard design practice with given limits.

- In the previous Czech standards ČSN 73 6206 and ČSN 73 6207 modulus of elasticity was overestimated by up to 10% for reinforced structures (ČSN 73 6206) and by 5-15% for prestressed structures (ČSN 73 6207), the difference is growing with the concrete class.

- In previous Czech standards no data were available on the time development of Ec.

- For evaluation of the pumping effect we have not sufficient dataset. However the tendency to 5% reduction behind the pump is clear.
Conclusions for the balanced cantilever bridges

- Reliable deflection control during construction as well as back analysis of executed structures is not possible without actual testing of modulus of elasticity of the concrete supplied to the site. This complies with the recommendation in EN 1992-1-1.

- Wide range of distribution for the samples from one concrete plant brings doubts about purposefulness of advance testing for the structural analysis. For slender structures with large span strict supervision during production, transport and casting is vital for successful applications.

- For demanding structures with many phases of construction and loading of young concrete computational method using time-dependent modulus should be used. Values received from samples are better however standardized procedures can be also implemented.

- Road vertical alignment should be designed as curved when possible.

- If any doubts are raised, the designer should propose a sufficient initial camber and provide details for additional superstructure strengthening by external prestressing if necessary during its lifetime.
### SLS: Limit state of cracking

as introduced in EN 1992-2

<table>
<thead>
<tr>
<th>Exposure Class</th>
<th>Reinforced members and prestressed members with unbonded tendons</th>
<th>Prestressed members with bonded reinforcement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Quasi-permanent load combination</td>
<td>Frequent load combination</td>
</tr>
<tr>
<td>X0, XC1</td>
<td>0,3&lt;sup&gt;a&lt;/sup&gt;)</td>
<td>0,2</td>
</tr>
<tr>
<td>XC2, XC3, XC4</td>
<td>0,3</td>
<td>0,2&lt;sup&gt;b&lt;/sup&gt;)</td>
</tr>
<tr>
<td>XD1, XD2, XD3, XS1, XS2, XS3</td>
<td>0,3</td>
<td>Decompression !</td>
</tr>
</tbody>
</table>

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<sup>a</sup> For X0, XC1 exposure classes, crack width has no influence on durability and this limit is set to guarantee acceptable appearance. In the absence of appearance conditions this limit may be relaxed.

<sup>b</sup> For these exposure classes, in addition, decompression should be checked under the quasi-permanent combination of loads.

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Design of partially/limited prestressed concrete structures
Example 1: Hačka Bridge – partially prestressed deck slab

Design of partially/limited prestressed concrete structures
Example 1: Hačka Bridge – partially prestressed deck slab

- EC2 requirement: RC or full prestressing
- Design: Economic solution, \( w_d = 0.2 \text{ mm} \)
  \[ \Rightarrow \text{Transversal partial prestressing } 4 \phi 15.7 / 500 \text{ mm} \]
Discrepancy: different requirements for longitudinal and transversal direction in spite of one exposure class and one protection level for prestressing
Example 2: Partial prestressing for continuity of precast girders

- Even very low level of prestressing is helpful for serviceability behaviour and robustness

- Progressive prestressing of composite structure is possible => cost effectiveness

Design of partially/limited prestressed concrete structures
Example 3: Net arch with partially prestressed tie

- calculated crack width of $w_d = 0.2$ mm does not represent any problem
Protection level of prestressing steel

fib Bulletin No. 33
Durability of post-tensioning tendons

<table>
<thead>
<tr>
<th>Aggressivity/Exposure</th>
<th>High</th>
<th>Medium</th>
<th>Low</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>PL3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medium</td>
<td>PL2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td>PL1</td>
<td></td>
<td></td>
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Design of partially/limited prestressed concrete structures
# SLS: Limit state of cracking

## Draft of the Model Code 2010

<table>
<thead>
<tr>
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<th>Reinforced members and prestressed members with unbonded tendons</th>
<th>Post-tensioned members with bonded grouted reinforcement and plastic ducts</th>
<th>Post-tensioned members with bonded grouted reinforcement and steel ducts</th>
<th>Pretensioned members with bonded reinforcement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Quasi-permanent load combination</td>
<td>Frequent load combination</td>
<td>Frequent load combination</td>
<td>Frequent load combination</td>
</tr>
<tr>
<td>X0</td>
<td>0.3</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>XC</td>
<td>0.3</td>
<td>0.2</td>
<td>0.2</td>
<td>Decompression</td>
</tr>
<tr>
<td>XD, XS, XF</td>
<td>0.3</td>
<td>0.2</td>
<td>Decompression</td>
<td>Decompression</td>
</tr>
</tbody>
</table>

Remarks: Prestressing protection level should be more emphasized, one load combination only would be better for design process, partial and limited prestressing should not be handicapped.
### SLS: Limit state of cracking

**Proposal for ČSN EN 1992-2 NA**

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<tr>
<td></td>
<td>Frequent load combination</td>
<td>Frequent load combination</td>
<td>Frequent load combination</td>
<td>Frequent load combination</td>
</tr>
<tr>
<td>X0</td>
<td>0.4</td>
<td>0.3</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>XC</td>
<td>0.4</td>
<td>0.3</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>XD, XS, XF</td>
<td>0.4</td>
<td>0.2</td>
<td>0.1</td>
<td>Decompression</td>
</tr>
</tbody>
</table>

**Remark:** Draft, not yet approved by the Czech Standards Committee for bridges.
Optimal prestressing

- Reinforced concrete
  - Structural Concrete
  - Fully prestressed concrete

Design of partially/limited prestressed concrete structures

- Frequent combination of loading
- 1st crack
- Design load $g + q$
- Loading at ultimate strain
- Gradient of working diagrams $= f(EA)$
- $Ap < As$
- Full prestressing
- Partial prestressing
- Dead load $g$
- Effect of prestressing $P$
- Camber due to prestressing for unloaded beam
- Deflection

Minimum reinforcement

EN 1992-1-1
2010
SLS: Limitation of concrete tensile stresses

No direct requirements in EN 1992-1 or MC2010 are available, however the design value of the concrete tensile strength is given in the material chapter by the formula:

\[ f_{ctd} = \alpha_{ct} f_{ctk0.05} / \gamma_c \]  

(i.e. for C30/37 ~ 2.0 MPa)

where the recommended values in SLS are:

\( \alpha_{ct} = 1.0 \) coefficient taking account of long-term effects on the tensile strength coefficient and of unfavourable effects, resulting from the way the load is applied,

\( \gamma_c = 1.0 \) partial safety factor for concrete in SLS.

For the combination of compression and bending this value can be increased by up to ~1.6, which depends on the depth, way of loading and sensitivity of the steel to corrosion.

For the prestressed structures we can assume that if the concrete tensile stress does not exceed the value of \( f_{ctd} = f_{ctm} \) for frequent and/or \( f_{ctd} = f_{ctk0.05} \) for quasi-permanent combination of load, no cracking is developed \( \Rightarrow \) structure comply with SLS conditions.
Thanks for your kind attention.