Imperial College London

Finite element modelling and design of welded stainless steel I-section columns

Stainless steel in structures – Fifth International Experts Seminar

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Outline

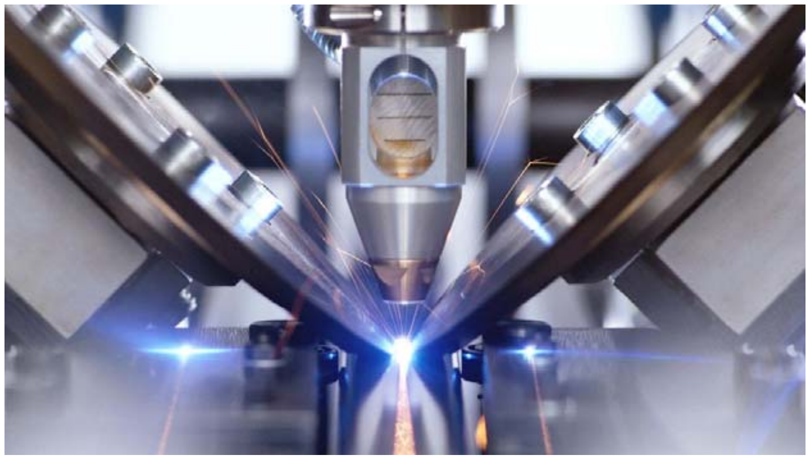
- Introduction
- FE modelling and parametric studies
- Design
    - Assessment of current design methods
    - New proposal
- Conclusions

Welded stainless steel members

Conventional welding methods: two pieces of material joined together by melting the base metal and an additional filler material

- Shielded metal arc welding (SMAW)
- Gas tungsten arc welding (GTAW/TIG)
- Gas metal arc welding (GMAW/MIG)

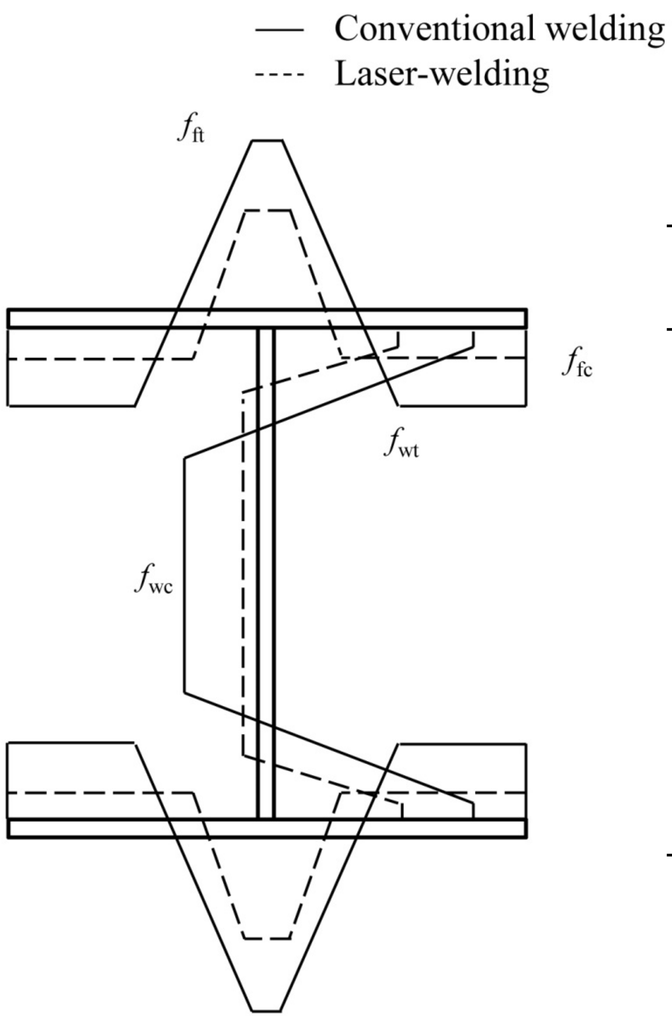
Laser-welding: laser beams to locally melt and join two pieces of metal without filler material



Laser-welding machine

Laser-welded profiles

Residual stress distributions



Parameters in predictive models for welded I-sections

Predictive model	Material	$f_{ft}=f_{wt}$	$f_{fc}=f_{wc}$
ECCS	Carbon steel	f_y	$0.25f_y$
BSK 99	Carbon steel	$0.5f_y$	From equilibrium
Conventional welding	Stainless steel	$0.8f_y$	From equilibrium
Laser-welding	Stainless steel	$0.5f_y$	From equilibrium

FE modelling and parametric studies

Previous tests

The FE models were developed and validated against 59 experimental results from previous studies on the flexural buckling of welded stainless steel I-section columns.

Welding type and references	No. of tests	Grade	Axis of buckling
Conventional welding Burgan et al. (2000)	15	1.4301 1.4462	Minor Major
Conventional welding Yang et al. (2016)	22	1.4301 1.4462	Minor Major
Laser-welding Gardner et al. (2016)	22	1.4307 1.4404 1.4571	Minor Major

FE modelling

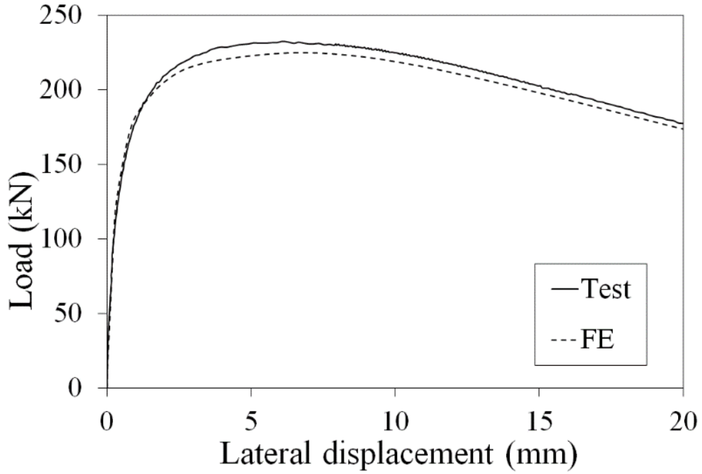
- Basic modelling assumptions:
  - S4R
  - Two stage Ramberg-Osgood material model
  - Imperfection amplitudes
  - Residual stress pattern

    Conventional welding

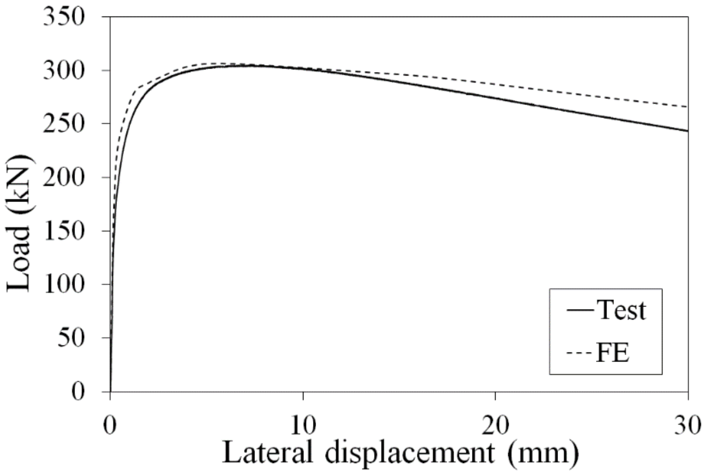
    Laser-welding
  - Boundary conditions

    In accordance with the test setups in the previous studies

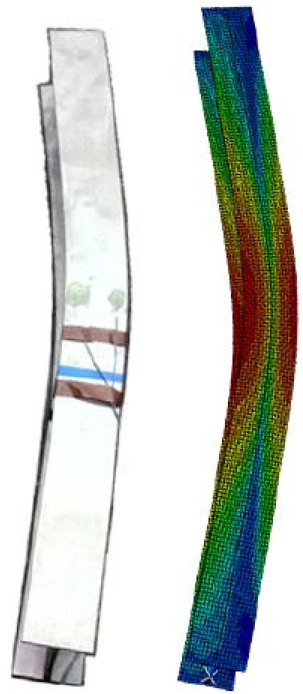
FE validation – comparison



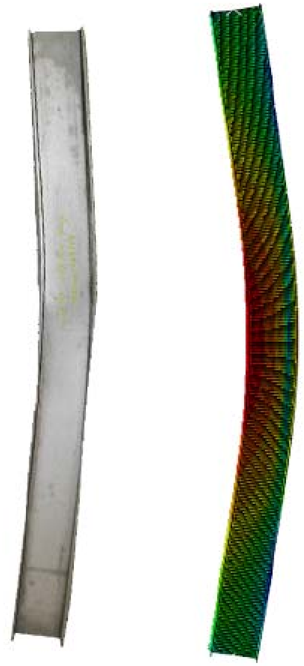
Minor axis buckling



Major axis buckling



Minor axis buckling



Major axis buckling

FE validation – ultimate loads comparison

Welding type and references	No. of tests	Axis of buckling	Geometric imperfection and residual stress combination			
			w_m+$w_{D\&W}$+RS	w_m+$w_{D\&W}$	L/1000+$w_{D\&W}$+RS	L/1000+$w_{D\&W}$
			N_{test}/N_{FE}	N_{test}/N_{FE}	N_{test}/N_{FE}	N_{test}/N_{FE}
Conventional welding Burgan et al. (2000)	15	Minor Major				
Conventional welding Yang et al. (2016)	22	Minor Major				
Laser-welding Gardner et al. (2016)	22	Minor Major				
Mean for all specimens			1.11	1.05	1.02	0.97
COV for all specimens			0.25	0.22	0.11	0.08

Good agreement between the test and FE results were achieved when using Combination 3, where the constant imperfection amplitude of *L*/1000 and residual stresses were included.

FE modelling – parametric studies

- Parameters investigated:
  - Buckling axis
  - *h/b* ratio: 1.0, 1.5, 2.0
  - Plate slenderness $\bar{\lambda}_{\mathrm{p,f}} \approx \bar{\lambda}_{\mathrm{p,w}}$: 0.27-0.81
  - Member slenderness $\bar{\lambda}$: 0.1-2.0
  - Global imperfection amplitude: *L*/1000
  - Local imperfection amplitude: $\omega_{\mathrm{D\&W}}$
  - Compressive 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

Design recommendation

EN 1993-1-4 (EC3)

The EC3 design approach for compression members is based on the Perry-Robertson buckling formula with an imperfection parameter η.

$$N_{\mathrm{b,Rd}} = \frac{\chi A f_{\mathrm{y}}}{\gamma_{\mathrm{M1}}},$$

$$\eta = \alpha(\bar{\lambda}_{\mathrm{EC}} - \bar{\lambda}_0),$$

$$\bar{\lambda}_{\mathrm{EC}} = \sqrt{\frac{A f_{\mathrm{y}}}{N_{\mathrm{cr}}}} = \frac{L_{\mathrm{cr}}}{i\pi}\sqrt{\frac{f_{\mathrm{y}}}{E}}, \qquad \chi_{\mathrm{EC}} = \frac{1}{\phi + \sqrt{\phi^2 - \bar{\lambda}_{\mathrm{EC}}^2}}, \qquad \phi = 0.5\left[1 + \eta + \bar{\lambda}_{\mathrm{EC}}^2\right].$$

Major axis buckling: curve c ($\bar{\lambda}_0$=0.2, α=0.49)

Minor axis buckling: curve d ($\bar{\lambda}_0$=0.2, α=0.76)

North American AISC Design Guide 27

The buckling stress F_{cr} is expressed in a similar manner to the Eurocode as a buckling reduction factor χ_{AISC}, multiplied by the yield stress F_y.

$$N_{b,Rd} = \phi_c P_n = \phi_c F_{cr} A_g = \phi_c \chi_{AISC} F_y A_g,$$

$$\bar{\lambda}_{AISC} = \frac{KL}{\pi r}\sqrt{\frac{F_y}{E}},$$

$$\chi_{AISC} = Q\left(0.50^{Q\bar{\lambda}^2_{AISC}}\right), \quad \text{for } \bar{\lambda}^2_{AISC} \leq 1.2,$$

$$\chi_{AISC} = \frac{0.531}{\bar{\lambda}^2_{AISC}}, \quad \text{for } \bar{\lambda}^2_{AISC} > 1.2.$$

Only a single buckling curve is provided in AISC Design Guide 27 to cover all cross-section types and buckling axes.

Chinese Standard (CECS-410)

The Chinese Standard CECS-410 for stainless steel compression members is also based on the Perry-Robertson formula.

$$\bar{\lambda}_{\mathrm{CECS}} = \frac{L_{\mathrm{cr}}}{i\pi}\sqrt{\frac{f_{\mathrm{y}}}{E}}.$$

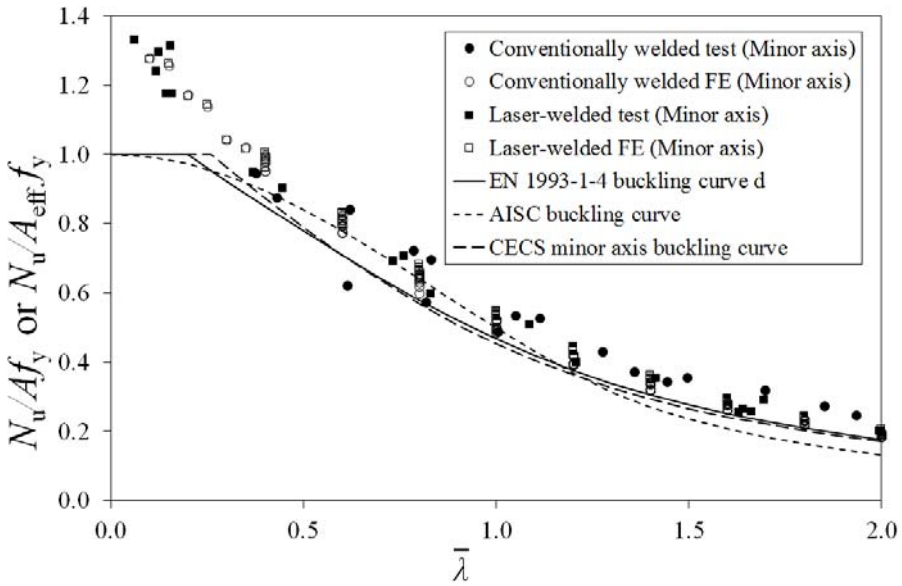
A set of 6 buckling curves, of the same form as EC3, were derived by regression analysis to test results.

Major axis buckling: curve with $\bar{\lambda}_0$=0.24, α=0.66

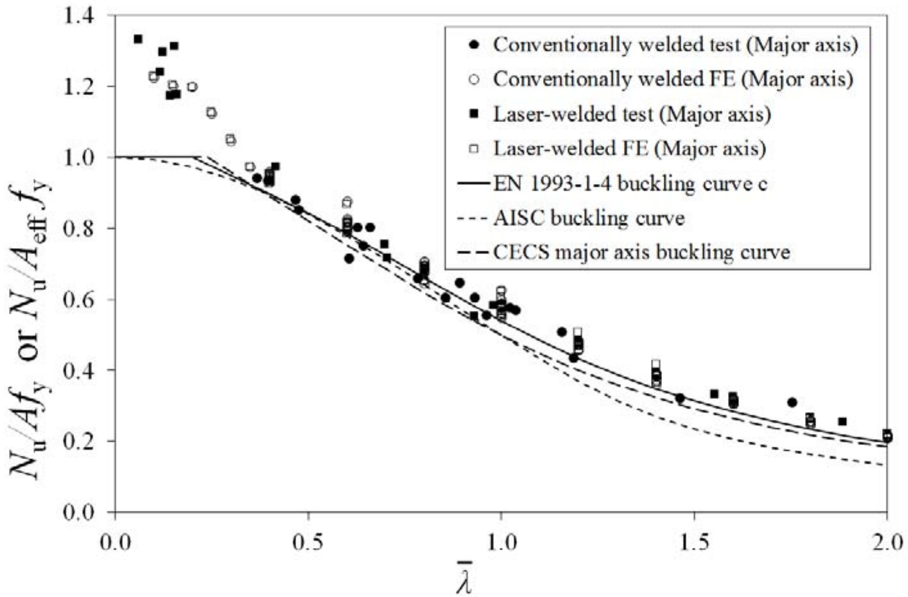
Minor axis buckling: curve with $\bar{\lambda}_0$=0.26, α=0.89

Assessment of current design methods

Minor axis buckling

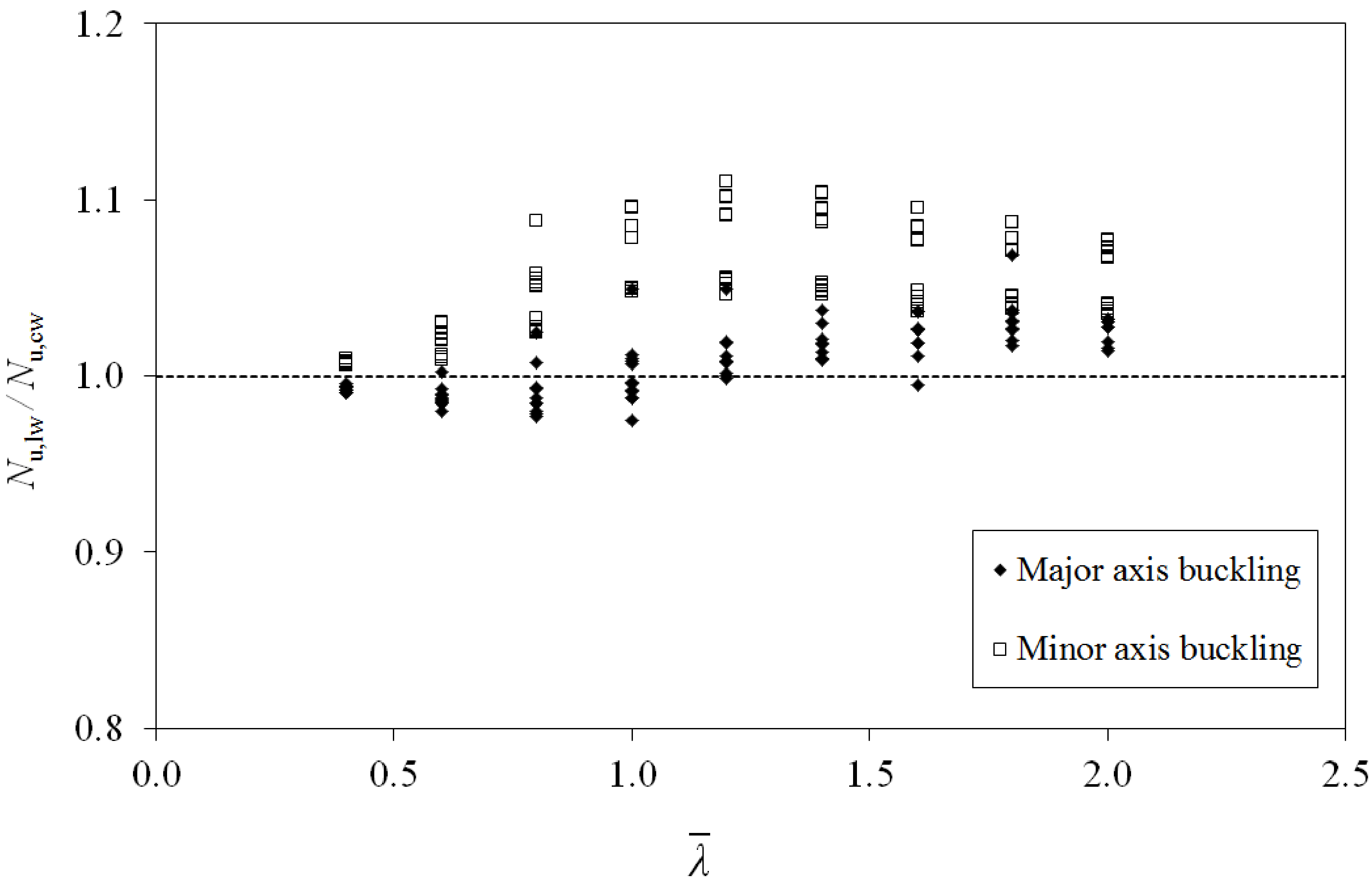


Major axis buckling



Welding type	Buckling axis	No. of tests	No. of FE models	N_u/N_{EC3}		N_u/N_{AISC}		N_u/N_{CECS}	
				Mean	COV	Mean	COV	Mean	COV
Conventional welding	Major	19	120	1.06	0.04	1.25	0.20	1.19	0.18
Conventional welding	Minor	18	120	1.10	0.07	1.20	0.17	1.20	0.10
Laser-welding	Major	8	120	1.08	0.05	1.24	0.28	1.17	0.22
Laser-welding	Minor	14	120	1.14	0.03	1.25	0.14	1.24	0.09

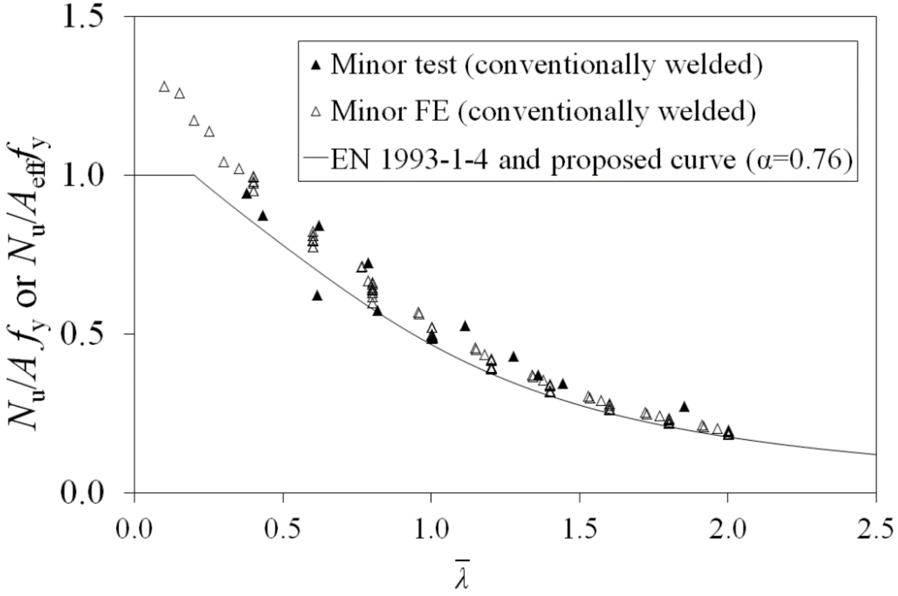
Assessment of current design methods

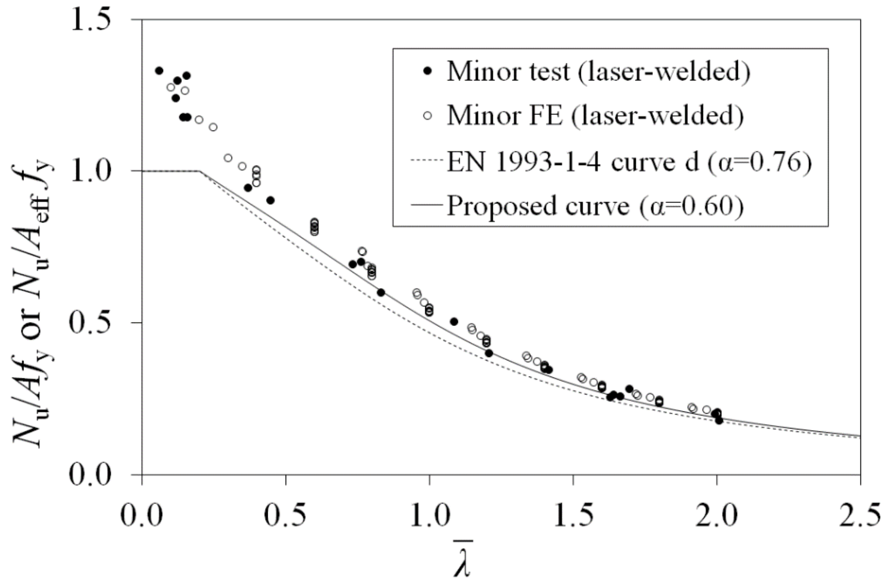


Comparison of ultimate strength of conventionally welded and laser-welded columns

New proposal

Welding type	Buckling axis	EN1993-1-4		Proposed	
		α	$\bar{\lambda}_0$	α	$\bar{\lambda}_0$
Conventional welding	Major	0.49	0.20	0.49	0.20
Conventional welding	Minor	0.76	0.20	0.76	0.20
Laser-welding	Major	0.49	0.20	0.49	0.20
Laser-welding	Minor	0.76	0.20	0.60	0.20

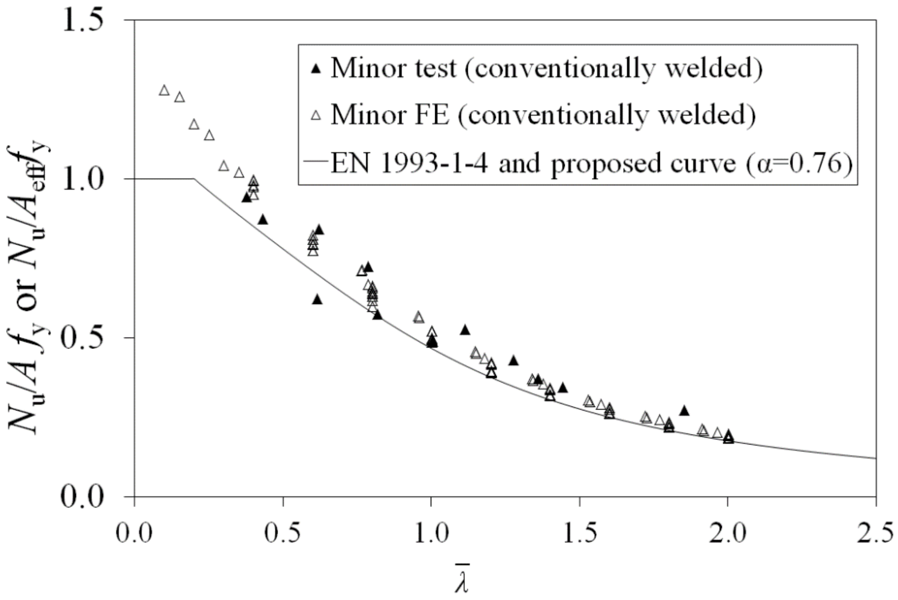


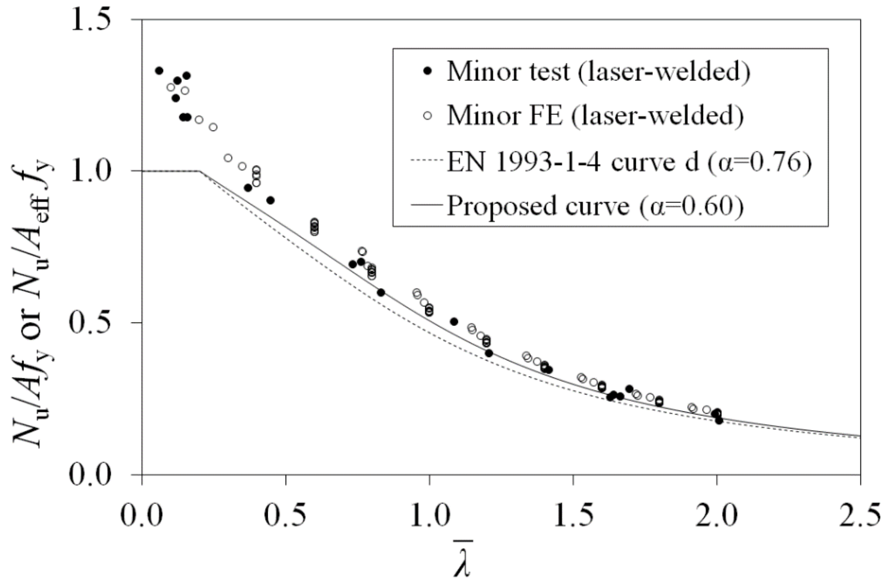


Existing and proposed buckling curves

New proposal

Welding type	Buckling axis	EN1993-1-4		Proposed	
		α	$\bar{\lambda}_0$	α	$\bar{\lambda}_0$
Conventional welding	Major	0.49	0.20	0.49	0.20
Conventional welding	Minor	0.76	0.20	0.76	0.20
Laser-welding	Major	0.49	0.20	0.49	0.20
Laser-welding	Minor	0.76	0.20	0.60	0.20





Existing and proposed buckling curves

New proposal – Reliability analysis

Summary of reliability analysis results for EN 1993-1-4 buckling curves

Welding type	Buckling axis	Dataset	n	b	$k_{d,n}$	V_δ	γ_{M1}
Conventional welding	Major	Tests+FE	95	1.06	3.11	0.039	1.02
Conventional welding	Major	Tests only	14	1.01	3.11	0.046	1.08
Conventional welding	Minor	Tests+FE	90	1.09	3.11	0.056	1.04
Conventional welding	Minor	Tests only	12	1.15	3.11	0.120	1.15
Laser-welding	Major	Tests+FE	89	1.09	3.11	0.052	1.04
Laser-welding	Major	Tests only	8	1.14	3.11	0.113	1.11
Laser-welding	Minor	Tests+FE	92	1.14	3.11	0.028	0.95
Laser-welding	Minor	Tests only	14	1.11	3.11	0.051	1.00

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Conclusions

- Based on 59 test results, FE models developed and 480 FE simulations conducted.
- EC3, AISC Design Guide 27 and CECS 410 assessed with all experimental and numerical results.
- Existing buckling curves for conventionally welded stainless steel I-sections offer reasonable results.
- New buckling curves for laser-welded stainless steel I-sections have been proposed.

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