Behaviour and design of stainless steel tubular members in fire

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Overview:

- Background
- Material properties
- Challenges
- Numerical modelling
- Analysis of results and design recommendations
- Concluding remarks

Background on stainless steel

- Widely used
- Family of corrosion resisting materials
- Invented 1912/13
- Nickel and Chromium (e.g. 8% - 18%)
- Austenitic, Duplex and Ferritic
- Dominant product forms are cold-formed sections.
- Long design life of structure (>100 years)
- Initial material cost/whole life costs

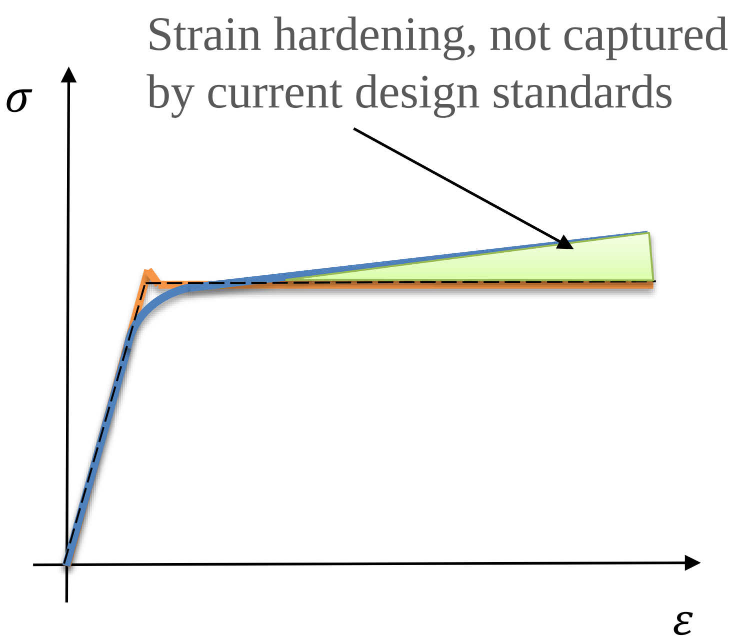
Stainless steel in structural application

Stainless steel columns, entrance canopy at Seven World Trade Centre, New York (SCI, 2017)

Millennium footbridge, York, UK. Welded duplex sections. (SCI, 2017)

Material properties: Stainless steel vs Carbon steel

Stainless steel Young's modulus and yield strength are broadly similar to carbon steel, but the form of stress-strain curve is fundamentally different



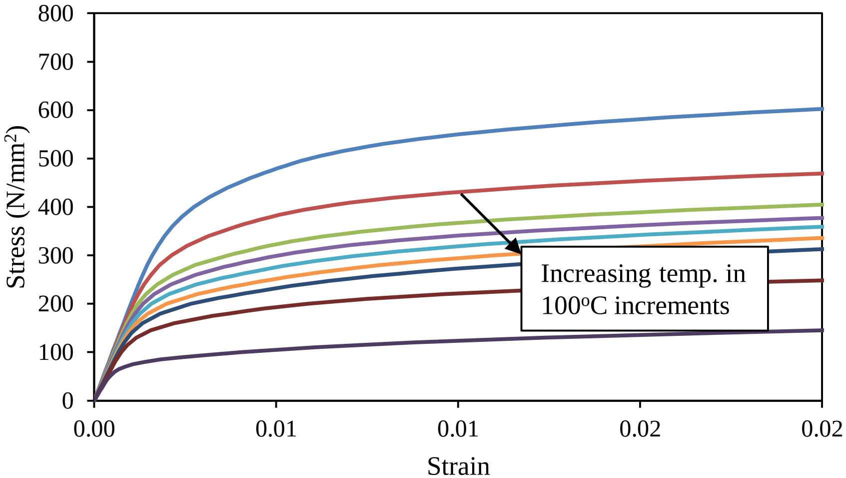
Carbon steel has a sharply defined yield point with a plastic yield plateau (followed later by strain hardening)

Stainless steel exhibits gradually yielding behaviour, with high strain hardening

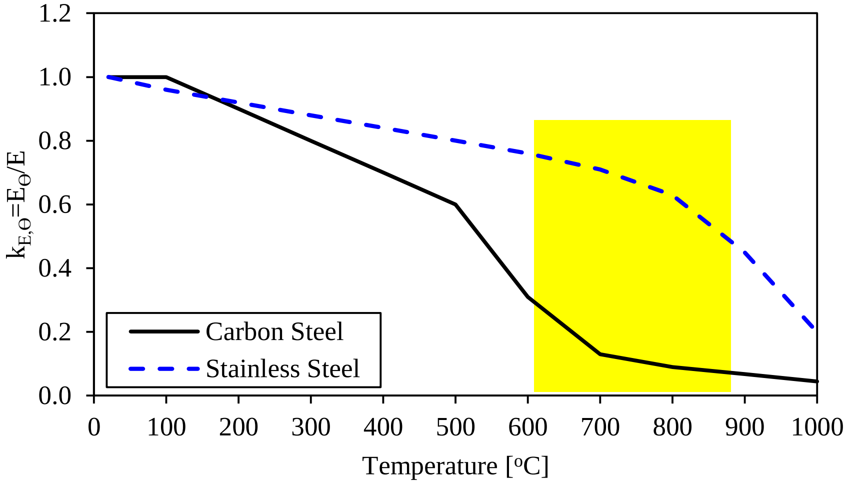
--------- Elastic, perfectly plastic model in current design standards

Material properties: Elevated temperatures

- Stainless steel drops its strength and stiffness at elevated temperatures
- Implication on structural fire design



Stainless steel stress-strain behaviour at elevated temperatures



Stiffness retention factors comparison

- Eurocode 3 states that stainless steel structural members, subjected to high temperatures, must be designed with the same expressions used for carbon steel members. However, as these two materials have different constitutive laws, it should be expected that different formulae for the member stability should be used

Challenges

- Initial cost
- Instability of the structural elements (columns and beam-columns)
- Efficient design guidelines for stainless steel members.

…… in fire conditions.

Numerical modelling-General

- Powerful tool used in the industry of research and practice.
- Can consider many more scenarios that would be impractical through testing
- Fire testing is extremely costly and time consuming.
- Numerical modelling has been successfully been performed by many researchers.

Numerical modelling

- **Software**: ABAQUS
- **Element type**: Shell elements, S4R
- **Mesh size**: Equal to the cross-section thickness, corner had four elements.
- **Boundary conditions**: Test boundary conditions were replicated by restraining suitable displacement and rotation degrees of freedom of the columns and beam-columns.
- **Material modelling**: measured material stress-strain curves at elevated temperatures were utilised in the form of true stress and log plastic strain.
- **Corner material modelling**: For enhanced corner strength in SHS and RHS numerical models, a distance of two times the material thickness was applied.
- **Initial geometric imperfections**: Introduced in the shape form of the lowest global and local buckling modes obtained from a linear elastic eigenvalue buckling analysis were utilised.
- **Residual stresses**: bending residual stresses were incorporated in the material properties, while membrane residual stresses were neglected, as they have little influence.
- **Analysis method**: Static method for anisothermal method and Riks method for isothermal method.

Numerical modelling-Validation

#1 Stainless steel column in fire

Zhao *et al.* (2016); Buchanan *et al.* (2018)

Cross-section	Grade	Length (mm)	Boundary condition	N_u (kN)
CHS 60.5 × 2.8	Austenitic EN 1.4301	1450	Pinned	90.5
CHS 76.3 × 3		1450		146
CHS 106 × 3	Austenitic EN 1.4432	550	Pinned	267
CHS 106 × 3		1150		248.8
CHS 106 × 3		3080		150.8
CHS 88.9 × 2.6	Duplex EN 1.4462	400		425.2
CHS 88.9 × 2.6		1650		243.4
CHS 88.9 × 2.6		3080		100.5
CHS 80 × 1.5	Ferritic EN 1.4512	700		111.1
CHS 80 × 1.5		900		105.8
CHS 80 × 1.5		1600		77.9

Isothermal conditions

Ala-Outinen and Oksanen, (1997); Gardner and Baddoo (2006); Tondini et al. (2013)

Cross-section	Grade	Length (mm)	Boundary condition	θ_{crit} (°C)
SHS 40×40×4-T1	Austenitic EN 1.4301	888.5	Pinned	872
SHS 40×40×4-T2		888.5		579
SHS 40×40×4-T3		888.5		649
SHS 40×40×4-T4		888.5		710
SHS 40×40×4-T5		888.5		832
SHS 40×40×4-T7		888.5		766
RHS 150×100×6	Austenitic EN 1.4301	3400	Fixed	801
RHS 150×75×6		3400		883
RHS 100×75×6		3400		806
SHS 80×80×3	Ferritic EN 1.4003	3000	Fixed	709 (1)
SHS 80×80×3		2500		708 (1)
RHS 120×80×3		2500		705 (1)

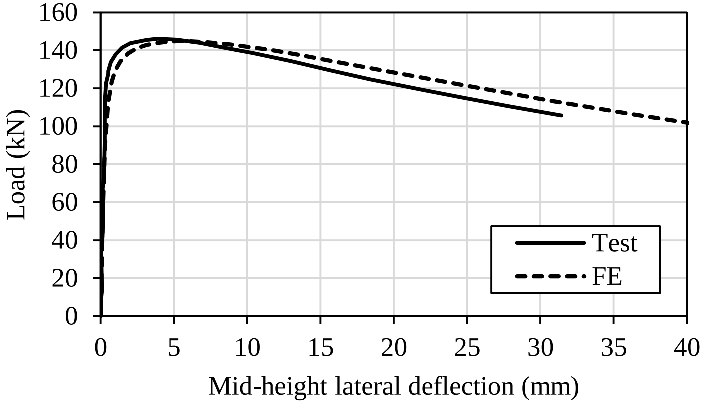
(1) Critical furnace temperature

Anisothermal conditions

Numerical modelling-Validation

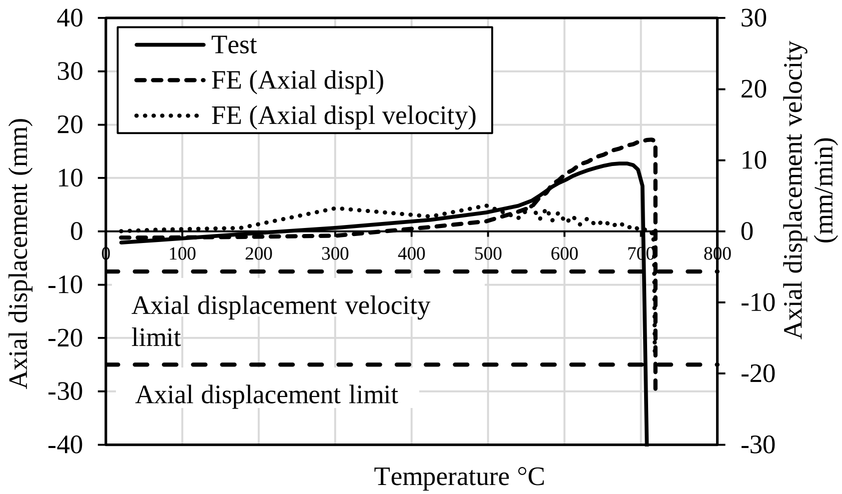
- Validation of column numerical models

Zhao *et al.* (2016)



Load versus mid-height lateral deflection. CHS 76×3-1450

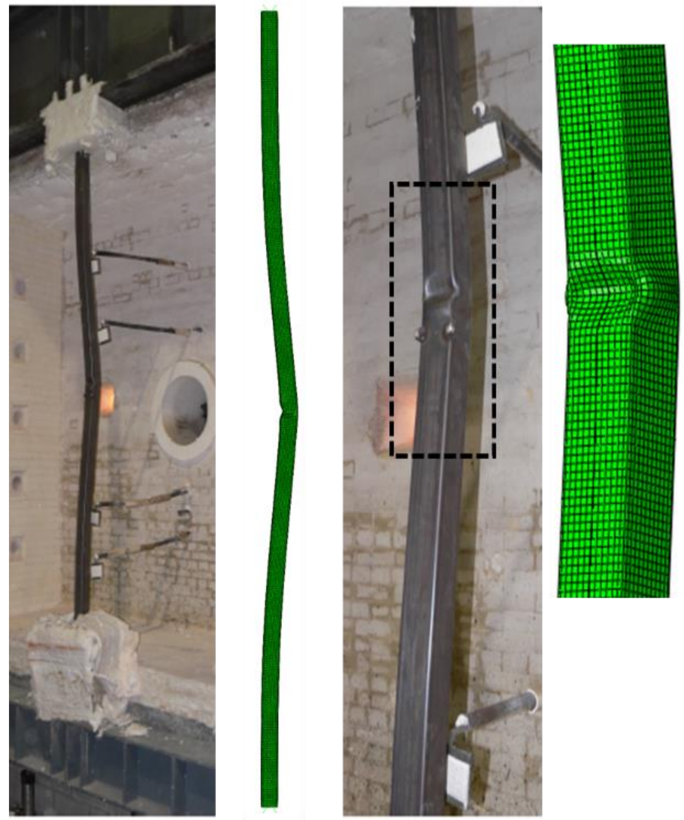
Tondini et al. (2013)



Vertical displacement versus temperature of ferritic SHS 80×80×3-2500 specimen

- Failure modes

CHS test and FE model column failure mode.



SHS 80×80×3-2500 specimen Failure mode.

Numerical modelling-Validation results

- Validation of the 23 column numerical models

#1 Stainless steel column in fire

Zhao *et al.* (2016); Buchanan *et al.* (2018)

Specimen reference	ω_g + t/10	
	$N_{u,FE}$/ $N_{u,test}$	$\delta_{u,FE}/\delta_{u,test}$
CHS 60.5 × 2.8	0.99	1.57
CHS 76.3 × 3	0.99	1.31
CHS 106 × 3	1.07	0.37
CHS 106 × 3	0.91	1.49
CHS 106 × 3	0.96	0.64
CHS 88.9 × 2.6	0.98	0.74
CHS 88.9 × 2.6	1.03	0.74
CHS 88.9 × 2.6	1.06	1.33
CHS 80 × 1.5	1.05	0.53
CHS 80 × 1.5	1.03	0.68
CHS 80 × 1.5	1.12	0.65
Mean	1.02	0.91
COV	0.06	0.46

Ala-Outinen and Oksanen, (1997); Gardner and Baddoo (2006); Rossi, (2012)

Specimen reference	Critical temperature (°C)		
	Test	FE	FE/Test
SHS 40×40×4-T1	872	750	0.86
SHS 40×40×4-T2	579	502	0.87
SHS 40×40×4-T3	649	608	0.94
SHS 40×40×4-T4	710	646	0.91
SHS 40×40×4-T5	832	722	0.87
SHS 40×40×4-T7	766	681	0.89
RHS 150×100×6	801	757	0.91
RHS 150×75×6	883	814	0.92
RHS 100×75×6	806	744	0.92
SHS 80×80×3	709	726	1.02
SHS 80×80×3	708	718	1.02
RHS 120×80×3	705	709	1.01
Mean			0.93
COV			0.06

Numerical modelling-Validation

#1 Stainless steel & steel beam-columns in fire

Fan *et al.* (2016)

Cross-section	Grade	Length (mm)	Eccentricity (mm)	θ_{crit} (°C)
SHS 100×100×4 (1)	Austenitic EN 1.4301	3300	13.2	701
SHS 100×100×4 (2)		3300	23.8	665

Anisothermal conditions
Boundary conditions: Pinned-Pinned

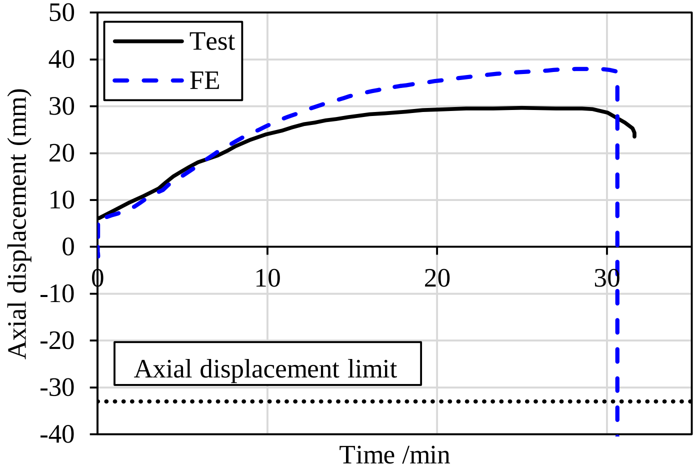
Pauli *et al.* (2012)

Cross-section	Grade	Length (mm)	Temperature (°C)	Eccentricity (mm)	N_u (kN)
RHS 120×60×4-(1)	S355	850	550	30	96
RHS 120×60×4-(2)		1840	400	0	242
RHS 120×60×4-(3)		1840	400	10	139
RHS 120×60×4-(4)		1840	400	50	73
RHS 120×60×4-(5)		1840	550	0	186
RHS 120×60×4-(6)		1840	550	10	111
RHS 120×60×4-(7)		1840	550	50	49
RHS 120×60×4-(8)		1840	700	0	71

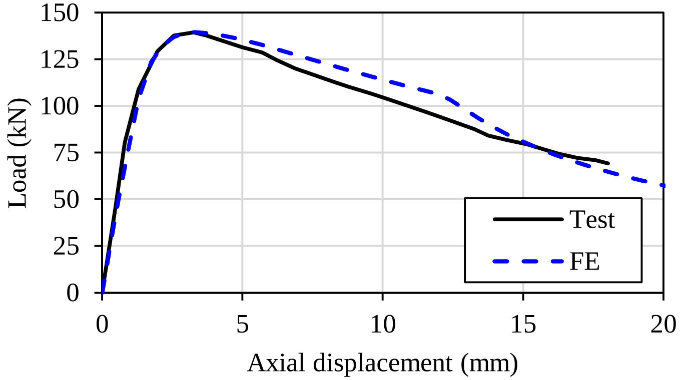
Isothermal conditions
Boundary conditions: Pinned-Pinned

Numerical modelling-Validation

- Validation of the beam-column numerical models



Axial displacement versus time of Austenitic SHS 100×100×4 (1) specimen



Load versus mid-height lateral deflection. RHS 120×60×4-(3)

Test and FE failure mode for elevated S355 steel beam-column specimen RHS 120×60×4-(7).

Numerical modelling – Validation results

- Validation of the 10 beam-column numerical models

#1 Stainless steel & steel beam-columns in fire

Fan *et al*. (2016)

Specimen reference	Critical temperature (^oC) Test	FE	FE/Test
SHS 120x120x4-(1)	701	689	0.98
SHS 120x120x4-(2)	665	666	1.00
Mean			0.99
COV			0.01

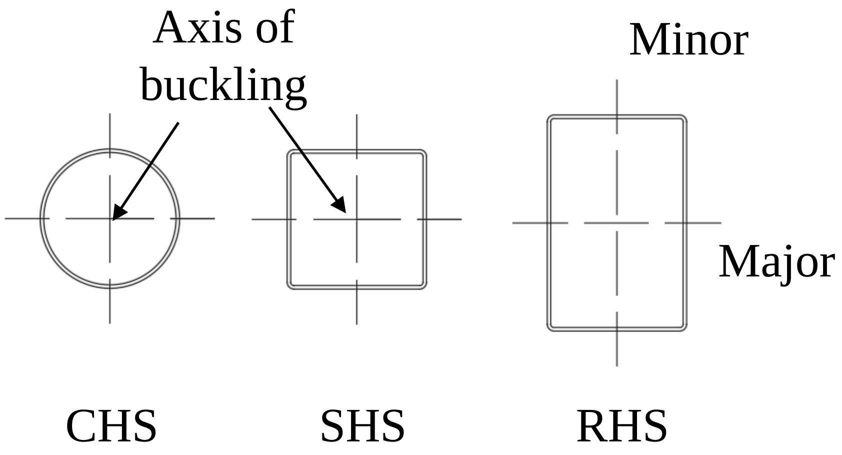
Pauli *et al*. (2012)

Specimen reference	Temperature (^oC)	$N_{u,test}$ (kN)	$N_{u,FE}$ (kN)	$N_{u,test}/N_{u,FE}$
RHS 120×60×4-(1)	550	96	102	0.94
RHS 120×60×4-(2)	400	242	206.8	1.17
RHS 120×60×4-(3)	400	139	143.1	0.97
RHS 120×60×4-(4)	400	73	75.3	0.97
RHS 120×60×4-(5)	550	186	195.4	0.95
RHS 120×60×4-(6)	550	111	102.4	1.08
RHS 120×60×4-(7)	550	49	53.6	0.91
RHS 120×60×4-(8)	700	71	71	1.00
Mean				1.00
COV				0.08

Numerical modelling

Parametric studies were performed to generate further structural performance data for:

- Stainless steel columns in fire
- Stainless steel beam-column in fire



Modelling parameters:

- Materials: Austenitic, Duplex and Ferritic
- SHS, RHS (Major and Minor) and CHS
- Class 1.
- Temperature range 20 ˚ C to 800˚C
- Global geometric imperfection: L/1000
- Local geometric imperfection b/200 and t/10 in accordance to EN 1993-1-5
- Boundary conditions: Pinned
- Isothermal conditions

Buckling curves

The buckling design ($N_{b,fi,t,Rd}$) for Class 1-3 member at elevated temperature from the Eurocode and Design Manual for Structural Stainless Steel (DMSS):

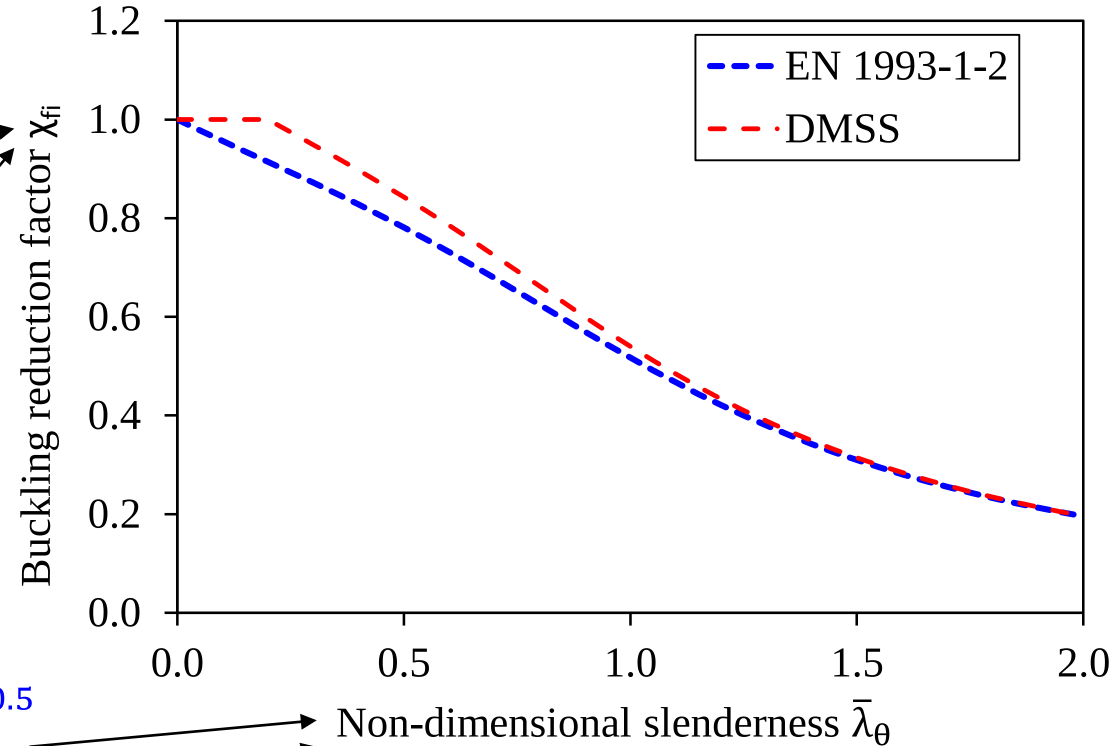
Eurocode approach:

$$\chi_{fi} = \frac{N_{b,fi,t,Rd}}{A k_{2,\theta} f_y}$$

Squash load at elevated temperature

DMSS

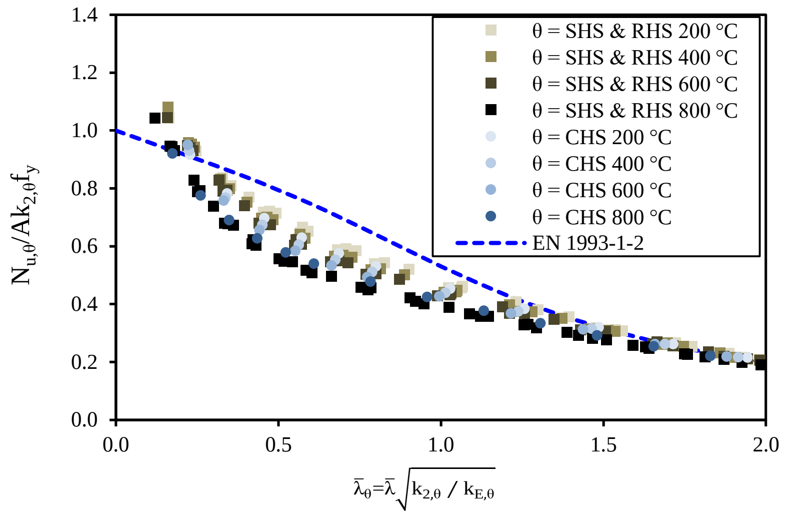
$$\chi_{fi} = \frac{N_{b,fi,t,Rd}}{A k_{p0,2,\theta} f_y}$$



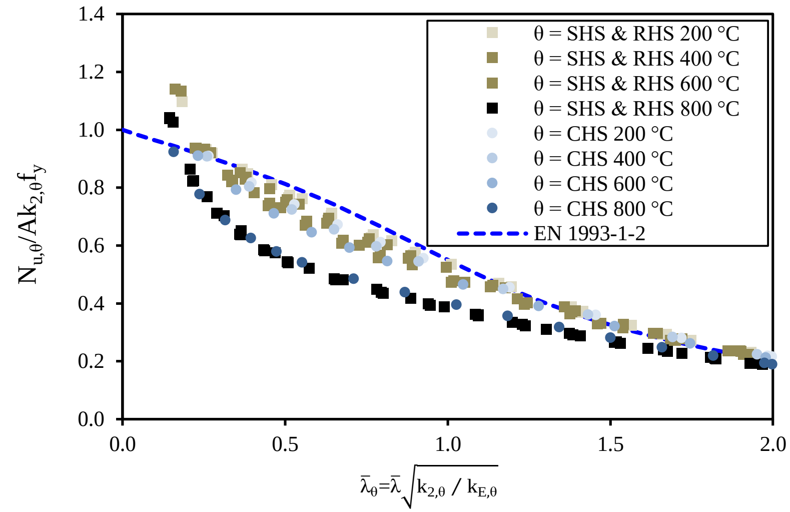
Eurocode approach: $\bar{\lambda}_\theta = \bar{\lambda}\left[\frac{k_{2,\theta}}{k_{E,\theta}}\right]^{0.5}$

DMSS: $\bar{\lambda}_\theta = \bar{\lambda}\left[\frac{k_{p0,2,\theta}}{k_{E,\theta}}\right]^{0.5}$

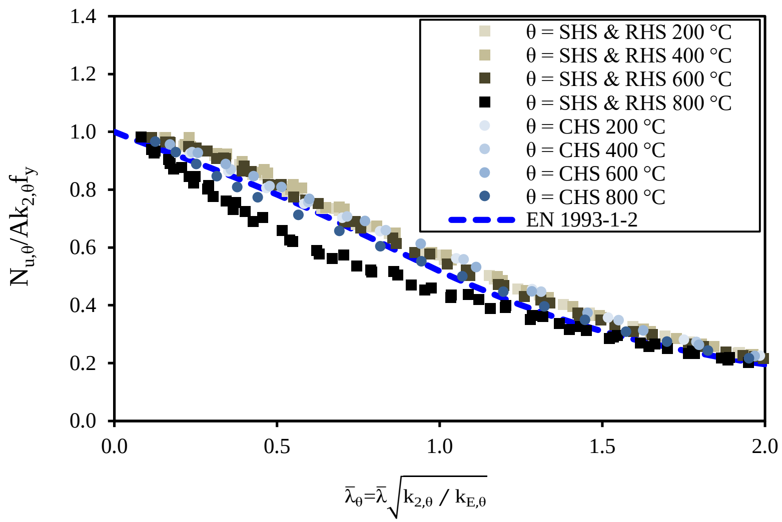
Analysis of results and discussion



Austenitic



Duplex

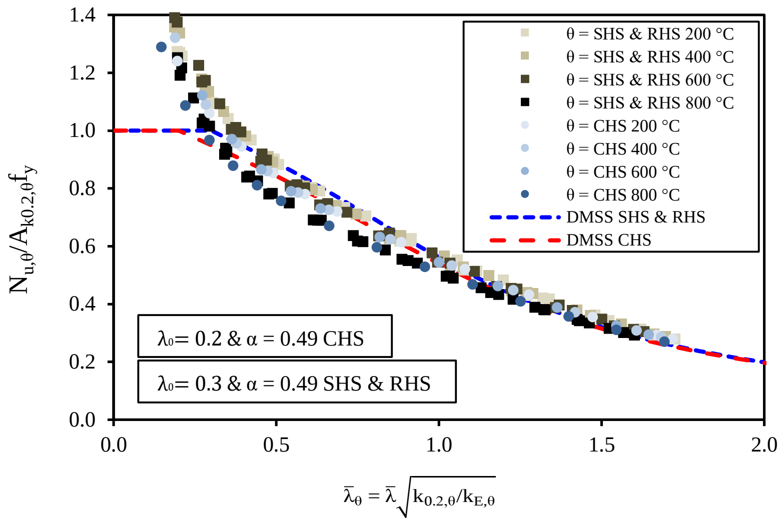


Ferritic

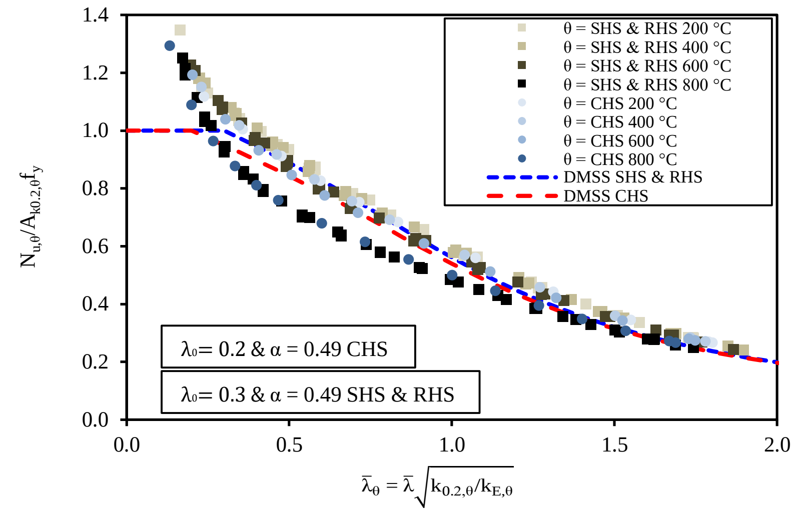
Observation

- Data show scatter
- Data sit considerably below the current buckling curve
- Data suggest need for temperature dependent buckling curves

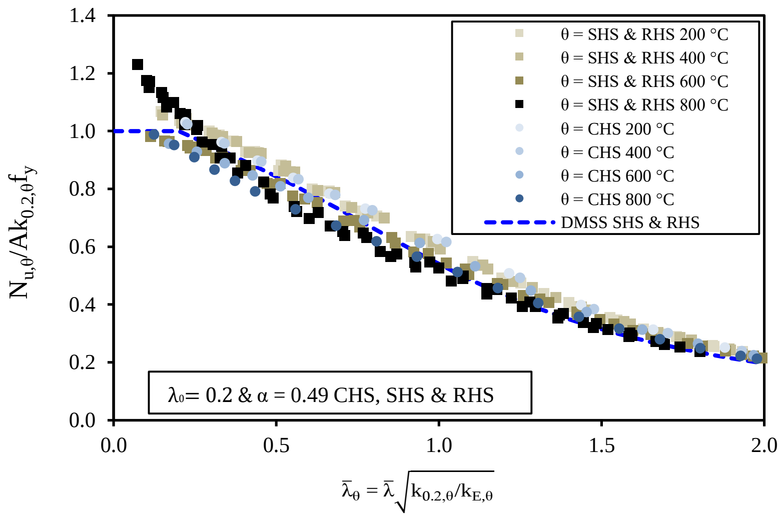
Analysis of results and discussion



Austenitic



Duplex



Ferritic

Observation

- Data show under prediction for stockier columns for low temperatures
- Data sit considerably below the current buckling curve
- Data suggest need for temperature dependent buckling curves

Discussion

Lopes et al. (2010) conducted a numerically study on axially loaded stainless steel welded I-sections in fire and proposed a modified version of the EN 1993-1-2 buckling curve which included:

1. β parameter was introduced in the non-dimensional slenderness χ_{fi} and φ_θ
2. Imperfection factor α was defined as a function of temperature.

Lopes *et al.* (2010)

$$N_{b,fi,t,Rd} = \chi_{fi} A k_{y,\theta} f_y / \gamma_{mfi}$$

$$\chi_{fi} = \frac{1}{\varphi_\theta + \sqrt{\varphi_\theta^2 - \beta \bar{\lambda}_\theta^2}} \leq 1.0$$

$$\varphi_\theta = \frac{1}{2}\left[1 + \alpha \bar{\lambda}_\theta + \beta \bar{\lambda}_\theta^2\right]$$

$$\alpha = \eta \sqrt{\frac{235}{f_y} \frac{E}{210000}} \sqrt{\frac{k_{E,\theta}}{k_{2,\theta}}}$$

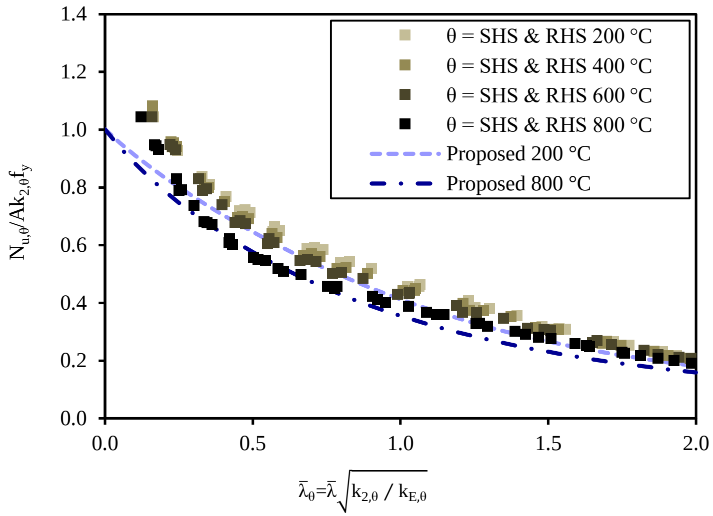
$$\bar{\lambda}_\theta = \bar{\lambda} \left[\frac{k_{y,\theta}}{k_{E,\theta}}\right]^{0.5}$$

Proposal

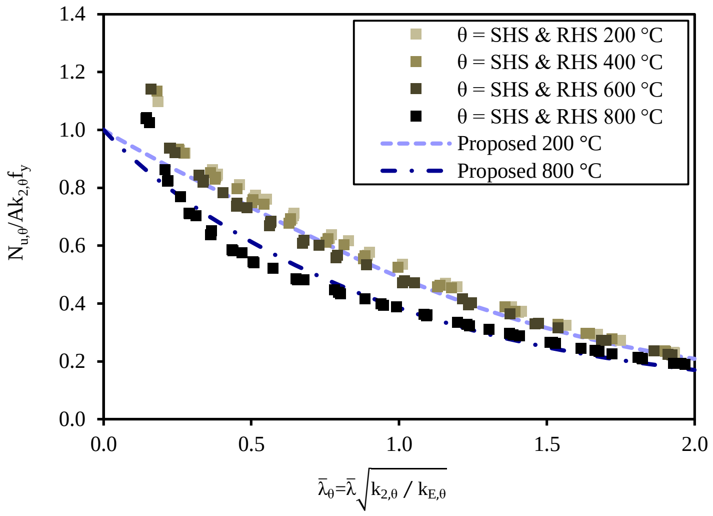
- Buckling curves of the same form as Lopes et al. (2010) formulation developed for welded I-section columns in fire were fitted to the normalised FE data for the cold-formed SHS/RHS and CHS stainless steel column generated.
- New β and η parameters were calibrated against the FE data for austenitic, duplex and ferritic stainless steel columns.
- β and η parameters for fire design of stainless steel flexural member is presented below.

Material	Section	β	η
Austenitic	SHS/RHS	0.8	1.5
	CHS	0.7	1.3
Duplex	SHS/RHS	0.8	1.1
	CHS	0.8	1.0
Ferritic	SHS/RHS	1.0	0.6
	CHS	1.0	0.5

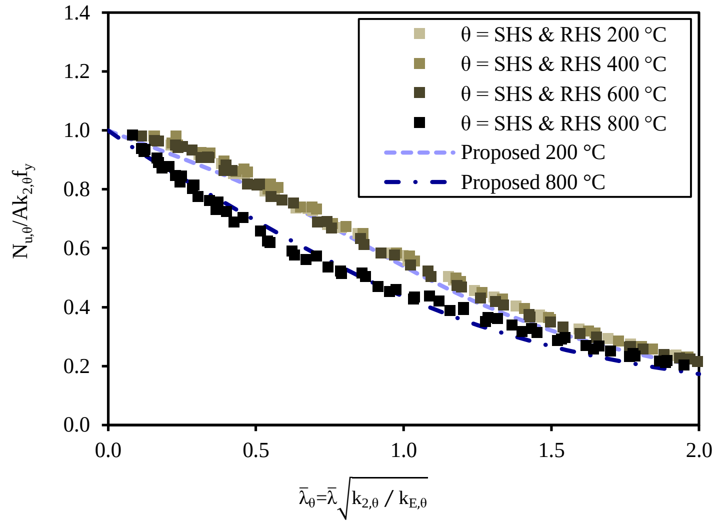
Results SHS & RHS



Austenitic

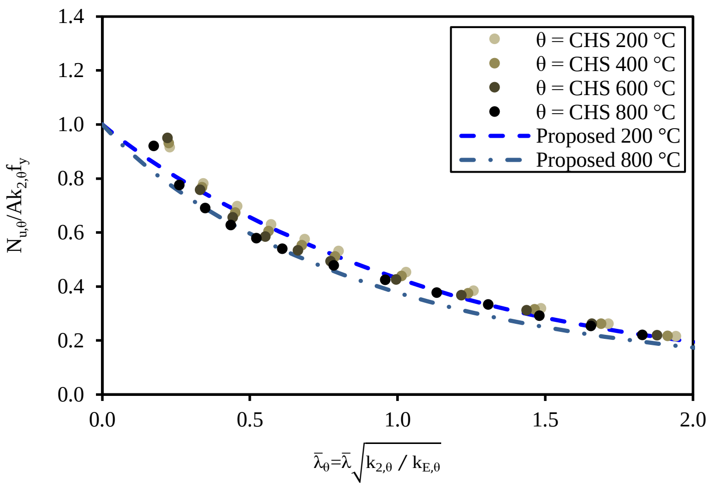


Duplex

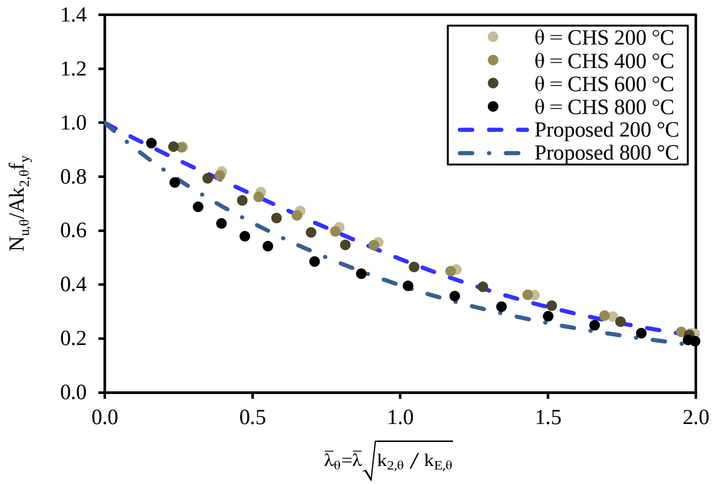


Ferritic

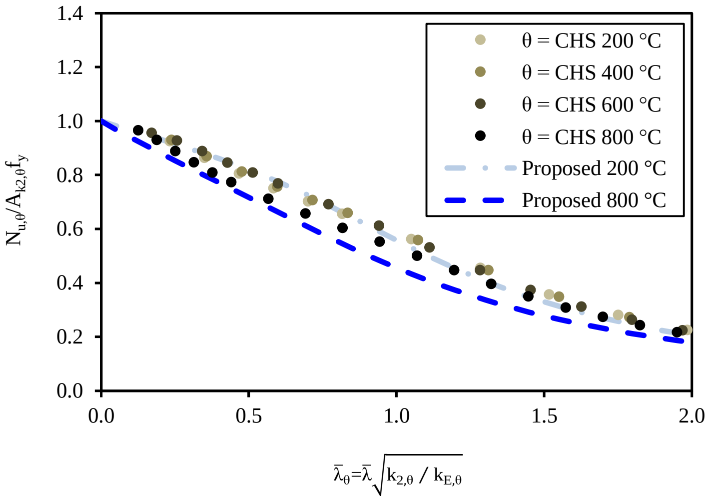
Results CHS



Austenitic



Duplex



Ferritic

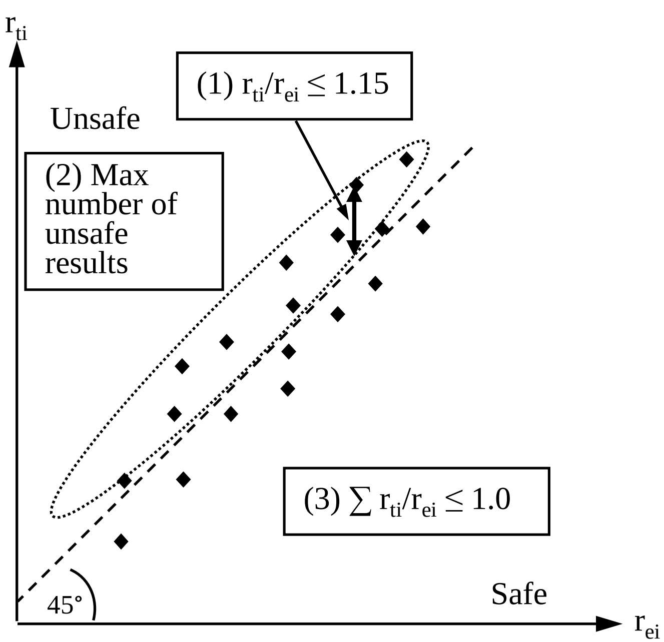
Comparison of EN 1993-1-2 (2005), DMSS and proposal

Comparison between the FE and predicted resistances.

Material	$N_{u,FE}/N_{u,pred}$	EN 1993-1-2	DMSS	Proposed
Austenitic	No.	361	361	361
	Mean	0.93	1.08	1.12
	COV	0.12	0.12	0.07
	Max	1.26	1.58	1.43
	Min	0.68	0.84	0.94
Duplex	No.	327	327	327
	Mean	0.94	1.07	1.08
	COV	0.14	0.11	0.07
	Max	1.21	1.53	1.27
	Min	0.64	0.79	0.87
Ferritic	No.	375	375	375
	Mean	1.07	1.05	1.08
	COV	0.08	0.09	0.06
	Max	1.30	1.30	1.25
	Min	0.80	0.83	0.92

Reliability analysis

- Safety analysis in accordance with the method recommended by Kruppa (1999) were performed to assess the reliability of the existing and proposed design methods to predict the flexural buckling methods of cold-formed stainless steel SHS, RHS and CHS in fire.
- Kruppa set out three distinct reliability criteria methods to compare against theoretical resistance to experimental or numerical results.



Summary of reliability results

Material	Criterion	EN 1993-1-2		DMSS		Proposed	
Austenitic	Criterion 1	40.85%	Fail	2.55%	Fail	0.00%	Pass
	Criterion 2	76.45%	Fail	37.85%	Fail	13.85%	Pass
	Criterion 3	0.122	Fail	-0.03	Pass	-0.07	Pass
Duplex	Criterion 1	28.00%	Fail	6.95%	Fail	0.00%	Pass
	Criterion 2	70.00%	Fail	30.50%	Fail	11.50%	Pass
	Criterion 3	0.104	Fail	-0.03	Pass	-0.06	Pass
Ferritic	Criterion 1	4.50%	Fail	0.00%	Pass	0.00%	Pass
	Criterion 2	20.40%	Fail	29.75%	Fail	14.15%	Pass
	Criterion 3	-0.05	Pass	-0.04	Pass	-0.07	Pass

Concluding remarks

- A numerical study was performed to investigate the flexural buckling response of stainless steel tubular columns in fire.
- Developed numerical models were validated against test data provided in literature.
- EN 1993-1-2 and Design Manual for Structural Stainless Steel results provide in inaccurate predictions for flexural buckling resistance for stainless steel columns in fire.
- New buckling curves for cold-formed stainless steel tubular columns were proposed on the basis of FE results.
- The suitability of the proposed curves was confirmed by the means of a reliability criteria set out by Kruppa.
- Further numerical studies on beam-columns and potential improvements to the design are underway.
- Improvements to the design expressions can lead to more efficient design, allowing more efficient use of the material, and reduced costs.

Thank you for your attention!