Design of steel and composite bridges
Highway bridges

Joël Raoul
Main selected features

• General presentation and scope of EC3 and EC4 related to steel and composite bridges
• Materials
• Structural analysis
• Cross-section analysis at ULS and SLS
• Treatment of instabilities
• Fatigue
Eurocode 3: Steel Structures
EN 1994 : composite steel-concrete structures

EN 1994-2 general rules and bridges ➢ (self-sufficient)

CONCRETE PART
EN 1992-2

STEEL PART
EN 1993-2
Scope of EN1993-2

All steel bridges (in general with an orthotropic deck) and the steel part of composite bridges
Scope of EN1994-2

Composite bridges
Girder bridges

Economy: two-girder bridges even for 2X2 lanes due to robustness rules
Box girders
Composite members
Tension members (tie of bowstring arch)
Composite plates
Filler beam decks

In the transversal direction

In the longitudinal direction
Materials

Concrete:

Between C20 and C60 for composite bridges (C 90 for concrete bridges)

Steel:

up to S460 for steel and composite bridges
(S 500 to S 700 in a separate part 1-12 for steel bridges)
Choice of material:
avoid brittle behaviour
• An overlooked defect is assumed during execution:
  e.g. : \( a = 2.2 \text{ mm} \) for \( t_f = 80 \text{ mm} \)

• It grows acc. to fracture mechanics laws (assuming fatigue is governing the design)

• Up to the critical defect depending on Charpy energy at service temperature

• Over a period depending on the inspection periodicity

NOTE: fabrication rules and quality plan are given in EN 1090. They are assumed to be met when using EN 1993
## EN 10025

<table>
<thead>
<tr>
<th>Grade</th>
<th>Quality</th>
<th>Energie Charpy K(_\text{u}) at T (^\circ\text{C})</th>
<th>(J_{\text{min}})</th>
<th>Temperature de référence (T_{\text{Ed}}) (^\circ\text{C})</th>
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<tbody>
<tr>
<td>S235</td>
<td>JR</td>
<td>20</td>
<td>27</td>
<td>90 75 65 55 45 40 35</td>
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<td>27</td>
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<td>-20</td>
<td>40</td>
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<td>ML,NL</td>
<td>-50</td>
<td>27</td>
<td>200 180 155 135 110 95 80</td>
</tr>
</tbody>
</table>

\(\sigma_{\text{Ed}} = 0.50 f_{\text{y}(t)}\)
Structural analysis

Elastic

Plastic (buildings, bridges in accidental situations)
Classes of steel cross-sections

- Cl.1
- Cl.2
- Cl.3
- Cl.4

$M_{pl}$

$M_{el}$
### Class of flanges

<table>
<thead>
<tr>
<th>Class</th>
<th>Part subject to compression</th>
<th>Part subject to bending and compression</th>
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<tbody>
<tr>
<td></td>
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<td>Tip in compression</td>
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<tr>
<td></td>
<td></td>
<td>Tip in tension</td>
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<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>c/t ≤ 9ε</td>
<td>c/t ≤ ( \frac{9\varepsilon}{\alpha} )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>c/t ≤ ( \frac{9\varepsilon}{\alpha \sqrt{\alpha}} )</td>
</tr>
<tr>
<td>2</td>
<td>c/t ≤ 10ε</td>
<td>c/t ≤ ( \frac{10\varepsilon}{\alpha} )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>c/t ≤ ( \frac{10\varepsilon}{\alpha \sqrt{\alpha}} )</td>
</tr>
<tr>
<td>3</td>
<td>c/t ≤ 14ε</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>c/t ≤ 2ε ( \sqrt{k_\sigma} )</td>
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</table>

For k_\sigma see EN 1993-1-5

<table>
<thead>
<tr>
<th>ε = ( \sqrt{\frac{235}{f_y}} )</th>
<th>f_y</th>
<th>ε</th>
<th>f_y</th>
<th>ε</th>
<th>f_y</th>
<th>ε</th>
<th>f_y</th>
<th>ε</th>
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<td>1,00</td>
<td>275</td>
<td>0,92</td>
<td>355</td>
<td>0,81</td>
<td>420</td>
<td>0,75</td>
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Global analysis of composite bridges:
two aspects are considered

Cracking of concrete on support

Non linear behaviour at mid span

Class 1

\[ M_{pl,Rd} \]

\[ M_{el,Rd} \]
Modular ratio used in a composite section

\[ n_L = n_0 \cdot (1 + \psi_L \phi_t) \]

\[ n_0 = \frac{E_a}{E_{cm}} \quad \text{and} \quad \phi_t = \phi(t - t_0) \quad \text{creep coefficient given by EC2} : \]

Value of \( t_0 \):

\[ t_0 = 1 \text{ day for shrinkage} \]
\[ t_0 = \text{a mean value in case of concrete cast in several stages} \]

SIMPLE CALCULATIONS

\( \psi_L \) is given by:

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Permanent loads</td>
<td>1,1</td>
</tr>
<tr>
<td>shrinkage</td>
<td>0,55</td>
</tr>
<tr>
<td>Imposed deformations</td>
<td>1,5</td>
</tr>
</tbody>
</table>
Plate buckling and shear lag

Effective \( P \) width
(plate buckling)

Effective \( S \) width
(shear lag)
Effective width of concrete slab (ULS and SLS)

\[ b_{ei} = \min\left( \frac{L_e}{8} ; b_1 \right) \]
Effective width of stiffened plates

Shear lag at ULS: 3 alternatives, black one recommended

Shear lag at SLS: elastic (red line)
Composite cross-section verification at ULS (M>0)

Elastic resistance
(for class 1, 2, 3)

plastic resistance
(for classes 1/2)

NOTE : $\gamma_M$ is 1.0 (recommended for resistance formulae)
Verification at SLS

- Limitation of stresses for steel and composite bridges
  - As in EN1992-2 and EN1993-2 ($f_y$ in the steel part)
- Limitation of crack widths for composite bridges
  - As in EN1992-2 with tension stiffening ($w_k=0.3\text{mm in general}$)
  - Using a simplified method
Treatment of instabilities

**expérimental behaviour**

**mechanical model**

\[ \sigma_1 = -\tau_{cr} \]

\[ A_{eff} \]
Principle of verification

\[ \alpha_u = \text{ultimate loading (without instability)/ ULS loading} \]

\[ \alpha_{cr} = \text{critical loading / ULS loading} \]

\[ \bar{\lambda} = \sqrt{\frac{\alpha_u}{\alpha_{cr}}} \]

\[ \chi = f(\bar{\lambda}) \]

\[ P_{Rd} = \frac{P_{Rk}}{\gamma_M} \]

\[ P_{Rk} = \chi P_u \]

NOTE: \( \gamma_M \) is 1.1 (recommended for « stability » formulae)
Plate buckling of stiffened plates in EC3
Fatigue verification in EC3

Calculation of $\Delta \sigma_{E,2}$ under a fatigue loading

- Influence of the type of influence line
- Influence of the type of traffic
- Influence of the number of lanes

$P = 480kN$

Verification

\[ \Delta \sigma_c = 80 \]

\[ \frac{\gamma_{Ff} \Delta \sigma_{E,2}}{\Delta \sigma_C / \gamma_{Mf}} \leq 1,0 \]

Category of detail

<table>
<thead>
<tr>
<th>Assessment method</th>
<th>Consequence of failure</th>
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<tbody>
<tr>
<td></td>
<td>Low consequence</td>
</tr>
<tr>
<td>Damage tolerant</td>
<td>1,00</td>
</tr>
<tr>
<td>Safe life</td>
<td>1,15</td>
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</table>

Partial factor for loading = 1,0
Orthotropic decks: recommended detailing

Deck plate thickness in the carriage way in the heavy vehicle lane

\( t \geq 14 \text{ mm for asphalt layer } \geq 70 \text{ mm} \)

crack initiation starting at weld root inside the stiffeners
1st bridge entirely designed to EC4 in Avignon
4500 t
Outstanding composite bridges

Max span 144 m: Verrières viaduct (composite box-girder bridge)

Max S460 thickness 120 mm: Guarrigue viaduct

Surface > 20000 m²: Vézère viaduct
SOME INNOVATIONS / ECONOMY ISSUES

• Enormous scientific work
• Simplicity of calculations
• Robustness (fatigue + brittle fracture)
• Full exploitation of the materials (postcritical range)
• Steels up to S690
• Hybrid girders
• Harmonization of the format and the reliability of all the instability formulae
• Treatment of stiffened plates
• Design of orthotropic decks