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Parametric study on the interaction between axial compression and bending on austenitic stainless steel members with hollow sections under fire situation

Nuno Lopes; Mónica Manuel; Ana Regina Sousa; Paulo Vila Real
RISCO – University of Aveiro

decivil universidade de aveiro
departamento de engenharia civil

Contents

Introduction

- It is still necessary to develop knowledge on stainless steel structural behaviour at elevated temperatures, as existing fire design guidelines, such as in Part 1-2 of EC3, are still based on the formulations developed for carbon steel.

- The beam-column is the most common structural element in construction. Due to the compression stresses beam-columns are susceptible to buckling.

- The walls slenderness of the cross-sections play an important role on the member behaviour. In EC3, Elements composed of Class 4 cross sections are more susceptible to the occurrence of local buckling.

Introduction

- Interaction behaviour between axial compression and bending in beam-columns at elevated temperatures has still not been completely understood.

- The main objective of this work is to present a parametric study on stainless steel structural elements, with square (SHS) and circular (CHS) hollow cross-sections, under fire conditions, applying geometrically and materially non-linear imperfect analysis with the program SAFIR.

- The accuracy and safety of EC3 interactions curves in case of fire are here analysed. Comparisons, between the numerical results and the EC3 rules (EN 1993-1-2) and the interaction curves from Part 1-1 of EC3 and Part 1-4 of EC3, are made.

Cross-section resistance

<table>
<tr><th>EC3</th><th>Square hollow sections</th><th>Circular hollow sections</th></tr>
<tr><td>Class 1 and 2 sections</td><td>$$\frac{M_{y,Ed}}{M_{N,y,Rd}} \leq 1$$ with $$M_{N,y,Rd} = \frac{M_{pl,y,Rd}\left(1 - \frac{N_{Ed}}{N_{pl,Rd}}\right)}{\left(1 - 0.5min\left(\frac{A - 2bt}{A}; 0.5\right)\right)} \leq M_{pl,y,Rd}$$</td><td>$$\frac{M_{y,Ed}}{M_{N,y,Rd}} \leq 1$$ with $$M_{N,y,Rd} = M_{pl,y,Rd}\left(1 - \left[\frac{N_{Ed}}{N_{pl,Rd}}\right]^{1.7}\right) \leq M_{pl,y,Rd}$$</td></tr>
<tr><td>Class 3 and 4 sections</td><td colspan="2">$$\frac{N_{Ed}}{N_{Rd}} + \frac{M_{y,Ed}}{M_{y,Rd}} \leq 1$$ Where:
N_{Rd} is determined using the gross cross section area (A) for Class 3 sections and the effective section area (A_{eff}) for Class 4 sections;
$M_{y,Rd}$ is determined using the elastic section modulus ($W_{el,y}$) for Class 3 sections and the effective section modulus ($W_{eff,y}$) for Class 4 sections.</td></tr>
</table>

Simplified calculation methods for fire design

Cross-section resistance

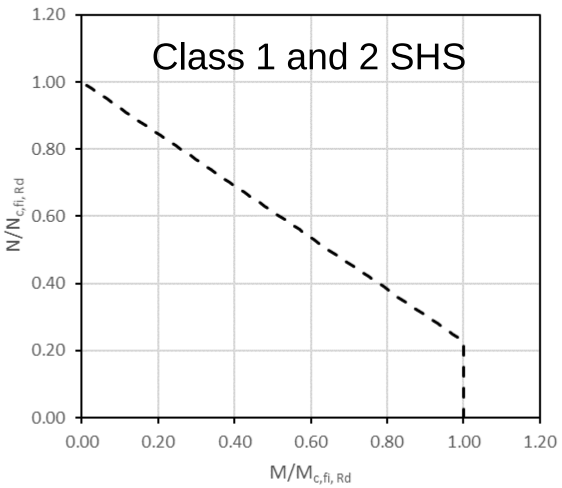
At elevated temperatures:

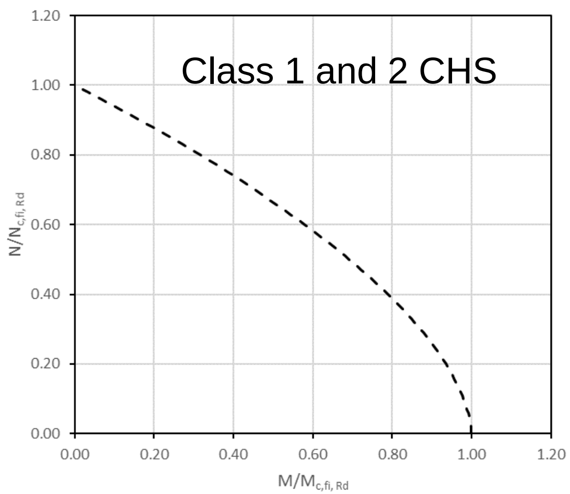
- ✓ For cross-section of classes 1, 2 and 3 it is used the stress at 2% of total strain

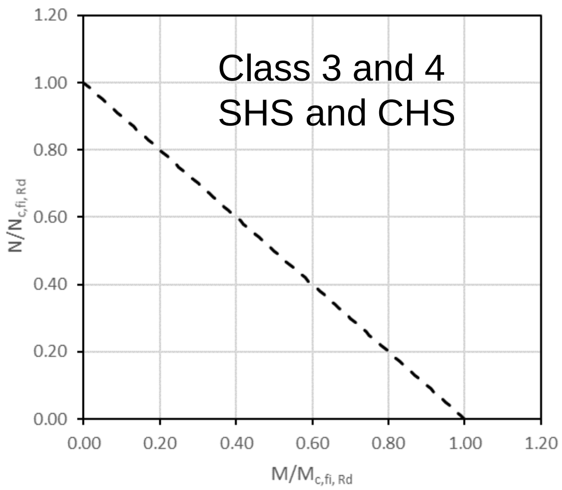
$$f_{y,\theta} = f_{2\%,\theta} = k_{2\%,\theta} f_y$$

- ✓ for Class 4 cross-sections the proof strength at 0.2% should be applied

$$f_{y,\theta} = f_{0.2p,\theta} = k_{0.2p,\theta} f_y$$







Simplified calculation methods for fire design

Interaction curves for member resistance

$$\frac{N_{fi,Ed}}{\chi_{fi} A \frac{f_{y,\theta}}{\gamma_{M,fi}}} + k \frac{M_{fi,Ed}}{W \frac{f_{y,\theta}}{\gamma_{M,fi}}} \leq 1$$

Different interaction factor k corresponded to the following methodologies were considered.

i. EN 1993-1-2;

ii. EN 1993-1-4 adapted at elevated temperatures;

iii. EN 1993-1-1 adapted to stainless steel at elevated temperatures.

$$\chi_{fi} = \frac{1}{\phi_\theta + \sqrt{(\phi_\theta)^2 - \left(\bar{\lambda}_\theta\right)^2}} \quad \text{with } \chi_{fi} \leq 1$$

$$\phi_\theta = \frac{1}{2}\left[1 + \alpha\bar{\lambda}_\theta + \left(\bar{\lambda}_\theta\right)^2\right]$$

$$\alpha = 0.65\sqrt{\frac{235}{f_y}} \qquad \bar{\lambda}_\theta = \bar{\lambda}\sqrt{\frac{k_{y,\theta}}{k_{E,\theta}}}$$

Simplified calculation methods for fire design

Interaction curves for member resistance

$$\frac{N_{fi,Ed}}{\chi_{fi} A \frac{f_{y,\theta}}{\gamma_{M,fi}}} + k \frac{M_{fi,Ed}}{W \frac{f_{y,\theta}}{\gamma_{M,fi}}} \leq 1$$

EN 1993-1-2

$$k = 1 - \frac{\mu N_{fi,Ed}}{\chi_{fi} A \frac{f_{y,\theta}}{\gamma_{M,fi}}} \leq 3$$

$$\mu = (2\beta_M - 5)\bar{\lambda}_\theta + 0.44\beta_M + 0.29 \leq 0.8 \ \text{ with } \ \bar{\lambda}_{20ºC} \leq 1.1$$

$$\beta_M = 1.8 - 0.7\psi$$

Simplified calculation methods for fire design

Interaction curves for member resistance

$$\frac{N_{fi,Ed}}{\chi_{fi} A \frac{f_{y,\theta}}{\gamma_{M,fi}}} + k \frac{M_{fi,Ed}}{W \frac{f_{y,\theta}}{\gamma_{M,fi}}} \leq 1$$

EN 1993-1-4 adapted at elevated temperatures

$$k = 1 + 2(\bar{\lambda} - 0.5) \frac{N_{Ed}}{N_{b,Rd}} \quad \text{but} \quad 1.2 \leq k \leq 1.2 + 2 \frac{N_{Ed}}{N_{b,Rd}}$$

- ✓ This expression does not depend on the bending diagram shape
- ✓ The proposed minimum limit to the interaction factor of 1.2 was not used
- ✓ Yield strength and Young modulus at elevated temperatures, as proposed in Annex C of Part 1-2 of EC3

Simplified calculation methods for fire design

Interaction curves for member resistance

$$\frac{N_{fi,Ed}}{\chi_{fi} A \frac{f_{y,\theta}}{\gamma_{M,fi}}} + k \frac{M_{fi,Ed}}{W \frac{f_{y,\theta}}{\gamma_{M,fi}}} \leq 1$$

EN 1993-1-1 adapted to stainless steel at elevated temperatures (method 2)

Class 1 and 2 sections $k = c_m \left(1 + \left(\bar{\lambda} - 0.2\right) \frac{N_{Ed}}{N_{b,Rd}}\right) \leq c_m \left(1 + 0.8 \frac{N_{Ed}}{N_{b,Rd}}\right)$

Class 3 and 4 sections $k = c_m \left(1 + 0.6 \bar{\lambda} \frac{N_{Ed}}{N_{b,Rd}}\right) \leq c_m \left(1 + 0.6 \frac{N_{Ed}}{N_{b,Rd}}\right)$

for end moments $c_m = 0.6 + 0.4\psi \geq 0.4$

The yield strength and Young modulus values were the one in Part 1-4 of EC3 reduced at elevated temperatures as proposed in Annex C of Part 1-2 of EC3

Case study

- ✓ Austenitic stainless steel grade 1.4301 (304)
- ✓ Three bending diagrams: uniform bending (ψ=1), triangular diagram (ψ=0) and bi-triangular diagram (ψ=-1).
- ✓ Uniform temperatures in the cross section: 350, 500 and 600 ºC
- ✓ Columns lengths (1, 3, 7 and 11 meters)

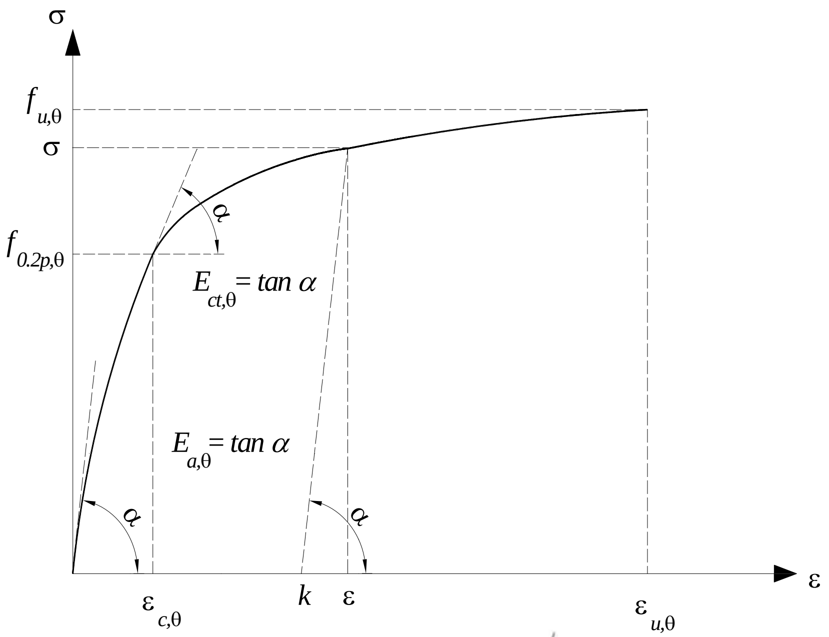
Section classification	SHS [mm]	CHS [mm]
Class 1 or Class 2 sections	200x200x10	244.5x8
Class 3 sections	200x200x7	244.5x2
Class 4 sections less slender	200x200x4	244.5x1.5
Class 4 sections more slender	200x200x2	244.5x1

Classification

$$\varepsilon = 0.85\left[\frac{235}{f_y}\frac{E}{210000}\right]^{0.5}$$

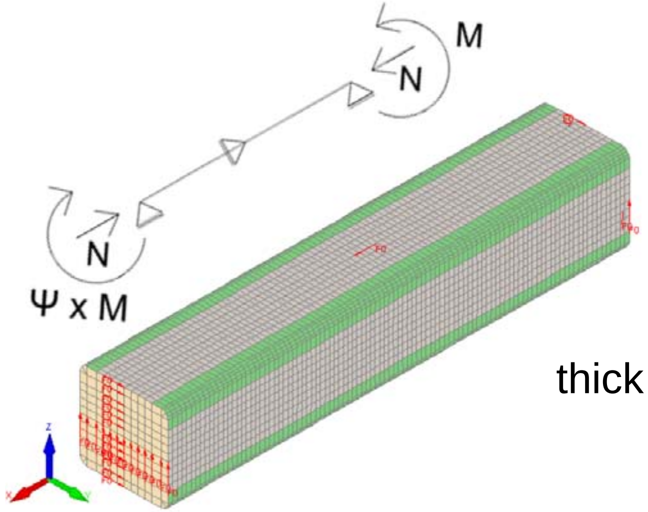
Numerical model

- ✓ Finite element software SAFIR
- ✓ Material model from Part 1-2 of EC3

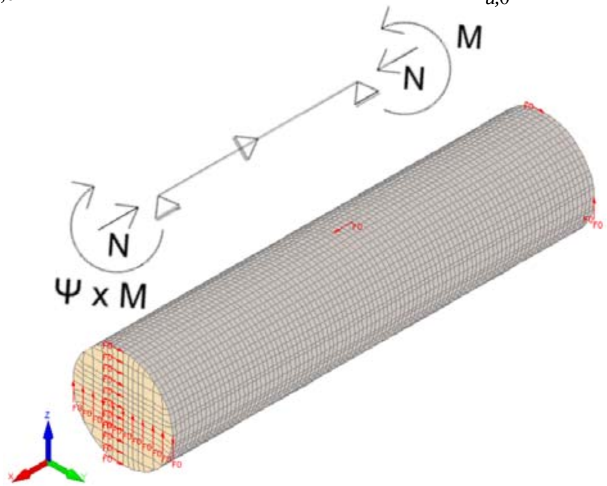


θ_a °C	$k_{E.\theta} = E_{a.\theta}/E_a$	$k_{0.2p.\theta} = f_{0.2p.\theta}/f_y$	$k_{u.\theta} = f_{u.\theta}/f_u$	$k_{Ect.\theta} = E_{ct.\theta}/E_a$	$\varepsilon_{u.\theta}$
350	0.86	0.62	0.725	0.02	0.4
500	0.8	0.54	0.67	0.02	0.4
600	0.76	0.49	0.58	0.02	0.35

- ✓ Mesh and restrictions



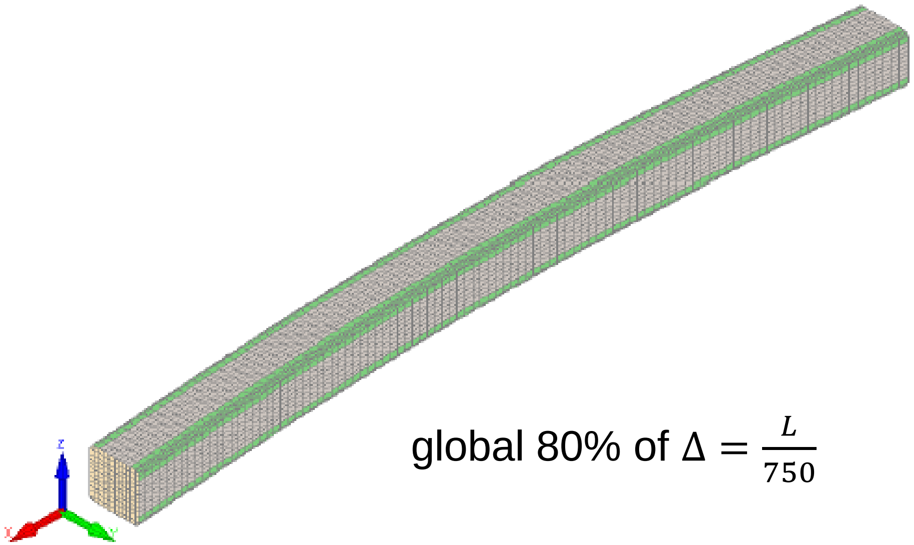
thick end plates at 20 ºC



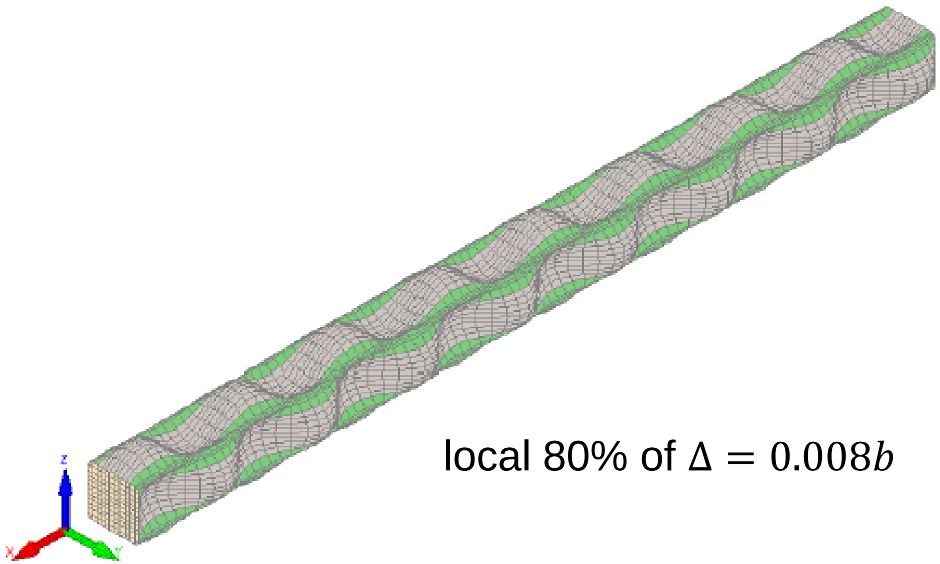
Numerical model

- ✓ Geometric initial imperfections

Annex C of Part 1-5 of EC3 was used, where the shape is obtained from the buckling modes and the amplitude is equal to 80% of the manufacturing tolerances (EN 1090-2:2008+A1 and EN10219-2)



global 80% of $\Delta = \frac{L}{750}$

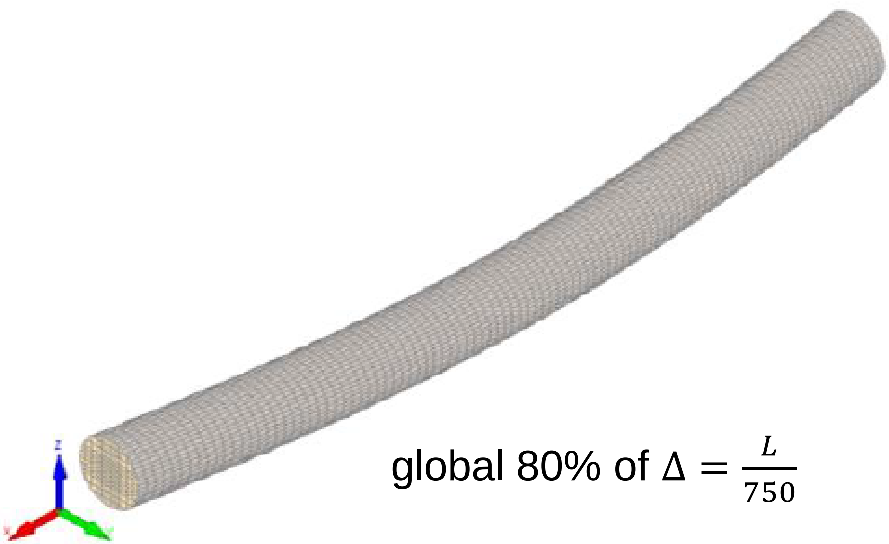


local 80% of $\Delta = 0.008b$

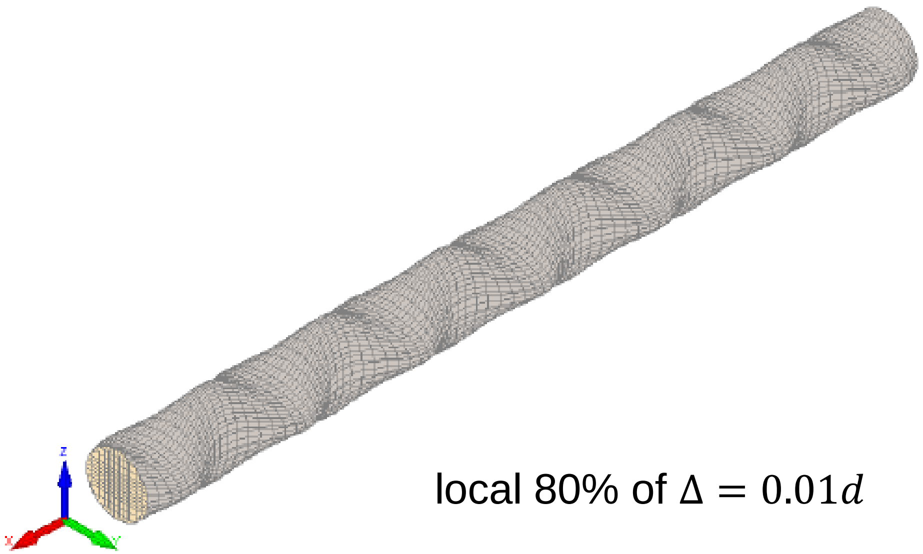
Numerical model

- ✓ Geometric initial imperfections

Annex C of Part 1-5 of EC3 was used, where the shape is obtained from the buckling modes and the amplitude is equal to 80% of the manufacturing tolerances (EN 1090-2:2008+A1 and EN10219-2)



global 80% of $\Delta = \frac{L}{750}$



local 80% of $\Delta = 0.01d$

Numerical model

✓ Residual stresses, as proposed by Gardner and Cruise (2009)

	Bending residual stresses	Membrane residual stresses
Central part of the plate	$\pm 0.63\sigma_{0.2}$	$+0.37\sigma_{0.2}$
External part of the plate	$\pm 0.63\sigma_{0.2}$	$-0.24\sigma_{0.2}$
Corners	$\pm 0.37\sigma_{0.2}$	$-0.24\sigma_{0.2}$

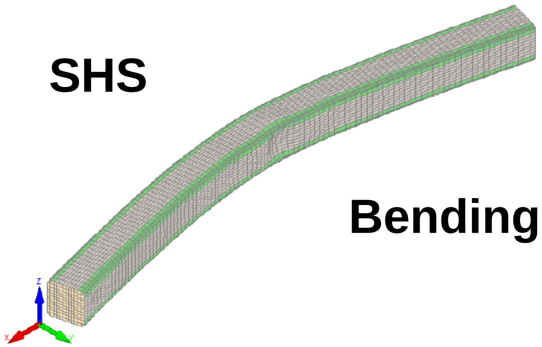
✓ Corner strength enhancement, as proposed by Ashraf et al. (2005)

Spread from the corner for a distance of twice the plate thickness

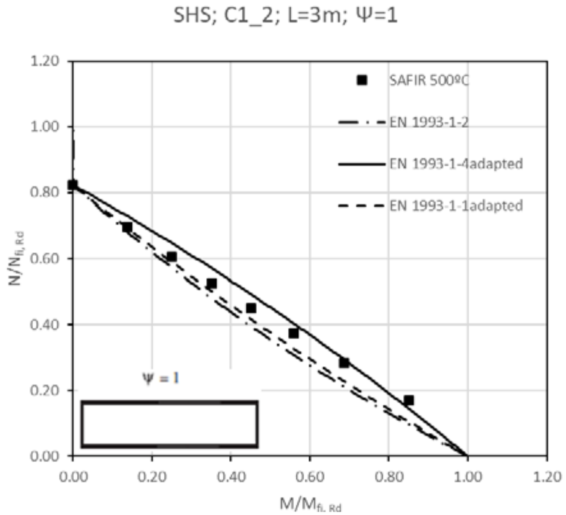
$$\sigma_{0.2,c} = \frac{1.881\sigma_{0.2,v}}{\left({}^{r_i}/_{t}\right)^{0.194}} \qquad \sigma_{u,c} = 0.75\sigma_{0.2,c}\frac{\sigma_{u,v}}{\sigma_{0.2,v}}$$

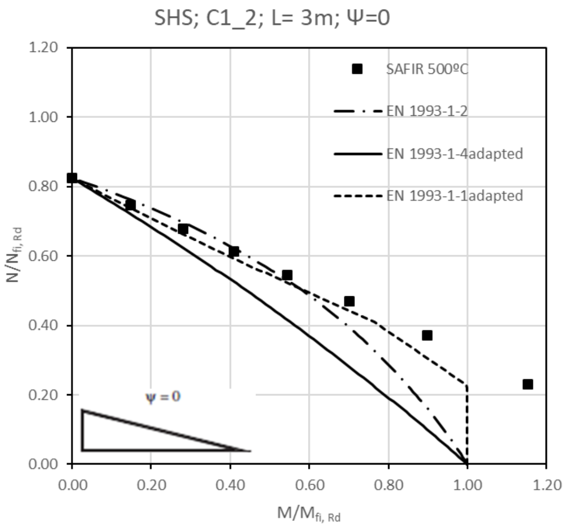
Comparison with interaction curves

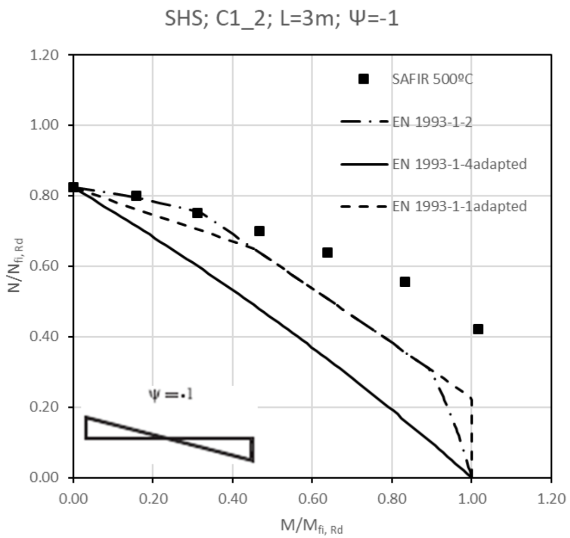
SHS



Bending diagram

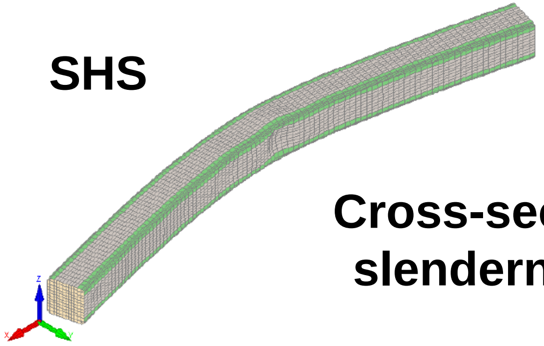




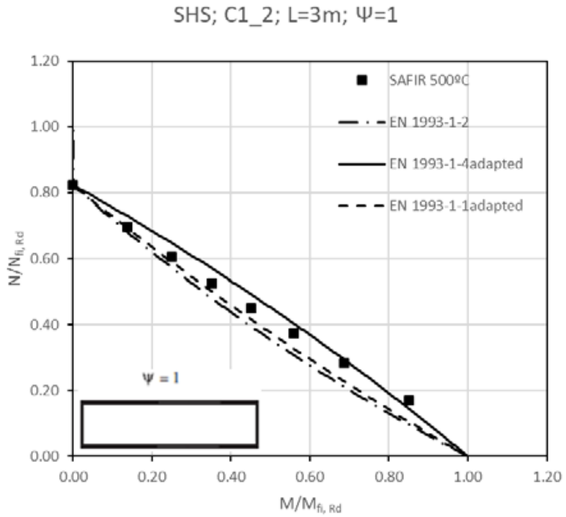


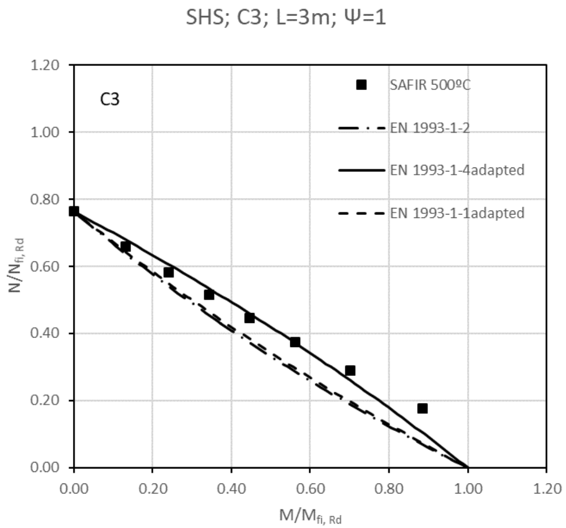
Comparison with interaction curves

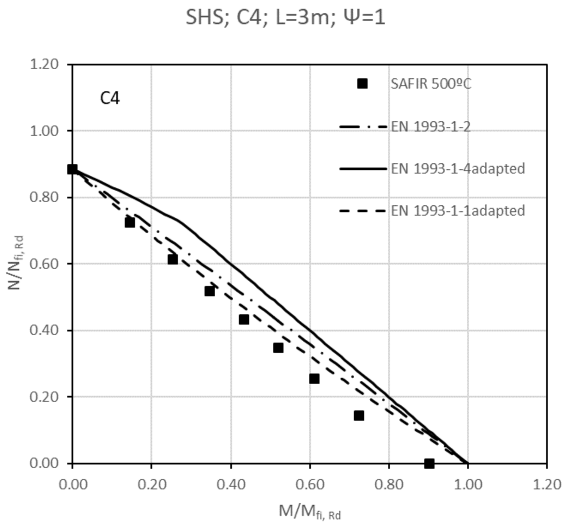
SHS

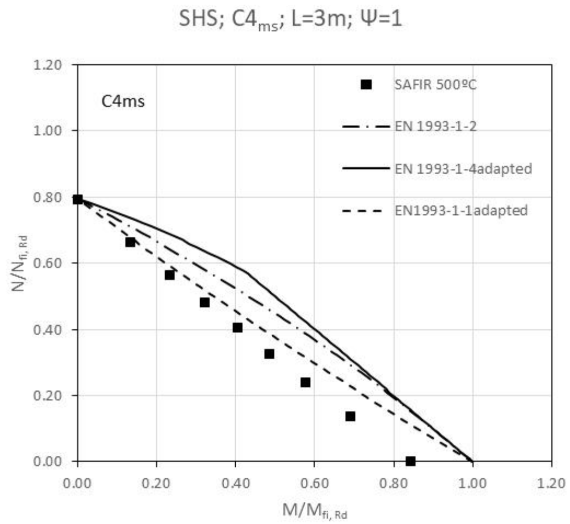


Cross-section slenderness



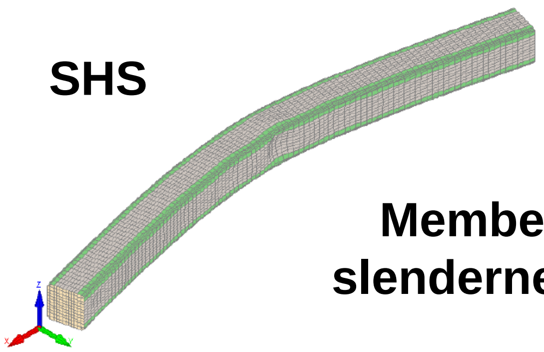




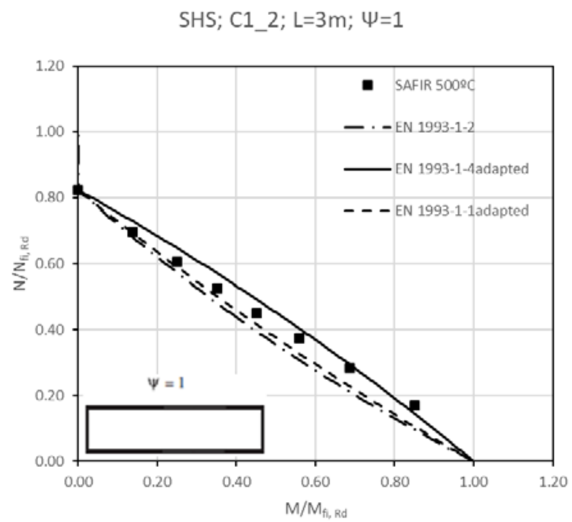


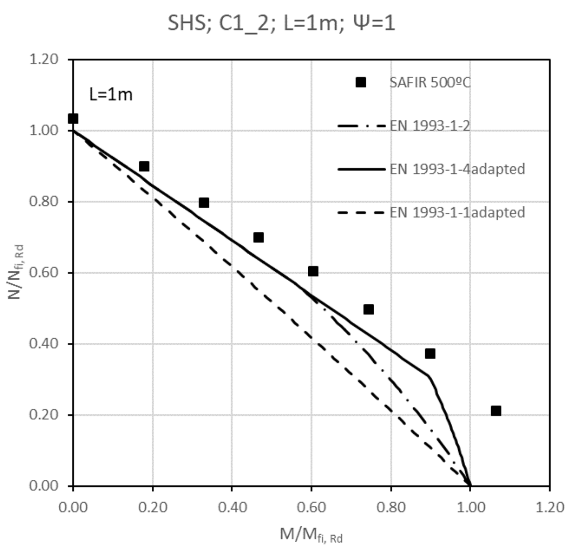
Comparison with interaction curves

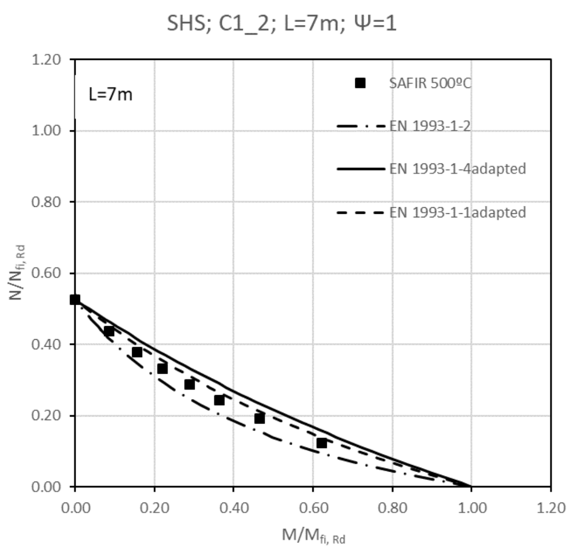
SHS

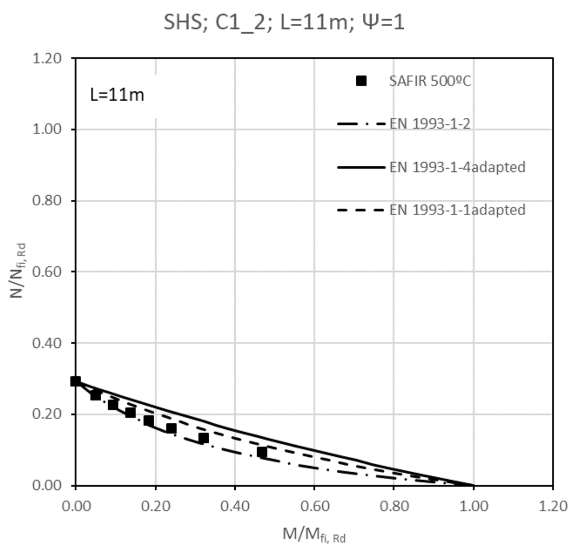


Member slenderness



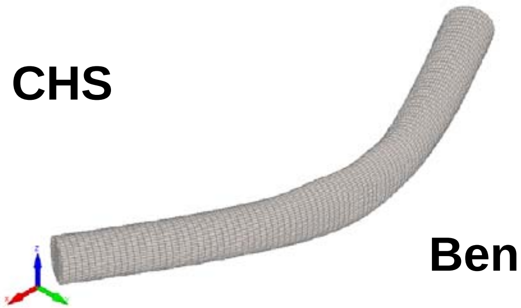




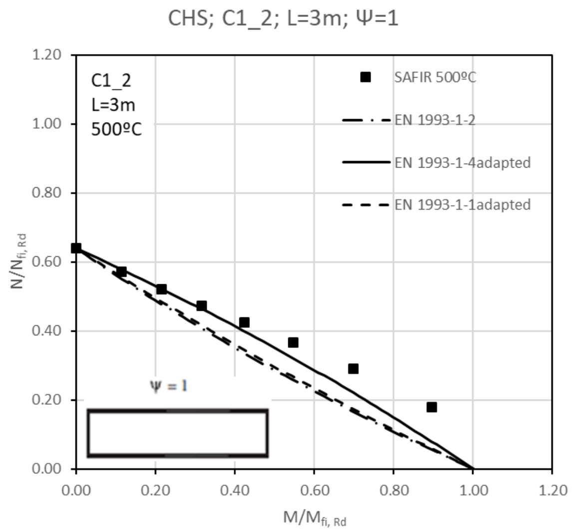


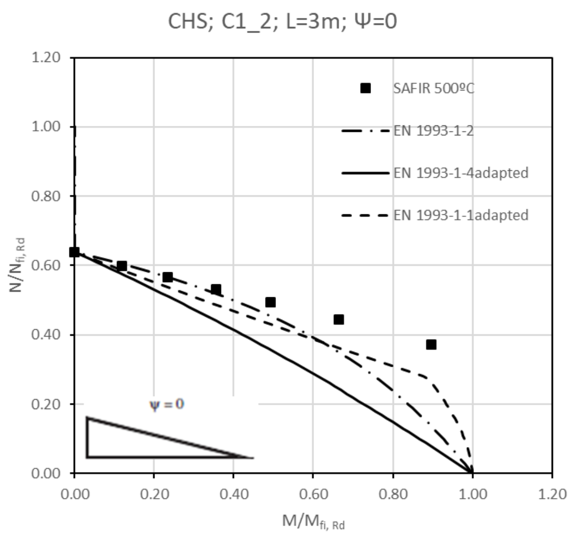
Comparison with interaction curves

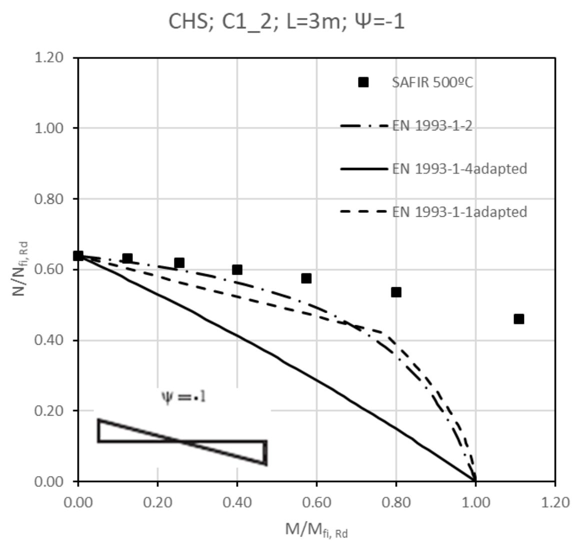
CHS



Bending diagram



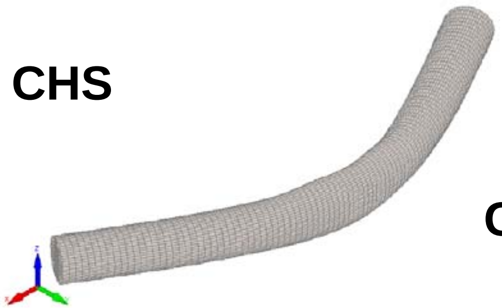




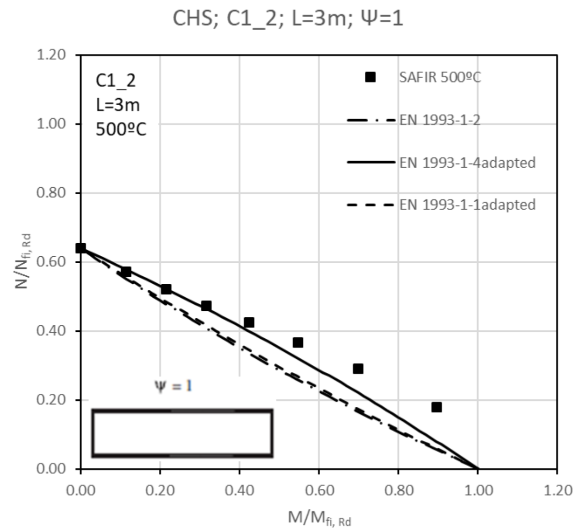
Parametric study

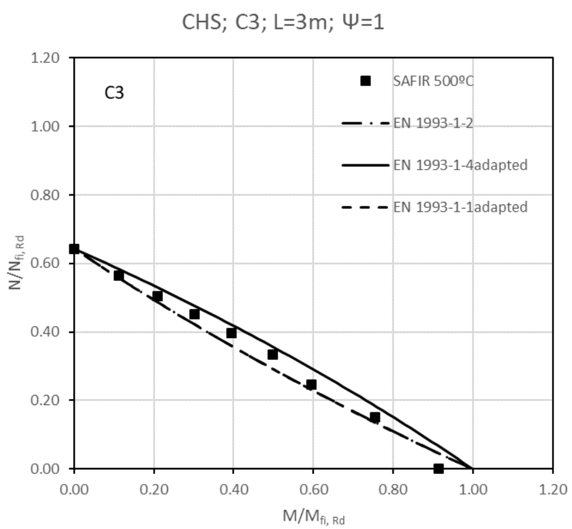
Comparison with interaction curves

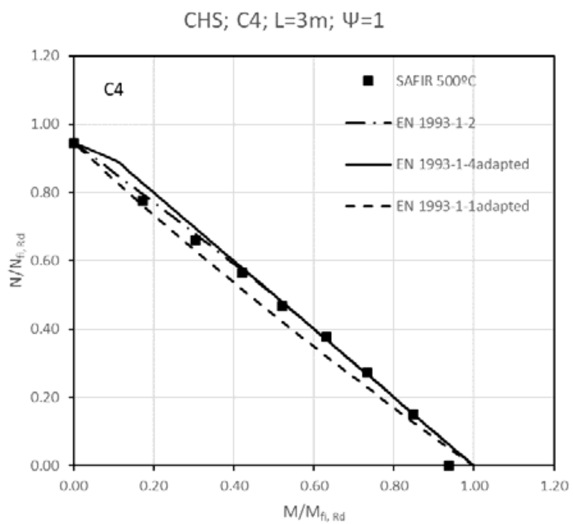
CHS

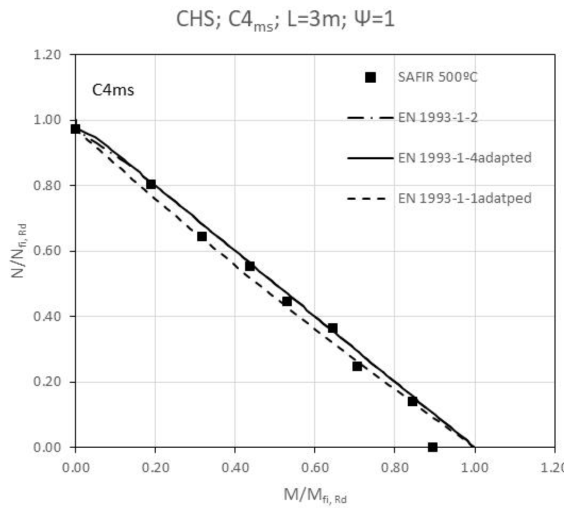


Cross-section slenderness



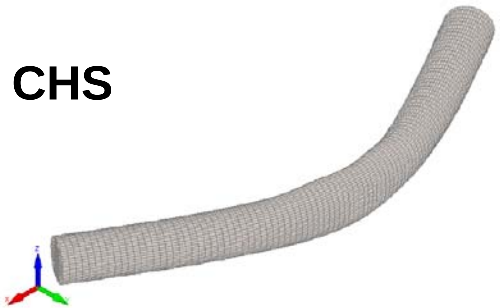




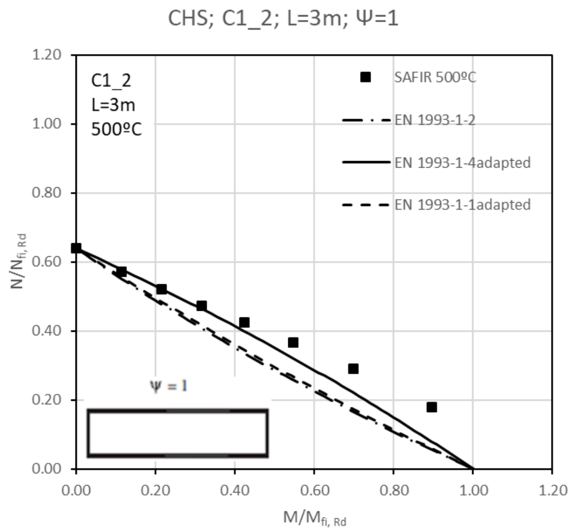


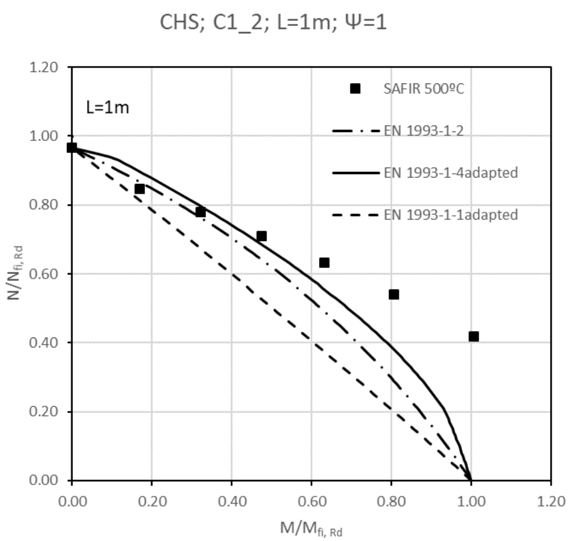
Comparison with interaction curves

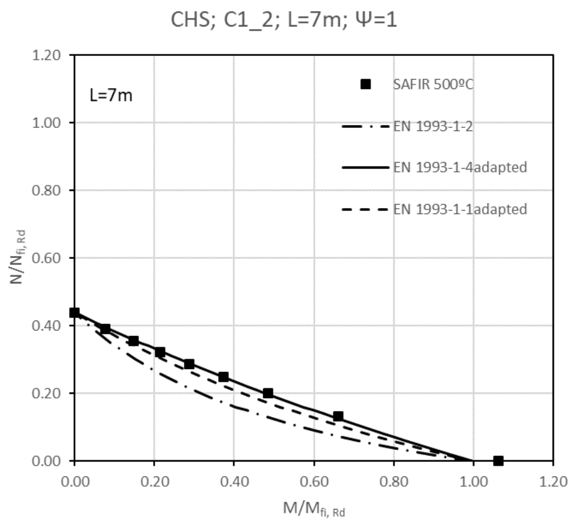
CHS

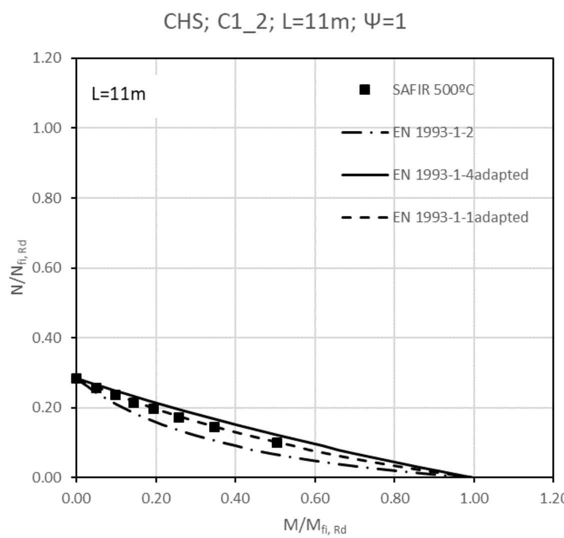


Member slenderness









Statistical evaluation of the different calculation methodologies

i. The average of the ratio between the numerical result and the analytical result is on the safe side (lower than 1.00);

ii. The percentage of the number of unsafe results is lower 20%;

iii. The maximum unsafe result provides a ratio lower of 1.5.

Statistical evaluation of the different calculation methodologies

SHS		Class 1 or 2 sections			Class 3 sections			Class 4 sections			
		ψ=1	ψ=0	ψ=-1	ψ=1	ψ=0	ψ=-1	ψ=1	ψ=0	ψ=-1	Global
Number of results		84	84	84	84	84	84	168	168	168	1008
EN1993-1-2	Average	0.93	0.91	0.90	0.91	0.90	0.90	1.10	1.03	1.08	0.99
	Standard deviation	0.03	0.08	0.09	0.07	0.09	0.09	0.10	0.13	0.21	0.15
	Unsafe results (%)	0	17	2	8	12	1	79	62	55	36
	Maximum unsafe	-	1.02	1.00	1.03	1.04	1.01	1.45	1.53	2.00	2.00
EN1993-1-4 adapted	Average	1.01	0.85	0.73	0.98	0.85	0.75	1.18	0.98	0.94	0.95
	Standard deviation	0.05	0.08	0.10	0.07	0.08	0.12	0.11	0.12	0.14	0.17
	Unsafe results (%)	71	0	0	55	4	0	99	48	26	40
	Maximum unsafe	1.07	-	-	1.08	1.03	-	1.62	1.40	1.39	1.62
EN1993-1-1 adapted	Average	0.99	0.96	0.87	0.96	0.95	0.86	1.13	1.07	1.06	1.01
	Standard deviation	0.09	0.09	0.06	0.09	0.10	0.07	0.12	0.16	0.20	0.16
	Unsafe results (%)	50	50	0	42	43	0	98	79	46	53
	Maximum unsafe	1.11	1.07	-	1.10	1.06	-	1.58	1.90	2.02	2.02

Statistical evaluation of the different calculation methodologies

CHS		Class 1 or 2 sections			Class 3 sections			Class 4 sections			
		ψ=1	ψ=0	ψ=-1	ψ=1	ψ=0	ψ=-1	ψ=1	ψ=0	ψ=-1	Global
Number of results		84	84	84	84	84	84	84	84	84	756
EN1993-1-2	Average	0.88	0.87	0.88	1.03	1.05	1.15	0.89	0.83	0.86	0.94
	Standard deviation	0.06	0.10	0.11	0.08	0.09	0.21	0.12	0.11	0.06	0.15
	Unsafe results (%)	4	11	0	50	75	79	26	1	0	27
	Maximum unsafe	1.02	1.02	-	1.42	1.45	2.00	1.09	1.01	-	2.00
EN1993-1-4 adapted	Average	0.96	0.82	0.72	1.11	0.99	0.95	0.90	0.83	0.86	0.91
	Standard deviation	0.06	0.10	0.13	0.10	0.07	0.09	0.13	0.11	0.06	0.14
	Unsafe results (%)	18	4	0	92	32	26	32	1	0	23
	Maximum unsafe	1.07	1.02	-	1.61	1.29	1.19	1.09	1.01	-	1.61
EN1993-1-1 adapted	Average	0.91	0.91	0.84	1.08	1.09	1.10	0.87	0.83	0.86	0.94
	Standard deviation	0.09	0.10	0.09	0.17	0.17	0.19	0.11	0.11	0.06	0.17
	Unsafe results (%)	21	0	0	50	61	64	8	1	0	23
	Maximum unsafe	1.01	-	-	1.74	1.80	1.92	1.06	1.01	-	1.92

Conclusions

- ✓ A numerical study on the behaviour of stainless steel members with square and circular hollow sections in fire subjected to compression plus bending was presented. Comparisons between the numerically obtained ultimate bearing loads and different interaction curves N-M were performed.

i. the design prescriptions of Part 1-2 of EC3 do not provide safe approximations for Class 4 square hollow sections and for Class 3 circular hollow sections;

ii. the formulae from Part 1-4 of EC3 adapted to elevated temperatures give too conservative results when non-uniform bending is considered;

iii. Part 1-1 of EC3 interaction curves adapted to elevated temperatures provide unsafe approximations for square hollow sections and for Class 3 circular hollow sections.

Conclusions

- ✓ Regarding the cross-section type, circular hollow sections provide more disperse numerical results when compared with the square hollow sections. However, the different design methodologies are generally safer for the members with circular hollow sections.
- ✓ When the cross-section classification is analysed, the different formulation provide unsafe approximations for Class 4 square hollow sections and Class 3 circular hollow sections.

It is clear that more studies are needed to better assess the behaviour of the interaction between axial compression and bending moments in these profiles, being expected the development of new design formulae to provide safer and more accurate approximations.

Parametric study on the interaction between axial compression and bending on austenitic stainless steel members with hollow sections under fire situation

Thank you for your attention!

Nuno Lopes; Mónica Manuel; Ana Regina Sousa; Paulo Vila Real
nuno.lopes@ua.pt
RISCO – University of Aveiro

decivil universidade de aveiro departamento de engenharia civil