ADVANCED DESIGN OF STEEL AND COMPOSITE STRUCTURES

Luís Simões da Silva

Module B: 20-21/2/2014

European Erasmus Mundus Master Course

Sustainable Constructions under Natural Hazards and Catastrophic Events

520121-1-2011-1-CZ-ERA MUNDUS-EMMC
COURSE CONTENTS

MODULE B – Design of Tubular Structures

1 – Overview
   ▪ Structural solutions. Materials and products
2 – Design of tubular members
3 – Design of joints
   ▪ I-beam to tubular column joints
     • fin-plate
     • end-plate
     • reverse channel
REFERENCES


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REFERENCES


SOFTWARE


SOFTWARE


REFERENCES

STANDARDS

ADVANCED DESIGN OF STEEL AND COMPOSITE STRUCTURES

Luís Simões da Silva
Module B: 20/2/2014

OVERVIEW

Structural solutions. Materials and products
BUILDINGS
HOLLOW STRUCTURAL SECTION
APPLICATIONS


http://www.atlastube.com/hss/hss-hollow-structural-sections
HOLLOW STRUCTURAL SECTION
APPLICATIONS


MODULE B – Design of tubular structures

HOLLOW STRUCTURAL SECTION
APPLICATIONS
TRUSS STRUCTURES

MODULE B – Design of tubular structures
BRACING IN INDUSTRIAL BUILDINGS
LONG SPAN ROOFS

Friends Arena (Hilong report)

STAYED COLUMNS

HILONG – High Strength Long Span Structures
Funding: 1.6 M€ Jul 2012 – Jul 2015

MODULE B – Design of tubular structures
BRIDGES

http://www.lera.com/pimg/mihomuseumbridge/3295149_large.jpg
STADIA

AMUSEMENT PARKS

http://www.geograph.org.uk/photo/1826891

http://lewebpedagogique.com/goossensphilippoe1/london-eye/london_eye/

http://anozer.deviantart.com/art/LONDON-EYE-tubes-213329953
WIND TOWERS

http://www.martifer.pt/pt/grupo/institucional/areas-de-negocio/martifer-renewables/

Modular tower
JOINTS

http://tboake.com/SSEF1/bolt.shtml

http://architectureau.com/articles/architecturally-exposed-structural-steel/#img=3
JOINTS

http://cms.esi.info/Media/documents/Linda_Cavityfixing_ML.pdf
JOINTS

http://www.steelconstruction.info/Expressed_connections

MODULE B – Design of tubular structures
JOINTS

http://architectureau.com/articles/architecturally-exposed-structural-steel/#img=3

http://www.designboom.com/architecture/jakob-macfarlane-la-ville-intelligente/
JOINTS

CASE STUDY 1: GAS EXAUST CHIMNEY (CELBI)
CASE STUDY 1: GAS EXAUST CHIMNEY (CELBI)

Fig. 1 – Estrutura original e enquadramento
CASE STUDY 1: GAS EXAUST CHIMNEY (CELBI)

Fig. 2 – Esquenos iniciais do projecto
CASE STUDY 1: GAS EXAUST CHIMNEY (CELBI)

Fig. 3a – A Folha

Fig. 3b – A Torre

Fig. 3c – O Cubo

Fig. 3 – Propostas preliminares
CASE STUDY 1: GAS EXAUST CHIMNEY (CELBI)

Fig. 4 – Propostas finais
CASE STUDY 1: GAS EXAUST CHIMNEY (CELBI)

Fig. 5a - PARTE 1

Fig. 5b - PARTE 2

Fig. 5c - PARTE 3

Fig. 5 – Subdivisão estrutural da “Folha”
CASE STUDY 1: GAS EXAUST CHIMNEY (CELBI)

Fig. 6 – Ligação à estrutura existente em betão armado

Fig. 7 – Apoio horizontal
CASE STUDY 1: GAS EXAUST CHIMNEY (CELBI)

Fig. 8 – Modelo global da estrutura

Fig. 9 – Montagem das partes da estrutura
CASE STUDY 1: GAS EXAUST CHIMNEY (CELBI)
CASE STUDY 2: PAPER PULP WAREHOUSE (CELBI)

Expansion of a paper pulp warehouse in the industrial facilities of CELBI - Celulose Beira Industrial, Leirosa, Figueira da Foz, Portugal.

**REQUIREMENTS:**
- pavilhão para armazenamento da pasta de papel que fosse amplo para permitir o acesso e a fácil manobragem dos camiões para transporte da pasta.
- execução faseada da obra de forma a mão diminuir a capacidade de armazenamento da pasta de papel no armazém adjacente.

A primeira fase que correspondia a ampliar a área de armazenamento em cerca de 1680m² não implicava qualquer demolição do pavilhão existente, apenas sendo necessário eliminar os paramentos exteriores de forma a garantir a circulação para a nova zona de armazenamento. A segunda fase envolve uma área de 3360 m² e a terceira fase uma área de 2688 m².
Phased construction: total expansion divided in modules.
PHASE 1: 1 module. PHASE 2 and PHASE 3: 2 modules each.
1st module was offset by 1m in order to safeguard the existing warehouse.
Structural layout of 28 x 60 m, with 1 span in the smaller side and 2 spans of 30 m each in the other direction.
CASE STUDY 2: PAPER PULP WAREHOUSE (CELBI)
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ADVANCED DESIGN OF STEEL AND COMPOSITE STRUCTURES

Luís Simões da Silva

Module B: 20/2/2014

DESIGN OF TUBULAR MEMBERS

ECCS Steel Member Calculator / FERPINTA Calculator
The software to be used with the ECCS Book

DESIGN OF TUBULAR MEMBERS
The software to be used with the ECCS Book

- HOW TO GET SOFTWARE
  - Download the following free software (Windows) according to the instructions from the course organizers
    - Download installation instructions for Semi-Comp Member Design Software (excel based) from www.steelconstruct.com
    - Download zipped file for Semi-Comp Member Design
The software to be used with the ECCS Book

- **HOW TO GET SOFTWARE**
  - From your iPhone or iPad launch the App Store application and search for **ECCS**.
  - Download and install the free application ECCS EC3 Steel Member Calculator (ECCS EC3).
  - From your iPhone or iPad launch the App Store application and search for **FERPINTA**.
  - Download and install the free application FERPINTA Calculator.
  - **CONGRATULATIONS! YOU ARE SET TO GO!**
Beam-column (IPE 360, S355)

Use:
- ECCS EC3 Steel Member Calculator (iPhone/iPad)
- Semi-Comp Member Design Software (Windows OS)
i) Cross section classification

EC3-1-1 does not provide criteria for the definition of the cross sectional class to be considered in the verification of the stability of a member, for the common case in which the class varies along the member as a consequence of varying internal forces. Following the guidance from the SEMI-COMP+ project (Greiner et al, 2011), the classification for member buckling design may be established as an equivalent class based on the cross section with maximum first-order utilization factor. In this case, since the utilization factor is maximum at cross section C (UF = 0.608), the classification of the beam-column for member buckling design corresponds to the cross sectional class of section C. As this section is subjected to bending and compression, the position of the neutral axis for the situation of complete plastification of the section, which is necessary for the classification of the web, depends on the relation between the bending moment and the axial force. According to
i) Cross section classification

sub-chapter 2.4, expression (2.27) may be used to estimate the position of the neutral axis, for fully plastic stress distributions, giving:

\[
\alpha = \frac{1}{2} + \frac{-220}{-280} \left( \frac{1}{298.6 \times 10^{-3}} - \frac{1}{2 \times 298.6 \times 10^{-3}} \right) \cdot \left(298.6 \times 10^{-3} \times \frac{-280}{-220} \right) + \frac{(-280)^2}{(-220)^2} \left( 4 \times 1019 \times 10^{-6} - (298.6 \times 10^{-3})^2 \times 8 \times 10^{-3} \right) + 4
\]

\[= 0.759\]

For the web in bending and compression,

\[
c/t = \frac{396 \varepsilon}{13 \alpha - 1} = \frac{396 \times 0.81}{13 \times 0.759 - 1} = 36.17 \quad \text{(not of Class 1)}
\]

\[
c/t = \frac{456 \varepsilon}{13 \alpha - 1} = \frac{456 \times 0.81}{13 \times 0.759 - 1} = 41.66 \quad \text{(Class 2)}
\]

Compressed flange,

\[
c/t = \frac{170/2 - 8/2 - 18}{12.7} = 5.0 < 9 \varepsilon = 9 \times 0.81 = 7.3. \quad \text{(Class 1)}
\]

Therefore, the section is class 2. Note that if the cross section class were established based on the internal forces at section A (compression only), the class of the member for the stability check would be 4.
DESIGN OF TUBULAR MEMBERS

ii) Verification of the cross section resistance

Based on the internal force diagrams, section B is the critical cross section, with $M_{y,Ed} = 220.0 \text{ kNm}$ and $N_{Ed} = 280.0 \text{ kN}$. Since

$$N_{pl,Rd} = f_y A / \gamma_{M0} = 2581.9 \text{ kN},$$

$$N_{Ed} = 280.0 \text{ kN} \leq 0.25 N_{pl,Rd} = 645.5 \text{ kN},$$

and

$$N_{Ed} = 280.0 \text{ kN} \leq 0.5 h_w t_w f_y / \gamma_{M0} = 475.1 \text{ kN},$$

according to clause 6.2.9.1(4) it is not necessary to reduce the plastic bending resistance, which is therefore given by:

$$M_{pl,y,Rd} = W_{pl,y} \frac{f_y}{\gamma_{M0}} = 361.7 \text{ kNm} > M_{y,Ed} = 220.0 \text{ kNm}.$$
iii) Verification of the stability of the member

In this example only Method 2 is applied. As the member is susceptible to torsional deformations (thin-walled open cross section), it is assumed that lateral-torsional buckling constitutes the relevant instability mode. Since $M_{z,Ed} = 0$, the following conditions must be verified:

\[
\frac{N_{Ed}}{\chi_y N_{Rk}/\gamma_{M1}} + k_{xy} \frac{M_{y,Ed}}{\chi_{LT} M_{y,Rk}/\gamma_{M1}} \leq 1.0;
\]

\[
\frac{N_{Ed}}{\chi_z N_{Rk}/\gamma_{M1}} + k_{zy} \frac{M_{y,Ed}}{\chi_{LT} M_{y,Rk}/\gamma_{M1}} \leq 1.0.
\]

The following steps are required to calculate the interaction factors $k_{xy}$ and $k_{zy}$.

- **Step 1**: characteristic resistance of the section

  \[
  N_{Rk} = A f_y = 72.73 \times 10^{-4} \times 355 \times 10^3 = 2581.9 \text{ kN} ;
  \]

  \[
  M_{y,Rk} = W_{pl,y} f_y = 1019 \times 10^{-6} \times 355 \times 10^3 = 361.7 \text{ kNm}.
  \]
- Step 2: reduction coefficients due to flexural buckling, $\chi_y$ and $\chi_z$

Plane $xz - L_{E,y} = 6.0\ m$.

\[
\frac{1}{\lambda_y} = \frac{L_{E,y}}{i_y} \frac{1}{\lambda_1} = \frac{6}{14.95 \times 10^{-2}} \times \frac{1}{93.9 \times 0.81} = 0.53;
\]

$\alpha = 0.21$ \quad Curve a (Table 6.2);

$\phi = 0.68$ \quad $\Rightarrow \chi_y = 0.90$.

Plane $xy - L_{E,z} = 3.0\ m$, assuming that secondary beams prevent displacements of the braced cross sections in the $y$ direction.

\[
\frac{1}{\lambda_z} = \frac{L_{E,z}}{i_z} \frac{1}{\lambda_1} = \frac{3.0}{3.79 \times 10^{-2}} \times \frac{1}{93.9 \times 0.81} = 1.04;
\]

$\alpha = 0.34$ \quad Curve b (Table 6.2);

$\phi = 1.18$ \quad $\Rightarrow \chi_z = 0.58$. 
- Step 3: calculation of the $\lambda_{LT}$ using the alternative method applicable to rolled or equivalent welded sections (clause 6.3.2.3)

The length between braced sections is $L = 3.0 \, m$. Using expression (3.100) and Table 3.5 for a member subjected to unequal end moments, gives:

$$\beta = -0.50 \Rightarrow \alpha_m = 1.30 \Rightarrow M_{cr} = 644.9 \, kNm \Rightarrow \lambda_{LT} = 0.75.$$  

As $\alpha_{LT} = 0.49$ (rolled I or H sections with $h/b > 2 \Rightarrow$ curve c and, from clause 6.3.2.3, taking $\lambda_{LT,0} = 0.4$ and, $\beta = 0.75$, gives:

$$\phi_{LT} = 0.80 \Rightarrow \lambda_{LT} = 0.79.$$  

The correction factor $k_c$, according to Table 3.10 (Table 6.6 of EC3-1-1), with $\Psi = 0.50$, is given by:

$$k_c = \frac{1}{1.33 - 0.33 \Psi} = 0.86.$$  

From expression (3.115),

$$f = 1 - 0.5 \times (1 - 0.86) \times \left[1 - 2.0 \times (0.75 - 0.8)^2\right] = 0.93,$$

The modified lateral-torsional buckling reduction factor is obtained:

$$\lambda_{LT,\text{mod}} = 0.79 / 0.93 = 0.85.$$
**DESIGN OF TUBULAR MEMBERS**

Calculation using:
- Semi-Comp Member Design (Windows OS)

### Member Check

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{eq}$</td>
<td>2581.888 kN</td>
</tr>
<tr>
<td>$M_{y, Rd}$</td>
<td>361.797 kNm</td>
</tr>
<tr>
<td>$M_{z, Rd}$</td>
<td>67.840 kNm</td>
</tr>
</tbody>
</table>

**Strong axis buckling**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{CS,y}$</td>
<td>6.000 m</td>
</tr>
<tr>
<td>$N_{eq,y}$</td>
<td>9364.562 kN</td>
</tr>
</tbody>
</table>

**Weak axis buckling**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{CS,z}$</td>
<td>3.000 m</td>
</tr>
<tr>
<td>$N_{eq,z}$</td>
<td>2402.974 kN</td>
</tr>
</tbody>
</table>

**Lateral torsional buckling**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{LT, max}$</td>
<td>644.900 kNm</td>
</tr>
</tbody>
</table>

### Method 2 auxiliary terms (if applicable):

- $C_{my} = 0.600 [-]$
- $C_{mez} = 0.000 [-]$
- $C_{rel,T} = 0.800 [-]$

### EN 1993-1-1, 6.3.3

*Uniform member in bending and axial compression*

- Eq. (6.61): $U = 0.561 \leq 1.0$, **ok**
- Eq. (6.62): $U = 0.875 \leq 1.0$, **ok**

*Global interaction factors*

- $k_{yy} = 0.623$
- $k_{zz} = 0.000$
- $k_{yz} = 0.965$
- $k_{zzz} = 0.000$

### Cross-section check at each end of the member

- Left end: $U = 0.106 \leq 1.0$, **ok**, $UF = 0.106$
- Right end: $U = 0.606 \leq 1.0$, **ok**, $UF = 0.606$

### Additional member checks

**EN 1993-1-1, 6.3.1**

*Strong axis flexural buckling check*

- Eq. (6.46): $N_{eq}/N_{y,Rd} = 0.118 \leq 1.0$, **ok**

*Weak axis flexural buckling check*

- Eq. (6.46): $N_{eq}/N_{y,Rd} = 0.109 \leq 1.0$, **ok**

**EN 1993-1-1, 6.3.2**

*Lateral torsional buckling*

- Eq. (6.54): $M_{LT}/M_{LT,Rd} = 0.711 \leq 1.0$, **ok**
Because the member is susceptible to torsional deformations, the interaction factors are obtained from Table 3.17 (Table B.2 of EC3-1-1). First, the equivalent factors of uniform moment $C_{my}$ and $C_{mLT}$ are obtained based on the bending moment diagram, between braced sections according to the $y$ direction in case of $C_{my}$ and in the $z$ direction in case of $C_{mLT}$. The factor $C_{my}$ is taken for a non-sway structure, in accordance with the second method described in 2.3.2.1 (5.2.2(7)b of EC3-1-1), that was adopted in this example. Assuming a member braced in $z$ direction and laterally at the base, mid-height and top, the factor $C_{mLT}$ must be calculated based on the bending moment diagram in the upper half of the column (most unfavourable), while $C_{my}$ is calculated based on the bending moment diagram My along the total length of the member; since the bending moment diagram is linear, defined by $M_{v,Ed,base} = 0$, $M_{1/2height} = -110 \text{ kNm}$ and $M_{v,Ed,top} = -220 \text{ kNm}$, based on Table 3.18,

$$\Psi = \frac{M_{v,Ed,base}}{M_{v,Ed,top}} = \frac{0}{(-220)} = 0;$$

$$C_{my} = 0.60 + 0.4 \times (0) = 0.60 \ (> 0.40).$$
DESIGN OF TUBULAR MEMBERS

\[ \Psi = \frac{M_{1/2\text{height}}}{M_{y,\text{Ed, top}}} = \frac{-110}{-220} = 0.5; \]

\[ C_{mLT} = 0.60 + 0.4 \times (0.5) = 0.80 \quad (> 0.40). \]

The interaction factors \( k_{yy} \) and \( k_{zy} \) are given by:

\[
k_{yy} = C_{my} \left[ 1 + \left( \bar{\lambda}_y - 0.2 \right) \frac{N_{Ed}}{X_y N_{Rk} / \gamma_{M1}} \right] = 0.60 \times \left[ 1 + (0.53 - 0.2) \times \frac{280.0}{0.90 \times 2581.9 / 1.0} \right] = 0.624; \]

as \( k_{yy} = 0.624 \leq C_{my} \left( 1 + 0.8 \frac{N_{Ed}}{X_y N_{Rk} / \gamma_{M1}} \right) = 0.658, \)

giving \( k_{yy} = 0.624. \)

\[
k_{zy} = \left[ 1 - \frac{0.1 \bar{\lambda}_z}{(C_{mLT} - 0.25) \chi_z N_{Rk} / \gamma_{M1}} \right] = \left[ 1 - \frac{0.1 \times 1.04}{(0.80 - 0.25) 0.58 \times 2581.9 / 1.0} \right] = 0.966 \]

as \( k_{zy} = 0.966 \geq \left[ 1 - \frac{0.1}{(C_{mLT} - 0.25) \chi_z N_{Rk} / \gamma_{M1}} \right] = 0.947, \)

then \( k_{zy} = 0.966. \)

Finally, the verification of expressions (3.144) yields:

\[
\frac{280.0}{0.90 \times 2581.9 / 1.0} + 0.624 \times \frac{220.0}{0.85 \times 361.7 / 1.0} = 0.56 < 1.0; \]

\[
\frac{280.0}{0.58 \times 2581.9 / 1.0} + 0.966 \times \frac{220.0}{0.85 \times 361.7 / 1.0} = 0.88 < 1.0. \]

It is concluded that the IPE 360 is adequate.
Calculation using:
- Semi-Comp Member Design (Windows OS)

**Member Check**

- Strong axis buckling:
  - $L_{pl,y} = 6.000$ m
  - $N_{pl,y} = 9364.562$ kN
  - $\alpha_y = 0.21$ [-]
  - $\lambda_y = 0.525$ [-]
  - $\chi_y = 0.916$ [-]

- Weak axis buckling:
  - $L_{pl,z} = 3.000$ m
  - $N_{pl,z} = 2402.974$ kN
  - $\alpha_z = 0.34$ [-]
  - $\lambda_z = 1.037$ [-]
  - $\chi_z = 0.574$ [-]

**EN 1993-1-1, 6.3.3**

- Uniform member in bending and axial compression:
  - Eq. (6.61): $U = \frac{0.537}{1.0} \leq 1.0$ ok
  - Eq. (6.62): $U = \frac{0.837}{1.0} \leq 1.0$ ok

- Global interaction factors:
  - $k_{yy} = 0.623$
  - $k_{zz} = 0.000$
  - $k_{yy} = 0.966$
  - $k_{zz} = 0.000$

- Cross-section check at each end of the member:
  - Left end: $U = \frac{0.108}{1.0} \leq 1.0$, ok
  - Right end: $U = \frac{0.008}{1.0} \leq 1.0$, ok
  - $U_F = 0.108$
  - $U_F = 0.008$

**Additional member checks**

- EN 1993-1-1, 6.3.1
  - Strong axis flexural buckling check:
    - Eq. (6.48): $N_{pl}/N_{pl,max} = \frac{0.118}{1.0} \leq 1.0$, ok
  - Weak axis flexural buckling check:
    - Eq. (6.48): $N_{pl}/N_{pl,max} = \frac{0.189}{1.0} \leq 1.0$, ok

- EN 1993-1-1, 6.3.2
  - Lateral torsional buckling:
    - Eq. (6.54): $M_{pl}/M_{pl,max} = \frac{0.671}{1.0} \leq 1.0$, ok
DESIGN OF TUBULAR MEMBERS

MAIN APPLICATION MENU

Where do you wish to go?

- TUBULAR
- EQUIVALENT TUBES
- SAVED REPORTS
- HELP

STEEL CALCULATOR

FERPINTA
DESIGN OF TUBULAR MEMBERS

FERPINTA
STEEL CALCULATOR

PROFILE LIST

IPE
IPE 100
IPE A 100
IPE 120
IPE A 120
IPE 140
IPE A 140
IPE 160
IPE A 160
IPE 180
IPE A 180

IPN
IPN 120
IPN A 120
IPN 140
IPN A 140
IPN 160
IPN A 160
IPN 180
IPN A 180
IPN 200
IPN A 200
IPN 220
IPN A 220
IPN 240
IPN A 240
IPN 260
IPN A 260
IPN 280
IPN A 280
IPN 300
IPN A 300
DESIGN OF TUBULAR MEMBERS

FERPINTA

STEEL CALCULATOR

PROFILE DETAILS

DESIGNATION
57.09 G [kg/m]

DIMENSIONS
360.00 h [mm]
170.00 b [mm]
8.00 t.w. [mm]
12.70 t.f. [mm]
18.00 r [mm]

AREA
72.73 A [cm²]

CROSS-SECTION

GEOMETRY
334.60 h.l [mm]
298.60 d [mm]
72.73 p.min [mm]
72.73 p.max [mm]

SURFACE
1.35 A.L [mm²]
23.70 A.G [m²]

SECTION

PROPERTIES:
STRONG AXIS YY
16265.62 l.y [mm]
903.65 W.el.y [mm]
1019.15 W.pl.y [mm]
14.95 iy [mm]
35.14 A.vz [mm]

ENTER INPUTS
DESIGN OF TUBULAR MEMBERS

MODULE B – Design of tubular structures
## DESIGN OF TUBULAR MEMBERS

### STEEL CALCULATOR

**MATCHING**

**ENTER MATCHING PARAMETERS**

**IPE 360**

**CROSS SECTION TYPE**

- **CHS**
- **SHS**
- **RHS**

**DIMENSIONS**

**SHS**

- $B_{\text{min}}$ ($>16$)
  - Value: 85.0
- $B_{\text{max}}$ ($<260$)
  - Value: 255.0

**WEIGHT**

- $G_{\text{min}}$ ($>0.8$)
- $G_{\text{max}}$ ($<91.88$)

**Number of matches to calculate: 53 (~ 1 min)**

**Replace**

**Matching**

- Calculate Profile: 51 of 53 (1 of 1)

**Full Report**
### Design of Tubular Members

**IPE 360**

<table>
<thead>
<tr>
<th>Name</th>
<th>G ↓ [kg/m³]</th>
<th>G ↓ [TubulHt]</th>
<th>AL ↓ [TubulHt]</th>
<th>Cross-section class</th>
<th>Cross-section resistance</th>
<th>Verification</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Pure Compression</td>
<td>Pure Bending</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Member class</td>
<td>Nc,Rd</td>
<td>My.c,Rd</td>
</tr>
<tr>
<td>IPE 360</td>
<td>57.09</td>
<td>-</td>
<td>-</td>
<td>4</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>SHS 100 x 12.5</td>
<td>29.08</td>
<td>0.509</td>
<td>0.248</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>SHS 120 x 10</td>
<td>31.84</td>
<td>0.555</td>
<td>0.323</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>SHS 120 x 12</td>
<td>35.84</td>
<td>0.628</td>
<td>0.309</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>SHS 120 x 12.5</td>
<td>36.83</td>
<td>0.647</td>
<td>0.307</td>
<td>1</td>
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<td>1</td>
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<tr>
<td>SHS 130 x 8</td>
<td>28.92</td>
<td>0.507</td>
<td>0.359</td>
<td>1</td>
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</tr>
<tr>
<td>SHS 140 x 8</td>
<td>31.43</td>
<td>0.551</td>
<td>0.389</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>SHS 140 x 10</td>
<td>38.12</td>
<td>0.658</td>
<td>0.382</td>
<td>1</td>
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</tr>
<tr>
<td>SHS 140 x 12</td>
<td>43.38</td>
<td>0.760</td>
<td>0.368</td>
<td>1</td>
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</tr>
</tbody>
</table>

**Full Report**
DESIGN OF TUBULAR MEMBERS

FERPINTA

STEEL CALCULATOR

MATCHING RESULTS

IPE 360

Default Inputs

Report Name

SHS 220 x 10 - Thu Feb 20 2014 22:42:25 GMT+0200 (EET)

Save

Cancel

FULL REPORT
ADVANCED DESIGN OF STEEL AND COMPOSITE STRUCTURES

Luís Simões da Silva

Module B: 21/2/2014

DESIGN OF JOINTS

I-beam to tubular column joints
COURSE CONTENTS

MODULE B – Design of Tubular Structures

1 – Overview
   ▪ Structural solutions. Materials and products
2 – Design of tubular members
3 – Design of joints
   ▪ I-beam to tubular column joints
     • (minor-axis)
     • fin-plate
     • end-plate
     • reverse channel
INTRODUCTION

• How to tighten the bolts from the inside?

• How to transfer bending moment to the column?
INTRODUCTION

Huck Ultra Twist system

Flowdrill System

Studs welded to the column face

Hollobolt System
Behaviour of the column web in transverse bending

Strains in the column web

Moment (kN.m)

Strain (µ)
Behaviour of the column web in transverse bending: initial stiffness

\[ \mu = \frac{L}{t_{wc}} \]
\[ \beta = \frac{b}{L} \]
\[ \alpha = \frac{c}{L} \]

\[ S_i = \frac{4Et_{wc}^3}{L^2} \left\{ \alpha + (1 - \beta) \tan \theta + 6S \frac{1 - \beta}{Et_{wc}^3} \right\} \]

\[ \beta = \frac{b}{L} \]
\[ \alpha = \frac{c}{L} \]
Behaviour of the column web in transverse bending: initial stiffness

\[ S_i = \frac{Et^3}{L^2} \frac{16}{(1 - \beta)^3 + \frac{10.4(k_1 - k_2 \beta)}{\mu^2}} \alpha + (1 - \beta) \tan \theta \]

\[ S_{i,\text{freeflanges}} = \frac{(\mu/\beta)^{1.25}}{230} S_{i,\text{fixedflanges}} \leq S_{i,\text{fixedflanges}} \]
Behaviour of the column web in transverse bending: initial stiffness

\[ S_{j,ini} = Sh_1 \left( h_1 - \frac{h_1 + h_2}{\frac{S_3}{S} + 2} \right) + Sh_2 \left( h_2 - \frac{h_1 + h_2}{\frac{S_3}{S} + 2} \right) \]
Behaviour of the column web in transverse bending: plastic resistance

i) Linhas de plastificação

ii) Corte

iii) Linhas de plastificação c/ rect equivalente

iv) diâmetro médio da cabeça dos parafusos $d_m = \frac{d_1 + d_2}{2}$
**Behaviour of the column web in transverse bending: plastic resistance**

Constants:

\[ m_p = \frac{1}{4} \left[ \frac{1}{L} \right] f_s \]

\[ \alpha = \frac{4}{1-b/L} \left( \sqrt{[1-b/L]} + 2c/L \right) \]

\[ k = \begin{cases} 1 & \text{if } (b+c)/L \geq 0.5 \\ 0.7 + 0.6(b+c)/L & \text{if } (b+c)/L \leq 0.5 \end{cases} \]

Local mechanism:

\[ F_{\text{local}} = k m_p \]

Global mechanism:

\[ F_{\text{global}} = \begin{cases} m_p \left\{ \frac{2b}{h} + \frac{2h}{L-b} + \frac{2b}{L-b} \right\} & \text{if } \frac{h}{L-b} \geq 1 \\ m_p \left\{ \frac{2b}{h} + \frac{2h}{L-b} + \frac{2b}{L-b} \right\} & \text{if } \frac{h}{L-b} \leq 1 \end{cases} \]

Punching shear failure:
- Punching shear around n bolts heads: \( F_{q(h)} = n d L f_y \frac{f}{\sqrt{3}} \)
- Punching shear around a rectangular area: \( F_{q(h)} = 2(b+c) f_y \frac{f}{\sqrt{3}} \)

Mixed failure (shear and bending):

\[ F_{q3} = 4m_p \left[ \frac{\pi a (a+x) + c}{a+x} + \frac{2c x + x^2}{\sqrt{3} \pi (a+x)} \right] \]

where: \( a = L-b \)

\[ x_c = 1.95 \left\{ \frac{L}{b} \right\}^{1/3} \]

\[ x_c = \frac{a + \sqrt{a^2 - 2ac + \frac{\sqrt{3} \pi (L(a+x)} + 2c} \right\} \]

If \( x_{c1} \leq 0 \) then \( F_{q3} = F_{\text{local}} \)

If \( x_{c1} \leq 20 \) and \( b/L \leq 0.8 \) then \( F_{q3} = F_{\text{local}} \)

Plastic force:

\[ F_{pl} = \min(F_{\text{local}}, F_{\text{global}}, F_{q3}, F_{q3}) \]

if the force is transmitted by two bolts, then

\[ F_{pl} = \min(F_{\text{local}}, F_{\text{global}}, F_{q3}, F_{q3}) \]

with a maximal error of 10%
Behaviour of the column web in transverse bending: plastic resistance

\[ \min \{ F_t; F_c \} \cdot h \]
Behaviour of the column web in transverse bending: post-limit stiffness

\[ f_1 = -0.24\beta - 0.012\mu + 0.72 \]

\[ f_2 = 0.55 + 1.07\alpha + 0.85 \]
I-beam to tubular column joints

- fin-plate
- end-plate
- reverse channel
I-beam to tubular column joints: reverse channel joint
I-beam to tubular column joints: reverse channel joint

- **Dimensions:**
  - **IPE 300**
  - **U 200x90x10 330 long**
  - Ø 26mm hole for M24 bolt
  - **Endplate 330x155x25**

- **CHS 244.5X10**
  - **U 200x135x8 330 long**
  - Ø 26mm hole for M24 bolt
  - **Endplate 330x155x25**
I-beam to tubular column joints: reverse channel joint

Component behaviour: Calibration of the model for parametric studies
I-beam to tubular column joints: reverse channel joint
• **Component behaviour**
  
  - Characterization of the behaviour of the composite joint components to establish the force-deflection-temperature relationship.

**Constant-temperature tests:**

- Testing **reverse channel and CFT column components**;
- Testing isolated joints under different combinations of **axial and shear forces and bending moments**;
- Testing **different reverse channel sections** to failure under tension and compression forces on the web;

  - **4 test temperatures**:
    - ambient temp.;
    - 550ºC;
    - 650ºC;
    - 750ºC.

**Composite column types:**

- CFT: SHS and CHS sections;
- Partially encased H-sections.

**Joint types:**

- Reverse channel;
- Fin-plate;
- Flush endplate.
Component behaviour

Component tests

- CFT component
- Reverse channel in compression
- Reverse channel in tension (1-2 bolt row)

3 different channel sections:
- Welded plates
- Cut from SHS
- Hot-rolled

Prototypes for tension and compression tests
• **Component behaviour**

  ➢ **Component tests**

  - CFT component
  - *Reverse channel in compression*
  - Reverse channel in tension (1-2 bolt row)

  ![Component tests images]

  **Before compression test**
  **After test (750°C)**
  **During test**
Component behaviour

Component tests

- CFT component
- Reverse channel in compression
- Reverse channel in tension (1-2 bolt row)
• **Component behaviour**
  
  ➢ **Isolated joint tests**
  
  - Reverse channel (CFT and PE columns);
  - Fin-plate (CFT columns);
  - Flush endplate (PE column).

  Combinations of axial and shear forces and bending moments
To develop and validate a component-based model for steel joints, and to extend it to composite joints, for applications under arbitrary fire conditions, including the cooling phase, and mechanical actions throughout the fire event.

Component-base model:
- Identification of the active components
- Unloading of the component
- Assembly of components
i) Design checks for vertical shear:

$$V_F$$

ii) Shear and bending resistance of the reverse channel to the column section:

iii) Shear and bending resistance of the reverse channel to the end plate:
ACKNOWLEDGEMENTS

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