Welcome to today's webinar!

19 January 2021: Introduction to the use of HSS in structures

26 January 2021: Design of HSS - plastic design

2 February 2021: Design of HSS - member stability & dynamic response

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9 February 2021: Weight, cost and carbon savings with HSS

Today's webinar:

Design of HSS members for stability	Prof Luís Simões da Silva (University of Coimbra)
Dynamic response of HSS floor beams	Dr Anqi Chen (Arup, formerly SCI)
Online design tool for HSS beams	Dr Fengyan Gong (Hochtief Engineering IKS Consult)

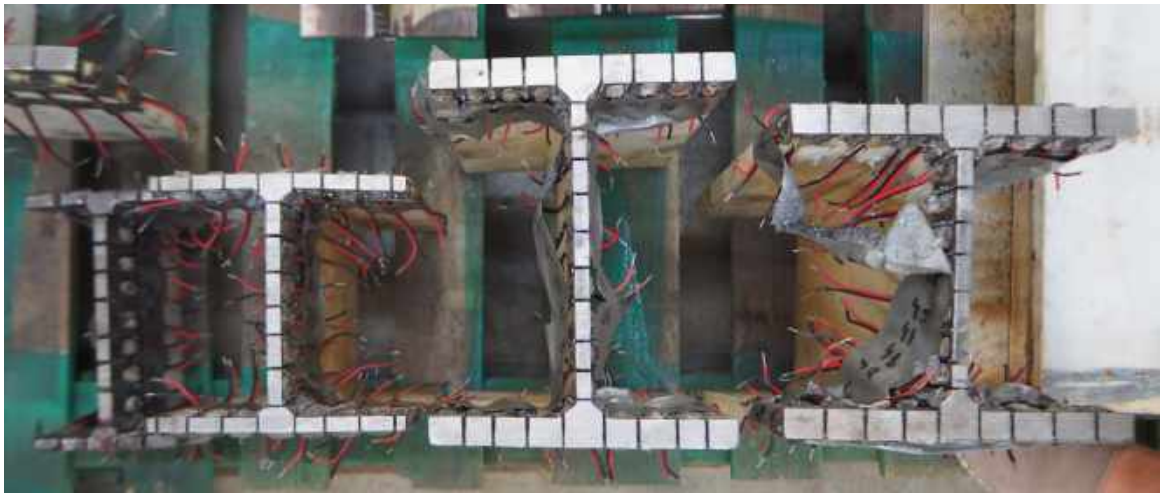
Design of High Strength Steel Members for Stability

Luís Simões da Silva

isise Institute for Sustainability and Innovation in Structural Engineering

1 2 9 0 UNIVERSIDADE D COIMBRA

Outline

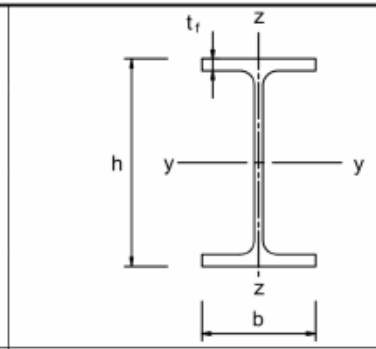
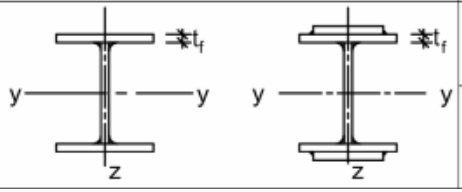


- Background
- Tests
- Improved design rules for HSS members

Buckling resistance of members

- Uniform members in compression (6.3.1)

Buckling curve	a_0	a	b	c	d
Imperfection factor α	0,13	0,21	0,34	0,49	0,76

Cross section		Limits		Buckling about axis	Buckling curve: S 235 S 275 S 355 S 420	Buckling curve: S 460
Rolled sections		h/b > 1,2	$t_f \le 40$ mm	y – y z – z	a b	a_0 a_0
			40 mm < $t_f \le 100$	y – y z – z	b c	a a
		h/b ≤ 1,2	$t_f \le 100$ mm	y – y z – z	b c	a a
			$t_f > 100$ mm	y – y z – z	d d	c c
Welded I-sections			$t_f \le 40$ mm	y – y z – z	b c	b c
			$t_f > 40$ mm	y – y z – z	c d	c d

$$N_{b,Rd} = \frac{\chi A f_y}{\gamma_{M1}} = \chi N_{c,Rd}$$

$$\chi = \frac{1}{\phi + \sqrt{\phi^2 - \bar{\lambda}^2}}$$

$$\phi = 0.5\left(1 + \alpha\left(\bar{\lambda} - 0.2\right) + \bar{\lambda}^2\right)$$

$$\bar{\lambda} = \sqrt{\frac{A f_y}{N_{cr}}}$$

Buckling resistance of members

- Uniform members in bending (6.3.2)

Buckling curve	a	b	c	d
Imperfection factor α_{LT}	0,21	0,34	0,49	0,76

Cross-section	Limits	Buckling curve
Rolled I-sections	h/b ≤ 2 h/b > 2	**a** **b**
Welded I-sections	h/b ≤ 2 h/b > 2	**c** **d**
Other cross-sections	-	**d**

$$M_{b,Rd} = \frac{\chi_{LT} W_y f_y}{\gamma_{M1}} = \chi_{LT} M_{c,Rd}$$

$$\chi_{LT} = \frac{1}{\phi_{LT} + \sqrt{\phi_{LT}^2 - \bar{\lambda}_{LT}^2}}$$

$$\phi_{LT} = 0.5\left(1 + \alpha_{LT}\left(\bar{\lambda}_{LT} - 0.2\right) + \bar{\lambda}_{LT}^2\right)$$

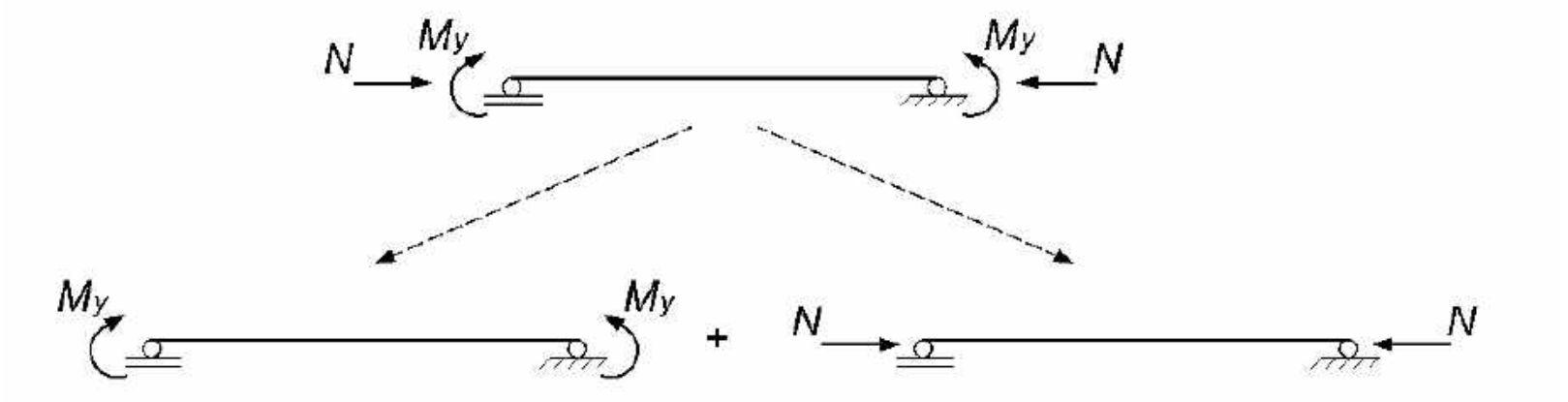
$$\bar{\lambda}_{LT} = \sqrt{\frac{W_y f_y}{M_{cr}}}$$

Buckling resistance of members

- Uniform members in bending (6.3.3)

$$\frac{N_{Ed}}{\chi_y N_{Rd}} + k_{yy}\frac{M_{y,Ed}}{\chi_{LT} M_{y,Rd}} + k_{yz}\frac{M_{z,Ed}}{M_{z,Rd}} \leq 1$$

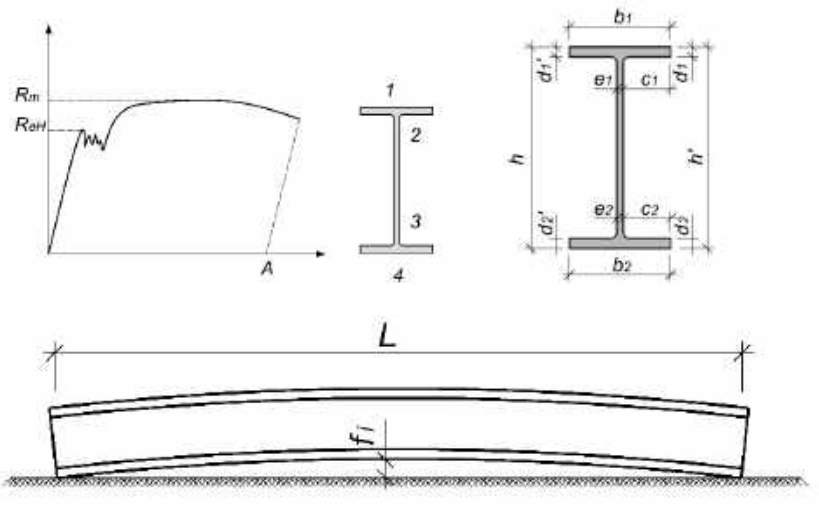
$$\frac{N_{Ed}}{\chi_z N_{Rd}} + k_{zy}\frac{M_{y,Ed}}{\chi_{LT} M_{y,Rd}} + k_{zz}\frac{M_{z,Ed}}{M_{z,Rd}} \leq 1$$



Background

- European buckling curves

1067 buckling tests

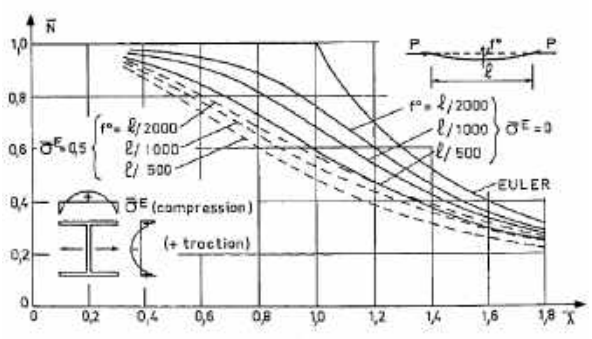


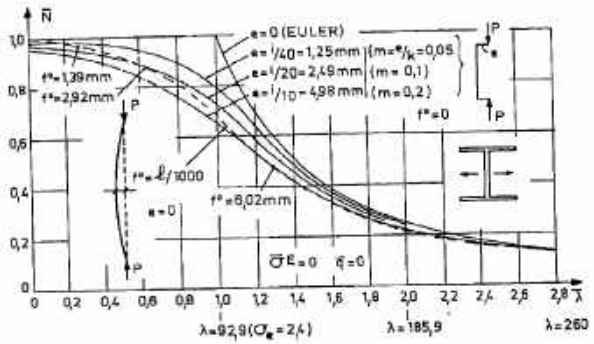
ECCS experimental programme

1970

Background

- European buckling curves





The residual stresses and the geometrical imperfection were compared for three levels of geometrical imperfection with or without considering the residual stresses

The limit of L/1000 as initial out-of-straightness could cover load eccentricities up to 5mm

Beer & Schultz

ECCS experimental programme

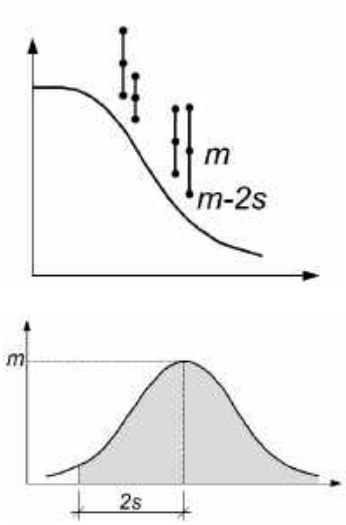
1970

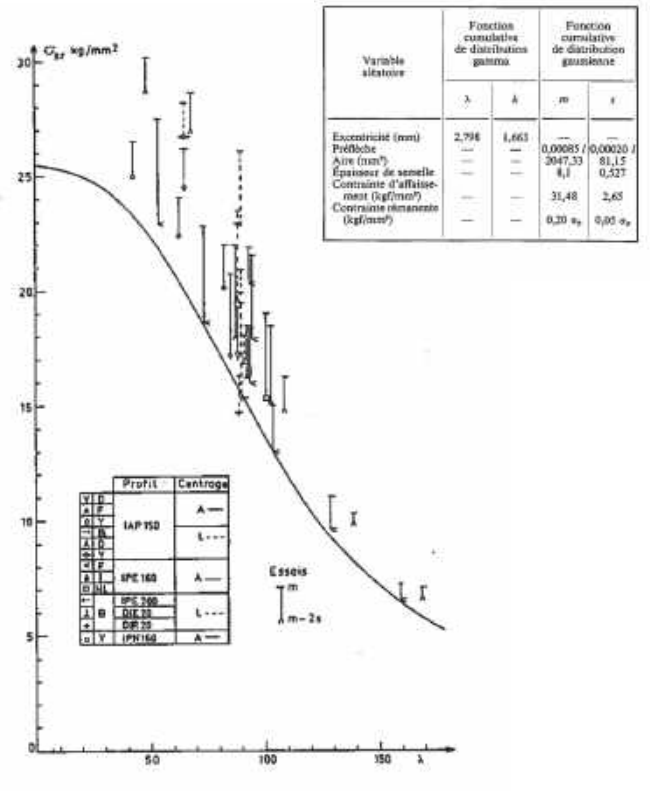
Background

- European buckling curves

Random variables:

- Load eccentricity
- Initial out-of-straightness
- Cross-section area
- Thickness
- Yield stress
- Residual stress





Beer & Schultz

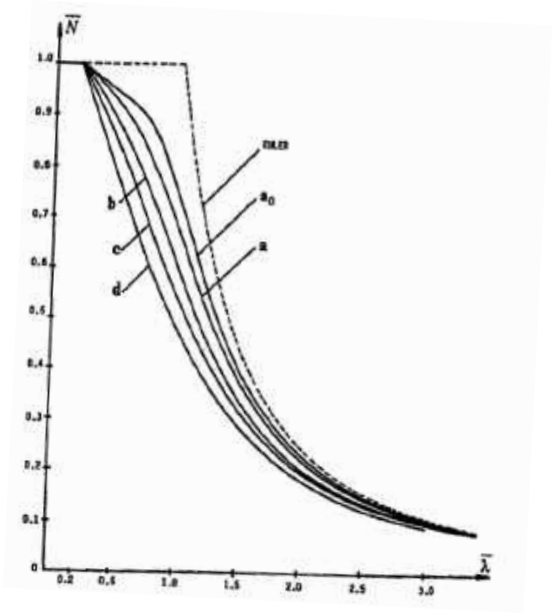
Strating & Vos

ECCS experimental programme

1970 1973

Background

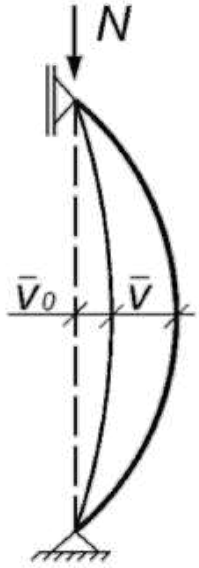
- European buckling curves



$$\chi = \frac{N_{Ed}}{Af_y} = \frac{1}{\phi + \sqrt{\phi^2 - \bar{\lambda}^2}}$$

$$\phi = 0.5\left(1 + \eta + \bar{\lambda}^2\right) \qquad \bar{\lambda} = \sqrt{\frac{Af_y}{N_{cr}}}$$

$$\eta = \frac{\bar{e}_0 A}{W} = \alpha\left(\bar{\lambda} - 0.2\right)$$



Strating & Vos

Beer & Schultz

ECCS experimental programme

Rondal & Maquoi

1970 1973 1978/1979

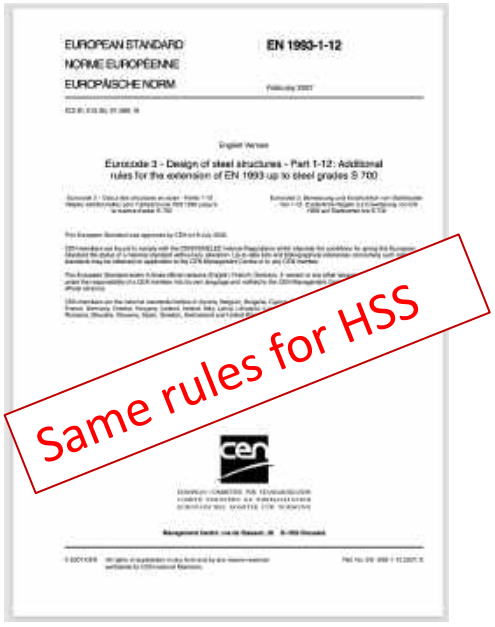
Background

- European buckling curves


EUROPEAN STANDARD
NORME EUROPÉENNE
EUROPÄISCHE NORM

EN 1993-1-1

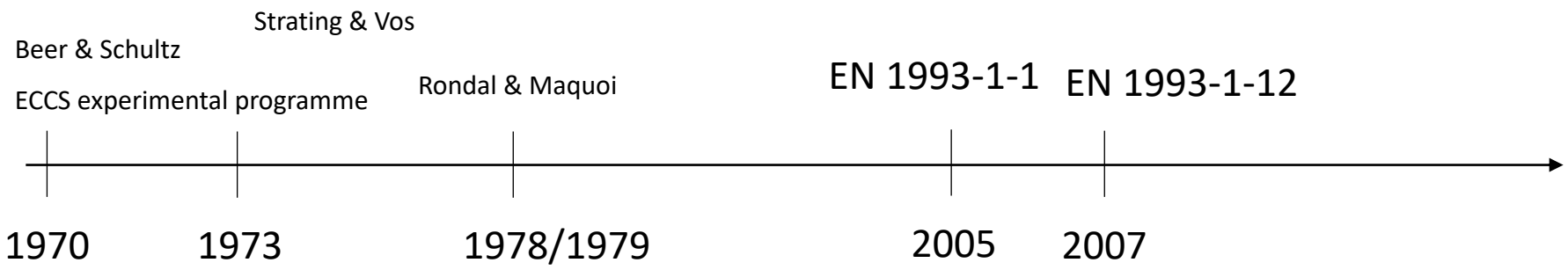
Eurocode 3: Design of steel structures - Part 1-1: General rules and rules for buildings


EUROPEAN STANDARD
NORME EUROPÉENNE
EUROPÄISCHE NORM

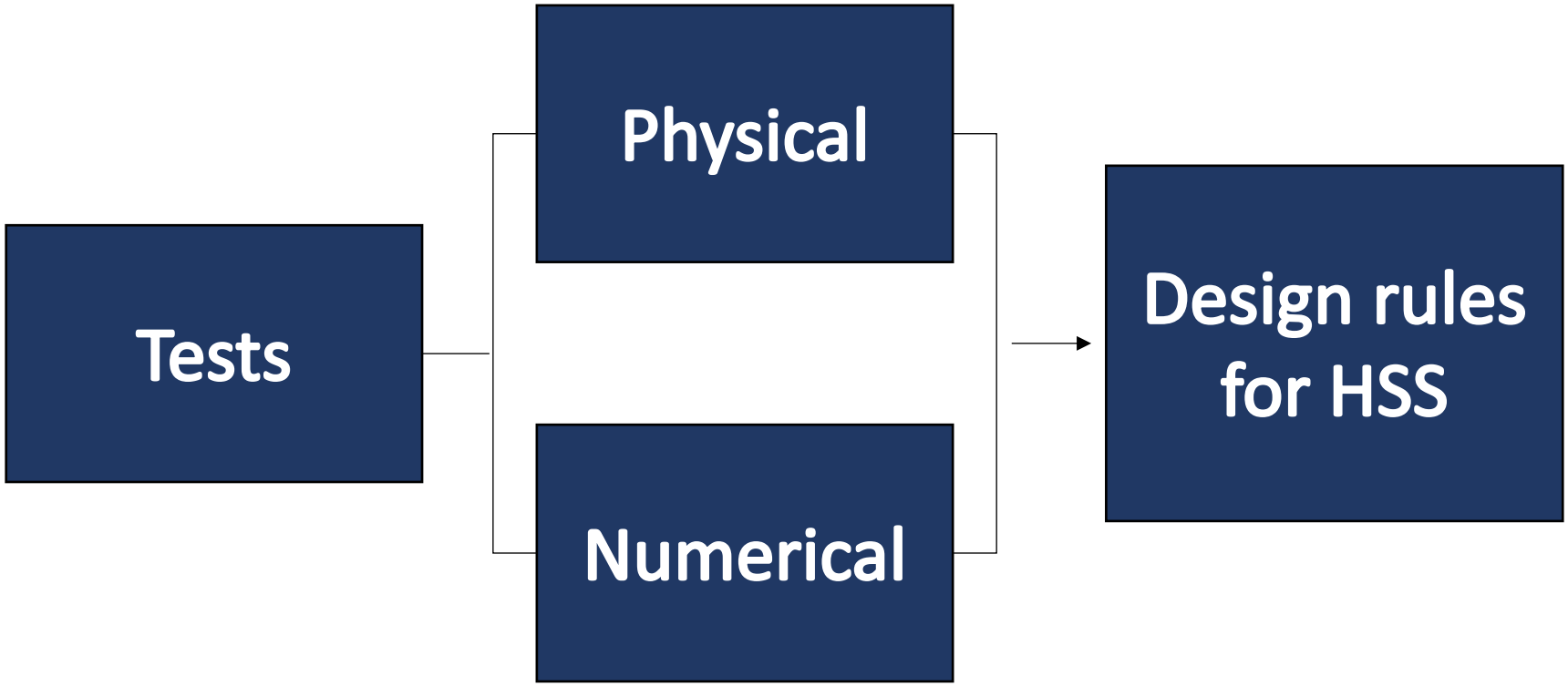
EN 1993-1-12

Eurocode 3 - Design of steel structures - Part 1-12: Additional rules for the extension of EN 1993 up to steel grades S 700

Same rules for HSS



Approach

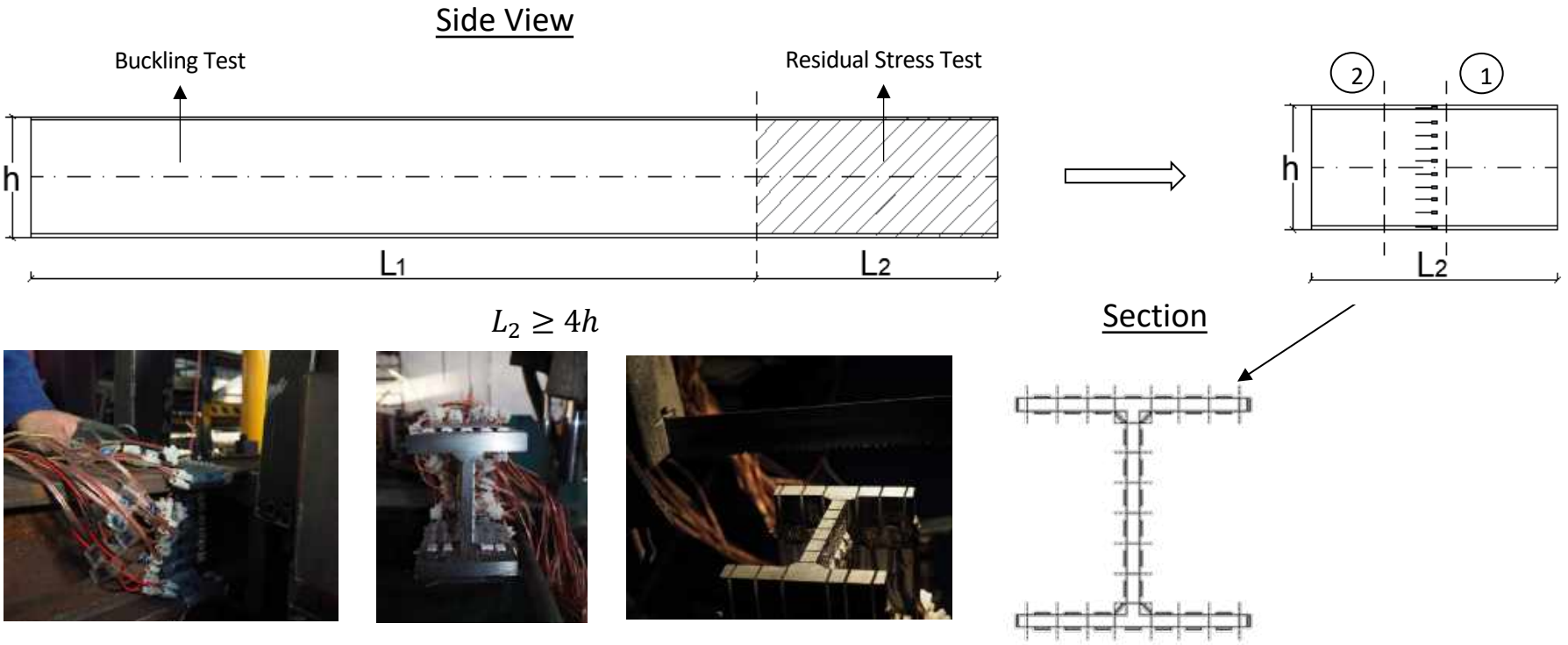


Experimental programme

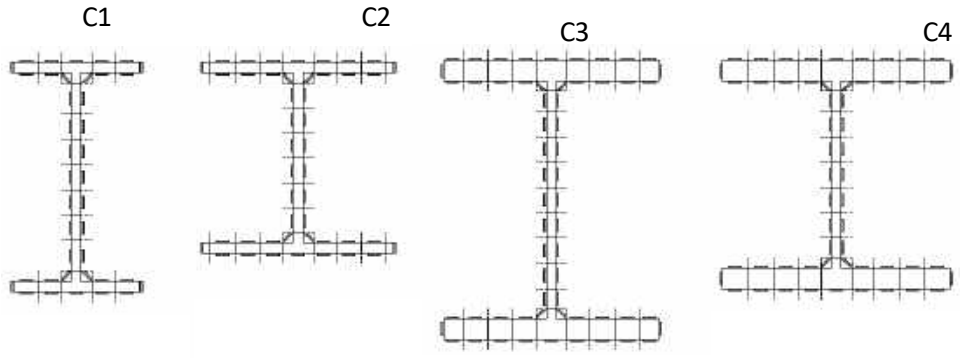
- Objectives
  - Characterise the resistance
  - Assess different steel grades
  - Member imperfections for HSS
  - Hybrid members
  - Different buckling modes

Experimental programme

- Fabrication

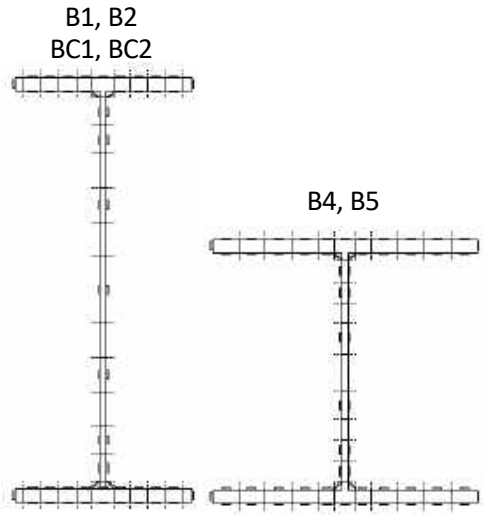


Experimental programme



Type	Member	Fabrication	Steel grade	
			Flanges	Web
C1 y-y	180 × 100 × 8 × 8	Welded	S 690	S 690
C2 y-y	150 × 150 × 8 × 8	Welded	S 690	S 690
C3 z-z	220 × 170 × 8 × 16	Welded	S 690	S 690
C4 z-z	180 × 180 × 8 × 16	Welded	S 690	S 690
B1	500 × 200 × 8 × 16	Welded	S 460	S 460
B2	500 × 200 × 8 × 16	Welded	S 690	S 690
B3	IPE 500	Rolled	S 460	S 460
BC1	500 × 200 × 8 × 16	Welded	S 690	S 690
BC2	500 × 200 × 8 × 16	Welded	S 690	S 355
B4	310 × 300 × 8 × 16	Welded	S 460	S 460
B5	310 × 300 × 8 × 16	Welded	S 690	S 690
B6	HE 320 A	Rolled	S 460	S 460
B7	750 × 200 × 8 × 16	Welded	S 690	S 690
B8_h	750 × 200 × 8 × 16	Welded	S 690	S 355
B11_m	750 × 200(400) × 8 × 16	Welded	S 690	S 690

Experimental programme



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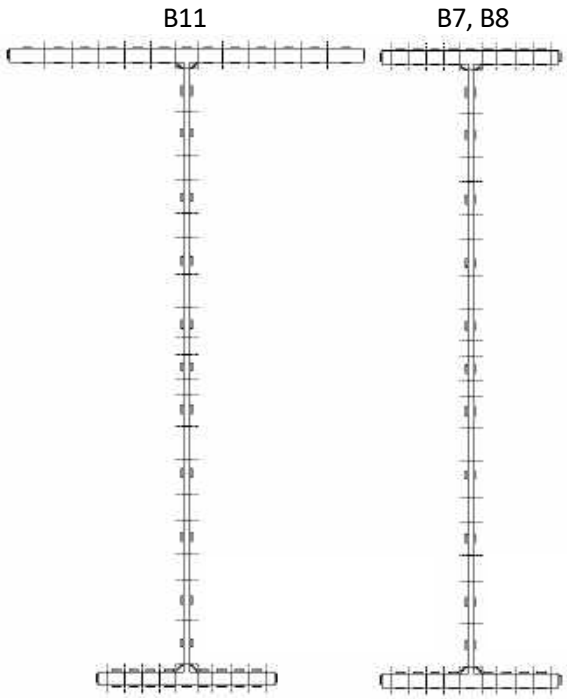
Experimental programme



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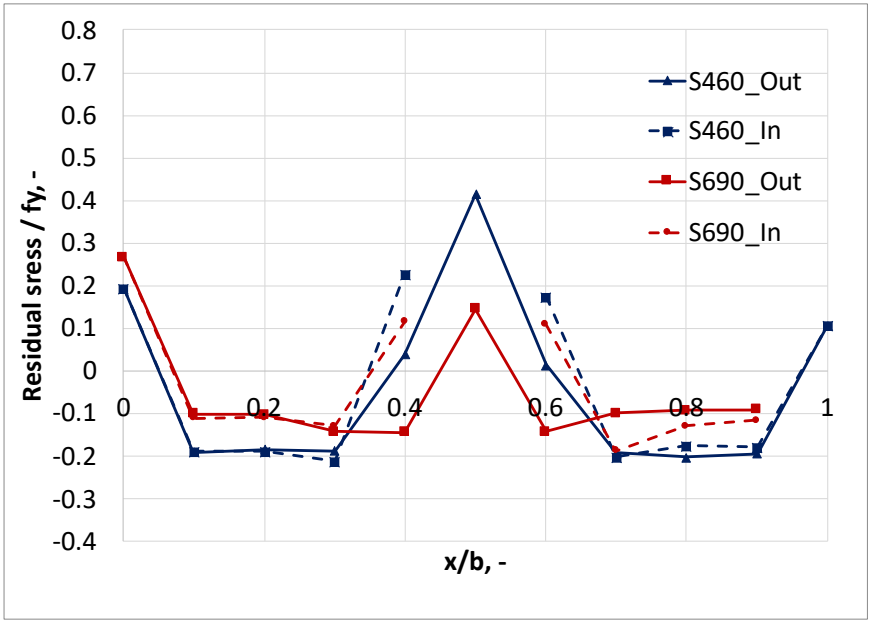
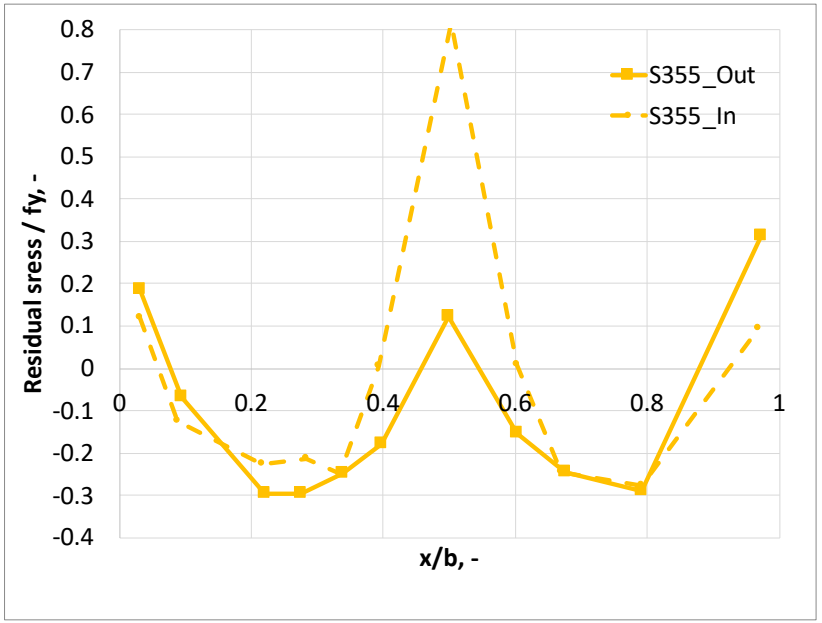
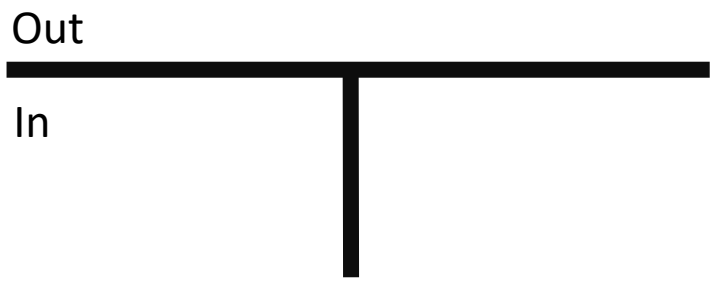
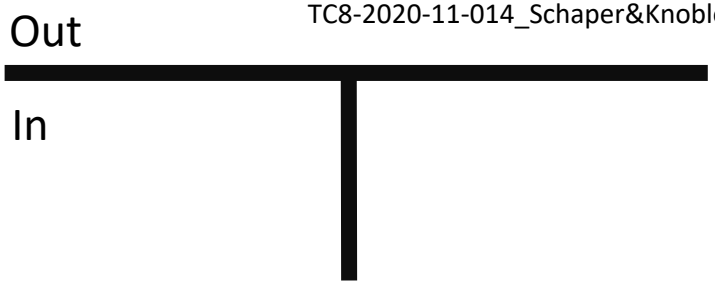
Experimental programme

- Residual stresses





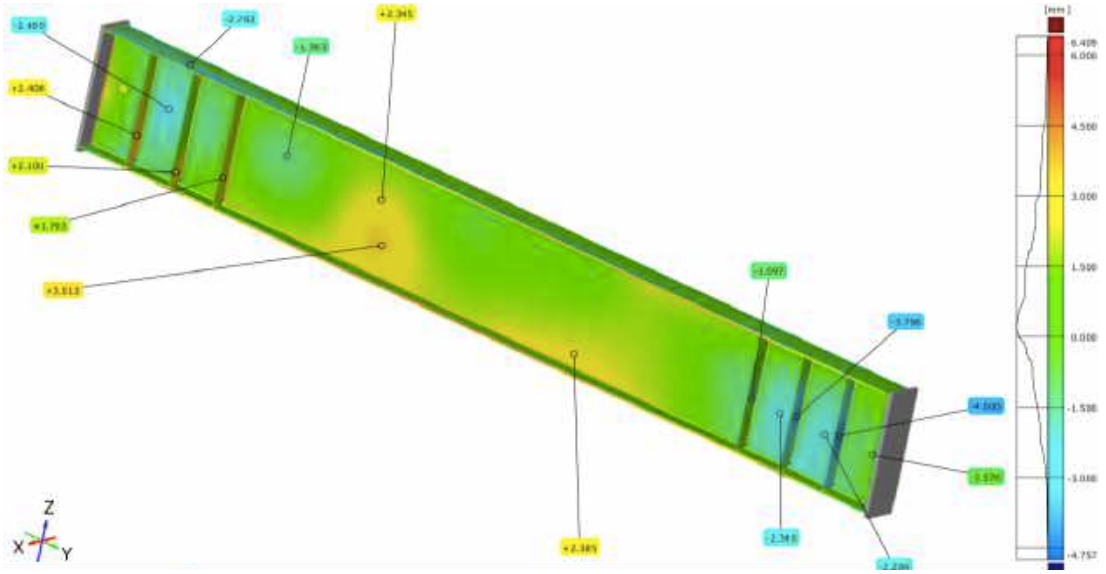




TC8-2020-11-014_Schaper&Knobloch

Experimental programme

- Geometrical imperfections



Measured out-of straightness less than L/1000

Experimental programme

- Columns



Experimental programme

- Beams

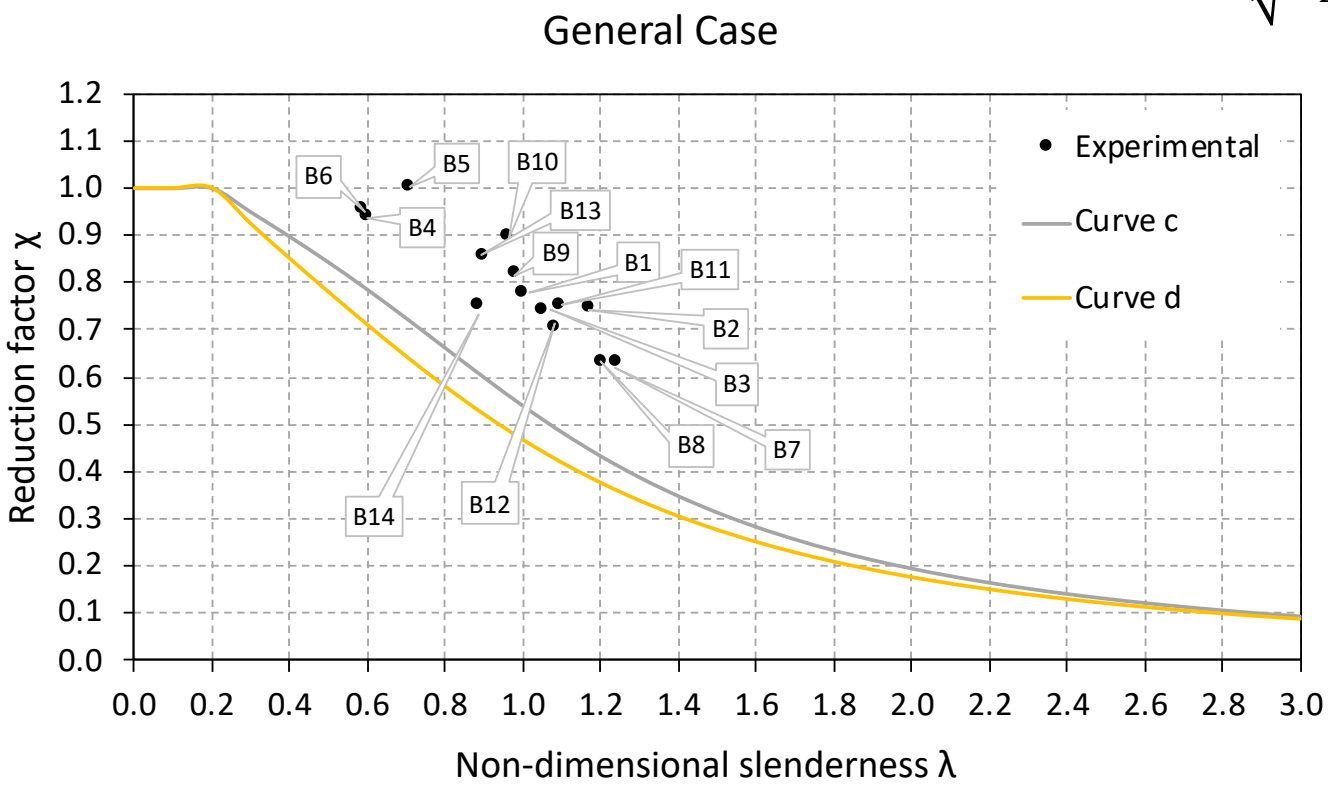
Experimental programme

- Beams



Experimental programme

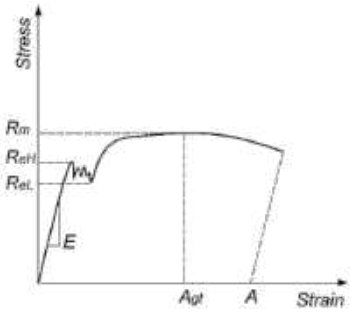
$$\bar{\lambda}_{LT} = \sqrt{\frac{W_y f_y}{M_{cr}}} \qquad \phi_{LT} = 0.5\left(1 + \alpha_{LT}\left(\bar{\lambda}_{LT} - 0.2\right) + \bar{\lambda}_{LT}^2\right) \qquad \chi_{LT} = \frac{1}{\phi_{LT} + \sqrt{\phi_{LT}^2 - \bar{\lambda}_{LT}^2}}$$

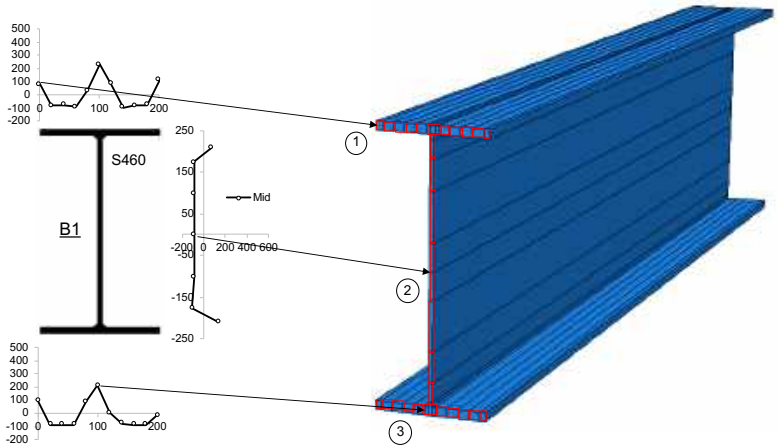


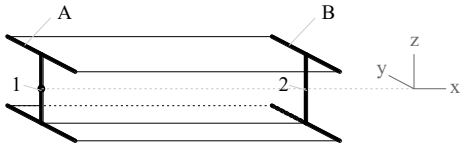
$$\bar{\lambda}_{LT,exp} = \sqrt{M_{Rd,exp}/M_{cr,LBA}} \qquad \chi = M_{exp.}/M_{Rd,exp} \longrightarrow M_{Rd,exp} \text{ based on } f_y \text{ obtained from coupon tests}$$

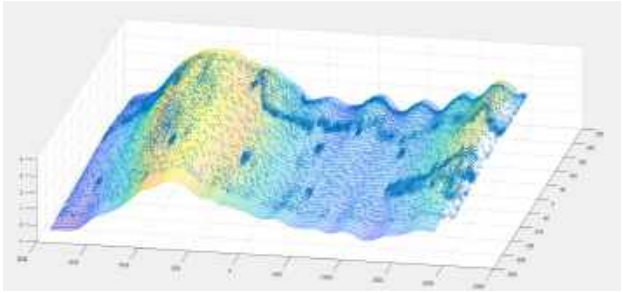
Numerical tests: calibration

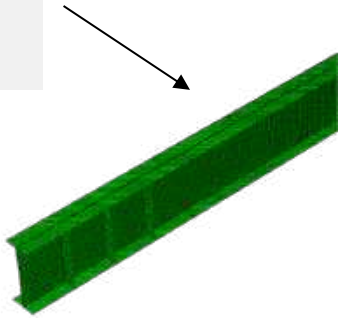
- Shell elements S4R
- Material behavior – as measured
- Residual stresses – as measured
- Geometrical imperfection – as measured
- Boundary conditions - according to test





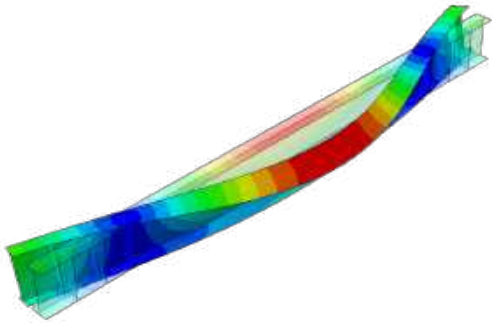


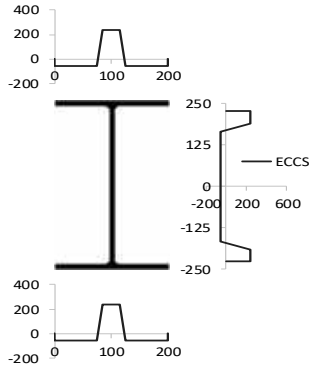


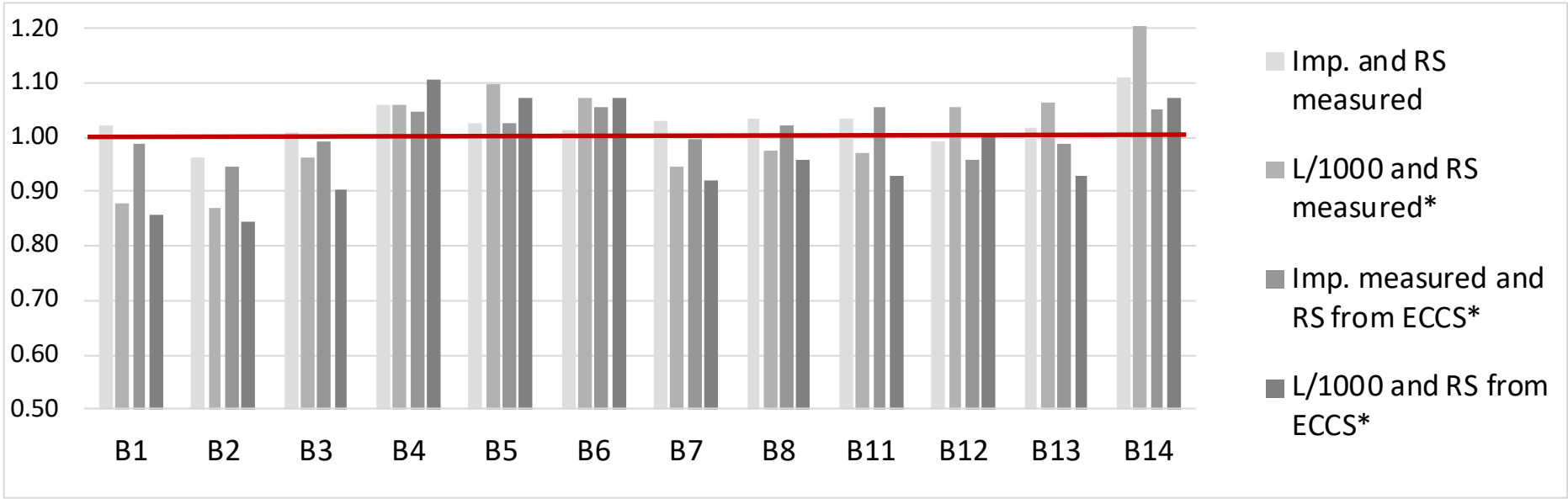


Numerical tests: calibration

- Sensitivity of the imperfection

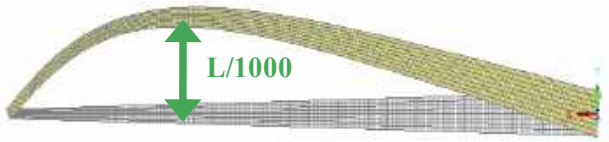


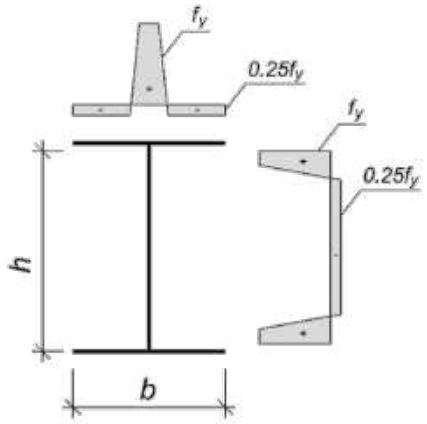


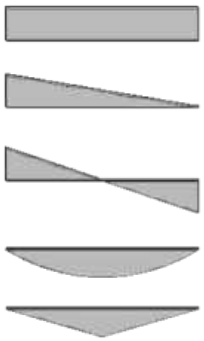
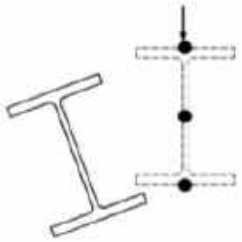


Numerical tests: parametric study

- Advanced analyses with imperfections
  - Residual stresses – ECCS welded (with 235MPa)
  - Geometrical imperfection - L/1000





Member type	$\bar{\lambda}$	Material standard for f_y	Buckling mode	Bending moment distribution	Point of load application
Columns Beams Beam-Columns	0.2 to 2.5	EN 10025: S460 S500 S690 Hybrid HSS + S355	FB y-y FB z-z LTB		

Cross-section (47)	
h	100 ÷ 1056 mm
b	55 ÷ 450 mm
h/b	0.95 ÷ 3.36
t_f	6 ÷ 77 mm
Steel	S460, S500, S690

More than 10 000 simulations

Improved design rules for HSS

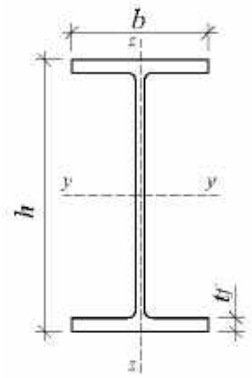
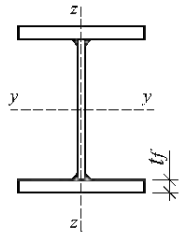
- Columns

$$N_{b,Rd} = \frac{\chi A f_y}{\gamma_{M1}} = \chi N_{c,Rd}$$

$$\chi = \frac{1}{\phi + \sqrt{\phi^2 - \bar{\lambda}^2}}$$

$$\phi = 0.5\left(1 + \alpha(\bar{\lambda} - 0.2) + \bar{\lambda}^2\right)$$

$$\bar{\lambda} = \sqrt{\frac{A f_y}{N_{cr}}}$$

	Fabrication	Limits		Axis	EC3-1-1 S235 S275 S355 S420	EC3-1-1 S460 to S700
Rolled profiles		h/b>1.2	$t_f \leq 40$ mm	y-y	a	a0
				z-z	b	a
			40 mm<t_f≤ 100 mm	y-y	b	a
				z-z	c	
		h/b≤1.2	$t_f \leq 100$ mm			
			t_f	z-z	d	c
Welded profiles		$t_f \leq 40$ mm		y-y	b	a
				z-z	c	b
		$t_f > 40$ mm		y-y	c	b
				z-z	d	c

STROBE Proposed rules for HSS

Improved design rules for HSS

- Beams

$$M_{b,Rd} = \frac{\chi_{LT} W_y f_y}{\gamma_{M1}} = \chi_{LT} M_{c,Rd}$$

$$\chi_{LT} = \frac{1}{\phi_{LT} + \sqrt{\phi_{LT}^2 - \bar{\lambda}_{LT}^2}}$$

$$\phi_{LT} = 0.5\left(1 + \alpha_{LT}\left(\bar{\lambda}_{LT} - 0.2\right) + \bar{\lambda}_{LT}^2\right)$$

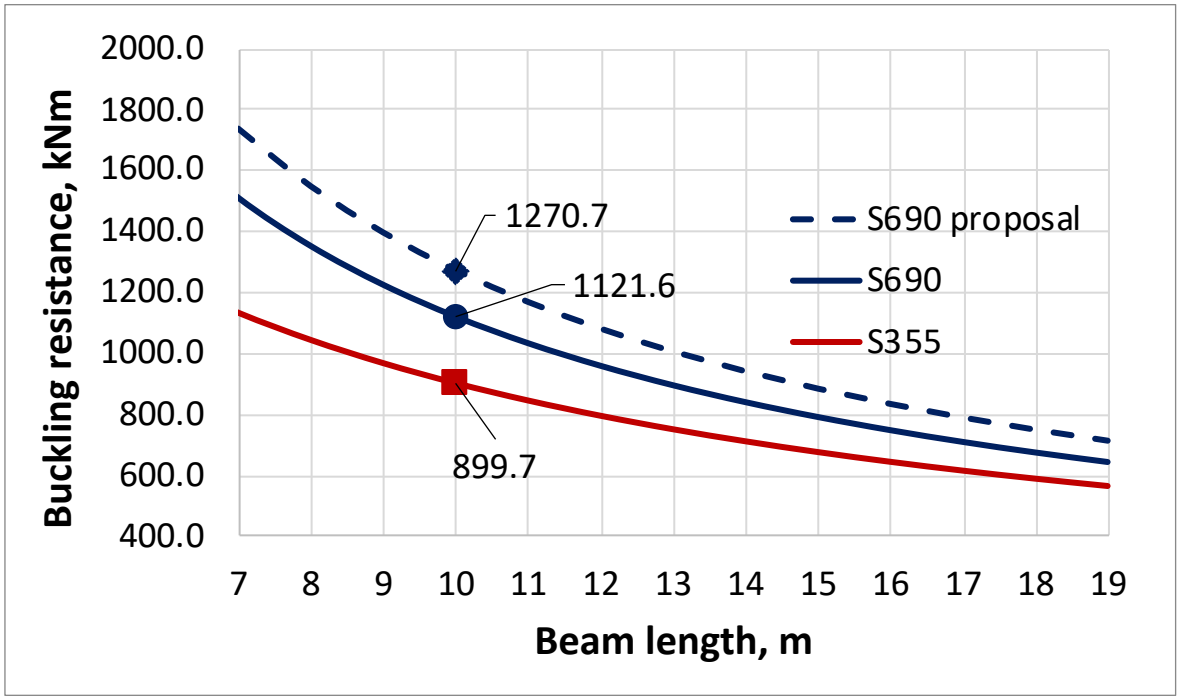
$$\bar{\lambda}_{LT} = \sqrt{\frac{W_y f_y}{M_{cr}}}$$

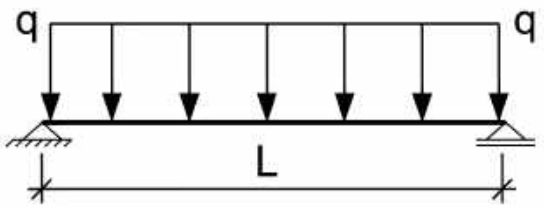
Cross section	Limits	Buckling curve (All)	Recommendation S460 to S700
Rolled I sections	$h/b \leq 2$	a	-
	$h/b > 2$	b	-
Welded Sections	$h/b \leq 2$	c	b
	$h/b > 2$	d	c
Other Sections	-	d	-

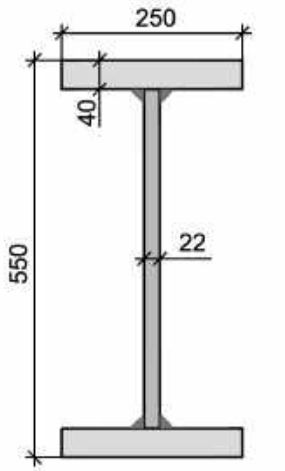
STROBE Proposed rules for HSS

Improved design rules for HSS

- Beams - impact



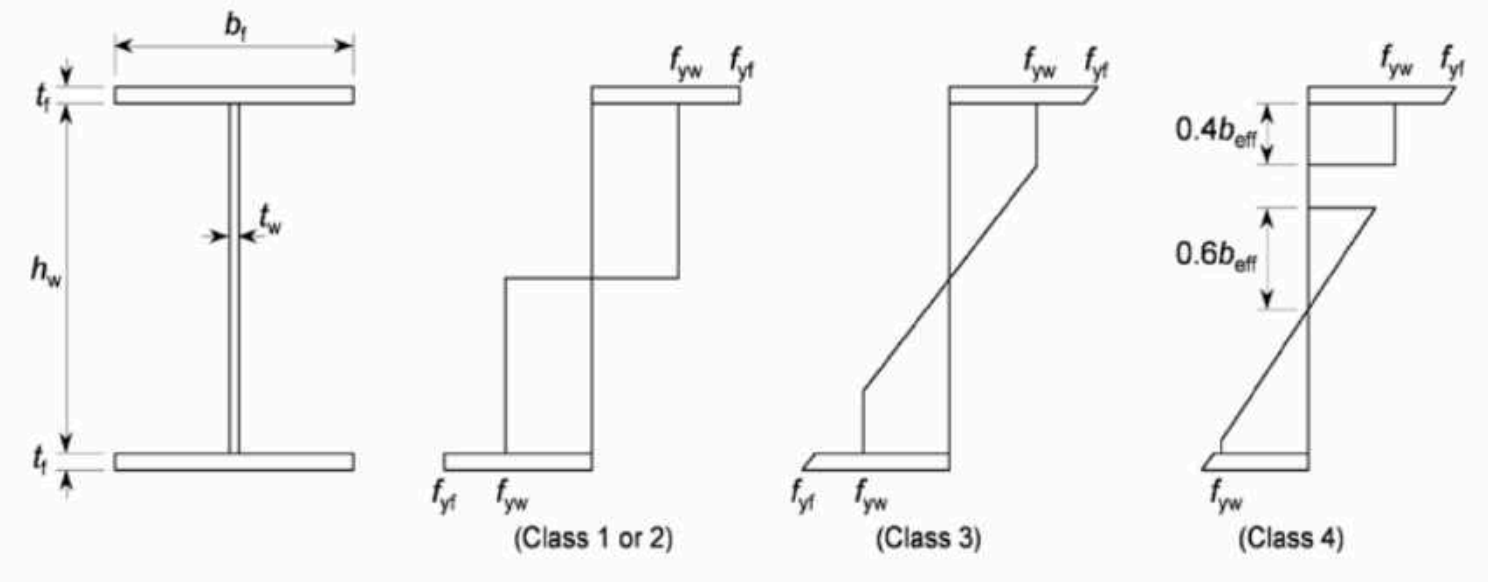




Hybrid beams

- Cross-section resistance

$$f_{y,f} / f_{y,w} \leq 2$$ Acc. EN 1993-1-5 (clause 4.3(6)



- $f_{y,f}$ should be used in determining the effective area of the web
- Stresses in the web are limited to $f_{y,w}$

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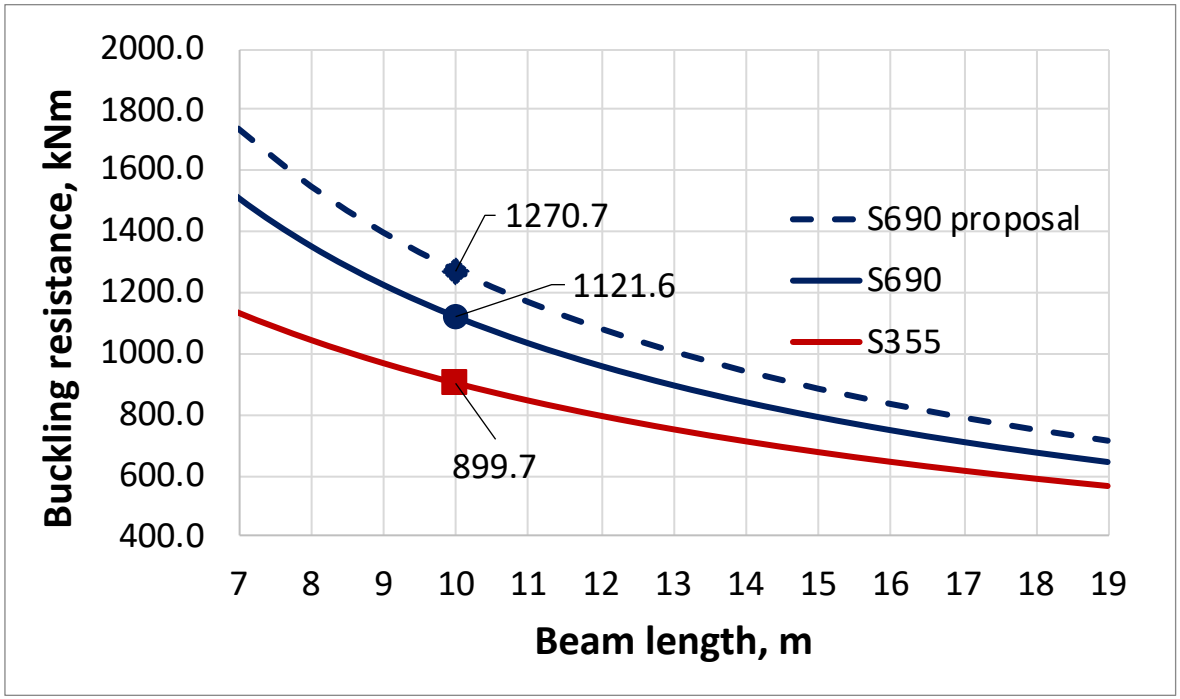
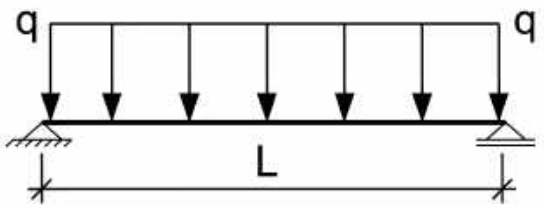
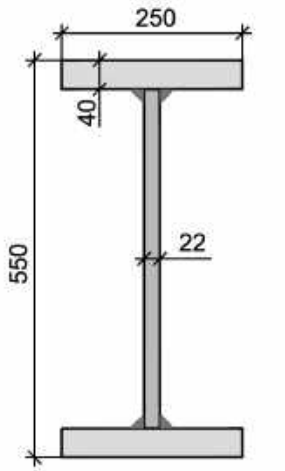
Improved design rules for HSS

- Beams – Hybrid girder







$$M_{b,Rd} = \mathbf{1092.9\ kNm\ (cf\ 1121.6\ kNm)}$$

Closure

- HSS steel members may provide structural solutions that are more efficient, with a smaller carbon footprint.
- Design rules were improved to take advantage of the properties of HSS.
- No extra complexity is necessary to use HSS members. Design procedures use the same format.
- Fabrication procedures are similar when compared to normal steel grades.
- Hybrid sections provide similar buckling resistance (max -10%) whenever shear buckling is not the controlling failure mode.