Imperial College London

Experimental and numerical studies of laser-welded stainless steel I-section beam-columns

Stainless steel in structures – Fifth International Experts Seminar

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Outline

- Testing
- FE modelling and parametric studies
- Design
    - Assessment of codified design provisions
    - Development of new proposal
- Conclusions

Testing

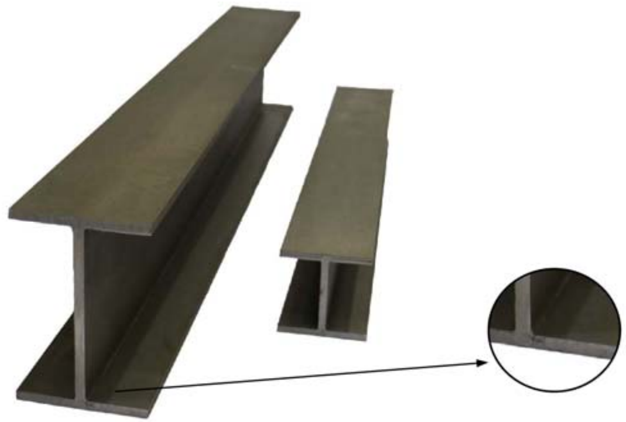
Testing

Specimens:

- Laser-welded from austenitic stainless steel hot-rolled plates
- Two section sizes – both Class 1

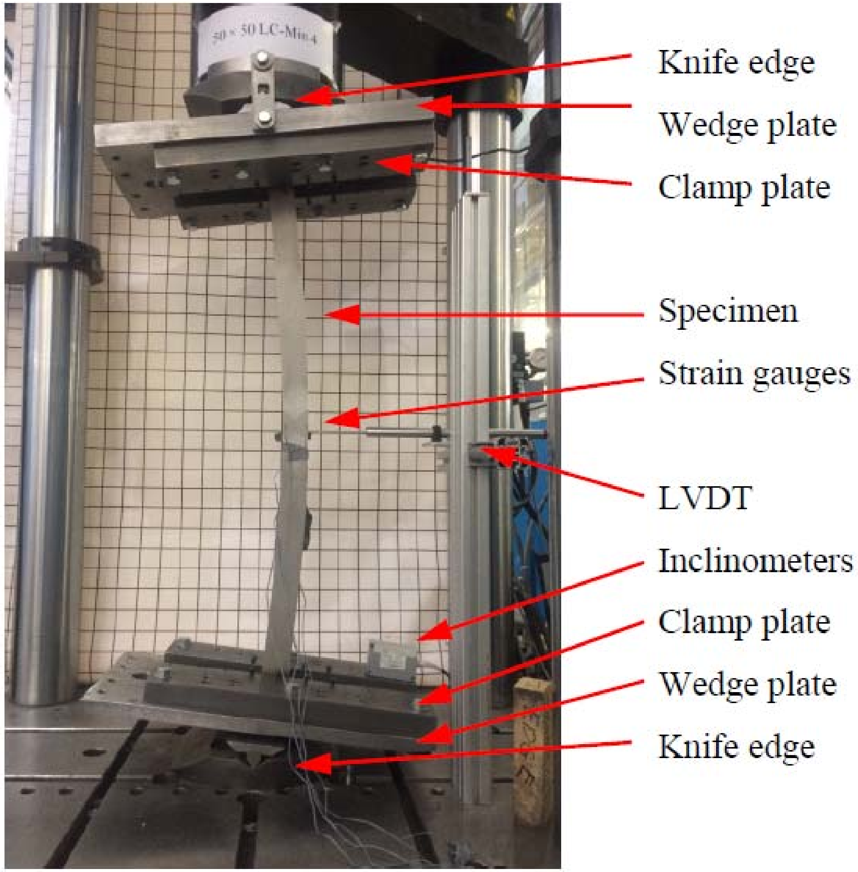
Tests conducted:

- Material coupon tests
- Combined loading member tests
  - 12 N + M_z beam-columns
  - 6 N + M_y beam-columns

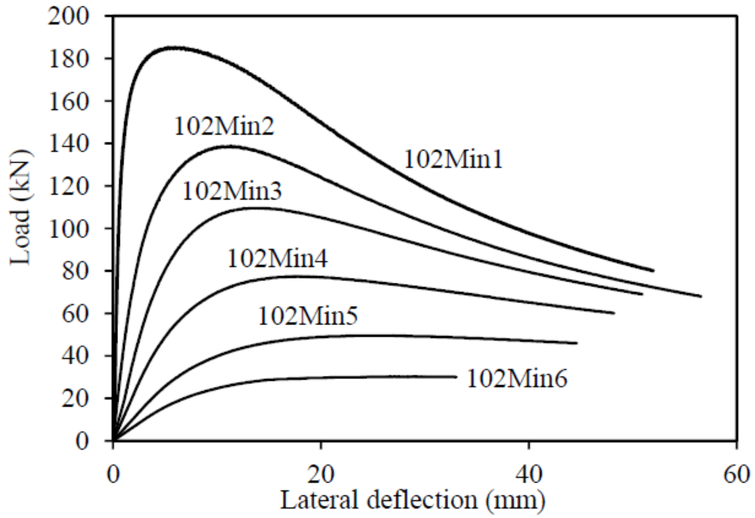


Thank you to Montanstahl for the supply of test specimens and financial support for the experimental programme

Combined loading tests – minor axis bending

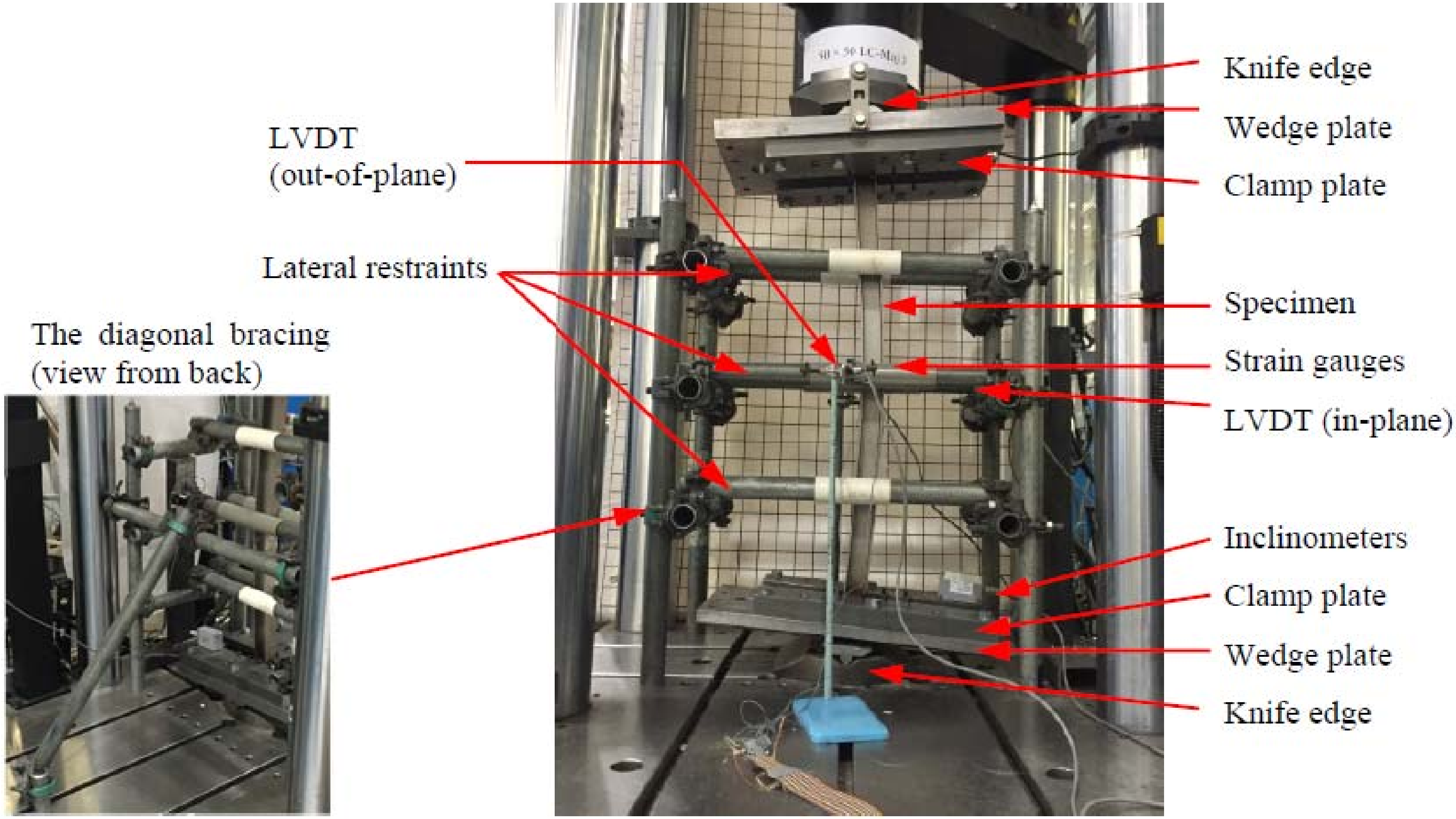


N + M_z beam-column test setup



Load-lateral deflection curves under varying load eccentricities

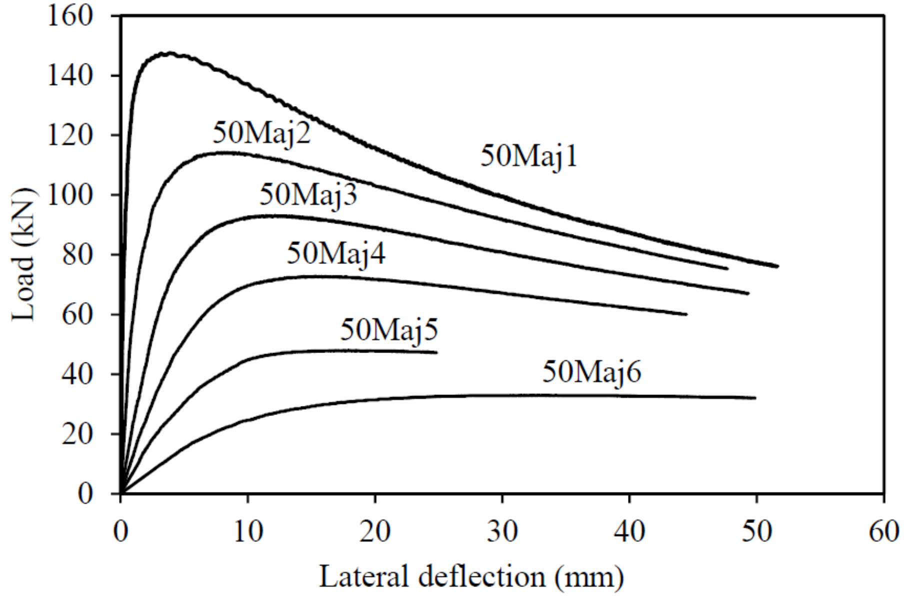
Combined loading tests – major axis bending



Lateral restraints to prevent out-of-plane deformations

N + M_y beam-column test setup

Combined loading tests – major axis bending



Load-lateral deflection curves under varying load eccentricities

Deformed beam-columns confirming major axis deformation only

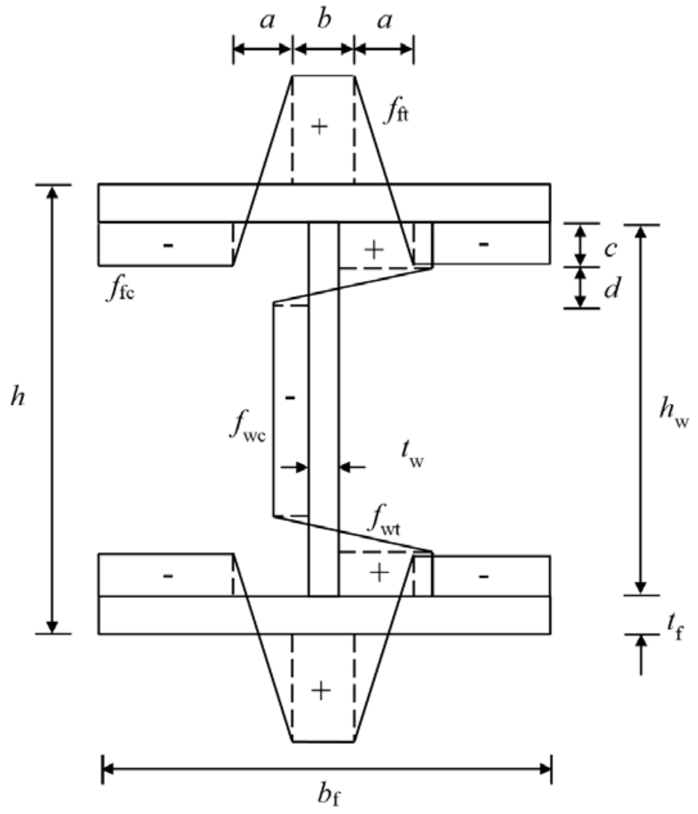
FE modelling and parametric studies

FE modelling

- Basic modelling assumptions:
  - S4R shell elements, with mesh size t × t
  - Two stage Ramberg-Osgood material model
  - Local and global geometric imperfections, with 3 amplitude combinations, including measured values
  - Residual stresses

FE models validated against tests from this study on laser-welded I-section beam-coulmns and other existing tests on conventionally welded I-section beam-columns (Burgan et al., 2000)

Residual stresses



From predictive models based on a series of experiments:

- Peak tensile residual stress: $0.8f_y$ for conventional welding, $0.5f_y$ for laser-welding
- Peak compressive residual stress: determined based on self-equilibrium

	Predictive model	$f_{ft}=f_{wt}$	$f_{fc}=f_{wc}$	a	b	c	d
Laser-welding	Gardner et al. [1]	$0.5f_y$	From equilibrium	$0.1b_f$	$0.075b_f$	$0.025h_w$	$0.05h_w$
Conventional welding	Yuan et al. [27]	$0.8f_y$	From equilibrium	$0.225b_f$	$0.05b_f$	$0.025h_w$	$0.225h_w$

FE validation – minor axis failure load comparison

Cross-section	References	Specimen ID	$N_{u,test}/N_{u,FE}$		
			w_g+w_l	$L_{cr}/1000+t_f/100$	$L_{cr}/1000+w_{D\&W}$
I-102×68×5×5	Section 2 of this paper	102Min1	1.03	1.04	1.04
		102Min2	1.05	1.05	1.05
		102Min3	1.09	1.09	1.09
		102Min4	1.04	1.04	1.04
		102Min5	1.04	1.05	1.05
		102Min6	0.97	0.98	0.98
I-50×50×4×4	Section 2 of this paper	50Min1	1.02	1.02	1.02
		50Min2	1.03	1.05	1.05
		50Min3	1.05	1.05	1.05
		50Min4	1.02	1.03	1.03
		50Min5	0.98	0.98	0.98
		50Min6	0.93	0.93	0.93
Mean			1.02	1.03	1.02
COV			0.04	0.04	0.04

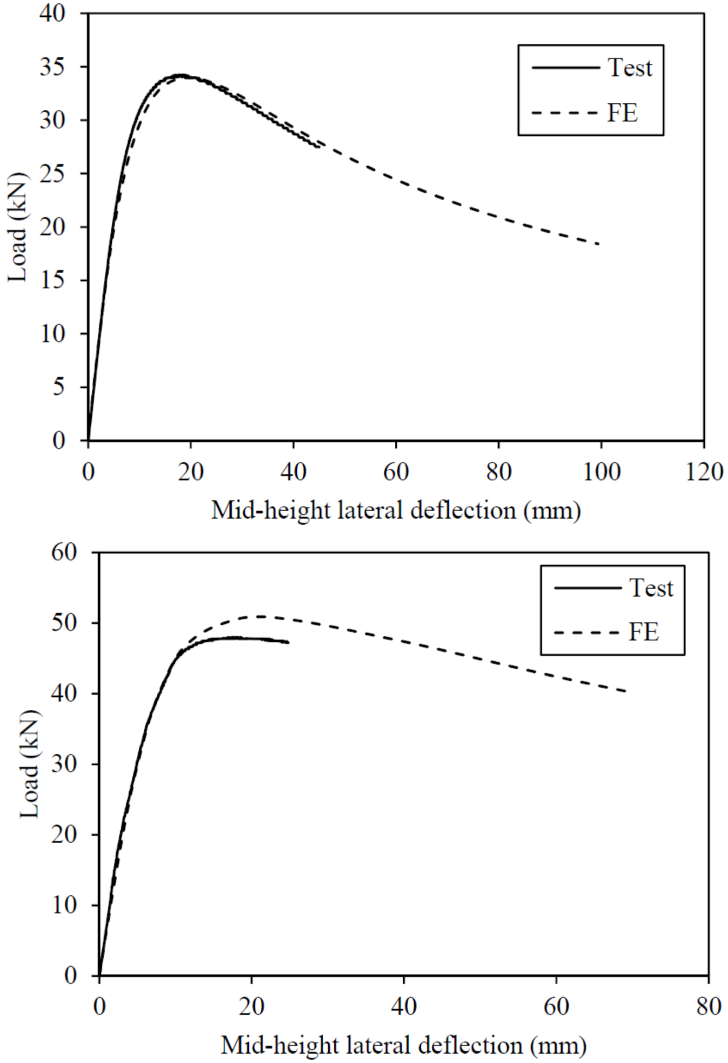
Numerical failure loads well predicted for all three considered combinations of global and local imperfection amplitudes

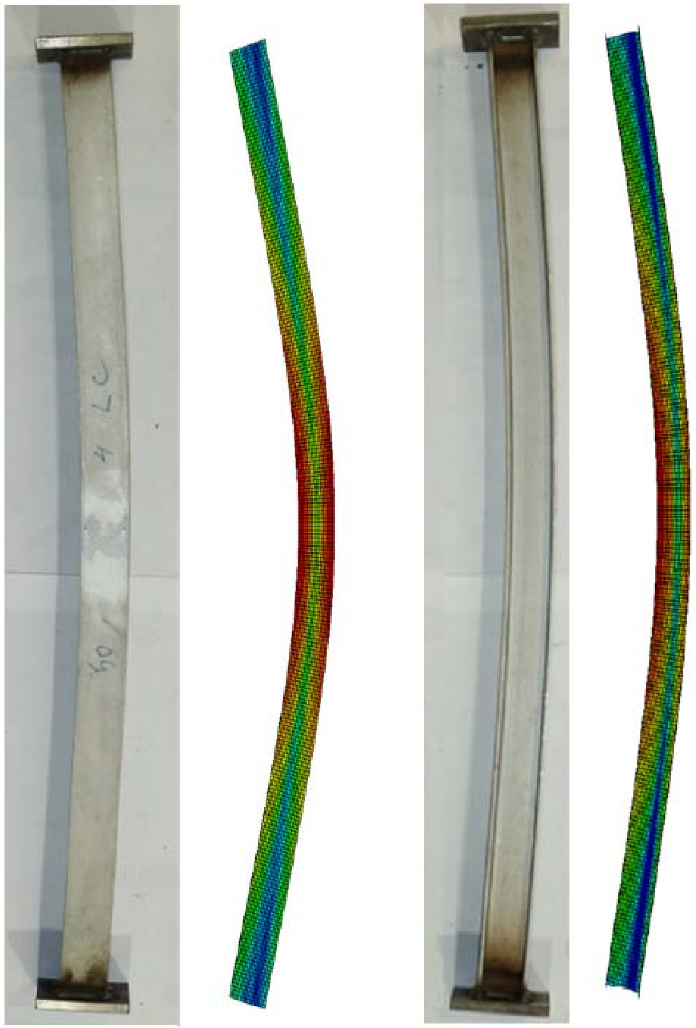
FE validation – major axis failure load comparison

Cross-section	References	Specimen ID	$N_{u,test}/N_{u,FE}$		
			w_g+w_l	$L_{cr}/1000+t_f/100$	$L_{cr}/1000+w_{D\&W}$
I-50×50×4×4	Section 2 of this paper	50Maj1	1.07	1.09	1.09
		50Maj2	1.06	1.09	1.09
		50Maj3	1.01	1.05	1.05
		50Maj4	1.01	1.03	1.03
		50Maj5	0.93	0.97	0.97
		50Maj6	1.01	1.03	1.03
I-160×80×6×10	Burgan et al. [7]	I-160×80-EC0	-	1.05	1.05
		I-160×80-EC1	-	0.98	0.98
		I-160×80-EC2	-	0.96	0.96
		I-160×80-EC3	-	1.05	1.05
I-160×160×6×10		I-160×160-EC0	-	0.95	0.95
		I-160×160-EC1	-	0.99	0.98
		I-160×160-EC2	-	0.95	0.94
		I-160×160-EC3	-	0.98	0.98
Mean			1.02	1.01	1.01
COV			0.05	0.05	0.05

Numerical failure loads well predicted for all three considered combinations of global and local imperfection amplitudes

FE validation – N-δ curves and failure modes





$N+M_z$ $N+M_y$

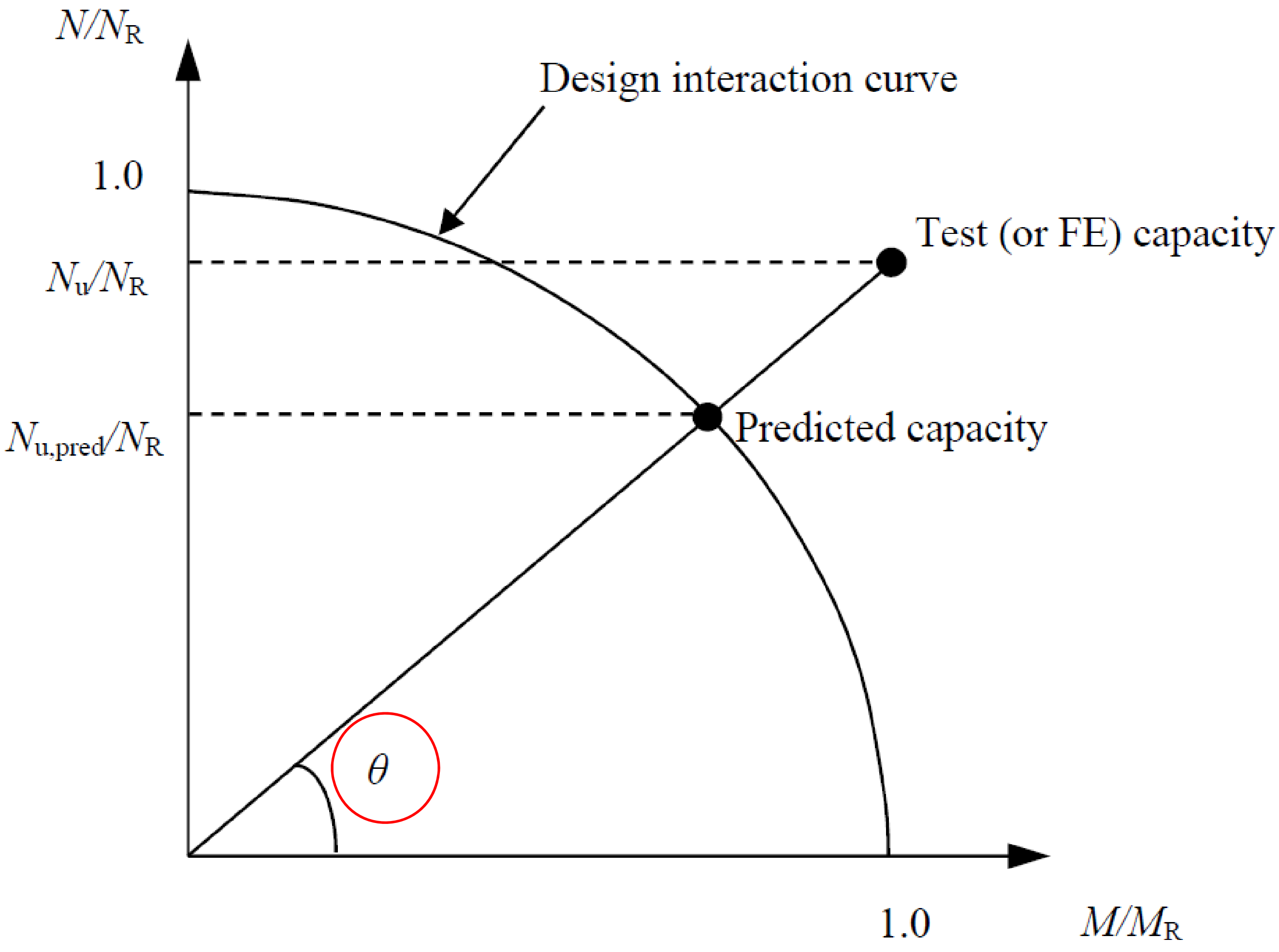
FE modelling – parametric studies

- Parameters investigated:
  - *h/b* ratio: 1.0, 1.5, 2.0 and 3.0
  - Loading eccentricities: 0 mm to 80 mm
  - Global imperfection amplitude: $L_{cr}/1000$
  - Local imperfection amplitude: t/100
  - Material properties of specimen I-102x68x5x5

Cross-section	E_c (N/mm^2)	$f_{y,c}$ (N/mm^2)	$f_{1.0,c}$ (N/mm^2)	$f_{u,c}$ (N/mm^2)	$\varepsilon_{u,c}$ (%)	$\varepsilon_{f,c}$ (%)	Compound R-O coefficients n_c	$n_{0.2,1.0,c}$	$n_{0.2,u,c}$
I-102×68×5×5	190800	291	354	580	50	-	6.4	3.9	3.8

Results and design

Load-moment interaction curve



EN 1993-1-4 (EC3)

EN 1993-1-4 employs the following interaction formulae:

$$\frac{N_{\mathrm{Ed}}}{N_{\mathrm{b,y,Rd}}} + k_{\mathrm{y}}\left(\frac{M_{\mathrm{y,Ed}}}{\beta_{\mathrm{W}} W_{\mathrm{pl,y}} f_{\mathrm{y}}}\right) \leq 1 \qquad \frac{N_{\mathrm{Ed}}}{N_{\mathrm{b,z,Rd}}} + k_{\mathrm{z}}\left(\frac{M_{\mathrm{z,Ed}}}{\beta_{\mathrm{W}} W_{\mathrm{pl,z}} f_{\mathrm{y}}}\right) \leq 1$$

The interaction factor k is a linear function of slenderness and axial load level, with an upper and lower bound, resulting in a nonlinear M-N interaction relationship.

$$1.2 \leq k_{\mathrm{y}} = k_{\mathrm{z}} = 1 + 2(\bar{\lambda} - 0.5)\frac{N_{\mathrm{Ed}}}{N_{\mathrm{b,Rd}}} \leq 1.2 + 2\frac{N_{\mathrm{Ed}}}{N_{\mathrm{b,Rd}}}$$

β_w = 1 for Class 1 and 2, = W_{el}/W_{pl} for Class 3 and = W_{eff}/W_{pl} for Class 4 cross-sections

AISC Design Guide 27

AISC Design Guide 27 employs a pair of formulae to give a bi-linear interaction curve:

$$\frac{N_{\mathrm{Ed}}}{N_{\mathrm{c}}}+\frac{8}{9}\left(\frac{M_{\mathrm{z,Ed}}}{M_{\mathrm{z,c}}}+\frac{M_{\mathrm{y,Ed}}}{M_{\mathrm{y,c}}}\right)\leq 1,\ \text{for}\ \frac{N_{\mathrm{Ed}}}{N_{\mathrm{c}}}\geq 0.2,$$

$$\frac{N_{\mathrm{Ed}}}{2N_{\mathrm{c}}}+\left(\frac{M_{\mathrm{z,Ed}}}{M_{\mathrm{z,c}}}+\frac{M_{\mathrm{y,Ed}}}{M_{\mathrm{y,c}}}\right)\leq 1,\ \text{for}\ \frac{N_{\mathrm{Ed}}}{N_{\mathrm{c}}}< 0.2,$$

Bending resistance is defined in AISC Design Guide 27 as a function of the local slenderness of the flanges and web.

Greiner and Kettler's proposal

Proposals derived following approach of Annex B of EN 1993-1-1 for carbon steel. Proposals differentiate between k_y and k_z, but apply to Class 1 and 2 cross-sections only.

$$\frac{N_{\mathrm{Ed}}}{N_{\mathrm{b,z,Rd}}} + k_{\mathrm{G\&K,z}} \frac{M_{\mathrm{z,Ed}}}{W_{\mathrm{pl,z}} f_{\mathrm{y}}} \leq 1,$$

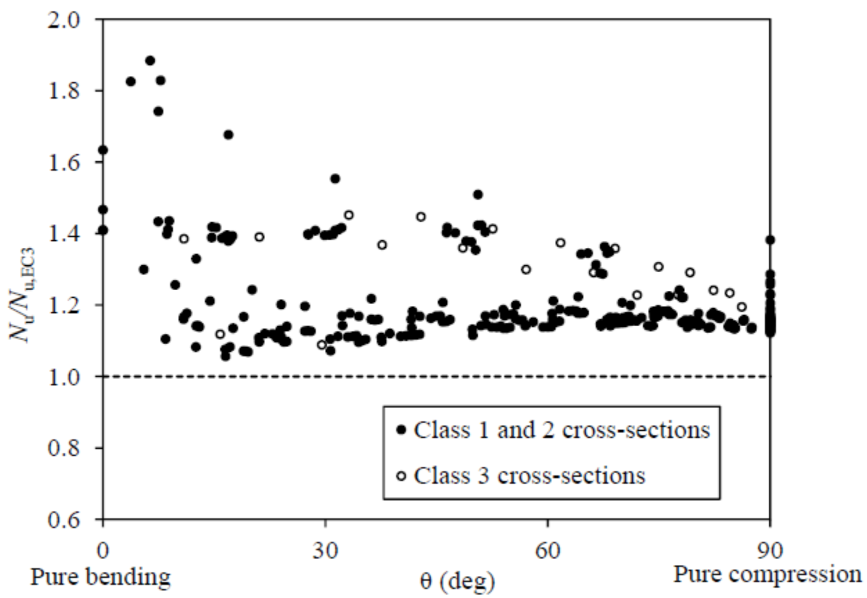
$$\frac{N_{\mathrm{Ed}}}{N_{\mathrm{b,y,Rd}}} + k_{\mathrm{G\&K,y}} \frac{M_{\mathrm{y,Ed}}}{W_{\mathrm{pl,y}} f_{\mathrm{y}}} \leq 1,$$

$$k_{\mathrm{G\&K,z}} = 1.2 + 1.5 \frac{N_{\mathrm{Ed}}}{N_{\mathrm{b,z,Rd}}} (\bar{\lambda}_{\mathrm{z}} - 0.7), \quad \text{but} \quad k_{\mathrm{G\&K,z}} \leq 1.2 + 1.95 \frac{N_{\mathrm{Ed}}}{N_{\mathrm{b,z,Rd}}},$$

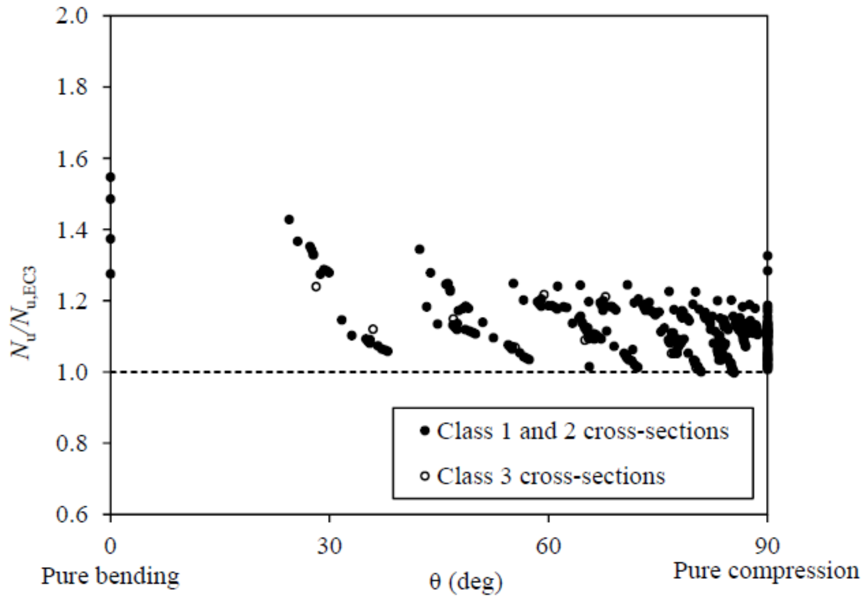
$$k_{\mathrm{G\&K,y}} = 0.9 + 2.2 \frac{N_{\mathrm{Ed}}}{N_{\mathrm{b,y,Rd}}} (\bar{\lambda}_{\mathrm{y}} - 0.4), \quad \text{but} \quad k_{\mathrm{G\&K,y}} \leq 0.9 + 2.42 \frac{N_{\mathrm{Ed}}}{N_{\mathrm{b,y,Rd}}}.$$

Assessment of EN 1993-1-4 (EC3)

Minor axis bending



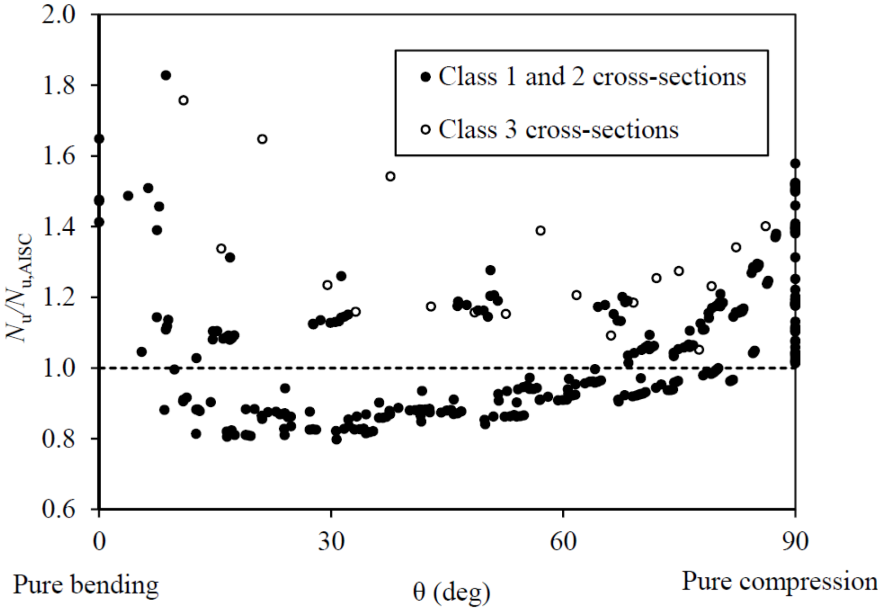
Major axis bending



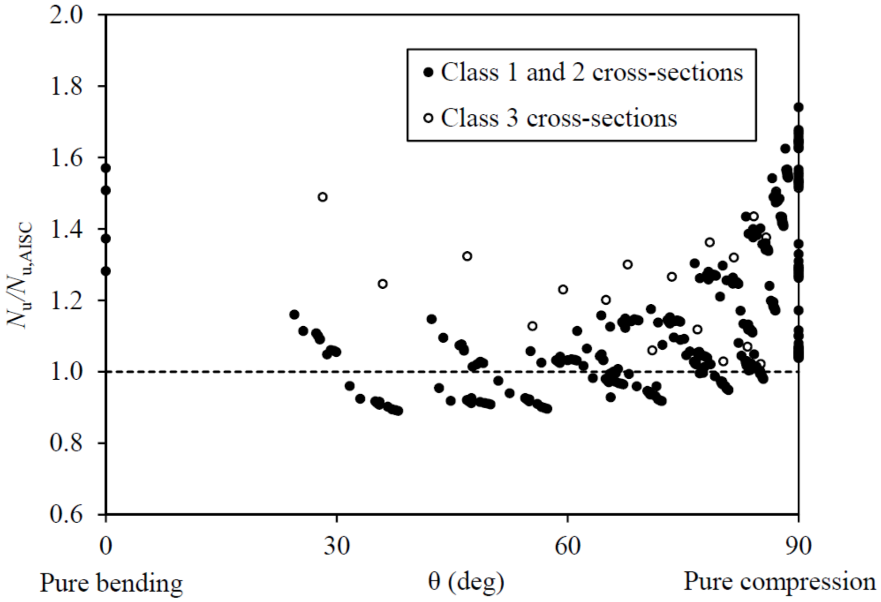
EC3 provides reasonable overall strength predictions, but scope for improved accuracy and consistency

Assessment of AISC Design Guide 27

Minor axis bending



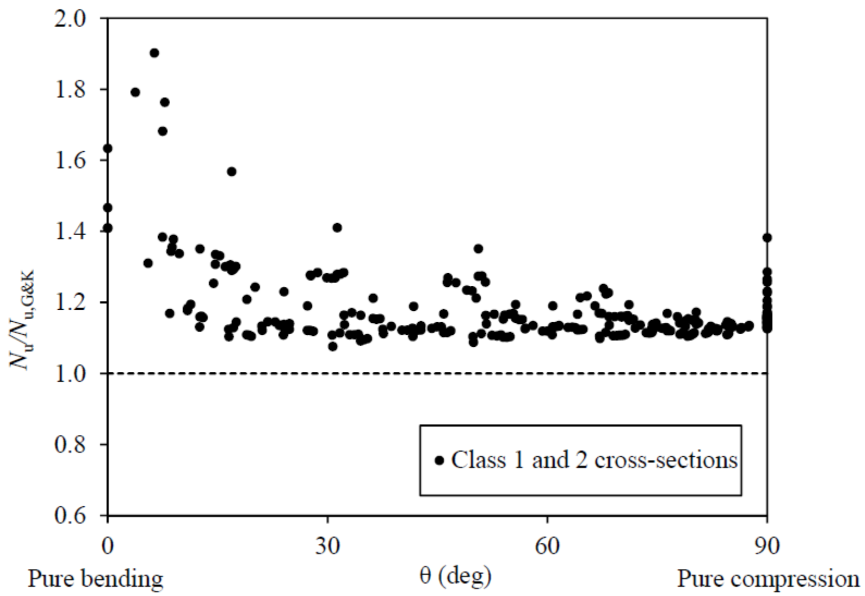
Major axis bending



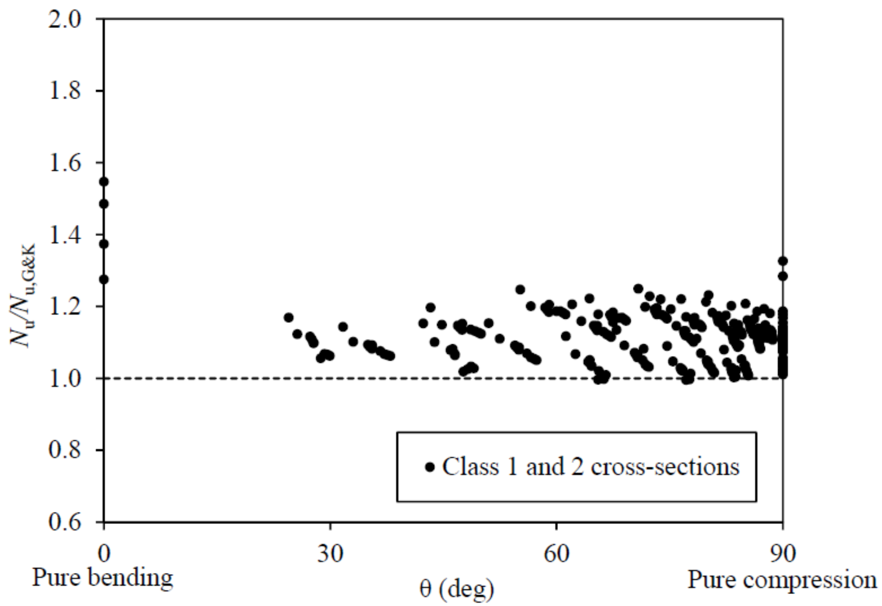
AISC Design Guide 27 provides better strength predictions on average, but rather scattered and a number of results on unsafe side

Assessment of Greiner and Kettler’s proposal

Minor axis bending



Major axis bending



Greiner and Kettler’s proposals lead to improved results over the current Eurocode predictions, but scope for further improvements remain.

Greiner and Kettler acknowledged that their proposed curves were partially accounting for interaction effects and partially compensating for inaccurate end points.

Summary of design predictions

Class 1 and 2 cross-sections:

Loading combinations	No. of tests: 18 No. of simulations: 600	$N_u/N_{u,EC3}$	$N_u/N_{u,AISC}$	$N_u/N_{u,G\&K}$
Compression and bending about minor axis	Mean	1.21	1.06	1.18
	COV	0.13	0.18	0.12
Compression and bending about major axis	Mean	1.12	1.17	1.11
	COV	0.06	0.18	0.05

Class 3 cross-sections:

Loading combinations	No. of tests: 0 No. of simulations: 360	$N_u/N_{u,EC3}$	$N_u/N_{u,AISC}$	$N_u/N_{u,G\&K}$
Compression and bending about minor axis	Mean	1.28	1.29	-
	COV	0.09	0.14	-
Compression and bending about major axis	Mean	1.11	1.28	-
	COV	0.06	0.15	-

New proposal

New proposal – CSM based

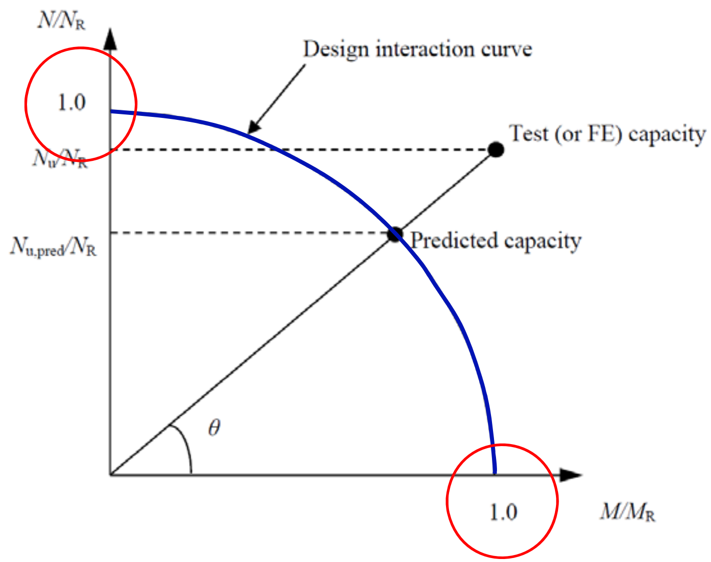
Improvements sought in two key areas:

1. Column buckling and bending resistance end points

2. Interaction factors that describe shape of interaction curves

$$\frac{N_{\mathrm{Ed}}}{N_{\mathrm{b,z,Rd}}} + k_{\mathrm{csm,z}} \frac{M_{\mathrm{z,Ed}}}{M_{\mathrm{csm,z,Rk}}/\gamma_{\mathrm{M1}}} \leq 1$$

$$\frac{N_{\mathrm{Ed}}}{N_{\mathrm{b,y,Rd}}} + k_{\mathrm{csm,y}} \frac{M_{\mathrm{y,Ed}}}{M_{\mathrm{csm,y,Rk}}/\gamma_{\mathrm{M1}}} \leq 1$$



New proposal – end points

Column buckling end point based on newly proposed column curves:

Welding type	Buckling axis	Proposed	
		α	$\bar{\lambda}_0$
Conventional welding	Major	0.49	0.20
Conventional welding	Minor	0.76	0.20
Laser-welding	Major	0.49	0.20
Laser-welding	Minor	0.60	0.20

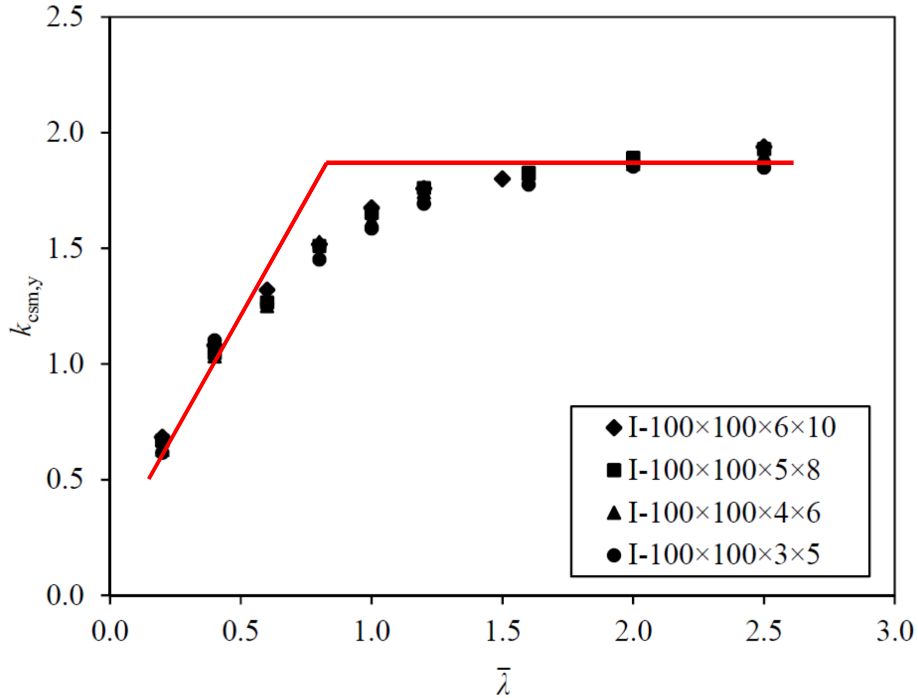
Bending end point based on CSM moment capacity:

$$M_{\mathrm{csm,z,Rk}} = W_{\mathrm{pl,z}} f_{\mathrm{y}} \left[1 + \frac{E_{\mathrm{sh}}}{E} \frac{W_{\mathrm{el,z}}}{W_{\mathrm{pl,z}}} \left(\frac{\varepsilon_{\mathrm{csm}}}{\varepsilon_{\mathrm{y}}} - 1 \right) - \left(1 - \frac{W_{\mathrm{el,z}}}{W_{\mathrm{pl,z}}} \right) \Big/ \left(\frac{\varepsilon_{\mathrm{csm}}}{\varepsilon_{\mathrm{y}}} \right)^{1.2} \right]$$

$$M_{\mathrm{csm,y,Rk}} = W_{\mathrm{pl,y}} f_{\mathrm{y}} \left[1 + \frac{E_{\mathrm{sh}}}{E} \frac{W_{\mathrm{el,y}}}{W_{\mathrm{pl,y}}} \left(\frac{\varepsilon_{\mathrm{csm}}}{\varepsilon_{\mathrm{y}}} - 1 \right) - \left(1 - \frac{W_{\mathrm{el,y}}}{W_{\mathrm{pl,y}}} \right) \Big/ \left(\frac{\varepsilon_{\mathrm{csm}}}{\varepsilon_{\mathrm{y}}} \right)^{2} \right]$$

New proposal - interaction factors

Interaction factors k were back-calculated using re-arranged interaction equation, inputting resistances, and N_{Ed} and M_{Ed} from FE results.



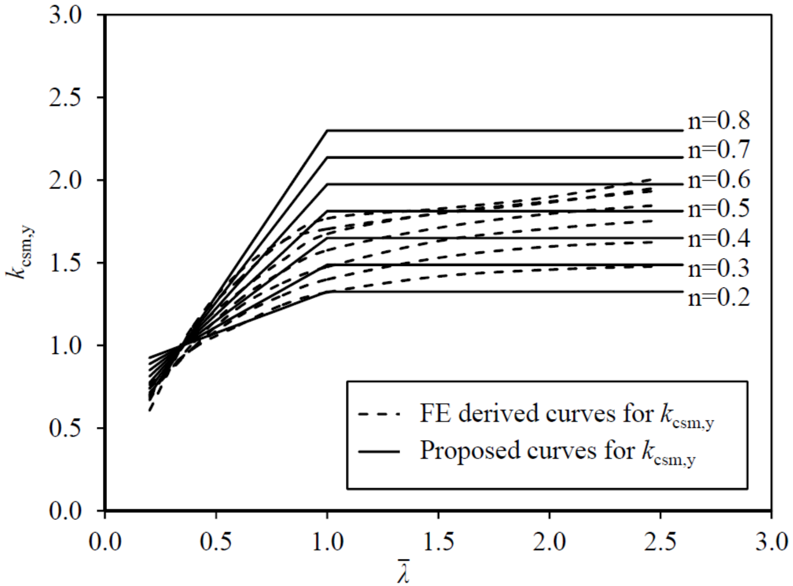
$$k_{csm} = \left(1 - \frac{N_{Ed}}{N_{b,Rd}}\right) \frac{M_{csm,Rd}}{M_{Ed}}$$

Results shown for a load level n = $N_{Ed}/N_{b,Rd}$ = 0.6.

New proposal - interaction factors

Same form of k expression as used in EN 1993-1-1 for carbon steel:

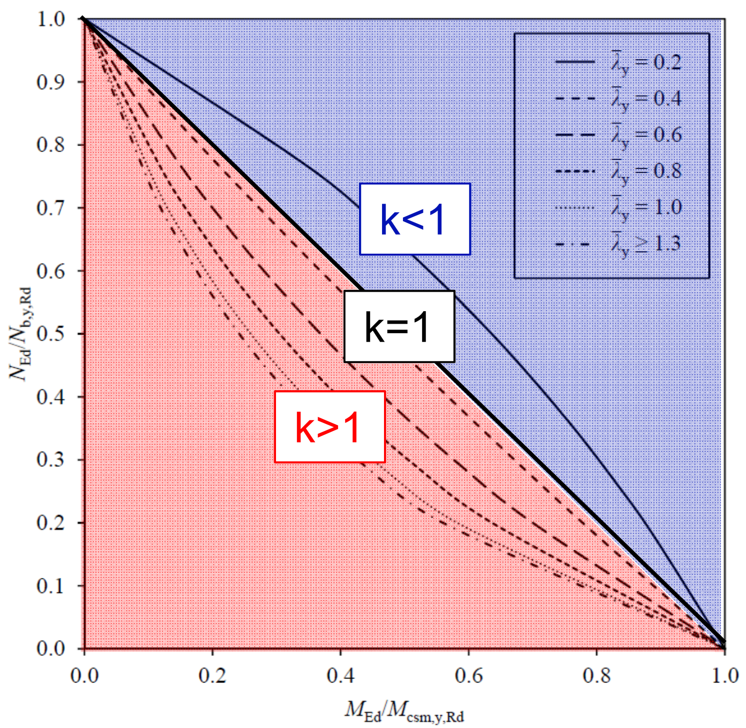
$$k_{csm} = 1+D_1\left(\bar{\lambda}\text{-}D_2\right)n, \text{ but } k_{csm} \leq 1+D_1\left(D_3\text{-}D_2\right)n$$



Loading combinations	D_1	D_2	D_3
Compression and minor axis bending ($k_{csm,z}$)	2.80	0.50	1.2
Compression and major axis bending ($k_{csm,y}$)	2.50	0.35	1.0

Coefficients fit by least squares regression to FE data for low n values. Discrepancies for high n values have little influence on overall accuracy since axial load is dominant.

Proposed design interaction curves



k=1 corresponds to a linear interaction

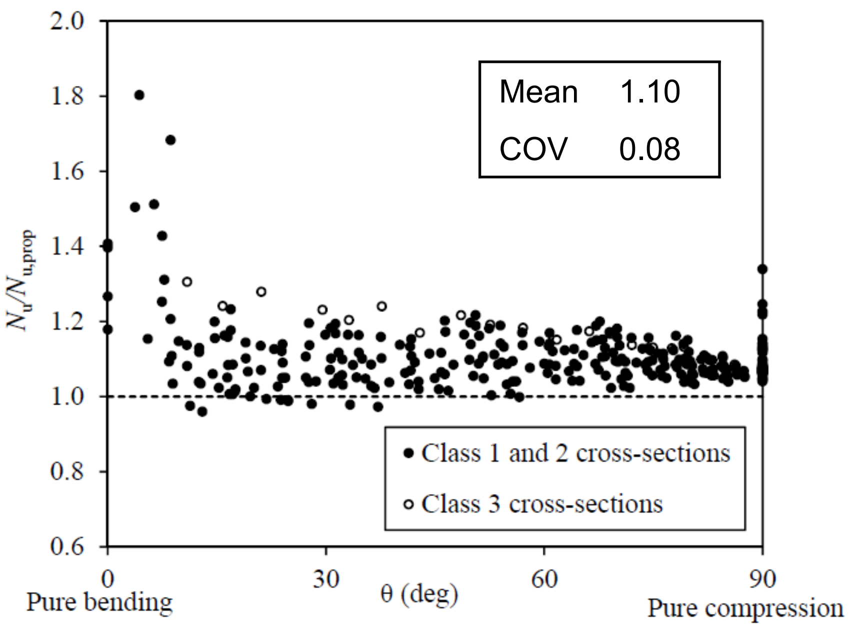
For low slenderness, k<1, corresponding to a convex interaction curve allowing for plastic redistribution of stresses

For high slenderness, k>1, corresponding to a concave interaction curve reflecting influence of second order effects

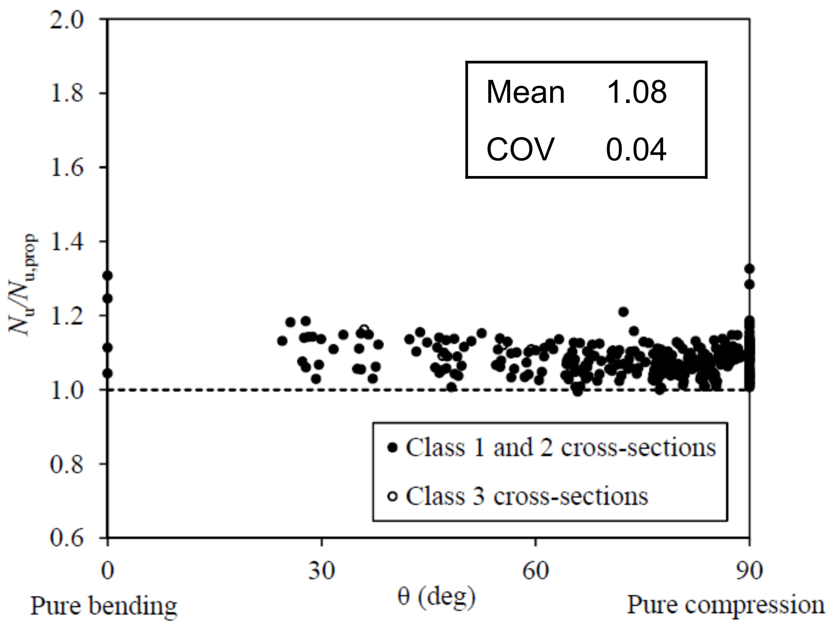
$$k_{csm} = 1 + D_1\left(\bar{\lambda} - D_2\right)n, \text{ but } k_{csm} \leq 1 + D_1(D_3 - D_2)n$$

New proposal – Assessment of applicability

Minor axis bending



Major axis bending



New proposal provides accurate results with only a very small number of over-predictions.

Mean predictions are improved and scatter is less than all existing provisions.

New proposal – Reliability analysis

EN 1990 statistical analysis performed to show reliability of new proposal, as should be done for all new proposals intended to be ‘code-ready’

Loading combinations	Dataset	n	b	$k_{d,n}$	V_{δ}	γ_{M1}
Compression and bending about minor axis	Tests+FE	492	1.102	3.11	0.056	0.94
	Tests only	12	1.137	3.11	0.076	0.95
Compression and bending about major axis	Tests+FE	494	1.090	3.11	0.034	0.92
	Tests only	6	1.035	3.11	0.061	1.01

Note: parameter b taken as the average of the ratios of the test and FE results to predicted resistances, which, unlike the least squares approach recommended in Annex D, does not bias the value of b towards the test or FE results with higher failure loads.

Afshan, S., Francis, P., Baddoo, N. R. and Gardner, L. (2015). Reliability analysis of structural stainless steel design provisions. Journal of Constructional Steel Research. **114**, 293-304.

Conclusions

Conclusions:

- 18 tests and 960 FE simulations conducted on stainless steel I-section beam columns
- Existing stainless steel beam-column design provisions assessed; scope for improvement identified
- New interaction curves with more accurate end points shown to yield substantial improvements

Imperial College London

Experimental and numerical studies of laser-welded stainless steel I-section beam-columns

Stainless steel in structures – Fifth International Experts Seminar

Yidu Bu Imperial College London

Leroy Gardner Imperial College London