Opening and Project Overview

OptiBri-Workshop
"Design Guidelines for Optimal Use of HSS in Bridges."
3 May 2017

Anne Marie Habraken
<table>
<thead>
<tr>
<th>Partners</th>
<th>Core Expertise</th>
</tr>
</thead>
<tbody>
<tr>
<td>University of Liège Be (Ulg)</td>
<td>\textit{(Coordinator)} Material scientist Modelling, Experimental Lab</td>
</tr>
<tr>
<td>Industeel Be</td>
<td>Producer of high quality steels</td>
</tr>
<tr>
<td>GRID Pt</td>
<td>Civil Engineering</td>
</tr>
<tr>
<td>University of Stuttgart Ge (USTUTT)</td>
<td>Bridge, Stability, Euro code, Experimental Lab</td>
</tr>
<tr>
<td>University of Coimbra Pt (UC)</td>
<td>Environmental and cost impact assessment</td>
</tr>
<tr>
<td>Belgian Welding Institute Be (BWI)</td>
<td>Welding procedure and Post Weld treatments</td>
</tr>
</tbody>
</table>
How the project was born?

For a **material scientist**, studying also forming process, High Strength Steel (**HSS**) means

- higher stress value, higher fatigue limit, specific microstructures,
- logical ways to decrease weight (cars, planes: transport industry)

![Graph showing fatigue strength vs tensile strength](image)

- **Sheet sample**
- **Bulk sample**
  → **Material study case A**

- **Beams, Plate with or without welding joints?**
- **Where?**
How the project was born?

For civil engineers, HSS means:

- higher material cost but potential decrease of the amount of material
  of welding time
  of transport
  of environmental impact…

Objectives of OPTIBRI Project

- Quantification of the interest of HSS use under current euro code rules
- Scientific study to define the need of Eurocode enhancement (Stability, Fatigue)
- Check fatigue issues of post treated weld joint of HSS
- Study weld joint and post treatment quality in HSS
My network + the one of my Civil Eng. colleagues ➔ Partnership ➔ Brainstorming in Summer 2013

**ULG**
HSS Material
Civil Eng Market ?
Industeel

**IBW**
Weld joint quality & effect on fatigue ➔ PIT, TIG

**USTUTT**
Stability issues if slender structures

**GRID**
Fatigue issues for bridge if slender structures

**UC**
Tools to assess the interest of HSS
LCA LCC LCP

**LCA Life cycle Assessment**
**LCC Life cycle Cost**
**LCP Life cycle Performance**

**Case study** = road bridge (continuous plate girder steel concrete composite deck, with internal spans 80 meters)

**OPTIimal use of HSS in BRIdges = OPTIBRI**
Case Design

- Road bridge with four traffic lanes

\[ \text{Total width} = 21.50 \text{ m} \]

- Five spans: \(60 + 3 \times 80 + 60 = 360 \text{ m}\)
3 designs for the same bridge

Design A: classical design using S355 steel based on current state of Eurocodes and national rules

Design B: design using S690QL steel, where it has an interest based on current state of Eurocodes and national rules

Design C: design using S690QL steel, where it has an interest based on
- real material behavior (experimental tests and fatigue damage simulations of bridge details)
- advanced stability law (experimental + FE analysis of the buckling of multiaxially stressed plates \(\rightarrow\) enhanced formula within of the code rules EN 1993-1-5)

J.O Pedro’s presentation: Challenges and Benefits of High Strength Steel (HSS) in Highway Bridges

P. Toussaint’s presentation: Usual application of High Strength Steel (HSS) Plates with focus on S690
Impact of Bridge Design
- Life Cycle Assessment
- Life Cycle Cost
- Life Cycle Performance

Design of BRIDGES
A: classical cases (no HSS) with current EUrocode
B: with optimal use of HSS with current Eurocode
C: with optimal use of HSS and studied behaviour

Fatigue study
- Tests
- small scale
- large(r) scale
- Models

Stability study
- Tests
- Models

Welding Study
- Samples Generation
- Post treatment Qualification

Quantification of interest to use HSS in bridges

Design guidelines for optimal use of HSS in bridges

Proposals of Eurocode modifications

Post treatment qualification procedure

Results dissemination

COORDINATION OF THE PROJECT
Design A provides a reference

Design B allows investigating different designs based on S690QL use discussions between USTUTT and GRID oriented the choices and verifications done (current Eurocode use)

Design C ongoing work based on the results of experimental fatigue curves of welded plates (Ulg) and beams (USTUTT) (with weld post treatments) + new formula of buckling verification (USTUTT)

Delays in material delivery → in test results → in model identification → in the simulation of bridge details → in Design C

C. Batista’s presentation: Improved Bridge Design by Use of High Strength Steel (HSS) with OPTIBRI Developments
WP2 Fatigue study (Ulg, USTUTT, BWI)

Ulg: *material scientist’s approach*

- Static tests ≠ loadings, **Base Metal**, **Heat Affected Zone** and **Weld Metal** (WBI) - *3 elasto plastic models* (BM, HAZ, WM)

- Fatigue tests on small specimens (mm) → parameters of *Lemaitre damage model* (1)

- Static and Fatigue tests on plates + welded transversal stiffeners (Ulg) + post treatment (PIT,TIC) (residual stress distribution) → parameters of *Lemaitre damage model* (2)

1st validation of the fatigue simulations with *Lemaitre model*

*C Bouffioux’s presentation: Characterization of Fatigue Behaviour, from Material Science to Civil Engineering Applications*
WP2 Fatigue study (Ulg, USTUTT, BWI)

- Fatigue tests on Beams + welded transversal stiffeners (USTUTT)

- 2nd validation of the fatigue simulations with Lemaitre model

Simulations of Bridge C detail:

Loading from Eurocode FLM5
→ 1 stress history
→ 1 damage distribution of the studied bridge detail
→ detail category confirmed or not
→ sensitivity analysis not performed: 1st approach of real behavior in HSS in bridges, ongoing work

- Representative HSS bridge potential rupture

S. Breunig’s presentation: Categorization of Fatigue Details in View of Post-Weld Treatments
WP3 Stability study (USTUTT)

→ FE element simulations that are validated by experiments
→ Parametric study
→ Enhancement of the reduced stress method, introduction of V factor in Eurocode formulae

Panel with bi axial loading

\[ \sigma_x \]
\[ \sigma_z \]
\[ b \]
\[ a \]

V. Pourostad’s presentation: Buckling Behavior of Slender Plates under Multiaxial Stresses
WP4 Welding study (BWI)

Study of Fatigue crack and microstructure to identify optimal welding procedure and Post Treatment Qualification.

Welding of all plates and beams

PIT (Pneumatic Impact Treatment) TIG (Tungsten Inert Gas) remelting were used as Post Treatments.

Initial choice LTT (Low Temperature Transformation filler material) dropped

LTT could not reach required toughness values (50 to 60 J) in bridges (results of FATWELDHSS project 2015)

T. Baaten’s presentation: Welding and Post-Welded Treatments of High Strength Steel (HSS) joints
WP5 Impact of Bridge Design (UC)

Work on
LCA Life cycle Assessment
LCC Life cycle Cost
LCP Life cycle Performance

Design A // B : on going work,
Design C = future

C. Rigueiro’s presentation:
Comparative Life-Time Assessment of the Use of High Strength Steel (HSS) in Bridges
Thank you for your attention!

Anne Marie Habraken

E-Mail Anne.Habraken@ulg.ac.be
Telefon +32 (0) 4 366 94 30
Fax +32 (0) 4 366 95 34

University of Liège
ARGENCO department
Quartier Polytech 1,
Allée de la découverte, 9 Bât B52/3
B-4000 Liège BELGIUM
Challenges and Benefits of High Strength Steel (HSS) in Highway Bridges

OptiBri-Workshop
„Design Guidelines for Optimal Use of HSS in Bridges“

José Oliveira
Pedro
Overview – Case study: general layout

- Five spans: $60 + 3 \times 80 + 60 = 360$ m

- Highway bridge with four traffic lanes
Overview – Case study: construction

• Studied span: typical 80m inner span

• Executed by incremental launching of the steel structure
Overview – Case study: Design A and B

- **Design A** – using standard S355 NL and present Eurocodes
- **Design B** – using HSS S690 QL and present Eurocodes
- **Design C** – using HSS S690 QL, welding treatment and possible upgrades to the EC 3-1-5
Design A – S355 NL ↔ Design B – S690 QL

Support Span

Main girders

**S355 NL**

- 1300
- 1300 x 100
- th = 26
- 3800
- 1500 x 120
- Support

**S690 QL**

- 1100
- 1100 x 40
- th = 20
- 3500
- 1300 x 70
- Support

**S690 QL**

- 1100
- 1100 x 30
- th = 15
- 3500
- 1300 x 45
- Mid span

**S355 NL**

- 1300
- 1300 x 35
- th = 18
- 3800
- 1500 x 50
- Mid span
Design A – S355 NL <> Design B – S690 QL

**S355 NL**

<table>
<thead>
<tr>
<th>Top Flanges (mm)</th>
<th>300 x 100</th>
<th>1300 x 70</th>
<th>1300 x 35</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4000</td>
<td>8000</td>
<td></td>
</tr>
<tr>
<td>Web thickness (mm)</td>
<td>26</td>
<td>22</td>
<td>18</td>
</tr>
<tr>
<td>Bottom Flanges (mm)</td>
<td>1500 x120</td>
<td>1500 x 80</td>
<td>1500 x 50</td>
</tr>
<tr>
<td></td>
<td>8000</td>
<td>12000</td>
<td>20000</td>
</tr>
<tr>
<td>Head Stud Connectors</td>
<td>Stud Connectors 5 φ22/300</td>
<td>Stud Connectors 5 φ22/400</td>
<td>Stud Connectors 3 φ22/400</td>
</tr>
<tr>
<td>Longitudinal Reinforcement</td>
<td>2.0%</td>
<td>1.5%</td>
<td>1.0%</td>
</tr>
<tr>
<td></td>
<td>12000</td>
<td>12000</td>
<td>16000</td>
</tr>
</tbody>
</table>

**S690 QL**

<table>
<thead>
<tr>
<th>Top Flanges (mm)</th>
<th>1100 x 40</th>
<th>1100 x 30</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>12000</td>
<td>28000</td>
</tr>
<tr>
<td>Web thickness (mm)</td>
<td>20</td>
<td>18</td>
</tr>
<tr>
<td>Bottom Flanges (mm)</td>
<td>1300 x 70</td>
<td>1300 x 60</td>
</tr>
<tr>
<td></td>
<td>8000</td>
<td>12000</td>
</tr>
<tr>
<td>Head Stud Connectors</td>
<td>Stud Connectors 5 φ22/200</td>
<td>Stud Connectors 5 φ22/300</td>
</tr>
<tr>
<td>Longitudinal Reinforcement</td>
<td>2.0%</td>
<td>1.5%</td>
</tr>
<tr>
<td></td>
<td>12000</td>
<td>12000</td>
</tr>
</tbody>
</table>

Structural steel distribution for the typical 80 m span
## Design A – S355 NL <> Design B – S690 QL

### Structural Materials

#### CONCRETE:

<table>
<thead>
<tr>
<th>Designation</th>
<th>EN 206-1</th>
<th>Exposure Classes</th>
<th>Cover (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Piers and Foundations</td>
<td>C30/37</td>
<td>XC3 / XF1</td>
<td>45</td>
</tr>
<tr>
<td>Deck - Slab</td>
<td>C35/45</td>
<td>XC4/ XF4</td>
<td>40</td>
</tr>
</tbody>
</table>

#### STEEL:

<table>
<thead>
<tr>
<th>Structural Steel</th>
<th>EN10025-2 S355 J2 (Z15 if th. ≤ 30mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EN10025-3 S355 N (Z15 if 30 &lt; th. ≤ 80mm)</td>
</tr>
<tr>
<td></td>
<td>EN10025-3 S355 NL (Z25 if th. &gt; 80mm)</td>
</tr>
<tr>
<td>Reinforcement</td>
<td>B500B (EN 10080)</td>
</tr>
<tr>
<td>Prestress Cables</td>
<td>$f_{p_{0.1k}} \geq 1637$ MPa / $f_{p_{uk}} \geq 1860$ MPa (EN 10138)</td>
</tr>
<tr>
<td>Stud Connectors</td>
<td>EN10025 S235 J2 + C450 (EN ISO 13918)</td>
</tr>
<tr>
<td>Structural Steel</td>
<td>EN10025-6 S690 QL (40J,-40°C) (Z15 if th. ≤ 40mm)</td>
</tr>
<tr>
<td></td>
<td>EN10025-6 S690 QL1 (40J,-40°C) (Z15 if th. &gt; 40mm)</td>
</tr>
</tbody>
</table>
Bridge design criteria


- **Structural behaviour** at ultimate and serviceability limit states (ULS, SLS), evaluated by finite frame element models, with due account for rheological effect from concrete.

- **Construction stages** are taken into account by superposition of results from:
  - steel structure frame model, for the application of its own weight and the slab concrete weight.
  - composite structure frame models with modular ratios for concrete, assessed for short-term actions, permanent actions and shrinkage effects (following EN 1994-2).
Bridge design criteria

- **Longitudinal safety verifications** included namely:
  - ULS – bending and shear girders resistance
  - SLS – stress limitations on structural steel, reinforcement and concrete slab, and deflections
  - ULS – fatigue of girders structural steel and stud connectors (welded joint between the transverse stiffeners and the bottom tension flange proves to be the most relevant detail for the design of the composite steel-concrete twin plate girder deck)

- **Flange induced buckling** following formulation from EN 1993-1-5

- **Transverse stiffeners** designed also according with EN 1993-1-5 (plate buckling of the webs near supports is a key issue when using HSS; close intermediate transverse stiffeners are used to increase web shear buckling resistance)
**ULS bridge deck design – Bending resistance (EN 1993-1-5)**

### Mid-span section

Class 1 – *Plastic section analysis*

<table>
<thead>
<tr>
<th></th>
<th>Design A</th>
<th>Design B</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{M_{Ed}}{M_{pl.Rd}} &lt; 1$</td>
<td>0.74</td>
<td>0.54</td>
</tr>
<tr>
<td>$\left{ \frac{\sigma_{Ed}}{f_{yf}} \left( \frac{1}{\gamma_{M0}} \right) \right}$ Bottom flange $&lt; 1$</td>
<td>0.93</td>
<td>0.65</td>
</tr>
</tbody>
</table>

- ULS bending resistance is not a critical design issue for S690
- All span sections can still be designed elastically
### ULS bridge deck design – Bending resistance (EN 1993-1-5)

**Support section**

<table>
<thead>
<tr>
<th>Class 4 – Elastic analysis with effective section</th>
<th>Design A S355</th>
<th>Design B S690</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \left{ \sigma_{Ed}/\left( f_{yf}/\gamma_{M0} \right) \right} \text{ Eff. bottom flange} &lt; 1 )</td>
<td>0.95</td>
<td>0.88</td>
</tr>
<tr>
<td>( \left{ \sigma_{Ed}/\left( \chi_{LT} f_{yf}/\gamma_{M1} \right) \right} \text{ Eff. bottom flange} &lt; 1 ) (*)</td>
<td>0.92</td>
<td>0.97</td>
</tr>
<tr>
<td>(*) at 0.25 ( L_k = 5 \text{ m} ) from the support</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- ULS bending resistance > elastic analysis for both designs
- For S690 also the bottom flange is in class 4 since \( \varepsilon = \sqrt{235/f_y} = 0.584 \)
- For S690 > web under compression with \( \rho = 0.49 \), bottom flange reduction \( \rho = 0.94 \); Lateral torsion buckling \( \chi_{LT} = 0.72 \)
**Effective Width Method (EN 1993-1-5, sections 4 to 7)**

<table>
<thead>
<tr>
<th>Support section (transversal stiffeners @ 2m)</th>
<th>Design A S355</th>
<th>Design B S690</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h_w \times t_w$ (mm$^2$)</td>
<td>3590 x 26</td>
<td>3390 x 20</td>
</tr>
<tr>
<td>$\lambda_w = 0.76 \sqrt{f_{yw}/\tau_{cr}}$</td>
<td>0.97</td>
<td>1.77</td>
</tr>
<tr>
<td>$\chi_w$</td>
<td>0.86</td>
<td>0.56</td>
</tr>
<tr>
<td>$V_{Ed}/V_{bw,Rd} = V_{Ed}/ (\chi_w h_w t_w f_{yw} / \sqrt{3} \gamma_{M1})$</td>
<td><strong>0.86</strong></td>
<td><strong>0.91</strong></td>
</tr>
<tr>
<td>$(M/V)$ Interaction with $\gamma_{M1}=1.1$ (*)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(*) at min ${t_w/2 ; a/2} = 1$ m from the support</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Using S690, web thickness is reduced from 26 mm to 20 mm
- Interaction $(M,V)$ makes the support panels work at the limit, if consistently a unique safety coefficient $\gamma_{M1} = 1.1$ is adopted
### ULS bridge deck design – Shear resistance (EN 1993-1-5)

#### Reduced Stress Method (EN 1993-1-5, sections 10)

<table>
<thead>
<tr>
<th>Support section</th>
<th>Design A S355</th>
<th>Design B S690</th>
</tr>
</thead>
<tbody>
<tr>
<td>( h_w \times t_w ) (mm(^2))</td>
<td>3590 \times 26</td>
<td>3390 \times 20</td>
</tr>
<tr>
<td>( \rho_x )</td>
<td>0.83</td>
<td>0.49</td>
</tr>
<tr>
<td>( \chi_w )</td>
<td>0.76</td>
<td>0.52</td>
</tr>
<tr>
<td>((\sigma_{x,Ed}, \tau_{Ed})) (MPa) bottom end of the web</td>
<td>(267.8,135.0)</td>
<td>(519.7,183.2)</td>
</tr>
<tr>
<td>( \sqrt{\left(\frac{\sigma_{x,Ed}}{\rho_x f_y/\gamma_{M1}}\right)^2 + 3 \left(\frac{\tau_{Ed}}{\chi_w f_y/\gamma_{M1}}\right)^2} \leq 1 )</td>
<td>((1.07+0.95)^{0.5}=1.42)</td>
<td>((2.83+0.94)^{0.5}=1.94)</td>
</tr>
<tr>
<td>Required ( t_w ) (mm)</td>
<td>34</td>
<td>32</td>
</tr>
</tbody>
</table>
Why so inconsistency between effective Width Method <> Reduced Stress Method?

- Using the reduced stress method – no partial plastic stress redistributions are allowed (as it is the case for the interaction criterion of section 7, EC3-1.5)

- Therefore, ULS bending moment and shear force cannot be primarily allocated to the support cross sectional elements:
  - hogging bending moment resisted by the {flanges + reinforcement} alone
  - so that, the web resistance can fully be used for the support shear force

- Moreover, the reduced stress method consistently uses \( \gamma_{M1} = 1.1 \) (which is more accurate) for plastic resistance and instability, but verifications are made for the cross-section over the support
**ULS bridge deck design – Shear resistance (EN 1993-1-5)**

**Reduced Stress Method (EN1993-1-5, sections 10)**

Longitudinal stiffeners on the outside of the web
Ref. Railway Bridge near Riesa, Germany – COMBRI Design manual

Longitudinal flat stiffeners on the inside of the web
Ref. Twin-girder Bridge in Triel-sur-Seine, France – COMBRI Design manual
Reduced Stress Method (EN1993-1-5, sections 10)

Design solution:
- keep the web thickness
- add a continuous longitudinal closed stiffener in the external compressed bottom part of the web
- extended up to 20 m from both sides of the supports.

ULS bridge deck design – Shear resistance (EN 1993-1-5)
ULS bridge deck design – Shear resistance (EN 1993-1-5)

**Reduced Stress Method (EN1993-1-5, sections 10)**

<table>
<thead>
<tr>
<th>S690 QL</th>
<th>Unstiffened Web</th>
<th>Stiffened Web</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_{ult,k}$</td>
<td>1.13</td>
<td>1.13</td>
</tr>
<tr>
<td>$\alpha_{cr,x}$</td>
<td>0.34</td>
<td>---</td>
</tr>
<tr>
<td>$\alpha_{cr,\tau}$</td>
<td>0.70</td>
<td>---</td>
</tr>
<tr>
<td>$\alpha_{cr}$</td>
<td>0.31</td>
<td>1.87 (EBplate)</td>
</tr>
<tr>
<td>$\tilde{\lambda}_p$</td>
<td>1.92</td>
<td>0.81</td>
</tr>
<tr>
<td>$\rho_x$</td>
<td>0.49</td>
<td>0.96</td>
</tr>
<tr>
<td>$\chi_w$</td>
<td>0.52</td>
<td>1.00</td>
</tr>
</tbody>
</table>

\[
\left(\frac{\sigma_{x,Ed}}{\rho_x f_y/\gamma_{M1}}\right)^2 = 2.83 \quad 0.75
\]

\[
3 \left(\frac{\tau_{Ed}}{\chi_w f_y/\gamma_{M1}}\right)^2 = 0.94 \quad 0.25
\]

\[
\leq 1 \quad 1.94 \quad 1.00
\]

Local plate mode due to \{bending + shear\}:

$\alpha_{cr,local} = 1.870$

Global plate mode due to \{bending + shear\}:

$\alpha_{cr,global} = 18.738$
OptiBri Workshop “Design Guidelines for Optimal Use of HSS in Bridges”

3rd May 2017

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ULS bridge deck design – Transversal stiffeners (EN 1993-1-5)

Design Case A - S355

Design Case B - S690
ULS bridge deck design – Transversal stiffeners (EN 1993-1-5)

**Design Case A - S355**

- 470x20
- 400x30
- 350x35

**Design Case B - S690**

- 415x20
- 500x35
- 415x20
- 500x35
**ULS bridge deck design – Transversal stiffeners (EN 1993-1-5 §9.3.3)**

---

**Minimum stiffness requirements for shear verification of the webs** – checked by imposing a second moment of the area of a stiffener $I_{st}$ higher than:

\[
I_{st} \geq 1.5 \frac{h_w^3}{a^2} \cdot t_w^3/a^2 \quad \text{if} \quad a/h_w < \sqrt{2}
\]

\[
I_{st} \geq 0.75 h_w \cdot t_w^3 \quad \text{if} \quad a/h_w \geq \sqrt{2}
\]

- **Resistance requirement** – verified with the axial force $N_{st}$ imposed by the tension field action given by:

\[
N_{st} = V_{Ed} - V_{cr,w}
\]

- **Safety to torsional buckling** – design rules for open stiffeners assume that torsional buckling should be completely prevented when loaded axially; thus EN 1993-1-5 provides the following general requirement for the $\sigma_{cr}$ the elastic critical stress of open stiffeners:

\[
\sigma_{cr} \geq \theta f_y
\]

- for T stiff. \( \theta = 6 \)
- for Flat stiff. \( \theta = 2 \)

\[
\text{This is the more difficult criteria to achieve; design replaces } f_y \text{ by the maximum actual stress } \sigma_{max,Ed} \text{ at the intermediate transverse stiffener}
\]

---
ULS bridge deck design – Flange Induced Buckling (EN 1993-1-5)

\[
\frac{h_w}{t_w} \leq K \frac{E}{f_{yf}} \sqrt{\frac{A_w}{A_{fc}}}
\]

<table>
<thead>
<tr>
<th>Condition</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic analysis</td>
<td>( k = 0.55 )</td>
</tr>
<tr>
<td>Plastic analysis</td>
<td>( k = 0.40 )</td>
</tr>
</tbody>
</table>
## ULS bridge deck design – Flange Induced Buckling (EN 1993-1-5)

<table>
<thead>
<tr>
<th>Design B - S690 deck section</th>
<th>1-2 support</th>
<th>3</th>
<th>4-5</th>
<th>6-8</th>
<th>9-11 mid-span</th>
</tr>
</thead>
<tbody>
<tr>
<td>( k )</td>
<td>0.55</td>
<td>0.55</td>
<td>0.55</td>
<td>0.55</td>
<td>0.55</td>
</tr>
<tr>
<td>( f_{yf} ) (MPa)</td>
<td>650</td>
<td>650</td>
<td>650</td>
<td>690</td>
<td>690</td>
</tr>
<tr>
<td>( A_w = h_w \times t_w ) (\text{mm}^2)</td>
<td>3390x20</td>
<td>3400x20</td>
<td>3410x18</td>
<td>3425x18</td>
<td>3425x15</td>
</tr>
<tr>
<td>( A_{fc} = b_{f,eff} \times t_f ) (\text{mm}^2)</td>
<td>1230x70</td>
<td>1100x60</td>
<td>1100x60</td>
<td>1300x45</td>
<td>1300x45</td>
</tr>
<tr>
<td>( k E / f_{yf} \sqrt{A_w / A_{fc}} )</td>
<td>158</td>
<td>180</td>
<td>172</td>
<td>172</td>
<td>157</td>
</tr>
<tr>
<td>( h_w / t_w &lt; \text{limit?} )</td>
<td>170</td>
<td>170</td>
<td>189</td>
<td>190</td>
<td>228</td>
</tr>
</tbody>
</table>

**Too conservative assumptions!**
OptiBri Workshop “Design Guidelines for Optimal Use of HSS in Bridges”

ULS bridge deck design – Flange Induced Buckling (EN 1993-1-5)

This expression has indeed several simplified assumptions:

- Symmetrical I-section girder subjected to pure bending > neutral axis $h_i = 1/2$ height
- Transversal stiffeners effect ignored
- Residual stress with a peak of $0.5f_{yf}$ in the region adjacent to the web-to-flange welded joint
- Both flanges attain yield strength $f_{yf}$
ULS bridge deck design – Flange Induced Buckling (EN 1993-1-5)

\[ \frac{h_w}{t_w} \leq K \frac{E}{\beta f_{yf}} \sqrt{\frac{A_w}{A_{fc}}} \]

Being parameter \( \beta \) function of:

\[ \beta^2 = \frac{h \alpha}{3h_i} (\alpha + 0.5) \leq 1, \quad \alpha = \frac{\sigma_{Ed}}{f_{yf}} \]

For:

- Non symmetrical composite girder sections > neutral axis at height \( h_i \) from bottom flange (not exactly at 1/2 height \( h \))

- ULS tension / compression \( \sigma_{Ed} \) installed at the flange, lower that the yielding strength \( f_{yf} \)
# ULS bridge deck design – Flange Induced Buckling (EN 1993-1-5)

<table>
<thead>
<tr>
<th>Design B - S690 deck section</th>
<th>1-2 support</th>
<th>3</th>
<th>4-5</th>
<th>6-8</th>
<th>9-11 mid-span</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k$</td>
<td>0.55</td>
<td>0.55</td>
<td>0.55</td>
<td>0.55</td>
<td>0.55</td>
</tr>
<tr>
<td>$\sigma_{Ed}$ (MPa)</td>
<td>570</td>
<td>411</td>
<td>302</td>
<td>346</td>
<td>447</td>
</tr>
<tr>
<td>$\sigma_{Ed}/f_{yf}$</td>
<td>0.88</td>
<td>0.63</td>
<td>0.46</td>
<td>0.50</td>
<td>0.65</td>
</tr>
<tr>
<td>$h/h_i$</td>
<td>2.07</td>
<td>1.82</td>
<td>1.95</td>
<td>1.51</td>
<td>1.59</td>
</tr>
<tr>
<td>$\beta$</td>
<td>0.91</td>
<td>0.66</td>
<td>0.54</td>
<td>0.50</td>
<td>0.63</td>
</tr>
<tr>
<td>$k\frac{E}{(\beta f_{yf})}\sqrt{\frac{A_w}{A_c}}$</td>
<td>173</td>
<td>274</td>
<td>318</td>
<td>342</td>
<td>250</td>
</tr>
<tr>
<td>$h_w/t_w &lt; \text{limit?}$</td>
<td>170</td>
<td>170</td>
<td>189</td>
<td>190</td>
<td>228</td>
</tr>
</tbody>
</table>
SLS bridge deck design – Deflections and Stresses

Deflection for frequent Highway Live Loads (LM1)

<table>
<thead>
<tr>
<th>Condition</th>
<th>Design A – S355</th>
<th>Design B – S690</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta(\psi_1Q_{k1}) \leq L/500 = 160$ mm (*)</td>
<td>49 mm ($= L/1632$)</td>
<td>74 mm ($= L/1081$)</td>
</tr>
</tbody>
</table>

(*) $L/500$ imposed by SIA 260

Stress ratios in structural steel ($\sigma_{Ed,ser,max} / f_y$), concrete slab ($\sigma_{c,ser,max} / 0.6 f_{ck}$), and slab reinforcement ($\sigma_{rs,ser} \leq 0.8 f_{sk}$)

<table>
<thead>
<tr>
<th>Section</th>
<th>Design A – S355</th>
<th>Design B – S690</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete slab / reinforcement</td>
<td>0.49</td>
<td>0.61</td>
</tr>
<tr>
<td>Top flange</td>
<td>0.71</td>
<td>0.59</td>
</tr>
<tr>
<td>Web</td>
<td>0.75</td>
<td>0.61</td>
</tr>
<tr>
<td>Bottom flange</td>
<td>0.73</td>
<td>0.53</td>
</tr>
</tbody>
</table>
Optibri Workshop “Design Guidelines for Optimal Use of HSS in Bridges”

International Consulting Engineers

Total width = 21.50 m

- Two vehicles FLM 3 in the same lane (EN 1991-2) (48 ton + 14.4 ton at 40m)
- Slow lanes in the actual position
- $N_{obs} = 2.0 \times 10^6$ Lories/year/slow lane
- Bridge design life of 100 years

$0.3 \times \text{FLM 3} = 144 \text{ kN}$

FLM 3 = 480 kN
ULS bridge deck design – Fatigue assessment (EN 1993-1-9)

FAT Detail categories

- no radius transition
- transition with chamfer
- smooth radius
- transition $r > 150$ mm

112° tapered in width or thickness with a slope $< 1/4$
90° $e < 0.1b$ and slope $< 1/4$
80° $e < 0.2b$ and slope $< 1/4$
71° full penetration made from one side only

* mult. by size factor $\frac{25}{t}$ for $t > 25$ mm

Values:
- $l < 50$ mm: 80
- $50 < l \leq 80$ mm: 71
- $80 < l \leq 100$ mm: 63
- $l > 100$ mm: 56
Critical fatigue detail = FAT 56 support; FAT 80 span
ULS bridge deck design – Fatigue assessment (EN 1993-1-9)

\[ \Delta \sigma_R = 50 \text{ MPa} < \text{FAT 56} \]
with \( l > 100 \text{ mm} \)

\[ \Delta \sigma_R = 78 \text{ MPa} < \text{FAT 80} \]
with \( l = (t_{\text{plate}} + 2t_{\text{welding}}) < 50 \text{ mm} \)

Critical detail
ULS bridge deck design – Fatigue assessment (EN 1993-1-9)

\[ \Delta \sigma_R = \Delta \sigma_E \gamma_{Mf} \gamma_{Ff} < \text{FAT (detail)} \]

\[ \gamma_{Mf} = 1.35 \quad \gamma_{Ff} = 1.0 \]

\[ \Delta \sigma_E = \lambda |\sigma_{Q,\text{max}} - \sigma_{Q,\text{min}}| \]

Damage equivalent factor
\[ \lambda = \lambda_1 \times \lambda_2 \times \lambda_3 \times \lambda_4 \leq \lambda_{\text{max}} \]

Support
- \[ \lambda_1 = 2.20 \]
- \[ \lambda_2 = 1.224 \]
- \[ \lambda_3 = 1.00 \]
- \[ \lambda_4 = 1.00 \]

Span
- \[ \lambda_1 = 1.85 \]
- \[ \lambda_2 = 1.224 \]
- \[ \lambda_3 = 1.00 \]
- \[ \lambda_4 = 1.00 \]

\[ \lambda = 2.69 < \lambda_{\text{max}} = 2.70 \]

\[ \lambda = 2.26 > \lambda_{\text{max}} = 2.00 \]

Influence line for the mid-span section

\[ \lambda \Delta \sigma = \lambda |\sigma_{Q,\text{max}} - \sigma_{Q,\text{min}}| = \]
\[ = \lambda (23.2 + 5.8) = 58 \text{MPa} \]
### ULS bridge deck design – Fatigue assessment (EN 1993-1-9)

\[ \Delta\sigma_R = \Delta\sigma_E \gamma_{Mf} \gamma_{Ff} < \text{FAT (detail)} \]

\[ \gamma_{Mf} = 1.35 \quad \gamma_{Ff} = 1.0 \]

\[ \Delta\sigma_E = \lambda |\sigma_{Q,max} - \sigma_{Q,min}| \]

**Damage equivalent factor**

\[ \lambda = \lambda_1 \times \lambda_2 \times \lambda_3 \times \lambda_4 \leq \lambda_{\text{max}} \]

---

#### Damage equivalent factor \( \lambda < > \lambda_{\text{max}} \)

<table>
<thead>
<tr>
<th></th>
<th>Support</th>
<th>Span</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \lambda_1 )</td>
<td>2.20</td>
<td>1.85</td>
</tr>
<tr>
<td>( \lambda_2 )</td>
<td>1.224</td>
<td>1.224</td>
</tr>
<tr>
<td>( \lambda_3 )</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>( \lambda_4 )</td>
<td>1.00</td>
<td>1.00</td>
</tr>
</tbody>
</table>

\[ \lambda = 2.69 < \lambda_{\text{max}} = 2.70 \]

\[ \lambda = 2.26 > \lambda_{\text{max}} = 2.00 \]

---

#### \( \Delta\sigma_E \gamma_{Mf} \gamma_{Ff} \) [MPa]

<table>
<thead>
<tr>
<th>Section</th>
<th>Top flange</th>
<th>Bottom flange</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design A – S355</td>
<td>23</td>
<td>26</td>
</tr>
<tr>
<td>Design B – S690</td>
<td>36</td>
<td>50</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Section</th>
<th>Support</th>
<th>Mid-span</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design B – S690</td>
<td>50</td>
<td>78</td>
</tr>
</tbody>
</table>

**Limit**

Support | Mid-span | FAT
---|----------|---------
36 | 7 | 56
50 | 78 | 56 / 80
## Bridge deck design – Structural steel weight

<table>
<thead>
<tr>
<th>Obtained values</th>
<th>Design A S355 NL (kg/m² deck)</th>
<th>Design B S690 QL (kg/m² deck)</th>
<th>Variation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural steel</td>
<td>219</td>
<td>165</td>
<td>-25%</td>
</tr>
<tr>
<td>Main girders</td>
<td>186</td>
<td>123</td>
<td>-34%</td>
</tr>
<tr>
<td>Cross girders + stiffeners</td>
<td>33</td>
<td>42</td>
<td>+27%</td>
</tr>
</tbody>
</table>

The use of HSS thinner plates enables an **overall reduction of the structural steel weight of about 25%**
The use of HSS thinner plates reduces the volume of full penetration welding joints in 65%, which is quite significant in terms of production benefits.
Bridge deck design – Drawings

Design A
Bridge deck design – Drawings
Bridge deck design – Final considerations

Comparison between the two designs shows that:

- The use of HSS S690 QL enables a reduction of 25% of the steel weight compared to the standard plate girder deck in S355 NL;
- Using HSS the deck can be slender and with thinner plates, but more susceptible to local buckling phenomena;
- Longitudinal stiffeners can be used to increase the web resistance and profit from the use of HSS thinner webs;
- A substantial cut on the volume of full penetration welding is obtained by using thinner plates;
- Girders in HSS are much more prone to fatigue, that proves to be the main issue of the design together with buckling phenomena;
- The critical fatigue detail is the FAT80 at the welded joints between the bottom flange and the transverse stiffeners.
Thank you for your attention!

José Oliveira Pedro

E-Mail      jose.pedro@grid.pt
Telefone    +351 213 191 220
Fax         +351 213 528 334

GRID International, Consulting Engineers
Av. João Crisóstomo, nº25-4 floor
1050-125 Lisbon, PORTUGAL
Industeel
High Strength
Steel Plates

OptiBri-Workshop
„Design Guidelines for Optimal Use of HSS in Bridges“

Dr Ir Patrick Toussaint
What are High Strength Steel plates?

**Quenched and Tempered**

High Strength Steel plates mostly for structural applications with minimum **yield strength of 690, 890, 960 and 1100 MPa**

Quenching and tempering provides the steel with high strength and ductility. Quenching and tempering consists of a two-stage heat-treatment process. Stage 1 includes hardening, in which the plate is austenitized to approximately 900°C and then quickly cooled. The material is water-quenched while somehow clamped to avoid warping. Stage 2 consists of tempering the material to obtain the intended material properties.
<table>
<thead>
<tr>
<th>Industeel trademark</th>
<th>Standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amstrong® Ultra 690</td>
<td>S690Q - S690QL - S690QL1 according to EN 10025-6</td>
</tr>
<tr>
<td>SuperElso® 690 CR</td>
<td>P690Q - P690QH - P690QL1 - P690QL2 according to EN 10028-6</td>
</tr>
<tr>
<td></td>
<td>ASTM A514 Grades B, E, F, H, Q / ASTM A517 Grades B, E, Q…</td>
</tr>
<tr>
<td></td>
<td>ASME SA-514 Grades B, E, F, H, Q / ASME SA-517 Grades B, E, Q…</td>
</tr>
<tr>
<td></td>
<td>ABS, DNV-GL, LRS,... EQ70, VLF690, FH69,...</td>
</tr>
<tr>
<td>Amstrong® Ultra 890</td>
<td>S890Q - S890QL - S890QL1 according to EN 10025-6</td>
</tr>
<tr>
<td>Amstrong® Ultra 960</td>
<td>S960 Q - S960 QL according to EN 10025-6</td>
</tr>
<tr>
<td>Amstrong® Ultra 1100</td>
<td>Industeel specification, no international standard at this strength level</td>
</tr>
</tbody>
</table>

Industeel produces all HSS grades according to international norms.
High Strength Steel plates typical size ranges

- Amstrong® Ultra 690
- A 514 Grades
- A 517 Grades

- Amstrong® Ultra 890
- Amstrong® Ultra 960

- Amstrong® Ultra 1100

Induststeel has the largest range of sizes and thicknesses available nowadays on the market

- Thickness: 5 to 300mm
- Length: up to 17 metres
- Width: up to 4350mm
- Weight: up to 80 tonnes
Main applications
Yellow Goods & Green Goods

Lifting & Handling
- Mobile crane
- Telescopic Handler

Mining & Construction & Transport
- Earth Moving Equipment, construction vehicles, quarrying and mining
  - Excavator
  - Wheeled loader
  - Rigid hauler
  - Articulated dump truck
  - Hydraulic Excavator
  - Dragline

Agricultural & Forestry
- Tractors
- Harvesters
  - Tractors
  - Feller Buncher
  - Skidder
  - Forwarder

OptiBri Workshop “Design Guidelines for Optimal Use of HSS in Bridges”

3rd May 2017
Lifting & Handling

- **Mobile cranes**
- **Chassis**

  Amstrong® Ultra 960: thickness = 8-60mm
  Amstrong® Ultra 1100: thickness = 8-15mm

Lighter and more innovative structures
Mining & Construction & Transport

- Dumpers
- Chassis - Canopy
  Amstrong Ultra®690 : thickness = 8-50mm

Reduced vehicle weight, reduced fuel consumption, heavier payload
Public work (demolition) - Jaw crushers

More maneuverable cranes and tools
Mining & Construction & Transport

- Lifting arm
  Amstrong Ultra® 690 thickness = 60-80mm

Ability to lift heavier loads than before
Jack-up

West Elara Jack Up SuperElso® 690 CR

Offshore Wind Mills

OptiBri Workshop “Design Guidelines for Optimal Use of HSS in Bridges”

3rd May 2017
Elements for jack-up rigs

**Racks**
- Length: 8 m up to 15.5 m
- Thickness: 160 mm up to 210 mm
- Width: 775 mm up to 1060 mm
- Weight: up to 23 tonnes

**Chords**
- Length: 4 m up to 10 m
- Thickness: 80 mm up to 120 mm
- Width: 380 mm up to 680 mm

**Welded elements**
- Length: 8 m up to 24.5 m
- Weight: 11 tonnes up to 70 tonnes
Welded elements for jack-up rigs
Offshore cranes

Lifting capacity up to 10 000 tonnes

**Structure**
Amstrong Ultra® 690 (QL and QL1 qualities) tuned to the particular specifications
thickness = 10–100+mm

Technical solutions adapted to customer requirements
Offshore liftboats and spud poles

Spud poles
EQ70 (ABS) - Neptune project - 1590 tonnes
thickness = 58 mm

Neptune will work mainly in the offshore windfarm installation market.

By increasing the strength of steel, the structural sections can be reduced.
LPG transportation vessel

- 6 LPG tanks: 2 x 4000 m³ and 4 x 7000 m³
- LPG tanks are constructed in China
- Shipyard: Estaleiro Promar in Brasil
- Client: Transpetro Brasil (Petrobras)

LPG carriers tanks
SuperElso®690 QL – Promar Project – 6175 tons
th = 10 – 50mm

Increases the transport capacity of the LPG Vessel
Mechanical construction

- Architecture, bridges,
- Steel buildings
- Penstocks
- Chassis of industrial machines

Reduction of wall thickness and weight with increasing strength of steel
Thank you for your attention!

Dr Ir Patrick Toussaint
E-Mail patrick.toussaint@arcelormittal.com
Phone +32 71 441 627
Fax +32 71 441 956

Industeel Belgium
Marketing Department
266 Rue de Châtelet
B-6030 Marchienne-au-Pont
Belgium
Welding and Post Weld Treatment of High Strength Steel Joints

Thomas Baaten
• Introduction
• Welding Procedure Qualification
• Physical simulation of thermal history, characterisation, generation of samples
• Welding of high strength steel
• Post Weld Treatment Qualification
  • Parameters
  • Imperfections caused by HFMI
  • Indentation map
  • Finite element model of PIT proces
  • Is Post Weld Treatment Qualification needed?
• Conclusions
Introduction

- Geometry
- Residual tensile stress
- Possible softening of the HAZ (f.e. S700MC, aluminium, … )
Welding Procedure Qualification

- Goal: make a weld method which fulfils EN 15614-1 requirements

- The mechanical and metallurgical properties of the weld metal and the heat affected zone are determined by:
  - Pre heat temperature
  - Welding parameters

- Tests needed for fillets welds:
  - Visual examination
  - Dye penetrant/magnetic examination
  - Cross section (looking for metallurgical changes in the HAZ as well)
  - Hardness measurements
  - Additional charpy impacts tests
Welding Procedure Qualification – pre heating

• Pre heating is done to avoid brittle zones (sensitive for hydrogen cracking)

• 4/5 factors are taking into account:
  • Hydrogen content of the filler metal
  • Heat-input of the welding process
  • Chemical composition of the base metal
  • Material thickness
  • Limitations/recommendations from fabricant
Welding Procedure Qualification – pre heating

- Solid ER100-SG welding wire -> scale D

- Heat-input: 1.5 kJ/mm
- Base material: CEV max. : 0.67
- Combined thickness: \(10+2\times15 = 40 \text{ mm}\) and \(10+2\times40\text{ mm} = 90 \text{ mm}\)

Table C.2 — Hydrogen scales

<table>
<thead>
<tr>
<th>Diffusible hydrogen content ml/100 g of deposited metal</th>
<th>Hydrogen scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 15</td>
<td>A</td>
</tr>
<tr>
<td>10 ≤ 15</td>
<td>B</td>
</tr>
<tr>
<td>5 ≤ 10</td>
<td>C</td>
</tr>
<tr>
<td>3 ≤ 5</td>
<td>D</td>
</tr>
<tr>
<td>≤ 3</td>
<td>E</td>
</tr>
</tbody>
</table>

For simultaneously deposited directly opposed twin fillet welds, combined thickness
\[= \frac{1}{2} (d_1 + d_2 + d_3)\]

Combined thickness = \(d_1 + d_2 + d_3\)
Welding Procedure Qualification – pre heating

- 40°C for 15 mm base plate and 90°C for 40 mm base plate

Key
1 Combined thickness, mm
2 Heat input, kJ/mm
3 Minimum preheating temperature, °C
4 Scale
5 To be used for carbon equivalent not exceeding

Figure C.2 — Conditions for welding steels with defined carbon equivalents
Welding Procedure Qualification

- Weld Procedure Qualification of welding case A and H was done according to EN ISO 15614-1

Start-stop on location with lowest stress

<table>
<thead>
<tr>
<th>weldprog</th>
<th>wire (m/min)</th>
<th>arc length corr. (%)</th>
<th>dynamic or pulse corr.</th>
<th>mode</th>
<th>welding speed m/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>5a</td>
<td>6</td>
<td>10</td>
<td>4</td>
<td>std</td>
<td>0,18</td>
</tr>
<tr>
<td>5b</td>
<td>6</td>
<td>10</td>
<td>4</td>
<td>std</td>
<td>0,24</td>
</tr>
<tr>
<td>6a</td>
<td>9,5</td>
<td>7</td>
<td>3</td>
<td>puls</td>
<td>0,3</td>
</tr>
<tr>
<td>6b</td>
<td>9,5</td>
<td>7</td>
<td>3</td>
<td>puls</td>
<td>0,24</td>
</tr>
<tr>
<td>7a</td>
<td>9</td>
<td>5</td>
<td>4</td>
<td>puls</td>
<td>0,3</td>
</tr>
<tr>
<td>7b</td>
<td>9</td>
<td>5</td>
<td>4</td>
<td>puls</td>
<td>0,25</td>
</tr>
</tbody>
</table>

OptiBri Workshop “Design Guidelines for Optimal Use of HSS in Bridges”

3rd May 2017

8
HAZ 1 OP_A_optim_00a

Weld Metal

Coarse Grain Size 1.3 mm

Base Metal

Throat thickness a = 5

HV 0.1

Belgian Welding Institute – ing. Thomas Baaten, IWE.
HAZ 1 OP_A_optim_00a

Weld Metal

Coarse Grain 1.3 mm

Fine Grain 0.5 mm

Intercritical 0.2 mm

Base Metal
HAZ 1 OP_A_optim_00a

Weld Metal  Coarse Grain  Fine Grain  Intercritical  Base Metal

1.3 mm  0.5 mm  0.2 mm

Peak Temp °C
Composite Region
Fusion Boundary
Coarse-Grained Supercritical
Fine-Grained Supercritical
Intercritical
Subcritical
Liquid + Austenite
Austenite
Liquid + Fe Carbide
Ferrite + Fe Carbide

True HAZ
Distance
0.15 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00 1.10 1.20 1.30 1.40 1.50 1.60 1.70 1.80 1.90 2.00
wt % C
HAZ 1 OP_A_optim_00a

Weld Metal  Coarse Grain  Fine Grain  Intercritical  Base Metal
1.3 mm      0.5 mm      0.2 mm

3rd May 2017
- input for physical weld simulations of thermal history of HAZ 1 and 2 (representing SC A and SC H)
- $\Delta t$ 8/5 HAZ 1 (welding case A) = 4.4s
- $\Delta t$ 8/5 HAZ 2 (welding case H) = 7 s
Physical simulation of thermal history, characterisation, generation of samples

Machining test samples of HAZ and WM:
- Tensile test samples
- Bauchinger shear samples
- Fatigue test samples
Physical simulation of thermal history, characterisation, generation of samples

- Tensile tests on weld simulation test samples of HAZ1 and HAZ2 (resp. welding case A and H).
Welding of HSS

- Quenched and tempered (Q&T)
  - S690QL
  - Thickness up to 200 mm
  - Low heat input can cause excessive hardness
  - Often preheating is needed
  - High heat input can cause softening
  - Centre of X joints is critical point in WPQ
  - Generaly good to weld

\[ \text{Heat Input} = k \cdot \frac{U \cdot I}{v} \text{ [J/mm]} \]

Gouging after pass 1
Welding of HSS

1. Step: Weld girder longitudinal weld without full penetration + fillet weld (s=8 mm) automatically
2. Step: Take dimensions from welded girder for stiffeners type 1 and 2 to adjust
3. Step: Take adjusted Stiffener 1 and weld around with fillet weld a = 5 mm
4. Step: Take Stiffener 2 and weld around with fillet weld a = 5 mm
5. Step: Take adjusted Stiffener 3 and only tack weld it to upper flange
Welding of HSS
Welding of HSS

Incorrect weld toe
Corrected by machining (manual labour)
Welding of HSS

PORT HOLES?
Welding of HSS

- Cutting of the web and flanges was already done in steel factory
- Cutting stiffeners: 1,5h
- Mounting, tackwelding: 12h
- SAW welding + 100°C preheating: 14h
- Flame straightening: 3h
- MAG welding of stiffeners: 24h
- Grinding edges: 3,5h
- Visual examination + MPI central stiffeners: 4h
- Machining incorrect weld toe in corners: 8h
- Extra visual examination + MPI after repair: 2h
- Project management: 18h
- PIT treatment: 2h

Ref. : Optistraight

2 hours of PIT treatment in a total of 92 hours labour
Welding of HSS: Considerations/arguments to skip preheating and concerns

- recommendations for preheating of EN 1011-2 (2010), mainly based on hydrogen cracking, are conservative.
- At the side of the **filler metal** fabricants, seamless flux cored wires were developed in the 90ties (as a better alternative for folded FCW). Entrance of hydrogen is limited massively since 1990.
- At the side of the **steel makers** CE equivalents and %C of HSS can be kept low. The maximum Vickers hardness of the steel used in Optibri is estimated 422 HV10, which is far below the maximum limit of 450HV10 of the EN ISO 15614-1 standard for welding procedure qualification.
- Recent experience of BWI: no hydrogen damage analysis
- Cost saving
Post Weld Treatment of HSS
Post Weld Treatment of HSS

- S355 original (not treated)
- S690QL PIT treated
Post Weld Treatment of HSS
Post Weld Treatment qualification

• Available finished fatigue tests samples with longitudinal stiffeners in S420MC and S700MC grades – thickness range 5 - 10 mm

• 5 PIT-parameters were applied (variations in pressure, diameter, frequency) (only 2 parameters were Ok for Pitec, based on their experience.)

<table>
<thead>
<tr>
<th>Condition</th>
<th>PIT parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6 bar, 90 Hz, r = 2 mm</td>
</tr>
<tr>
<td>2</td>
<td>6 bar, 90 Hz, r = 4 mm</td>
</tr>
<tr>
<td>3</td>
<td>6 bar, 90 Hz, r = 1,5 mm</td>
</tr>
<tr>
<td>4</td>
<td>6 bar, 120 Hz, r = 2 mm</td>
</tr>
<tr>
<td>5</td>
<td>4 bar, 90 Hz, r = 2 mm</td>
</tr>
</tbody>
</table>

• Examination for Post Weld Treatment qualification:
  • Metallographic examination
  • Dimensional check
  • Hardness measurements
Post Weld Treatment qualification

S700MC - 10mm: As Welded and all PIT results

- Stress range (MPa)
- Number of cycles

- AW
- PIT 1
- PIT 2
- PIT 3
- PIT 4
- PIT 5

- IIW FAT 140, slope=5
- All PIT results, FAT 151, slope 5
- AW FAT 61, slope 3
Post weld treatment qualification

- Metallographic examination example S700MC-5-087-PIT1
Post weld treatment qualification

3 imperfections were found on 21 samples:

1. Spread out
2. Inclusion of oxides
3. Sharp notch

OptiBri Workshop “Design Guidelines for Optimal Use of HSS in Bridges”
Post weld treatment qualification

3 imperfections were found on 21 samples:

1. Spread out
2. Inclusion of oxides
3. Sharp notch
Post Weld Treatment Qualification

![Image showing weld treatment samples with labels OP 5690QL, OP 5700MC, OP 5420MC, and OP 5355.]
Post weld treatment qualification: Hertz theory

\[ E^* = \left( \frac{1 - \nu_1^2}{E_1} + \frac{1 - \nu_2^2}{E_2} \right)^{-1} \]

\[ R^* = \left( \frac{1}{R_1} + \frac{1}{R_2} \right)^{-1} \]

\[ p_0 = \frac{2}{\pi} E^* \left( \frac{d}{R} \right)^{1/2} \]

if \( p_m < 1.1 \sigma_y \), elastic deformation occurs
Post weld treatment qualification: Hertz theory

\[
E^* = \left( \frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2} \right)^{-1} = 224.000 \text{ N/mm}^2
\]

\[
R^* = \left( \frac{1}{R_1} + \frac{1}{R_2} \right)^{-1} = 1.5 \text{ mm}
\]

\[
p_0 = \frac{2}{\pi} E^* \left( \frac{a}{R} \right) \frac{1}{2} = 76.617 \text{ N/mm}^2 > 2.8 \times 355 \text{ N/mm}^2
\]

if \( p_m > 1.8 \sigma_y \), contained plastic deformation occurs

PIT treatment on S355 base material
Indentor: compressed air 6 bar – indentor radius \( r = 2 \text{ mm} \) – frequency \( f = 90 \text{ Hz} \)
### Post weld treatment qualification: indentation map

<table>
<thead>
<tr>
<th>Material</th>
<th>Test</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>S355</td>
<td>PIT 1</td>
<td>0.54</td>
</tr>
<tr>
<td>S355</td>
<td>PIT 2</td>
<td>0.25</td>
</tr>
<tr>
<td>S355</td>
<td>PIT 3</td>
<td>0.69</td>
</tr>
<tr>
<td>S355</td>
<td>PIT 4</td>
<td>0.19</td>
</tr>
<tr>
<td>S355</td>
<td>PIT 5</td>
<td>0.43</td>
</tr>
<tr>
<td>S420</td>
<td>PIT 1</td>
<td>0.38</td>
</tr>
<tr>
<td>S420</td>
<td>PIT 2</td>
<td>0.23</td>
</tr>
<tr>
<td>S420</td>
<td>PIT 3</td>
<td>0.61</td>
</tr>
<tr>
<td>S420</td>
<td>PIT 4</td>
<td>0.19</td>
</tr>
<tr>
<td>S420</td>
<td>PIT 5</td>
<td>0.35</td>
</tr>
<tr>
<td>S690</td>
<td>PIT 1</td>
<td>0.41</td>
</tr>
<tr>
<td>S690</td>
<td>PIT 2</td>
<td>0.36</td>
</tr>
<tr>
<td>S690</td>
<td>PIT 3</td>
<td>0.38</td>
</tr>
<tr>
<td>S690</td>
<td>PIT 4</td>
<td>0.13</td>
</tr>
<tr>
<td>S690</td>
<td>PIT 5</td>
<td>0.39</td>
</tr>
<tr>
<td>S700</td>
<td>PIT 1</td>
<td>0.35</td>
</tr>
<tr>
<td>S700</td>
<td>PIT 2</td>
<td>0.25</td>
</tr>
<tr>
<td>S700</td>
<td>PIT 3</td>
<td>0.48</td>
</tr>
<tr>
<td>S700</td>
<td>PIT 4</td>
<td>0.07</td>
</tr>
<tr>
<td>S700</td>
<td>PIT 5</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Indentation map of University of Cambridge (Norman Fleck)
Post weld treatment qualification: dimensional check

FE calculation of PIT done by OCAS (P. Goes)
Conclusions

- Welding of HSS depends on the chemical composition and the fabrication method.
- The robustness of PIT is proven by means of fatigue test of different parameters, cross sections and dimensional checks.
- **If** a Post Weld Treatment Qualification (PWTQ) is needed for Eurocode, a simple cross section is needed to show that a/R>0.2.
- New ‘IIW Recommendations for the HFMI Treatment For Improving the Fatigue Strength of Welded Joints’ is interesting.
Thank you for your attention!

ing. Thomas Baaten, IWE
Project Engineer
T +32 (0)9 292 14 20
F +32 (0)9 292 14 01
M +32 (0)479 89 45 58
thomas.baaten@bil-ibs.be

Belgisch Instituut voor Lastechniek vzw
Technologiepark 935, B-9052 Zwijnaarde
info@bil-ibs.be | www.bil-ibs.be | www.nal-ans.be
Characterization of Fatigue Behaviour, from Material Science to Civil Engineering Applications

OptiBri-Workshop
"Design Guidelines for Optimal Use of HSS in Bridges"
3rd May 2017

Chantal Bouffioux
Outline

Small samples
- Static & fatigue tests
  - Material behaviour
    - Static
    - Fatigue (small size)

Large welded plates
- Fatigue tests
- Residual stress
- Effect of:
  - size & machining
  - welding
  - post-treatments

Future applications
- Beams
  - Size effect
  - Laws validation

Critical bridge detail
- interest of HSS

Static & fatigue tests
- Small samples

3rd May 2017
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Static & fatigue tests

Material behaviour
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Small samples

- **4 materials:**
  - **Base Material:** BM (HSS - S690QL)
  - **Heat Affected Zone:**
    - HAZ1 (25 mm thick)
    - HAZ2 (40 mm thick)
  - **Welded Metal:** WM
Small samples

- Static tests:

  - Tensile test
  - Large tensile test
  - Shear test
  - Bauschinger shear test
Small samples

Static behavior – material laws & parameters:

**Elastic part:** Hooke's law: \( E \) \( \nu \)

**Plastic part:** Hill's law (Hill48):

\[
F_{HILL}(\sigma) = \frac{1}{2} \left[ H(\sigma_{xx} - \sigma_{yy})^2 + G(\sigma_{xx} - \sigma_{zz})^2 + F(\sigma_{yy} - \sigma_{zz})^2 + 2N(\sigma_{xy}^2 + \sigma_{xz}^2 + \sigma_{yz}^2) \right] - \sigma_F^2 = 0
\]

**Isotropic hardening:** Voce formulation:

\[
\sigma_F = \sigma_0 + K(1 - exp(-n.\dot{\varepsilon}^{pl}))
\]

**Back-stress** (kinematic hardening): Armstrong-Frederick's equation:

\[
\dot{X} = C_X (X_{sat} \dot{\varepsilon}^{pl} - \varepsilon^{pl} \cdot X)
\]

\( E \) & \( \nu \): defined by tensile tests

\( F, G, H \): defined by tensile tests in 3 directions (RD, TD, 45°)

\( N, \sigma_0, K, n, C_X, X_{sat} \): defined by Optim
Small samples

- **Static behavior – material data (inverse method):**

- **BM**: hardening fully kinematic
- **HAZ1 ≈ HAZ2**: same static behaviour
- **WM**

For fatigue tests:

\[ \sigma_{u,\text{eng}} = \frac{F_i}{A_0} \]

For FEM:

\[ \sigma_{u,\text{true}} = \frac{F_i}{A_i} \]

<table>
<thead>
<tr>
<th>Material</th>
<th>(\sigma_{u,\text{eng}})</th>
<th>(\sigma_{u,\text{true}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>BM (S690QL)</td>
<td>838</td>
<td>905</td>
</tr>
<tr>
<td>HAZ1, HAZ2</td>
<td>1338</td>
<td>1424</td>
</tr>
<tr>
<td>WM</td>
<td>1008</td>
<td>1101</td>
</tr>
</tbody>
</table>

### Data for Hooke, Hill, Voce and Armstrong-Frederick laws (units: MPa, s)

<table>
<thead>
<tr>
<th>Material</th>
<th>Elast. data</th>
<th>Yield locus</th>
<th>Isotropic hardening</th>
<th>Kinematic hardening</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(E)</td>
<td>(v)</td>
<td>(F)</td>
<td>(G)</td>
</tr>
<tr>
<td>BM (S690QL)</td>
<td>210 116</td>
<td>0.3</td>
<td>1 1 1</td>
<td>3.9</td>
</tr>
<tr>
<td>HAZ1, HAZ2</td>
<td>210 000</td>
<td>0.3</td>
<td>1 1 1</td>
<td>4.45</td>
</tr>
<tr>
<td>WM</td>
<td>210 000</td>
<td>0.3</td>
<td>1 1 1</td>
<td>3.2</td>
</tr>
</tbody>
</table>
Small samples

• Static behavior – comparison of material behavior:

![Graphs showing comparisons of material behavior](image-url)
Small samples

- **Fatigue tests:**
  - On vibrophore
  - Axial loading
  - Frequency: 100 – 150 Hz
  (→ correction factor)

\[ R = \frac{\sigma_{\text{min}}}{\sigma_{\text{max}}} = 0.1 \text{ or } 0.2 \text{ or } ... \]

<table>
<thead>
<tr>
<th>Material</th>
<th>Smooth</th>
<th>Notch</th>
</tr>
</thead>
<tbody>
<tr>
<td>BM (S690QL)</td>
<td>4 R</td>
<td>3 geom.</td>
</tr>
<tr>
<td>HAZ1</td>
<td>1 R</td>
<td>1 geom.</td>
</tr>
<tr>
<td>HAZ2</td>
<td>2 R</td>
<td>1 geom.</td>
</tr>
<tr>
<td>WM</td>
<td>2 R</td>
<td>1 geom.</td>
</tr>
</tbody>
</table>
Small samples

• Fatigue behavior – material laws & parameters:

Multiaxial Lemaître Chaboche fatigue model

\[
\frac{\partial D}{\partial N} = \begin{cases} 
0 & \text{if } f_D < 0 \\
[1 - (1 - D)^{\beta + 1 + \alpha}] \left( A_{II}^* \right)^{-\beta} & \text{if } f_D \geq 0 
\end{cases}
\]

\[
f_D = A_{II} - A_{II}^*
\]

\[
A_{II} = \frac{1}{2} \sqrt{\frac{3}{2}} (\bar{\sigma}_{ij_{\text{max}}} - \bar{\sigma}_{ij_{\text{min}}})^2 (\bar{\sigma}_{ij_{\text{max}}} - \bar{\sigma}_{ij_{\text{min}}}) \quad \text{with} \quad \bar{\sigma}_{ij} = \sigma_{ij} - \sum_k \frac{1}{3} \sigma_{kk}
\]

\[
A_{II}^* = \sigma_{l0} (1 - 3b\sigma_{Hm}) \quad \text{(Sines' criterion)}
\]

\[
\bar{A}_{II} = \frac{A_{II}}{1 - D}
\]

\[
M = M_0 (1 - 3b\sigma_{Hm})
\]

\[
\alpha = 1 - a \left[ \frac{A_{II} - A_{II}^*}{\sigma_u - \sigma_{\text{eqmax}}} \right]
\]

\[
\sigma_{Hm} = \frac{1}{3} \left[ \frac{1}{T} \int_T \text{Tr} \left( \sigma(t) \right) dt \right]
\]

D: damage val., 0: sound material, 1: rupture
N: number of cycle
A_{II}: 2nd invar. of amplit. deviator of \( \sigma \) tensor
A_{II}^*: fatigue limit
f_D: damage yield locus
\( \sigma_{Hm} \): mean hydrostatic stress
\( \sigma_{eqmax} \): maximum Von Mises stress per cycle
\( <x> \): = x if x > 0 else = 0
b = 1/\( \sigma_u \)
\( \sigma_u \): ultimate tensile stress
\( \sigma_{l0} \): endurance limit= fatigue limit at null \( \sigma_{\text{mean}} \)
a, M0, \( \beta \): other material data to define
Small samples

• Fatigue behavior – material laws & parameters:

**Volume averaged stress gradient method**

For each element, variables $\chi_{ip}$: replaced by an average value of all the elements with their integration point inside the circle with a radius $Ra$

$$\bar{\chi_{ip}} = \frac{1}{V} \cdot \sum_{i=1}^{Nelem} \chi_{ip,i} \cdot V_i$$

$$\chi_{ip} = \{ A_{II}, \sigma_{eqmax}, \sigma_{Hm} \}$$

$$V = \sum_{i=1}^{Nelem} V_i$$

- $A_{II}$: 2nd invar. of amplit. deviator of $\sigma$ tensor
- $\sigma_{eqmax}$: maximum Von Mises stress per cycle
- $\sigma_{Hm}$: mean hydrostatic stress
- $Ra$: material data to define
Small samples

- Fatigue behavior – material data (inverse modelling):

HAZ1 ≈ HAZ2: same fatigue behavior

<table>
<thead>
<tr>
<th>Material</th>
<th>$\sigma_U$ (Mpa)</th>
<th>$\sigma_l^0$ (Mpa)</th>
<th>b</th>
<th>$\beta$</th>
<th>a</th>
<th>M0</th>
<th>Ra (mm)</th>
<th>$a^*(M0^{-\beta})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BM</td>
<td>905.0</td>
<td>580.0</td>
<td>1.10E-03</td>
<td>0.17</td>
<td>1</td>
<td>5.385E+30</td>
<td>0.06</td>
<td>5.966E-06</td>
</tr>
<tr>
<td>HAZ1, HAZ2</td>
<td>1424.0</td>
<td>428.4</td>
<td>7.02E-04</td>
<td>2.094</td>
<td>1</td>
<td>4.410E+05</td>
<td>0.00</td>
<td>1.516E-12</td>
</tr>
<tr>
<td>WM</td>
<td>1101.0</td>
<td>319.4</td>
<td>9.08E-04</td>
<td>0.161</td>
<td>1</td>
<td>7.245E+32</td>
<td>0.00</td>
<td>5.182E-06</td>
</tr>
</tbody>
</table>
Small samples

- Fatigue behavior – comparison experiments & fatigue law:

**Base material (BM)**

**Smooth samples, 4 R**

**Notched samples, 3 geom.**
Small samples

- Fatigue behavior – comparison experiments & fatigue law:

Heat affected zone (HAZ) with HAZ1 ≈ HAZ2

**Smooth samples, 2 R**

**Notched samples, 1 geom.**
Small samples

- Fatigue behavior – comparison experiments & fatigue law:

**Weld metal (WM)**

**Smooth samples, 2 R**

**Notched samples, 1 geom.**
Outline

Small samples
- Static & fatigue tests
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    - Static
    - Fatigue (small size)

Large welded plates
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  - Residual stress
  - Effect of:
    - size & machining
    - welding
    - post-treatments
  - Fatigue behaviour

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  - Size effect
  - Laws validation
- Critical bridge detail
  - interest of HSS

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- Beams
- Critical bridge detail

OptiBri Workshop “Design Guidelines for Optimal Use of HSS in Bridges”

3rd May 2017
### Large welded plates

**Fatigue tests on plates (length= 1070 mm):**

<table>
<thead>
<tr>
<th>Case</th>
<th>Post-treatment</th>
<th>plate thickness (mm)</th>
<th>Stiffener thickness (mm)</th>
<th>Stiffener length (mm)</th>
<th>distance to edge</th>
<th>stress ratio $R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plate</td>
<td>No weld</td>
<td>25</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.1</td>
</tr>
<tr>
<td>A (ref case)</td>
<td>PIT</td>
<td>25</td>
<td>15</td>
<td>60</td>
<td>✓</td>
<td>0.1, 0.3, 0.5</td>
</tr>
<tr>
<td>B</td>
<td>PIT</td>
<td>15</td>
<td>15</td>
<td>60</td>
<td>✓</td>
<td>0.1</td>
</tr>
<tr>
<td>E</td>
<td>PIT</td>
<td>25</td>
<td>15</td>
<td>60</td>
<td>no</td>
<td>0.1</td>
</tr>
<tr>
<td>H</td>
<td>PIT</td>
<td>40</td>
<td>15</td>
<td>60</td>
<td>no</td>
<td>0.1</td>
</tr>
<tr>
<td>C</td>
<td>TIG remelting</td>
<td>15</td>
<td>15</td>
<td>60</td>
<td>✓</td>
<td>0.1</td>
</tr>
<tr>
<td>D</td>
<td>TIG remelting</td>
<td>25</td>
<td>15</td>
<td>60</td>
<td>✓</td>
<td>0.1</td>
</tr>
<tr>
<td>F</td>
<td>TIG remelting</td>
<td>25</td>
<td>15</td>
<td>40</td>
<td>✓</td>
<td>0.1</td>
</tr>
<tr>
<td>G</td>
<td>TIG remelting</td>
<td>15</td>
<td>6</td>
<td>60</td>
<td>✓</td>
<td>0.1</td>
</tr>
<tr>
<td>I</td>
<td>No post-treatment</td>
<td>15</td>
<td>15</td>
<td>60</td>
<td>✓</td>
<td>0.1</td>
</tr>
</tbody>
</table>
Large welded plates

- Fatigue behavior – material data (inverse modelling):

<table>
<thead>
<tr>
<th>Material</th>
<th>$\sigma_U$ (Mpa)</th>
<th>$\sigma_{l0}$ (Mpa)</th>
<th>$b$</th>
<th>$\beta$</th>
<th>$a$</th>
<th>$M0$ (mm)</th>
<th>$Ra$ (mm)</th>
<th>$a^*(M0^{-\beta})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BM-SS</td>
<td>905.0</td>
<td>580.0</td>
<td>1.10 E-03</td>
<td>0.17</td>
<td>1</td>
<td>5.385 E+30</td>
<td>0.06</td>
<td>5.966E-06</td>
</tr>
<tr>
<td>BM-plate</td>
<td>905.0</td>
<td>203.0</td>
<td>1.10 E-03</td>
<td>0.17</td>
<td>1</td>
<td>5.385 E+30</td>
<td>0.06</td>
<td>5.966E-06</td>
</tr>
</tbody>
</table>

$\sigma_{l0} =$ endurance limit = fatigue limit at null $\sigma_{mean}$

Small samples, $Ra = 0.8 \mu m$, length: 96 mm

Plates, as produced, length: 1070 mm

BM - Small samples & plates - $R = 0.1$

Size, machining effects

![Graph showing fatigue behavior](image_url)
Large welded plates

- Fatigue tests: *welding effect*

---

**Plates**

**Welded plates**

---

**Welding effect**

- Cycles to failure, N
- Δσ (MPa)

---

**Welding effect**

- I
- BM-Plate
Large welded plates

- Fatigue tests: **PIT post-treatment effect**

![Diagram showing welded plates and welded plates with PIT, non-geometric effect](image)

![Graph showing PIT effect with cycles to failure and stress difference](image)

PIT: 4 cases
- low effect of geometry
Large welded plates

- Fatigue tests: **TIG remelting post-treatment effect**

![Welded plates](image1)

![Weld. plates + TIG rem. , ≠ geom.](image2)

![Graph](image3)

- Fatigue tests:
  - TIG remelting post-treatment effect
  - Large welded plates: Welded plates + TIG rem. ≠ geom.
  - Ongoing TIG remelting effect
Large welded plates

- Fatigue tests: **Stress ratio effect**

![Welded plates + PIT](image)

Effect of stress ratio on A

\[ R = \frac{\sigma_{\text{min}}}{\sigma_{\text{max}}} = 0.1 \text{ or } 0.3 \text{ or } 0.5 \]

- **Fatigue tests:** Stress ratio effect
  - Welded plates + PIT
  - \( R = \frac{\sigma_{\text{min}}}{\sigma_{\text{max}}} \) = 0.1 or 0.3 or 0.5

![Stress vs. N cycles graph](image)
Large welded plates

- Fatigue tests

Summary, all cases, $R = 0.1$

EN 1993-1-9, $\Delta\sigma_c = 80$ MPa

![Graph showing cycles to failure vs. stress range for different types of welded plates and conditions.](image)
Large welded plates

- Residual stress measurement

Several cases:
- 3 geometries
- 3 cases: PIT, TIG remelting, no post-treat.
- Mid-weld (MW), weld edge (WE), RD, TD
- X-ray, neutron diffraction

Welding & post-treatment effects:
- up to depth ≈ 3-4 mm
- up to weld toe distance ≈ 6-7 mm

Ex: ref. case: A, with post-treatment (X-ray)
Large welded plates

- Fatigue - numerical analysis

FEM model & symmetry conditions

Typical cycle

σ nominal

N cycles

Typical cycle
Large welded plates

- Fatigue - numerical analysis

Example of results without post-treatment, no $\sigma_{\text{res}}$

$\sigma_{xx}$ (Mpa) for nominal stress = 600 Mpa \ ($\sigma_{\text{nom}} = F/A_0$ and $A_0$ = section of web)

Stress concentration at weld toe:
- up to depth ≈ 2 mm (in HAZ)
- up to weld toe distance ≈ 3 mm
Large welded plates

- Fatigue - numerical analysis
  1. Mesh analysis  \(\rightarrow\) element size at weld toe: 0.1 mm (results not mesh dependent)
  2. For several stress ranges and a specified stress ratio (here: 0.1):
     - Numerical analysis  \(\rightarrow\) Stress distribution  \(\rightarrow\) number of cycle at rupture

Next steps:
- to add \(\sigma_{\text{res}}\) to model (welding + post-treatment)
- to improve fatigue mat. data of HAZ (\(\sigma_{10}\))
- to study beams and critical bridge detail
Large welded plates

- Fatigue - numerical analysis, crack propagation

Kill element approach – FE²
Important test campaign has been done to prepare numerical fatigue study of bridge details:

- **Static tests** on small samples
- **Fatigue tests**
- **Fatigue tests on large welded plates**
- **Residual stresses measurements**
- **Mesh analysis**
- **Crack propagation**

<table>
<thead>
<tr>
<th>Static behaviour BM, HAZ, WM</th>
<th>Fatigue behaviour (small size)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effects of size, surface roughness, welding, geometry, post-treatments</td>
<td></td>
</tr>
<tr>
<td>Effect of post-treatments for num. analysis</td>
<td></td>
</tr>
<tr>
<td>welded plates: elem. size at weld toe: 0.1 mm</td>
<td></td>
</tr>
<tr>
<td>deep analysis of fatigue study</td>
<td></td>
</tr>
</tbody>
</table>

Positive effect in fatigue life is shown on welded plates

Fatigue characterisation almost ready for analysis on critical bridge detail
Thank you for your attention!

E-Mail  chantal.bouffioux@ulg.ac.be
Telefon  +32 (0) 4 366 92 19
Fax  +32 (0) 4 366 95 34

University of Liège
ARGEnCO department
Quartier Polytech 1,
Allée de la découverte, 9  Bât B52/3
B-4000 Liège BELGIUM
Categorization of Fatigue Details in View of Post-Weld Treatments

OptiBri-Workshop
„Design Guidelines for Optimal Use of HSS in Bridges“

Stephanie Breunig
Overview

„Categorization of Fatigue Details in View of Post-Weld-Treatments“

1.) General information on **High Frequency Mechanical Impact** (HFMI) Treatment

2.) Improvement and categorization of appropriate construction details
   a) Benefits and influences on fatigue resistance of HFMI-treated construction details (example: transverse stiffener)
   b) Possible existing approaches

3.) Beam Tests
   a) Motivation of test series
   b) Experimental procedure
   c) Results of beam tests

4.) Conclusions and outlook
1.) General information on High Frequency Mechanical Impact (HFMI) Treatment

a) Classification of Post-Weld Treatments

- Improvement of notch geometry
  - Grinding
  - TIG dressing
  - Plasma dressing
- Improvement of residual stress state
  - Hammering
  - Needle
  - Shot peening
  - High Frequency Mechanical Impact (HFMI) Treatment
1.) General information on High Frequency Mechanical Impact (HFMI) Treatment

b) Mechanism and variants of HFMI

**Pneumatic Impact Treatment (PIT)**

- By pneumatic pressure mechanical impacts are given with a pneumatically controlled muscle over a hardened pin into the construction.

- The intensity is not depending on the applied compressive force due to an integrated spring system.

---

**PITec**

**UIT**

**HiFIT**
1.) General information on High Frequency Mechanical Impact (HFMI) Treatment

c) Technical requirements

<table>
<thead>
<tr>
<th>Suitable for HFMI</th>
<th>Not suitable HFMI</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Suitable" /></td>
<td><img src="image2" alt="Not suitable" /></td>
</tr>
</tbody>
</table>

- For welded construction details with fatigue failure from weld toe HFMI-treatment can improve fatigue resistance
- If fatigue failure cracks come from weld root, HFMI application is not successful
- **Accessability** to the welds, weld toe is needed
2.) Improvement and categorization of appropriate construction details

a) Benefits and influences on fatigue resistance of HFMI-treated construction details (example: transverse stiffener)

**Investigated** construction details:
- Butt weld and variants (a.v.)
- Transverse stiffener (a.v.)
- Longitudinal stiffener (a.v.)
- …

**Quantity of improvement** depends on **further parameters**:
- Yield strength $f_y$
- Stress ratio $R$
- Type of loading (height, quantity, time …)
- Plate thickness $t$

Amount of improvement depends on construction detail
2.) Improvement and categorization of appropriate construction details

a) Benefits and influences on fatigue resistance of HFMI-treated construction details (example: transverse stiffener)

Results of non-treated tests with different yield strength $f_y$

- Higher fatigue resistance for higher yield strength
2.) Improvement and categorization of appropriate construction details

a) Benefits and influences on fatigue resistance of HFMI-treated construction details (example: transverse stiffener)

- Higher fatigue resistance for higher yield strength
- **Benefit** in using HFMI-treatment on welded details of **S690 steels**
2.) Improvement and categorization of appropriate construction details

b) Possible existing design approaches

Mainly 2 different procedures of existing design approaches considering HFMI-treatment on welded details

- **Stepwise** improvement in accordance with existing FAT-Classes
  - +1 FAT-Class
  - +2 FAT-Class
  - ....
  - + x-FAT-Class depending on conditions (R, S355 - S690, ...)

- **Consideration** of increasing fatigue resistance by **improvement factor** $k$
  \[
  \Delta \sigma_{C, \text{Imp}} = \Delta \sigma_C \cdot k
  \]
  \[
  k = k_f \cdot k_L \cdot k_R
  \]
  $k_i$ depending on conditions (R, S355 - S690, ...)

According to [Dürr] or [Weich]
3.) Beam Tests
a) Motivation of beam test series

- Improvement of fatigue resistance of several construction details is proved by **small scale tests** under **laboratory conditions**
- Component tests show **drop of improvement of fatigue** resistance due to:
  - More complex **residual stress state**
  - More complex **welding conditions**

Differences in fatigue resistance of small specimen and true scale specimen

- **drop of fatigue** strength according to (Duerr, 2006)

<table>
<thead>
<tr>
<th>Condition</th>
<th>Small Specimen</th>
<th>Beam Tests</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>As welded</td>
<td></td>
<td></td>
<td>16% less</td>
</tr>
<tr>
<td>UIT-treated</td>
<td></td>
<td></td>
<td>15% less</td>
</tr>
</tbody>
</table>
3.) Beam Tests
b) Experimental procedure – test setup

\[ F_{\text{max}} = 800 \text{kN} \]

\[ \Delta \sigma = 400 \text{N/mm}^2 \]
3.) Beam Tests
b) Experimental procedure

HFMI treatment of stiffener welds leads to improved detail, so that other details become relevant.

 failure: Crack crossing the longitudinal fillet weld

T1 (HFMI: Stiffener) and T2 (HFMI: Stiffener)
3.) Beam Tests

c) Results

- Crack at longitudinal fillet weld Use as minimum result
- Crack at fixing point on longitudinal fillet weld
  Use as minimum result
- HFMI-treated bottom longitudinal fillet weld; Crack at upper longitudinal fillet weld
- Crack at fixing point
  Use as minimum result
- AW transverse stiffener
  Crack at transverse stiffener
- HFMI-treated transverse stiffener
  Crack at transverse stiffener
- HFMI-treated longitudinal fillet weld
3.) Beam Tests
c) Results

T5 and T6 show typical failure from weld toe as for small scale tests and EC3-1-9.
3.) Beam Tests

c) Test results – depending on failure modes

![Beam Test Results Graph]

- **Nominal Stress Range $\Delta\sigma$ [MPa]**
- **Cycles to failure, N**

**Beam Test Results**

- **Weld toe failure (trans. stiff)**
- **Failure of longit. weld**

- **Beam test (aw)**
- **Beam test (HFMI: Stiffener)**
- **Beam test (HFMI: Stiffener + Longi Weld)**
- **Failure Stiff (HFMI: Stiffener + Longi Weld)**

![Beam Test Diagram]
3.) Beam Tests

c) Results for transverse stiffener

- Very high fatigue resistance for single aw-beam test, compared to FAT 80

---

**Beam Test Results**

- Weld toe failure (trans. stiff)
- Failure of Longit. weld

<table>
<thead>
<tr>
<th>Nominal Stress Range $\Delta\sigma$ [MPa]</th>
<th>Cycles to failure, N</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^4$</td>
<td></td>
</tr>
<tr>
<td>$10^5$</td>
<td></td>
</tr>
<tr>
<td>$10^6$</td>
<td></td>
</tr>
<tr>
<td>$10^7$</td>
<td></td>
</tr>
</tbody>
</table>

- Beam test (aw)

**Nominal Stress Range $\Delta\sigma_c = 80$ N/mm$^2$**
3.) Beam Tests
c) Results for **transverse stiffener**

![Beam Test Results Diagram](image)

- **Positive influence** by HFMI treatment for transverse stiffener
- Results between FAT 140 and 160

### Beam Test Results

<table>
<thead>
<tr>
<th>Nominal Stress Range $\Delta \sigma$ [MPa]</th>
<th>Cycles to failure, N</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta \sigma_c = 80$ N/mm²</td>
<td></td>
</tr>
<tr>
<td>$\Delta \sigma_c = 125$ N/mm²</td>
<td></td>
</tr>
<tr>
<td>$\Delta \sigma_c = 140$ N/mm²</td>
<td></td>
</tr>
<tr>
<td>$\Delta \sigma_c = 160$ N/mm²</td>
<td></td>
</tr>
</tbody>
</table>

- **Weld toe failure** (trans. stiff)
- **Failure of Longit. weld**

- **Beam test** (aw)
- **Beam test (HFMI: Stiffener + Longi Weld)**
- **Failure Stiff (HFMI: Stiffener + Longi Weld)**
3.) Beam Tests

c) Results for transverse stiffener – comparison to small scale tests

Comparison to small scale tests shows:
Beam tests have lower fatigue resistance

Compared to EC3-FAT Class: improvement is valid from around 100,000 Load Cycles

Due to longitudinal failure, no statistically verified scale factor derivable

Slope seems to be close to 3 for beams

![Diagram showing beam test results with nominal stress range and cycles to failure.](image-url)
3.) Beam Tests
c) Results for **longitudinal weld failure**

- **Beam Test Results**

- **Nominal Stress Range $\Delta \sigma$ [MPa]**
- **Cycles to failure, $N$**

<table>
<thead>
<tr>
<th>Test Type</th>
<th>$\Delta \sigma_c$ [N/mm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam test (HFMI: stiffener)</td>
<td>112</td>
</tr>
<tr>
<td>Beam test (HFMI: Stiffener + Longi Weld)</td>
<td>125</td>
</tr>
<tr>
<td>Beam test (HFMI: stiffener)</td>
<td>140</td>
</tr>
<tr>
<td>Beam test (HFMI: Stiffener + Longi Weld)</td>
<td>160</td>
</tr>
</tbody>
</table>

Positive influence by HFMI-treatment can be seen for longitudinal weld failure.
4.) Conclusions and Outlook

- Effectiveness of HFMI treatment could be shown for
  - Transverse stiffener beam tests (results between FAT 140 – 160)
  - Longitudinal fillet weld

- General uncritical construction details, such as **longitudinal fillet welds**, become decisive

- There is still **improvement potential** by HFMI for construction details not yet investigated (see longitudinal fillet welds)

- **Clear and verified design guidelines** have to be integrated into EC 3-1-9
Thank you for your attention!

Any questions???

Stephanie Breunig

E-Mail  Stephanie.breunig@ke.uni-stuttgart.de
Telefon +49 (0) 711 685- 69257
Fax +49 (0) 711 685-66236

University of Stuttgart
Institute of Structural Design
Prof. Dr.-Ing. Ulrike Kuhlmann
Pfaffenwaldring 7
70569 Stuttgart
Buckling Behavior of Slender Plates under Multiaxial Stresses

OptiBri-Workshop
„Design Guidelines for Optimal Use of HSS in Bridges“

Vahid Pourostad
Introduction

Motivation

→ Biaxial stress states

tension/compression or compression/compression

Influence of tension stresses?

[Lennetal Bridge, Hagen]

[Zizza; CTICM]
Stability behavior of flat plates

Biaxial compression

- Investigations conducted by (Braun, 2010)
- Proposal of „V-Factor“ in the domain of biaxial compression:

\[
\left( \frac{\sigma_{xEd}}{\rho_x \cdot f_y / \gamma M1} \right)^2 + \left( \frac{\sigma_{zEd}}{\rho_z \cdot f_y / \gamma M1} \right)^2 - V \cdot \left( \frac{\sigma_{xEd}}{\rho_x \cdot f_y / \gamma M1} \right) \cdot \left( \frac{\sigma_{zEd}}{\rho_z \cdot f_y / \gamma M1} \right) \leq 1
\]

\( \alpha = 1 \)  
\( b/t = 100 \)

\( \alpha = 3 \)  
\( b/t = 30 \)

→ Verified by numerical calculations for biaxial compression and unstiffened plates

→ Existing EN 1993-1-5 partly unsafe. Meanwhile official amendment is added.
Stability behavior of flat plates

Consideration of tensile stresses?

- EN 1993-1-5, Ch. 10(5)) Note 2: In case of panels with tension and compression it is recommended to apply equations (10.4) and (10.5) only for the compressive parts.

- That means: “on the safe side the positive effect of tension stresses should be neglected when calculating the reduction factors”

\[
\left( \frac{\sigma_{xEd}}{\rho_x \cdot f_y / \gamma_{M1}} \right)^2 + \left( \frac{\sigma_{zEd}}{\rho_z \cdot f_y / \gamma_{M1}} \right)^2 - \left( \frac{\sigma_{xEd}}{\rho_x \cdot f_y / \gamma_{M1}} \right) \cdot \left( \frac{\sigma_{zEd}}{\rho_z \cdot f_y / \gamma_{M1}} \right) + 3 \cdot \left( \frac{\tau_{Ed}}{\chi_{w,y} / \gamma_{M1}} \right)^2 \leq 1
\]

\[
\bar{\lambda}_p = \sqrt{\frac{\alpha_{ult,k}}{\alpha_{cr}}}
\]

→ The assumption leads to conservative results.
Stability behavior of flat plates
Investigation in the frame of OptiBri

Buckling verification becomes more important for HSS plates:

AIM: To allow for taking account of positive effects of tension stresses
Experimental investigations

Test program and setup

<table>
<thead>
<tr>
<th>Test</th>
<th>A1</th>
<th>A2</th>
<th>A3</th>
<th>B1</th>
<th>B2</th>
<th>B3</th>
</tr>
</thead>
<tbody>
<tr>
<td>a [mm]</td>
<td>900</td>
<td>900</td>
<td>900</td>
<td>1500</td>
<td>1500</td>
<td>1500</td>
</tr>
<tr>
<td>b [mm]</td>
<td>900</td>
<td>900</td>
<td>900</td>
<td>500</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>α</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>t [mm]</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>b/t</td>
<td>150</td>
<td>150</td>
<td>150</td>
<td>83</td>
<td>83</td>
<td>83</td>
</tr>
<tr>
<td>β</td>
<td>0</td>
<td>-0.25</td>
<td>-0.5</td>
<td>0</td>
<td>-1.5</td>
<td>-1</td>
</tr>
</tbody>
</table>

- Variation of aspect-ratio $α$ and slenderness
- Variation of stress-ratio $β = \frac{σ_z}{σ_x}$
- Material: S690

$→$ $β = 0$ as reference tests for the evaluation of the influence of tension stresses
Experimental investigations
Test results

→ Evaluations show increase of loading capacity by increased tension stresses

→ Evaluation of the deformations shows the influence of tension stresses on the buckling shape
Numerical investigation

Recalculations of tests

Numerical model in ABAQUS

→ The numerical model has been developed using the material curve from tensile tests and the measured imperfections

Comparison of failure modes

Experiment

Numerical model

A1

A2

A3
Numerical investigation

Recalculations of tests

→ Good agreement between numerical and experimental buckling shapes

→ Good agreement between numerical and experimental ultimate load
Parametric study
Parametric study using ABAQUS (WP3.2)

- Influence of b/t- and aspect-ratio
- Influence tension stresses on compression
- Influence of boundary conditions

- Influence of imperfection shape and amplitude

→ Calculations for S690
Parametric Study on Square Plates

- Investigated parameters:
  - interaction angle $\theta = \tan^{-1} \frac{\sigma_z}{\sigma_x}$
  - b/t-ratio
  - imperfection shape and amplitude
  - boundary conditions

$b/t = 45$

$b/t = 65$

$b/t = 100$

→ Lower envelope considers decisive imperfection shape

---

OptiBri Workshop “Design Guidelines for Optimal Use of HSS in Bridges”

3rd May 2017
Parametric study
Parametric Study on Square Plates

- Investigated parameters:
  - interaction angle $\theta$
  - b/t-ratio

- Imperfection shape and amplitude
- Boundary conditions

BC-A; $\alpha=1$; b/t=100
1 half-wave imperfection shape

→ With increasing tension buckling shape changes from one half-wave to 3 half-wave
Enhancement of the reduced stress method

For compression-tension

- Verification formula acc. to EN 1993-1-5 for direct stresses:
  \[
  \left( \frac{\sigma_{xEd}}{\rho_x \cdot f_y / \gamma_{M1}} \right)^2 + \left( \frac{\sigma_{zEd}}{\rho_z \cdot f_y / \gamma_{M1}} \right)^2 - \left( \frac{\sigma_{xEd}}{\rho_x \cdot f_y / \gamma_{M1}} \right) \cdot \left( \frac{\sigma_{zEd}}{\rho_z \cdot f_y / \gamma_{M1}} \right) \leq 1
  \]

- Modification of verification formula with „V-Factor“ for direct stresses:
  \[
  \left( \frac{\sigma_{xEd}}{\rho_x \cdot f_y / \gamma_{M1}} \right)^2 + \left( \frac{\sigma_{zEd}}{\rho_z \cdot f_y / \gamma_{M1}} \right)^2 - V \cdot \left( \frac{\sigma_{xEd}}{\rho_x \cdot f_y / \gamma_{M1}} \right) \cdot \left( \frac{\sigma_{zEd}}{\rho_z \cdot f_y / \gamma_{M1}} \right) \leq 1
  \]

- „V-Factor“ in case of biaxial compression proposed by (Braun, 2010)
  \[
  V = \rho_{c,x} \cdot \rho_{c,z}
  \]

- „V-Factor“ in case of compression-tension proposed by (Zizza, 2016)
  \[
  V = 1/(\rho_{c,x} \cdot \rho_{c,z}^{2/\varphi_z})
  \]
Enhancement of the reduced stress method

Proposed formula for calculation of buckling coefficient by Zizza for interaction of tension and compression

\[ k_{\sigma}^{\text{min}} = 4(1 - \beta) \]

→ Neglecting the peaks in the calculation of the buckling coefficient for tension compression using:

\[ \beta = \frac{\sigma_z}{\sigma_x} \]
Enhancement of the reduced stress method

Comparison of current design rules with proposed V-Factor (tension-compression)

→ Current design rules neglecting tension stresses lead to conservative results

→ Current design rules applying tension for calculating ρ without V factor partially on unsafe side

→ Proposal considering of V factor and neglecting the peak of buckling coefficient leads to good results
Enhancement of the reduced stress method
Comparison of current design rules with proposed V-Factor (compression-compression)

→ Proposed verification with V factor corresponds very well to FE results
Flowchart of using MRS (sec. 10)

For longitudinal stresses (x-direction)

\[
\lambda_p = \frac{\alpha_{ult}}{\alpha_{crit}}
\]
[eq. (10.2)]

For transverse stresses (z-direction)

\[
\phi_p = 0.5 \cdot (1 + \alpha_p \cdot (\lambda_p - \lambda_{p0}) + \lambda_p)
\]
[Annex B]

\[
\rho_{p,z} = \frac{1}{\phi_p + \sqrt{\phi_p^2 - \lambda_p}}
\]
[Annex B eq.(B.1)]

\[
\xi_z = \frac{\sigma_{cr,p,z}}{\sigma_{cr,z}} - 1
\]
[4.5.4]

\[
\rho_{c,z} = (\rho_{pz} - \chi_c) \cdot \xi_z \cdot (2 - \xi_z) + \chi_c
\]
[4.5.4(1) eq.(4.13)]

\[
\chi_c = \frac{1}{\phi + \sqrt{(\phi^2 - \lambda_p^2)}}
\]
[EN 1993-1-1, 6.3.1.2]

\[
\sqrt{\left(\frac{\sigma_{x,Ed}}{\rho_{c,x} \cdot f_y / \gamma_{M1}}\right)^2 + \left(\frac{\sigma_{z,Ed}}{\rho_{c,z} \cdot f_y / \gamma_{M1}}\right)^2} - V \cdot \left(\frac{\sigma_{x,Ed}}{\rho_{c,x} \cdot f_y / \gamma_{M1}}\right) \cdot \left(\frac{\sigma_{z,Ed}}{\rho_{c,z} \cdot f_y / \gamma_{M1}}\right) + 3 \cdot \left(\frac{\tau_{Ed}}{\chi_w \cdot f_y / \gamma_{M1}}\right)^2 \leq 1
\]
[10(5), eq. (10.5)]

[reference numbers refer to EN 1993-1-5]
Example

Panels subjected to tension and compression

**Acting stresses:**

\[
\sigma_{x, Ed} = 242 \text{ N/mm}^2 \quad \sigma_{z, Ed} = -89 \text{ N/mm}^2
\]

**Equivalent stress:**

\[
\sigma_v = \sqrt{\left(\sigma_{y, Ed}\right)^2 + \left(\sigma_{z, Ed}\right)^2 + \left(\sigma_{x, Ed}\right)\left(\sigma_{z, Ed}\right)} = 296.69 \text{ N/mm}^2
\]

**Buckling value acc. to proposal of Zizza:**

\[
\beta = \frac{\sigma_{z, Ed}}{\sigma_{x, Ed}} = \frac{-89}{242} = -0.367 \quad k_\sigma = k_\sigma^{\text{min}} = 4(1 - (-0.368)) = 5.47
\]

**Elastic critical plate-buckling stress and column-buckling stress**

\[
\sigma_e = 27.33 \text{ N/mm}^2 \quad \sigma_{cr, p} = k_\sigma \cdot \sigma_e = 5.47 \cdot 27.33 = 149.6 \text{ N/mm}^2
\]

\[
\sigma_{cr, c,x} = \frac{\pi^2 E t^2}{12(1 - \nu^2)a^2} = 18.98 \text{ N/mm}^2
\]

**Slenderness and reduction factors:**

\[
\alpha_{cr} = \frac{\sigma_{cr, p}}{\sigma_{x, Ed}} = \frac{149.6}{242} = 0.618 \quad \alpha_{ult} = \frac{f_y}{\sigma_v} = \frac{690}{296.69} = 2.326 \quad \lambda_p = \sqrt{\frac{\alpha_{ult}}{\alpha_{cr}}} = 1.94 \quad \rho_x = \frac{\lambda_p - 0.055 \cdot (3 + \psi)}{\lambda_p^2} = 0.457
\]

\[
\xi_x = \frac{\sigma_{cr, p, x}}{\sigma_{cr, c, x}} \geq 1 \Rightarrow \xi_x = 1 \Rightarrow \rho_{c, x} = \rho_x = 0.457
\]

\[
\rho_{c, z} = 1
\]
Example

Panels subjected to tension and compression

Verification acc. to proposal of Zizza:

\[ V = 1 / \left( \rho_{c,x} \cdot \rho_{c,z}^{2 - \xi z} \right) = 1 / (0.457) = 2.188 \]

\[ \eta = \sqrt{\left( \frac{242}{0.457 \cdot 690 / 1.1} \right)^2 + \left( \frac{-89}{1 \cdot 690 / 1.1} \right)^2 - 2.188 \cdot \left( \frac{242}{0.457 \cdot 690 / 1.1} \right) \cdot \left( \frac{-89}{1 \cdot 690 / 1.1} \right)} = 1 \leq 1 \]

Comparison of proposal and current design rule with required thickness of panel

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>S690</td>
<td>S690</td>
<td>S355</td>
<td>S355</td>
<td></td>
</tr>
<tr>
<td>t [mm]</td>
<td>14</td>
<td>12</td>
<td>24.7</td>
<td>21.2</td>
</tr>
<tr>
<td>( \eta )</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

→ Proposed verification considering tension stresses and V factor leads to efficient design of the panels
Summary and Outlook

- Six tests have been conducted and recalculated using the FEM
- Tension stresses may change the failure mode of a square panel from one half-wave into more half-waves.
- Tension stresses increase the buckling resistance of the panels.
- The ultimate loads acc. to Sec 10, EN 1993-1-5 with considering the positive effect of tension stresses on the reduction factors and proposed V factor by Zizza, enhance the accuracy of the “reduced stress method” and leads to more efficient design of the panels.

Outlook

- Extension of the numerical investigations for interaction of tension and shear
- Investigations on stiffened plates
Thank you for your attention!

Vahid Pourostad

E-Mail  Vahid.pourostad@ke.uni-stuttgart.de
Telephone  +49 (0) 711 685- 66243
Fax  +49 (0) 711 685-66236

University of Stuttgart
Institute of Structural Design
Prof. Dr.-Ing. Ulrike Kuhlmann
Pfaffenwaldring 7
70569 Stuttgart
Improved Bridge Design by Use of High Strength Steel (HSS) with OPTIBRI developments

OptiBri-Workshop „Design Guidelines for Optimal Use of HSS in Bridges“

Cláudio Baptista
OVERVIEW OF IMPROVEMENTS (DESIGN A TO B)

- **Design A** – S355 NL (current Eurocode versions)
- **Design B** – S690 QL (current Eurocode versions)
- **Design C** – S690 QL (upgrade Eurocode versions)

Direct Improvements for Bridge Design:

- Reduction of maximum steel plate thickness: 120 to 70 mm
- Reduction of the welding volume: 65%
- Reduction of overall steel weight: 25%

However...

- Fatigue has become the critical ULS check!
OVERVIEW OF IMPROVEMENTS (DESIGN A TO B)

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- **Design C** – S690 QL, (upgrade Eurocode versions)

**Direct Improvements for Bridge Design:**
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OVERVIEW OF IMPROVEMENTS (DESIGN A TO B)

Direct Improvements for Bridge Design:

Reduction of the welding volume: 65%
OVERVIEW OF IMPROVEMENTS (DESIGN A TO B)

Direct Improvements for Bridge Design:

- Reduction of brittle failure risk

**Design A (S355NL):**  
\[ \sigma_{Ed} = 0.63 \ f_y(t) \ -- \ t_{max} = 92\text{mm} \ (t=120\text{mm}) \]

**Design B (S690QL1):**  
\[ \sigma_{Ed} = 0.53 \ f_y(t) \ -- \ t_{max} = 63\text{mm} \ (t=70\text{mm}) \]

<table>
<thead>
<tr>
<th>Steel Class</th>
<th>Quality</th>
<th>KV at T [°C]</th>
<th>Jmin</th>
<th>( \sigma_{Ed} = 0.75 \ f_y(t) )</th>
<th>( \sigma_{Ed} = 0.50 \ f_y(t) )</th>
<th>( \sigma_{Ed} = 0.25 \ f_y(t) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>S355</td>
<td>J2</td>
<td>-20</td>
<td>27</td>
<td>40</td>
<td>65</td>
<td>110</td>
</tr>
<tr>
<td></td>
<td>K2,M,N</td>
<td>-20</td>
<td>40</td>
<td>50</td>
<td>80</td>
<td>130</td>
</tr>
<tr>
<td></td>
<td>ML,NL</td>
<td>-50</td>
<td>27</td>
<td>75</td>
<td>110 (120)</td>
<td>175</td>
</tr>
<tr>
<td>S690</td>
<td>QL</td>
<td>-20</td>
<td>40</td>
<td>25</td>
<td>45</td>
<td>85</td>
</tr>
<tr>
<td></td>
<td>QL1</td>
<td>-40</td>
<td>40</td>
<td>40</td>
<td>65 (70)</td>
<td>120</td>
</tr>
<tr>
<td></td>
<td>QL1</td>
<td>-60</td>
<td>30</td>
<td>50</td>
<td>80</td>
<td>140</td>
</tr>
</tbody>
</table>

Reference temperature: \( T_{ref} = -30°C \)

Design A: \( t \leq 120 \text{mm} \) (S355 NL);  
Design B: \( t \leq 70 \text{mm} \) (S690 QL1, 40J at -40°C)
### ULS BRIDGE DECK BENDING DESIGN

<table>
<thead>
<tr>
<th></th>
<th>Mid-span section</th>
<th>Support section</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Class 1</strong></td>
<td><strong>Plastic section analysis</strong></td>
<td><strong>Class 4</strong></td>
</tr>
<tr>
<td><strong>Design A</strong></td>
<td>Design A S355</td>
<td><strong>Design A</strong></td>
</tr>
<tr>
<td><strong>Design B</strong></td>
<td>Design B S690</td>
<td><strong>Design B</strong></td>
</tr>
<tr>
<td>$M_{Ed}/M_{pl.Rd} &lt; 1$</td>
<td>0.74</td>
<td>0.93</td>
</tr>
<tr>
<td>${\sigma_{Ed}/(f_{yf}/\gamma_{M0})}$ Bottom flange</td>
<td>0.93</td>
<td>0.65</td>
</tr>
<tr>
<td>${\sigma_{Ed}/(f_{yf}/\gamma_{M0})}$ Eff. bottom flange</td>
<td>0.95</td>
<td>0.88</td>
</tr>
<tr>
<td>${\sigma_{Ed}/(\chi_{LT}f_{yf}/\gamma_{M1})}$ Eff. bottom flange</td>
<td>0.92</td>
<td>0.97</td>
</tr>
</tbody>
</table>

(*) at 0.25 $L_k = 5$ m from the support
CRITICAL FAT DETAILS (DESIGN A to C)

Bottom flange at support bearings:

\[ \Delta s_{E,2} = 50 \text{ MPa (Design B S690)} \]

- SN curve for plates with holes
- Solution: Bolted Plates

FAT 56

Bearing plate

FAT 90
Transversal stiffener at support:

\[ \Delta s_{E,2} = 50 \text{ MPa (Design B S690)} \]

Solution: Rounded stiffener flange
CRITICAL FAT DETAILS (DESIGN A to C)

Cope holes on main beams:

\[ \Delta s_{E,2} = 57 \text{ MPa (Design A S355)} \]
\[ \Delta s_{E,2} = 78 \text{ MPa (Design B S690)} \]

Solution: Avoid Cope holes
## Critical Fat Details (Design A to C)

### Shear Connectors:

<table>
<thead>
<tr>
<th>Section (X)</th>
<th>1 (0.0)</th>
<th>2 (4.0)</th>
<th>3 (8.0)</th>
<th>4 (12.0)</th>
<th>5 (16.0)</th>
<th>6 (20.0)</th>
<th>7 (24.0)</th>
<th>8 (28.0)</th>
<th>9 (32.0)</th>
<th>10 (36.0)</th>
<th>11 (40.0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta \sigma_{E2} ) (MPa)</td>
<td>27.0</td>
<td>23.1</td>
<td>18.6</td>
<td>21.4</td>
<td>15.5</td>
<td>13.3</td>
<td>13.3</td>
<td>5.1</td>
<td>5.1</td>
<td>5.2</td>
<td>5.1</td>
</tr>
<tr>
<td>( \gamma_{fj}/\Delta \sigma_{E2} )</td>
<td>0.46</td>
<td>0.39</td>
<td>0.31</td>
<td>0.36</td>
<td>0.26</td>
<td>0.23</td>
<td>0.22</td>
<td>0.09</td>
<td>0.09</td>
<td>0.09</td>
<td>0.09</td>
</tr>
<tr>
<td>( \Delta \tau_{E2} ) (MPa)</td>
<td>16.1</td>
<td>15.5</td>
<td>22.7</td>
<td>21.2</td>
<td>20.2</td>
<td>20.4</td>
<td>33.7</td>
<td>33.5</td>
<td>32.8</td>
<td>32.9</td>
<td>32.7</td>
</tr>
<tr>
<td>( \gamma_{fj}/\Delta \tau_{E2} )</td>
<td>0.31</td>
<td>0.30</td>
<td>0.43</td>
<td>0.40</td>
<td>0.38</td>
<td>0.39</td>
<td>0.64</td>
<td>0.64</td>
<td>0.62</td>
<td>0.62</td>
<td>0.62</td>
</tr>
</tbody>
</table>

**Direct Stress on the Top Flange (FAT 80 m=3)**

**Shear Stress on the Stud (FAT 90 m=8)**

**Interaction:** \( \gamma_{fj}/\Delta \sigma_{E2} + \gamma_{fj}/\Delta \tau_{E2} \leq 1.3 \)

\[
\text{Int.exp.} \leq 1.3
\]
CRITICAL FAT DETAILS (DESIGN A to C)

Transversal attachment on bottom flange of main beams:

\[ \Delta s_{E,2} = 78 \text{ MPa (Design B S690)} \]

SN curve for transversal attachments

Solution: Detail FAT 80 is unavoidable!
### Design A

<table>
<thead>
<tr>
<th>Section (X)</th>
<th>1 (0.0)</th>
<th>2 (4.0)</th>
<th>3 (8.0)</th>
<th>4 (12.0)</th>
<th>5 (16.0)</th>
<th>6 (20.0)</th>
<th>7 (24.0)</th>
<th>8 (28.0)</th>
<th>9 (32.0)</th>
<th>10 (36.0)</th>
<th>11 (40.0)</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>t</em>&lt;sub&gt;f&lt;/sub&gt; (mm)</td>
<td>120</td>
<td>120</td>
<td>120/80</td>
<td>80</td>
<td>80</td>
<td>80/50</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>γ&lt;sub&gt;Mf&lt;/sub&gt; γ&lt;sub&gt;Ff&lt;/sub&gt; Δσ&lt;sub&gt;E,2&lt;/sub&gt;</td>
<td>25.5</td>
<td>21.7</td>
<td>32.1</td>
<td>36.5</td>
<td>29.9</td>
<td>47.6</td>
<td>51.0</td>
<td>53.0</td>
<td>56.9</td>
<td>57.4</td>
<td>56.6</td>
</tr>
<tr>
<td>FAT</td>
<td>56</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>80</td>
</tr>
</tbody>
</table>

### Design B

<table>
<thead>
<tr>
<th></th>
<th>1 (0.0)</th>
<th>2 (4.0)</th>
<th>3 (8.0)</th>
<th>4 (12.0)</th>
<th>5 (16.0)</th>
<th>6 (20.0)</th>
<th>7 (24.0)</th>
<th>8 (28.0)</th>
<th>9 (32.0)</th>
<th>10 (36.0)</th>
<th>11 (40.0)</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>t</em>&lt;sub&gt;f&lt;/sub&gt; (mm)</td>
<td>70</td>
<td>70</td>
<td>70/60</td>
<td>60</td>
<td>60</td>
<td>60/45</td>
<td>45</td>
<td>45</td>
<td>45</td>
<td>45</td>
<td>45</td>
</tr>
<tr>
<td>γ&lt;sub&gt;Mf&lt;/sub&gt; γ&lt;sub&gt;Ff&lt;/sub&gt; Δσ&lt;sub&gt;E,2&lt;/sub&gt;</td>
<td>49.8</td>
<td>42.7</td>
<td>57.9</td>
<td>65.8</td>
<td>55.2</td>
<td>66.9</td>
<td>71.9</td>
<td>70.7</td>
<td>76.5</td>
<td>77.8</td>
<td>77.1</td>
</tr>
<tr>
<td>FAT</td>
<td>56</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>80</td>
</tr>
</tbody>
</table>

- HSS allows for 34% overall steel reduction in main beams
- Fatigue becomes the leading ULS check at span sections
CRITICAL FAT DETAILS (DESIGN A to C)

PWT Transversal attachment (beams and plates):
CRITICAL FAT DETAILS (DESIGN A to C)

Butt welds on bottom flange of main beams:

FAT 112

---

OptiBri Workshop “Design Guidelines for Optimal Use of HSS in Bridges”
Web-to-flange longitudinal weld:

Beam Test Results

<table>
<thead>
<tr>
<th>Detail Category</th>
<th>Description</th>
<th>Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>125</td>
<td>Continuous longitudinal welds:</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1) Automatic butt welds carried out from both sides.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2) Automatic fillet welds. Cover plate ends to be checked using detail 6 or 7 in Table 8.5.</td>
<td></td>
</tr>
<tr>
<td>112</td>
<td>3) Automatic fillet or butt weld carried out from both sides but containing stop/start positions.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4) Automatic butt welds made from one side only, with a continuous backing bar, but without stop/start positions.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4) When this detail contains stop/start positions category 100 to be used.</td>
<td></td>
</tr>
</tbody>
</table>

FAT 125
### OVERVIEW OF FAT CHECK

#### Design B

<table>
<thead>
<tr>
<th>Section (X)</th>
<th>1 (0.0)</th>
<th>2 (4.0)</th>
<th>3 (8.0)</th>
<th>4 (12.0)</th>
<th>5 (16.0)</th>
<th>6 (20.0)</th>
<th>7 (24.0)</th>
<th>8 (28.0)</th>
<th>9 (32.0)</th>
<th>10 (36.0)</th>
<th>11 (40.0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_f$ (mm)</td>
<td>70</td>
<td>70</td>
<td>70/60</td>
<td>60</td>
<td>60</td>
<td>60/45</td>
<td>45</td>
<td>45</td>
<td>45</td>
<td>45</td>
<td>45</td>
</tr>
<tr>
<td>$\gamma_M \gamma_{Ff} \Delta\sigma_{E,2}$</td>
<td>49.8</td>
<td>42.7</td>
<td>57.9</td>
<td>65.8</td>
<td>55.2</td>
<td>66.9</td>
<td>71.9</td>
<td>70.7</td>
<td>76.5</td>
<td>77.8</td>
<td>77.1</td>
</tr>
<tr>
<td>FAT</td>
<td>56</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>80</td>
</tr>
</tbody>
</table>

#### Design C

| $t_f$ (mm)  | 70      | 70      | 70/45   | 45       | 45       | 45/30    | 30       | 30       | 30       | 30        | 30        |
| $\gamma_M \gamma_{Ff} \Delta\sigma_{E,2}$ | 49.8    | 42.7    | 88.7    | 100.3    | 83.4     | 90.5     | 96.9     | 100.8    | 109.1    | 110.3     | 102.6     |
| Detail      | 112     | 112     |         | 112      | 112      |         |         | 112      |         | 112       | 112       |
| Size effect | 0.89    | 0.96    | 0.96    | 0.96     | 0.96     | 0.96     | 0.96     | 0.96     | 0.96     | 0.96      | 0.96      |
| FAT         | 56      | 125     | 100     | 125      | 125      | 108      | 125      | 108      | 125      | 125       | 108       |

- PWT allows for 7% overall steel reduction
TRANSVERSAL STIFFENERS

Design Requirements:

- Safety to torsional buckling
- Minimum stiffness requirement for shear verification of the webs
- Resistance to tension field action
TRANSVERSAL STIFFENERS

✓ Safety to torsional buckling

\[ \sigma_{cr} \geq \theta f_y \]

\( \sigma_{cr} \) = elastic critical stress for torsional buckling of the stiffener
\( \theta \) = 6 for T stiffeners or \( \theta = 2 \) for flat stiffeners
\( f_y \) = is taken as the maximum stress \( \sigma_{max} \) and not the yielding stress

For DESIGN B:

\[ \sigma_{cr} = 2969 \text{MPa} \approx 6 \sigma_{\text{max}, Ed} = 6 \times 472.78 \text{MPa} \gg 6\sigma_{\text{max}, Ed} / \sigma_{cr} = 0.96 \]

Often the critical criterion to design the transversal stiffeners

✓ Minimum stiffness required to the stiffeners to act as rigid supports for shear verification web panels

Usually verified by a large margin

\[
\begin{align*}
I_{st} & \geq 1,5 h_w^3 \cdot t_w^3 / a^2 & \text{if} & & a/h_w < \sqrt{2} \\
I_{st} & \geq 0,75 h_w \cdot t_w^3 & \text{if} & & a/h_w \geq \sqrt{2}
\end{align*}
\]
TRANSVERSAL STIFFENERS

✓ Resistance of the stiffener to tension field action

\[ P_{st} = V_{Ed} - 1 \frac{f_{yw} h_w t}{\lambda_w^2 \sqrt{3} \gamma_{M1}} \]
\[ = V_{Ed} - V_{cr,w} \]

Tests show \( P_{exp} \leq 56\%P_{st} \) [Sinur & Beg, 2012]
Re-design of stiffeners allows for 7% overall steel reduction
CONCLUSIONS

Advantages:

- The use of S690 HSS instead of S355 enables a reduction up to
  - 25% (Design B)
  - 35% (Design C)

<table>
<thead>
<tr>
<th>Comparative analysis</th>
<th>Steel in the deck</th>
<th>Reduction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design A – S355</td>
<td>219 kg/m²</td>
<td>---</td>
</tr>
<tr>
<td>Design B – S690</td>
<td>165 kg/m²</td>
<td>-25%</td>
</tr>
<tr>
<td>Design C – S690</td>
<td>143 kg/m²</td>
<td>(-14%) -35%</td>
</tr>
</tbody>
</table>
CONCLUSIONS

Advantages:

- The use of S690 HSS instead of S355 enables a reduction up to:
  - 25% (Design B)
  - 35% (Design C)
- Aesthetics of bridge is improved by increased deck slenderness
- S690 allows the use of thinner plates which:
  - Reduces the full penetration weld volume more than 65%
  - Reduces the brittle fracture problems
  - Reduces the size effect and thus increases fatigue resistance
- PWT details are effective and useful to take full advantage of the HSS steel
Thank you for your attention!

Claudio Baptista
E-Mail  Claudio.baptista@grid.pt
Telefone  +351 213 191 220
Fax  +351 213 528 334

GRID International, Consulting Engineers
Av. João Crisóstomo, nº25-4 floor
1050-125 Lisbon, PORTUGAL
Comparative Life-Time Assessment of the Use of HSS in Bridges

OptiBri-Workshop
„Design Guidelines for Optimal Use of HSS in Bridges“

Constança Rigueiro
Life Cycle Analysis

ISO STANDARDS 14040/14044

Goal and scope definition

Inventory analysis

Impact assessment

Interpretation

Mandatory elements

Selection of indicators

Classification

Characterization

\[ IA_{jk} = \sum_{i=1}^{n} I_{ij} \times IA_{factor_i} \]

Normalization

Weighting

\[ IAScore_{jk} = \frac{IA_{jk} \times IVwt_k}{Norm_k} \]

Optional elements

Other relevant standards (CEN TC350):
EN15643 & EN 15978 – Sustainability of construction works
Life-time assessment of bridges

SCOPE OF THE ANALYSIS

Material Production
- Raw material acquisition
- Transportation to production site
- Production of construction materials
- Transportation to construction site

Construction
- Transportation of construction equipment
- Use of construction equipment
- Construction processes
- Traffic congestion

Operation
- Transportation of equipment
- Maintenance operations
- Rehabilitation processes
- Traffic congestion

End of life
- Demolition of structure
- Use of equipment
- Transportation of materials/waste to disposal site
- Traffic congestion
# Life-time assessment of bridges

## SCOPE OF THE ANALYSIS ACCORDING TO EN 15978

<table>
<thead>
<tr>
<th>PRODUCT stage</th>
<th>CONSTRUCTION PROCESS stage</th>
<th>USE stage</th>
<th>END-OF-LIFE stage</th>
<th>Benefits and loads beyond the system boundary</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1 Raw material supply</td>
<td>A4 Transport</td>
<td>B1 Use</td>
<td>C1 Deconstruction demolition</td>
<td>D Reuse-Recycling-potential</td>
</tr>
<tr>
<td>A2 Transport</td>
<td>A5 Construction - installation process</td>
<td>B2 Maintenance</td>
<td>C2 Transport</td>
<td></td>
</tr>
<tr>
<td>A3 Manufacturing</td>
<td></td>
<td>B3 Repair</td>
<td>C3 Waste processing</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>B4 Replacement</td>
<td>C4 Disposal</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>B5 Refurbishment</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>B6 Operational energy use</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>B7 Operational water use</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Mandatory**

EPD cradle-to-gate

**Mandatory**

EPD cradle-to-gate with option

**Mandatory**

EPD cradle-to-grave

---

OptiBri Workshop “Design Guidelines for Optimal Use of HSS in Bridges”

3rd May 2017
Life-time assessment of bridges

INVENTORY ANALYSIS

✓ Environmental data for different steel grades

2. Product

2.1 Product description
This EPD applies to 1 t of structural steel (sections and plates). It covers steel products of the grades S235 to S960 rolled out to structural sections, merchant bars and heavy plates.

5. LCA: Results

<table>
<thead>
<tr>
<th>DESCRIPTION OF THE SYSTEM BOUNDARY (X = INCLUDED IN LCA; MND = MODULE NOT DECLARED)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRODUCT STAGE</td>
</tr>
<tr>
<td>Raw material supply</td>
</tr>
<tr>
<td>X</td>
</tr>
</tbody>
</table>

RESULTS OF THE LCA - ENVIRONMENTAL IMPACT: 1 tone structural steel

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>A1 - A3</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global warming potential</td>
<td>kg CO2-Eq</td>
<td>1773</td>
<td>0.669</td>
</tr>
<tr>
<td>Depletion potential of the stratospheric ozone layer</td>
<td>kg CFC11-Eq</td>
<td>1.39E-7</td>
<td>6.29E-8</td>
</tr>
<tr>
<td>Acidification potential of land and water</td>
<td>kg SO2-Eq</td>
<td>3.52</td>
<td>1.18</td>
</tr>
<tr>
<td>Eutrophication potential</td>
<td>kg PO4-Eq</td>
<td>3.71E-2</td>
<td>1.28E-1</td>
</tr>
<tr>
<td>Formation potential of tropospheric ozone photochemical oxidants</td>
<td>kg NOx-Eq</td>
<td>6.96E-1</td>
<td>4.14E-1</td>
</tr>
<tr>
<td>Abiotic depletion potential for non-fossil resources</td>
<td>kg 50 Eq</td>
<td>2.85E-4</td>
<td>1.11E-4</td>
</tr>
<tr>
<td>Abiotic depletion potential for fossil resources</td>
<td>MJ</td>
<td>17000</td>
<td>3.74E-1</td>
</tr>
</tbody>
</table>
Life-time assessment of bridges

INVENTORY ANALYSIS

✓ Environmental data for different steel grades

Cumulated energy demand (CED) for heavy plates (closed-loop-approach) made of various steel grades

Life-time assessment of bridges

INVENTORY ANALYSIS

✓ Environmental data for different steel grades referring to S235J2

Life-time assessment of bridges

INVENTORY ANALYSIS

√ Environmental data for different steel grades referring to S235J2

Relation of CED, GWP100 and AP of heavy plates for various steel grades referring to S235J2

Required weight saving ΔG in [%] compared to steel grade S235J2

<table>
<thead>
<tr>
<th></th>
<th>S355J2</th>
<th>S420N</th>
<th>S460N</th>
<th>S420M</th>
<th>S460M</th>
<th>S460Q</th>
<th>S500Q</th>
<th>S550Q</th>
<th>S620Q</th>
<th>S690Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>heavy plates</td>
<td>6.6</td>
<td>9.3</td>
<td>10.6</td>
<td>3.3</td>
<td>4.1</td>
<td>10.2</td>
<td>11.1</td>
<td>13.4</td>
<td>15.5</td>
<td>17.1</td>
</tr>
<tr>
<td>rolled sections</td>
<td>6.7</td>
<td>8.8</td>
<td>9.9</td>
<td>3.4</td>
<td>4.2</td>
<td>10.0</td>
<td>10.7</td>
<td>12.6</td>
<td>14.2</td>
<td>15.6</td>
</tr>
</tbody>
</table>

Life-time assessment of bridges

INVENTORY ANALYSIS

✓ Environmental data for different steel grades

Stainless steel - Cradle to gate: GWP

Base case & Net results including [Burden for scrap inputs - Credit for scrap outputs]

Steel (EN 1.4162)
Analysis: 21.5 % Cr, 1.5 % Ni & 0.3 % Mo
Scrap input: 56 % of Cr & 27 % Ni from virgin

Steel (EN 1.4301)
Analysis: 16.1 % Cr & 8.3 % Ni
Scrap input: 32 % of Cr & 22 % Ni from virgin

Cradle-to-gate results of two stainless steel grades.

Life-time assessment of bridges

INVENTORY ANALYSIS

✓ Cost of different steel grades (*production and fabrication*)

![Steel prices and mass reduction graphs](image)

Economic efficiency - Relative price comparison for heavy plates of various steel grades

A moderate increase in price that may be compensated by appropriate weight savings.

*Source: Stroetmann, R. HSS for improvement of sustainability. Eurosteel 2011.*
## Life-time assessment of bridges

### IMPACT ASSESSMENT

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Brief description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Abiotic depletion</strong></td>
<td>Depletion of natural resources</td>
<td>kg of antimony (Sb) eq.</td>
</tr>
<tr>
<td><strong>Acidification</strong></td>
<td>Atmospheric pollution arising from anthropogenically derived sulphur (S) and nitrogen (N), which enhances the rates of acidification of soils and may then exceed its natural neutralising capacity</td>
<td>kg SO\textsubscript{2} eq.</td>
</tr>
<tr>
<td><strong>Eutrophication</strong></td>
<td>The gradual increase and enrichment of ecosystems by nutrients such as nitrogen (N) and/or phosphorus (P)</td>
<td>kg PO\textsubscript{4} eq.</td>
</tr>
<tr>
<td><strong>Global warming</strong></td>
<td>The potential contribution of a substance to the greenhouse effect.</td>
<td>kg CO\textsubscript{2} eq.</td>
</tr>
<tr>
<td><strong>Ozone layer depletion</strong></td>
<td>Defines ozone depletion potential of different gasses</td>
<td>kg CFC-11 eq.</td>
</tr>
<tr>
<td><strong>Photochemical oxidation</strong></td>
<td>Formation of reactive substances (mainly ozone) which are injurious to human health and ecosystems</td>
<td>kg of ethylene (C\textsubscript{2}H\textsubscript{4}) eq.</td>
</tr>
</tbody>
</table>
Life-time assessment of bridges

Life cycle performance - Analysis of use stage (modules B1-B5)

Focus on fatigue assessment
Life-time assessment of bridges

PROGRAM DEVELOPMENT

➢ **Scope**: Composite girder-bridge with numerous spans.

➢ Program developed in PYTHON 2.7.12.

➢ Organised in 4 Main Modules

1. Beam Analysis
2. Influence line and FLM3
3. Traffic simulation
4. Cross-section and detail verification to fatigue

➢ Databases using SQLite
Life-time assessment of bridges

PROGRAM DEVELOPMENT

FLOWCHART
Life-time assessment of bridges

PROGRAM DEVELOPMENT

➢ Scope: Composite girder-bridge with numerous spans.

➢ Program developed in PYTHON 2.7.12.

➢ Organised in 4 Main Modules

1. Beam Analysis
   This module aims to get the load effects on the main girders
   (shear and bending moment).

2. Influence line and FLM3

3. Traffic simulation

4. Cross-section and detail verification to fatigue
Life-time assessment of bridges

PROGRAM DEVELOPMENT

BEAM ANALYSIS

INPUTS
- Segments
- OutPoints
- Supports
- Distributed Loads
- Point Loads

START
- Support = 1
- Number of supports = 1
- Number of supports = 2

NO
- Number of spans < 2
- Number of supports > 2

YES
- Use Cantilever
- Use SSSpan

Find deflection and slope @ intermediate supports
Vertical reaction @ intermediate supports (PVW)
Store reactions together with PLoads in PLoads2 and eliminate internal supports
Use Macaulay
Use SSSpan with SSSupports and PLoads2

Support with imposed displacement

NO
- Add support displacement to the deflection

YES

END

OUTPUTS
- Shear
- Bending moment
- Slope
- Deflection
Life-time assessment of bridges

PROGRAM DEVELOPMENT

- **Scope:** Composite girder-bridge with numerous spans.
- Program developed in PYTHON 2.7.12.
- Organised in 4 Main Modules
  1. Beam Analysis
  2. Influence line and FLM3

Calculates the shear and moment influence lines for a particular cross-section and applies the FLM3 in order to get the absolute maximum load effects for that section.
  3. Traffic simulation
  4. Cross-section and detail verification to fatigue
Life-time assessment of bridges

PROGRAM DEVELOPMENT

INFLUENCE LINE

This module allow us to study where should the loads be positioned in order to get maximum and minimum load effects in the cross-section where the detail under study is located.
The Eurocode proposes a load model - FLM3 - for fatigue design and verification when considering a finite life of the structure, which is most commonly used in practice along with the simplified damage equivalent factor method.
Life-time assessment of bridges

PROGRAM DEVELOPMENT

➤ Scope: Composite girder-bridge with numerous spans.

➤ Program developed in PYTHON 2.7.12.

➤ Organised in 4 Main Modules

1. Beam Analysis
2. Influence line and FLM3
3. Traffic simulation
   Generates a random stream of heavy load traffic and evaluates its action effects on the structure
4. Cross-section and detail verification to fatigue
Life-time assessment of bridges

PROGRAM DEVELOPMENT

TRAFFIC SIMULATION

Generate a stream of truck traffic in one lane

Calculate the bridge load effects for a stream of truck traffic

INPUTS

- Min and max truck speed [km/h]
- Min gap between vehicles [sec] (safety)
- Period of time [hr]
- Start of day period [hr]
- End of day period [hr]

- Min and max flow rate during day period [truck/h]
- Min and max flow rate during day night [truck/h]
- Time step [sec]
Life-time assessment of bridges

PROGRAM DEVELOPMENT

- **Scope**: Composite girder-bridge with numerous spans.

- **Program developed in PYTHON 2.7.12**.

- **Organised in 4 Main Modules**
  1. Beam Analysis
  2. Influence line and FLM3
  3. Traffic simulation
  4. Cross-section and detail verification to fatigue

  Calculates the cross-section properties and checks the verification of the detail under fatigue using both damage equivalent and damage accumulation methods.
Life-time assessment of bridges

PROGRAM DEVELOPMENT

CROSS SECTION

- Steel cross-section
- Effective properties (local buckling)
- Shear lag (effective width)
- Concrete cracking
- Creep (modular ratios)
Case study

GENERAL DESCRIPTION

• Composite steel-concrete girder bridge with a continuous multiple-span configuration
• Steel grades - **CASE A: S355** and **CASE B: S690** (HSS).
• Concrete C35/45. Reinforcement steel B500B. Head stud connectors S235.
• 2 lanes of traffic per direction.
• 1 slow lane per direction.
# Case study

**Bill of main materials (case A vs. case B)**

<table>
<thead>
<tr>
<th></th>
<th>Case A</th>
<th>Case B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete slab (kg)</td>
<td>1373100</td>
<td>1367810</td>
</tr>
<tr>
<td>Steel girders (kg)</td>
<td>159021</td>
<td>110097</td>
</tr>
<tr>
<td>Connectors (kg)</td>
<td>790</td>
<td>790</td>
</tr>
<tr>
<td>Stiffners (kg)</td>
<td>15084</td>
<td>14028</td>
</tr>
<tr>
<td>Reinforcement (kg)</td>
<td>67521</td>
<td>67261</td>
</tr>
</tbody>
</table>

≈- 30%
Case study

Comparison of results - case A vs. case B
Case study

Comparison of results - case A vs. case B

Sensitivity analysis: assuming +10% for HSS
Case study

Comparison of results - case A vs. case B

STRUCTURAL STEEL DISTRIBUTION

![Diagram showing structural steel distribution]
Case study

Comparison of results - case A vs. case B

CUMULATIVE DAMAGE METHOD

- Initial conditions:

<table>
<thead>
<tr>
<th>Days of analysis</th>
<th>min speed</th>
<th>max speed</th>
<th>min gap</th>
<th>time analysis</th>
<th>min flow day</th>
<th>max flow day</th>
<th>min flow night</th>
<th>max flow night</th>
<th>start time day</th>
<th>end time day</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[km/h]</td>
<td>[km/h]</td>
<td>[sec]</td>
<td>[hrs]</td>
<td>[hr]</td>
<td>[hr]</td>
<td>[hr]</td>
<td>[hr]</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>28</td>
<td>60</td>
<td>110</td>
<td>1.5</td>
<td>720</td>
<td>200</td>
<td>10</td>
<td>100</td>
<td>6</td>
<td>22</td>
</tr>
</tbody>
</table>

- Maximum stress range:

\[ \Delta \sigma_L = 32.4 \times 1.35 = 24 \text{ MPa} \]

- Damage:

<table>
<thead>
<tr>
<th></th>
<th>1 month</th>
<th>50 years</th>
<th>100 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cumulative damage</td>
<td>S355</td>
<td>S690</td>
<td>S355</td>
</tr>
<tr>
<td>At intermediate support</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>At mid-span</td>
<td>8.524 E-4</td>
<td>9.94 E-4</td>
<td>0.511</td>
</tr>
</tbody>
</table>

\[ D > 1 ! \]

- Thus, minor repairs are expected to occur in both cases;
- However, as there is not traffic under the bridge, no significant differences are estimated for the environmental performance of the bridges over their service lives.
Conclusions

 ✓ The use of HSS enables to reduce the amount of steel used in the structural system of bridges;

 ✓ This reduction leads to improvements in the life cycle environmental performance of the bridge as resources are saved and emissions are reduced;

 ✓ Steel structures made by HSS may be more vulnerable to fatigue problems;

 ✓ The use of post-welding treatments may enable to reduce this vulnerability (this will be assessed in the near future).
Thank you for your attention!

Constança Rigueiro

E-Mail  mcsr@dec.uc.pt
Telefon +351 239 797166
Fax      +351 239 797166

University of Coimbra
Department of Civil Engineering
Rua Luís Reis Santos – Polo II
3030 Coimbra