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The Continuous Strength Method for stainless steel columns

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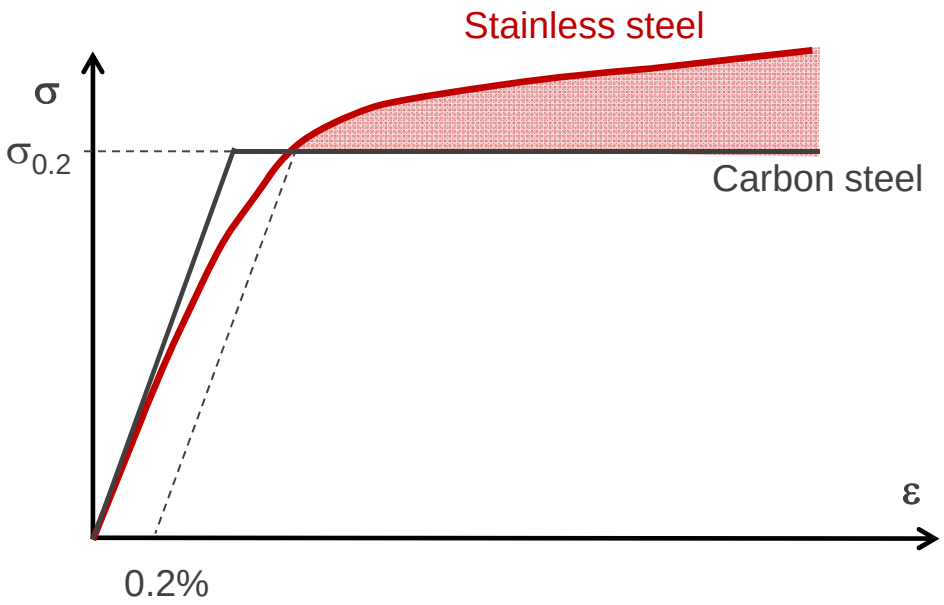
Fifth International Experts Seminar: Stainless Steel in Structures
London, UK
18-19 September 2017

Stainless steel

Mechanical behaviour:

- Different from carbon steel
- Nonlinear stress-strain diagram
- Strain hardening



Main standards for structural stainless steel:

- EN1993-1-4
- SEI/ASCE 8-02
- AS/NZS4673

Based on carbon steel standards, provide supplementary rules and modifications

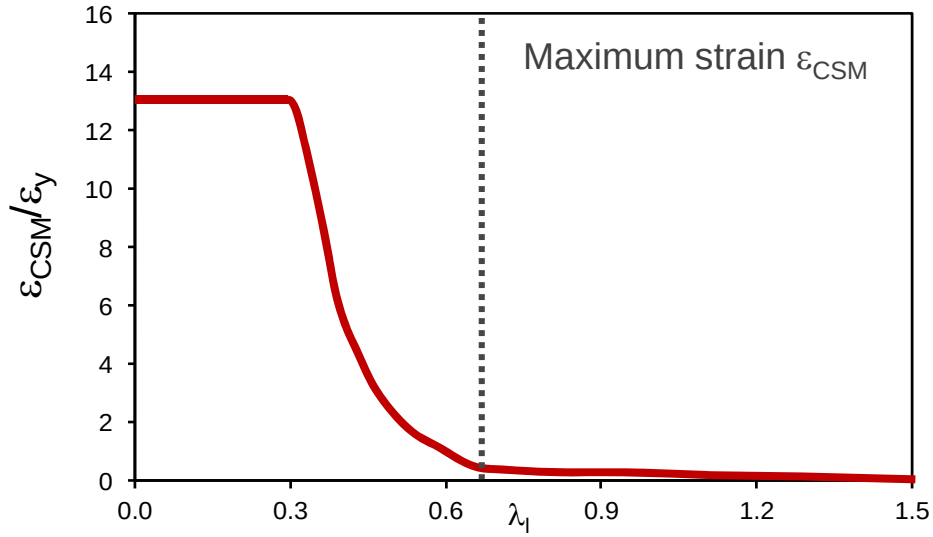
Nonlinear behaviour and strain hardening effects **not** considered

Continuous Strength Method

Deformation-based design approach that:

- incorporates strain hardening effects for stocky cross-sections
- avoids effective width calculations for slender cross-sections

Base curve



$$\frac{\varepsilon_{CSM}}{\varepsilon_y} = \begin{cases} \frac{0.25}{\bar{\lambda}_p^{3.6}} \leq min\left(15, \frac{C \cdot \varepsilon_u}{\varepsilon_y}\right) & \overline{\lambda_p} \leq 0.68 \\ \frac{1}{\bar{\lambda}_p^{1.05}}\left(1 - \frac{0.222}{\bar{\lambda}_p^{1.05}}\right) & \overline{\lambda_p} > 0.68 \end{cases}$$

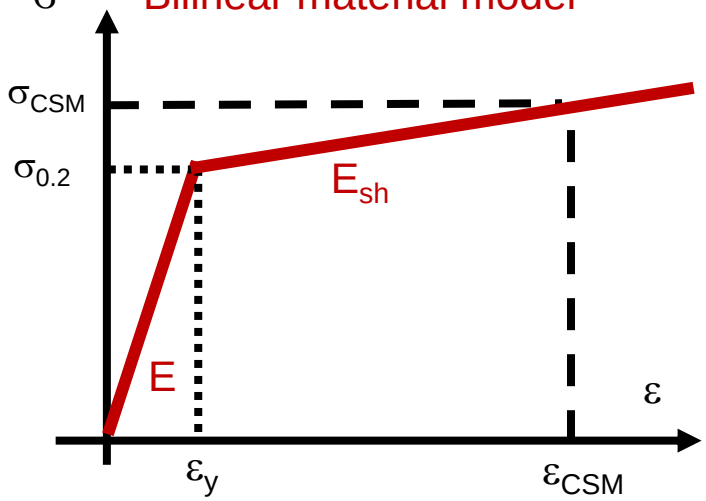
Cross-section slenderness

$$\lambda_p = \sqrt{\frac{\sigma_{0.2}}{\sigma_{cr}}}$$

$\sigma_{0.2}$ yield strength

σ_{crl} critical elastic local buckling stress

Bilinear material model



Flexural buckling of stainless steel columns

Traditional approach:
reduction of the cross-sectional strength $N_{c,Rk}$ due to flexural buckling

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

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

$$\phi = 0.5 \cdot \left[1 + \eta + \bar{\lambda}^2\right]$$

$\bar{\lambda}$ member slenderness

Different Standards: generalized imperfection factor $\boldsymbol{\eta}$

EN1993-1-4:

$$\eta = \alpha\left(\bar{\lambda} - \bar{\lambda}_0\right)$$

Buckling curve *c*: $\alpha = 0.49$, $\bar{\lambda}_0 = 0.4$

AS/NZS4673:

$$\eta = \alpha\left[\left(\bar{\lambda} - \bar{\lambda}_1\right)^{\beta} - \bar{\lambda}_0\right]$$

α, β, $\bar{\lambda}_0$ and $\bar{\lambda}_1$ parameters for SS grades

<u>Revised buckling curves</u>

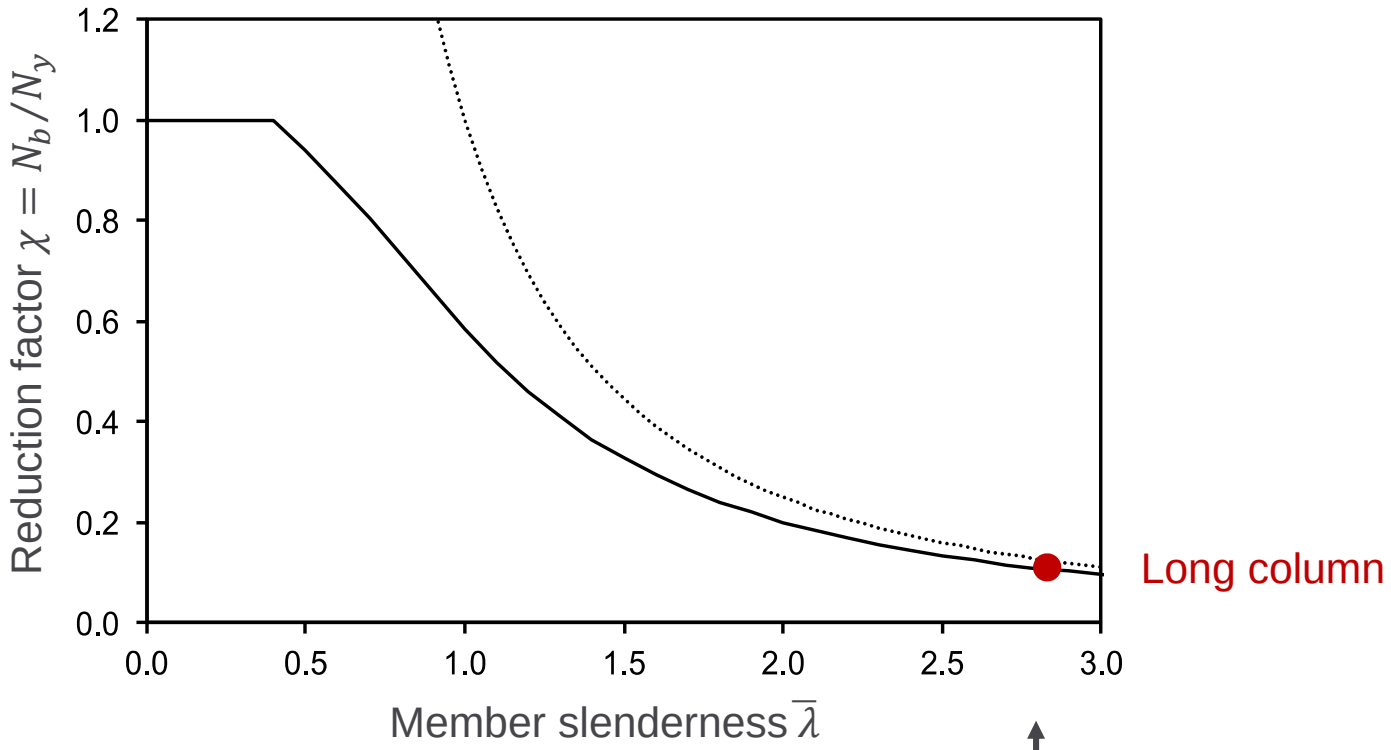
Partial safety factor γ_{M1} for buckling curve *c* exceeded 1.10

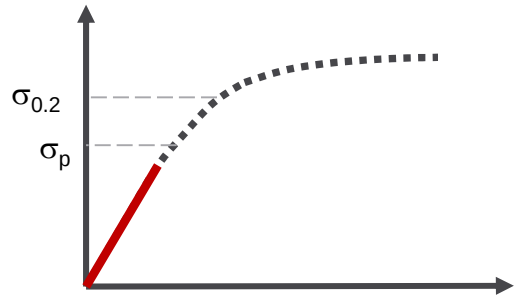
$\alpha = 0.49$, $\bar{\lambda}_0 = 0.3$ austenitic and duplex

$\alpha = 0.49$, $\bar{\lambda}_0 = 0.2$ ferritic

Afshan et al. (2017)

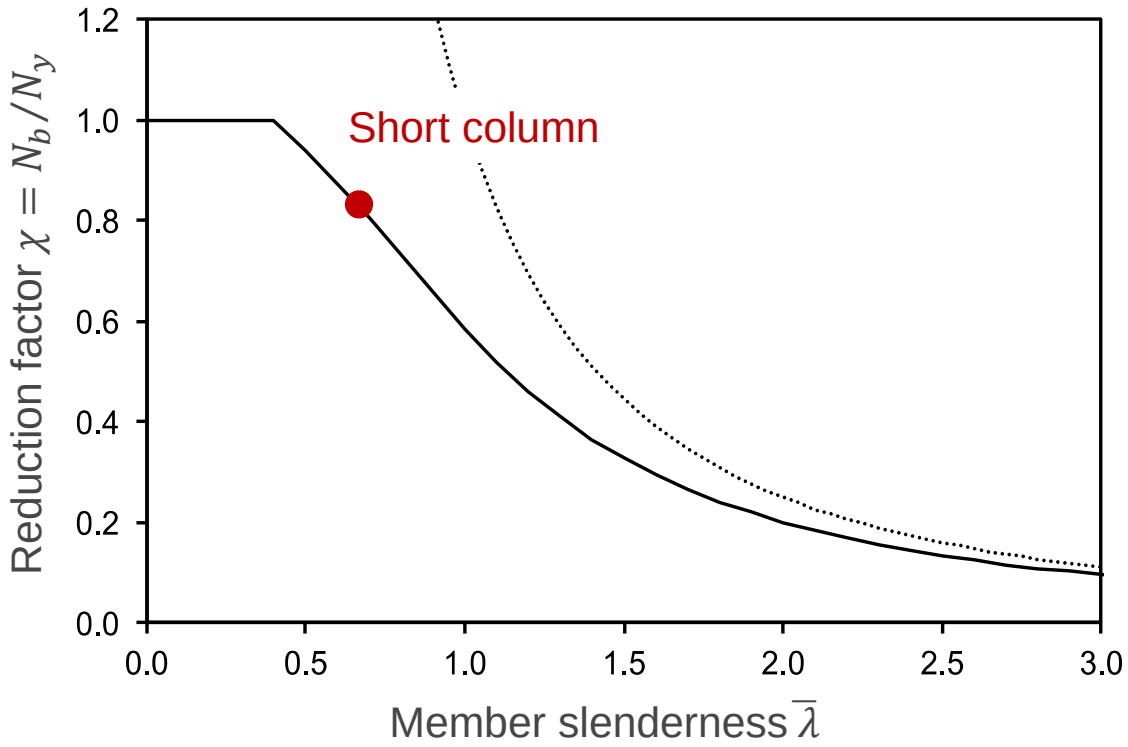
Flexural buckling of stainless steel columns

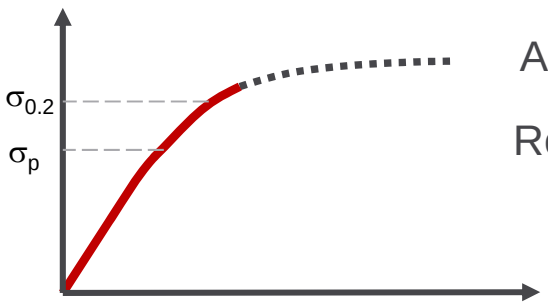




Failure at low stresses (before σ_p is reached)

Flexural buckling of stainless steel columns





Axial stress will potentially exceed $\sigma_{0.2}$ (if member stable enough)

Resistances underestimated since strain hardening not contemplated

The **CSM** excellent resistance predictions for cross-section resistance

Some stainless steels columns might exceed yielding ($\sigma_{0.2}$)

The extension of the **CSM** to **member** behaviour to improve column resistance predictions

The aim of this paper is to:

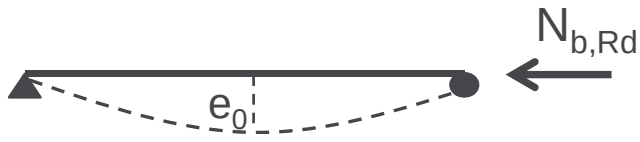
1) Develop the CSM approach for columns
2) Assess the method for stainless steel RHS columns against exp. and FE data
3) Validate the method (reliability analysis)

Development of the method

From the classical elastic flexural equilibrium equation, second order elastic check of the most heavily loaded cross-section:

$$\frac{N_{b,Rd}}{N_{c,Rd}} + \frac{1}{\left(1 - \frac{N_{b,Rd}}{N_{cr}}\right)} \frac{N_{b,Rd} \cdot e_0}{M_{c,Rd}} = 1$$

Traditionally limited to yielding



CSM compressive and bending resistances can be adopted in cross-section check:

$$\frac{N_{b,CSM}}{N_{CSM}} + \frac{1}{\left(1 - \frac{N_{b,CSM}}{N_{cr}}\right)} \frac{N_{b,CSM} \cdot e_0}{M_{CSM}} = 1$$

Solving the equation the CSM flexural buckling resistance $\mathbf{N_{b,CSM}}$ can be determined

Development of the method (cont.)

The equation can be re-written in terms of stresses considering:

$$\sigma_{b,CSM} = N_{b,CSM}/A$$

$$\sigma_{CSM} = N_{CSM}/A$$

$$\sigma_{cr} = N_{cr}/A$$

Auxiliary function *g*

$$g = \frac{M_{CSM}}{M_{pl}} \frac{\sigma_{0.2}}{\sigma_{CSM}} \psi$$

ψ: shape factor

Ayrton-Perry expression

$$\left(\sigma_{CSM} - \sigma_{b,CSM}\right) \cdot \left(\sigma_{cr} - \sigma_{b,CSM}\right) = \sigma_{b,CSM} \cdot \sigma_{cr} \cdot \eta^*$$

with $\eta^* = \dfrac{e_0 \cdot A}{W_{el} \cdot g}$

Modified generalized imperfection factor

$$\eta = \frac{e_0 \cdot A}{W_{el}}$$

"Classic" generalized imperfection factor

Introducing the non-dimensional slenderness $\bar{\lambda}$ and slenderness plateau $\bar{\lambda}_0$

$$\eta^* = \frac{\alpha}{g}\left(\bar{\lambda} - \bar{\lambda}_0\right) = \frac{1}{g}\alpha\left(\bar{\lambda} - \bar{\lambda}_0\right) = \frac{1}{g}\eta$$

with $\alpha = \dfrac{\pi \sqrt{E/\sigma_{0.2}}}{\gamma \cdot \frac{L}{\nu}}$

Development of the method (cont.)

From $\left(\sigma_{CSM} - \sigma_{b,CSM}\right) \cdot \left(\sigma_{cr} - \sigma_{b,CSM}\right) = \sigma_{b,CSM} \cdot \sigma_{cr} \cdot \eta^*$

considering $\chi_{CSM} = \frac{\sigma_{b,CSM}}{\sigma_{CSM}}$ $\sigma_{cr} = \frac{\sigma_{CSM}}{\bar{\lambda}^2}$ $\frac{\sigma_{b,CSM}}{\sigma_{cr}} = \chi_{CSM} \cdot \bar{\lambda}^2$

$$\boldsymbol{\chi_{CSM}^2 \cdot \bar{\lambda}^2 - \chi_{CSM}\left[1 + \eta^* + \bar{\lambda}^2\right] + 1 = 0}$$

$$N_{b,CSM} = \frac{\chi_{CSM} \cdot N_{CSM}}{\gamma_{M1}}$$

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

equivalent to the traditional approach with

$$\phi_{CSM} = 0.5 \cdot \left[1 + \eta^* + \bar{\lambda}^2\right]$$

Modified generalized imperfection factor $\eta^* = \frac{1}{g}\alpha\left(\bar{\lambda} - \bar{\lambda}_0\right) = \frac{\sigma_{CSM} W_{el}}{M_{CSM}}\alpha\left(\bar{\lambda} - \bar{\lambda}_0\right)$

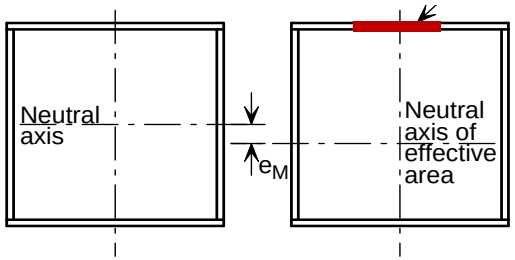
Approach still based on buckling curves through α and $\bar{\lambda}_0$

η^* depends on cross-section slenderness and material (σ_{CSM} and M_{CSM})

Strain hardening effects directly introduced in the formulation

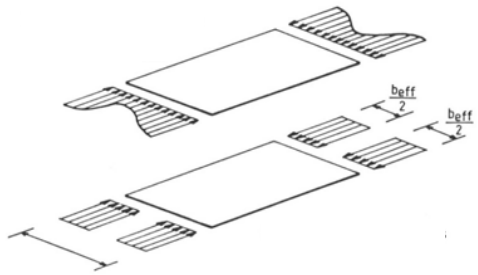
Development of the method for slender cross-sections

STANDARDS: Effective Width Method (EWM)



$$\rho = \frac{0.772}{\bar{\lambda}_p} - \frac{0.079}{\bar{\lambda}_p^2} \leq 1.0$$

EN1993-1-4



CSM: Strength curve based on gross-section properties

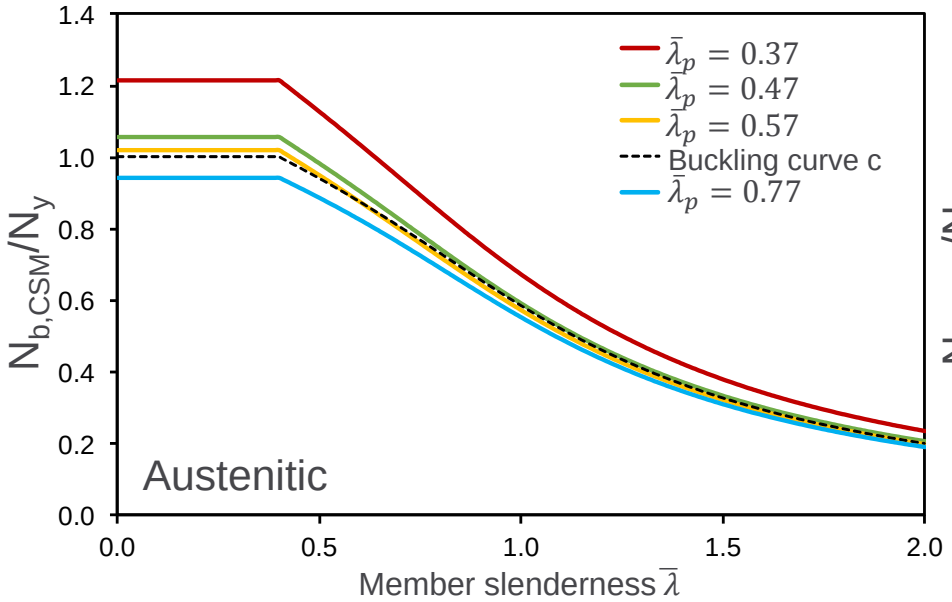
From previous formulation: $g = 1 \longrightarrow \eta^* = \frac{1}{g}\eta = \eta$

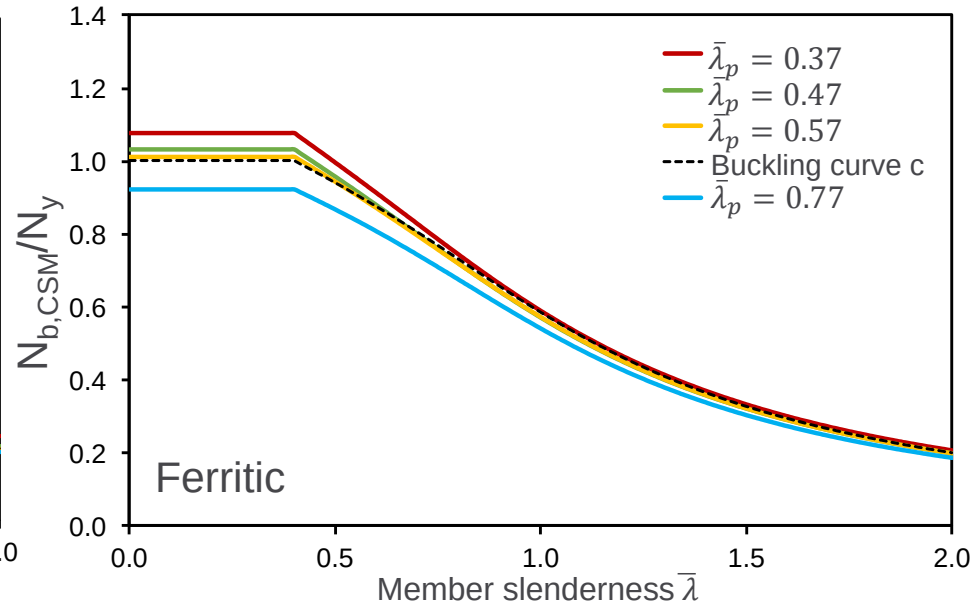
$$\frac{N_{b,CSM}}{N_{b,0}} = \frac{1}{\bar{\lambda}_p^{1.05}}\left(1 - \frac{0.222}{\bar{\lambda}_p^{1.05}}\right)$$

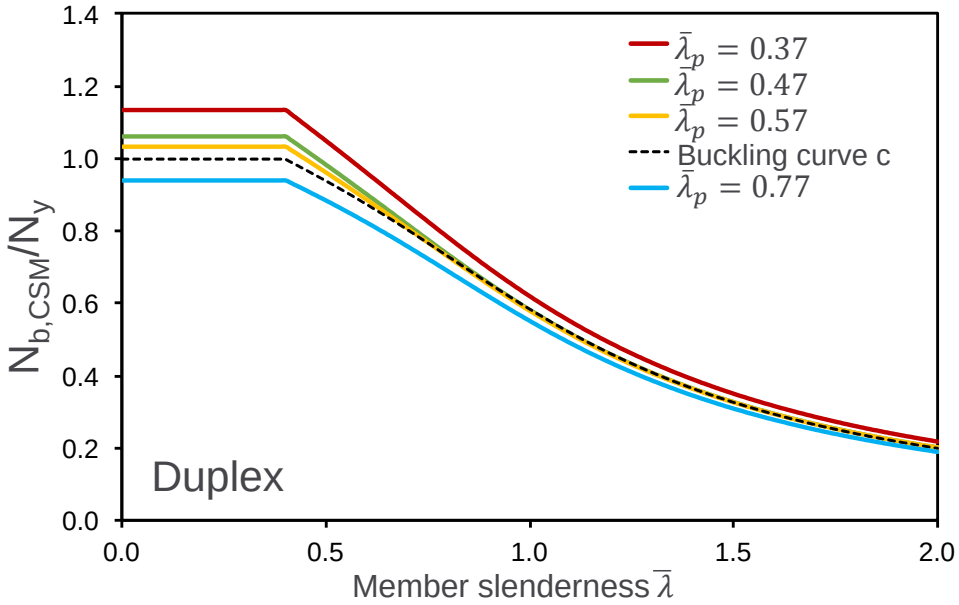
$N_{b,0}$ is the flexural buckling resistance of the fully effective cross-section

Susceptibility to local buckling measured by $\bar{\lambda}_p = \sqrt{\frac{N_{b,0}}{N_{cr,l}}}$

"Modified" buckling curves





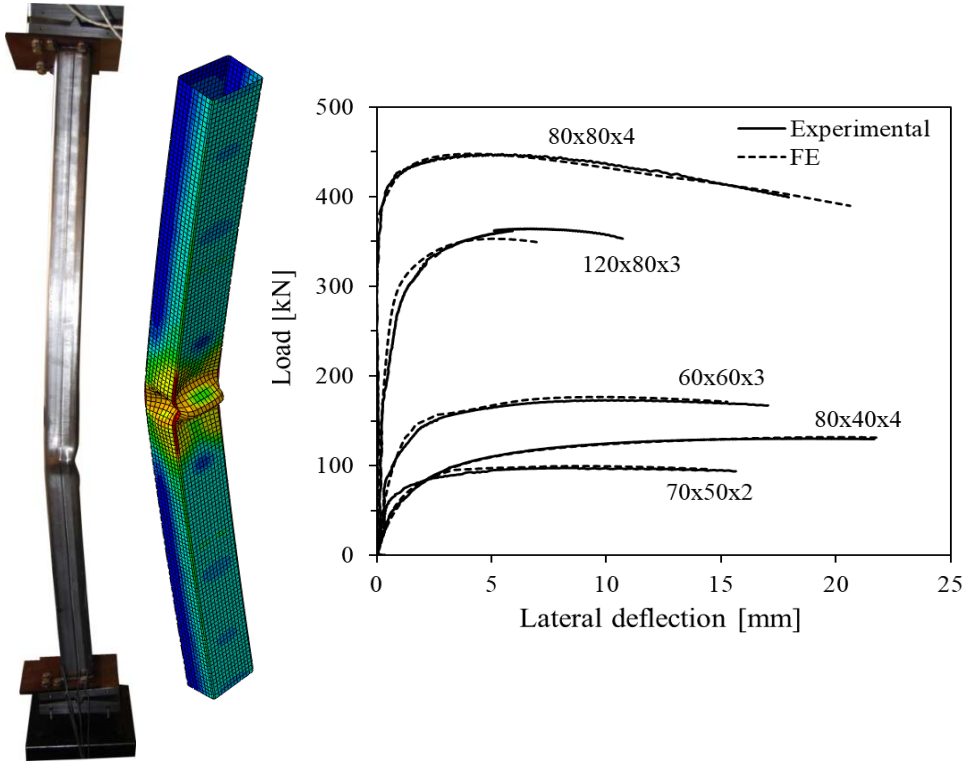


From these figures, it is evident:

- Highest curves obtained for lowest cross-section slenderness for a given material
- Highest curves correspond to materials for which strain hardening is more evident (austenitic)

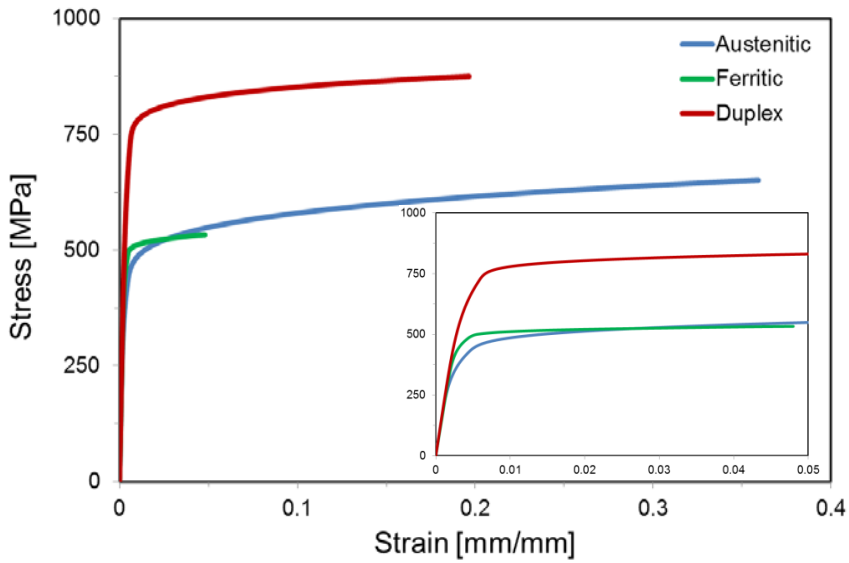
Validation of the FE model

- Against tests on stainless steel RHS columns
- Abaqus, S4R elements



Parametric study

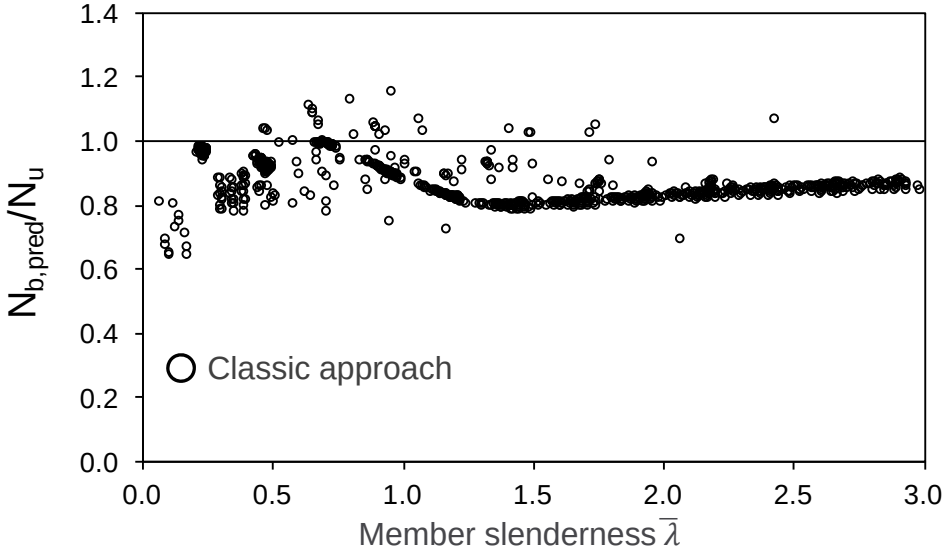
- RHS and SHS
- Full cross-section $\overline{\lambda}_p$ and member $\overline{\lambda}$ slenderness ranges covered
- Austenitic, ferritic and duplex grades

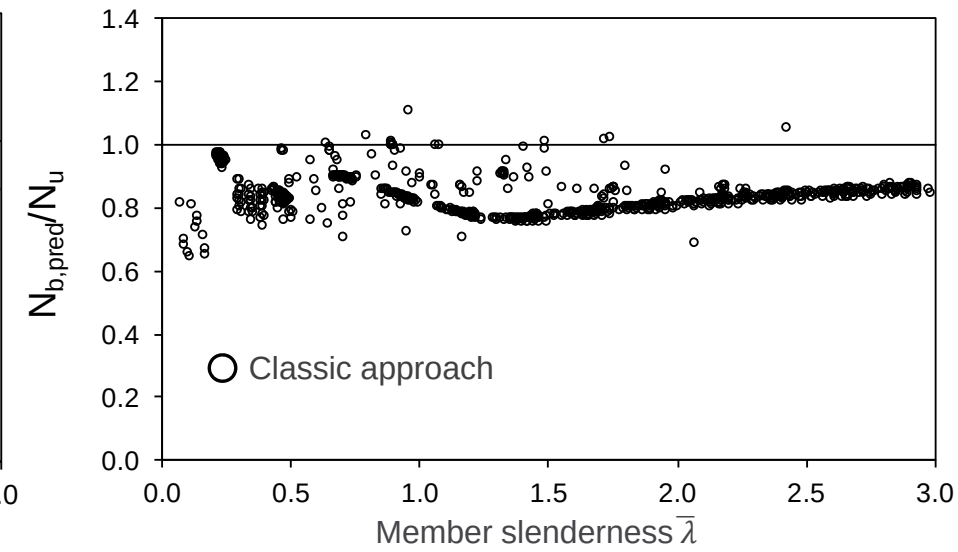


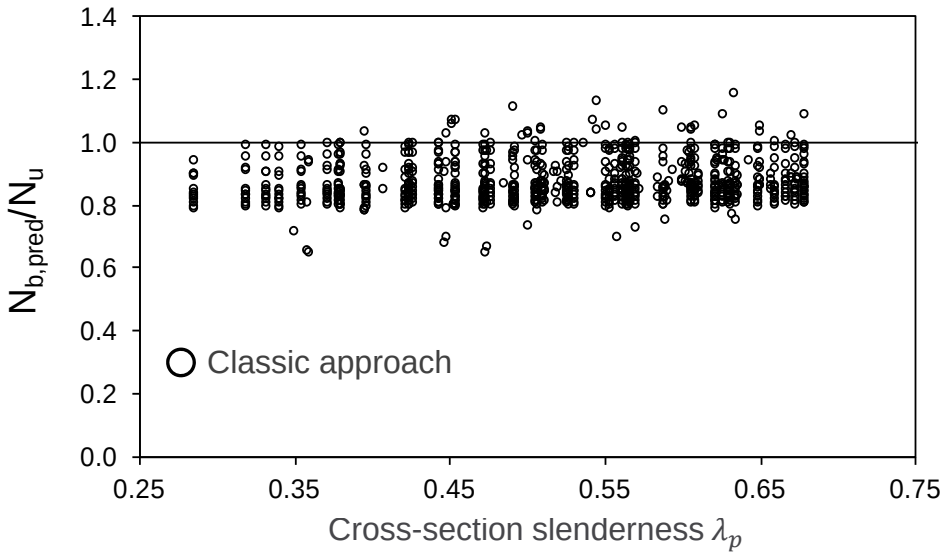
1500 FE models and 188 exp. results

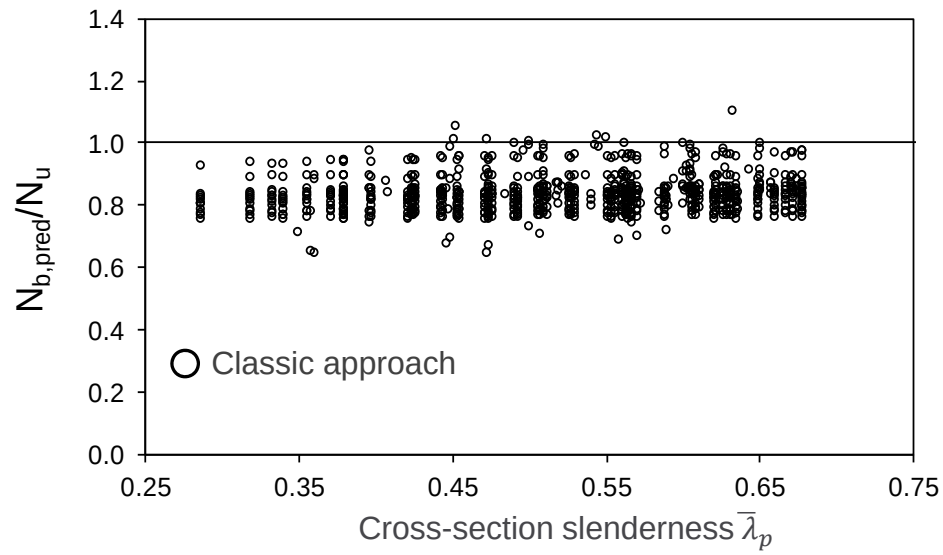
EN1993-1-4 buckling curve

Revised curves



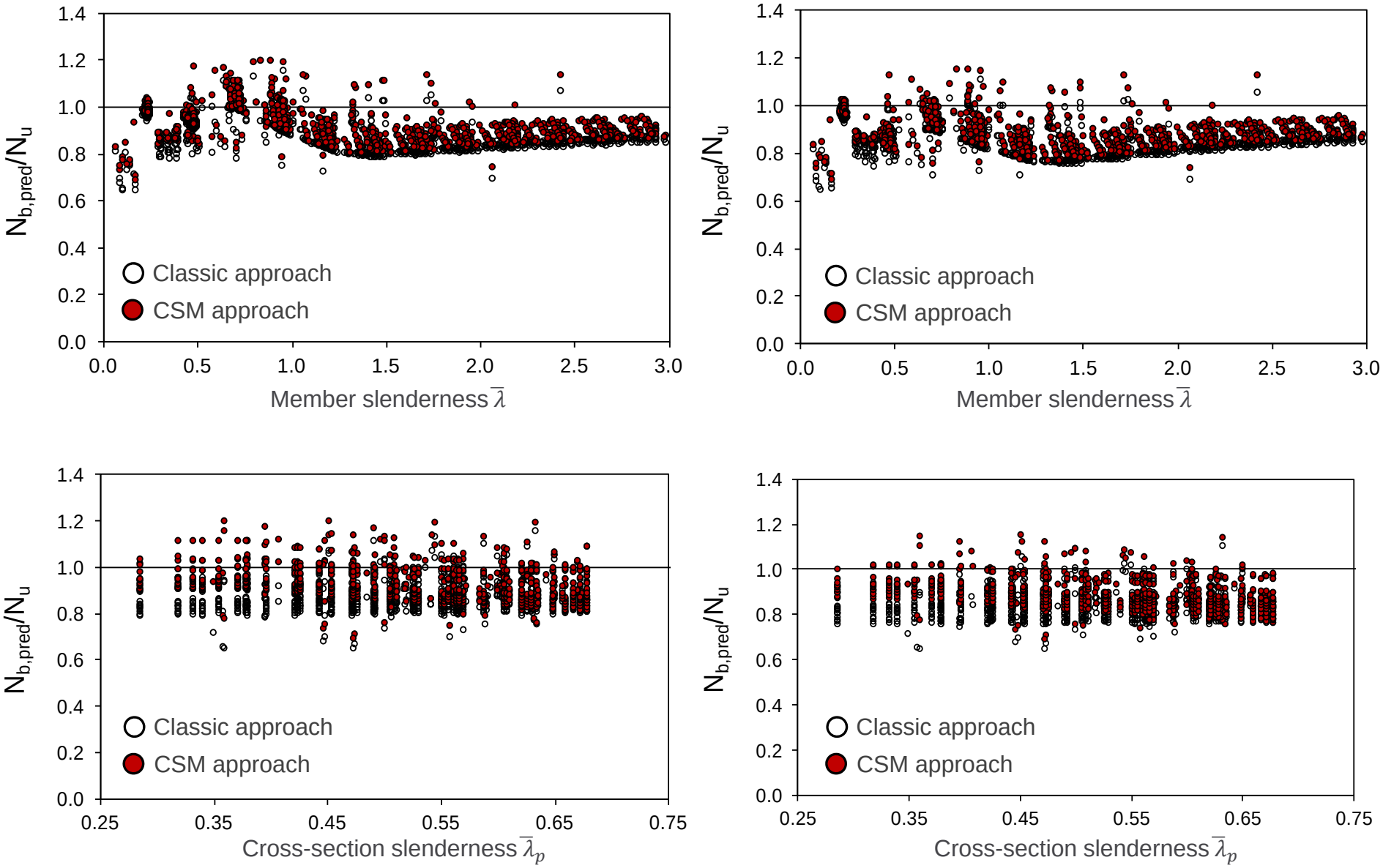






EN1993-1-4 buckling curve

Revised curves



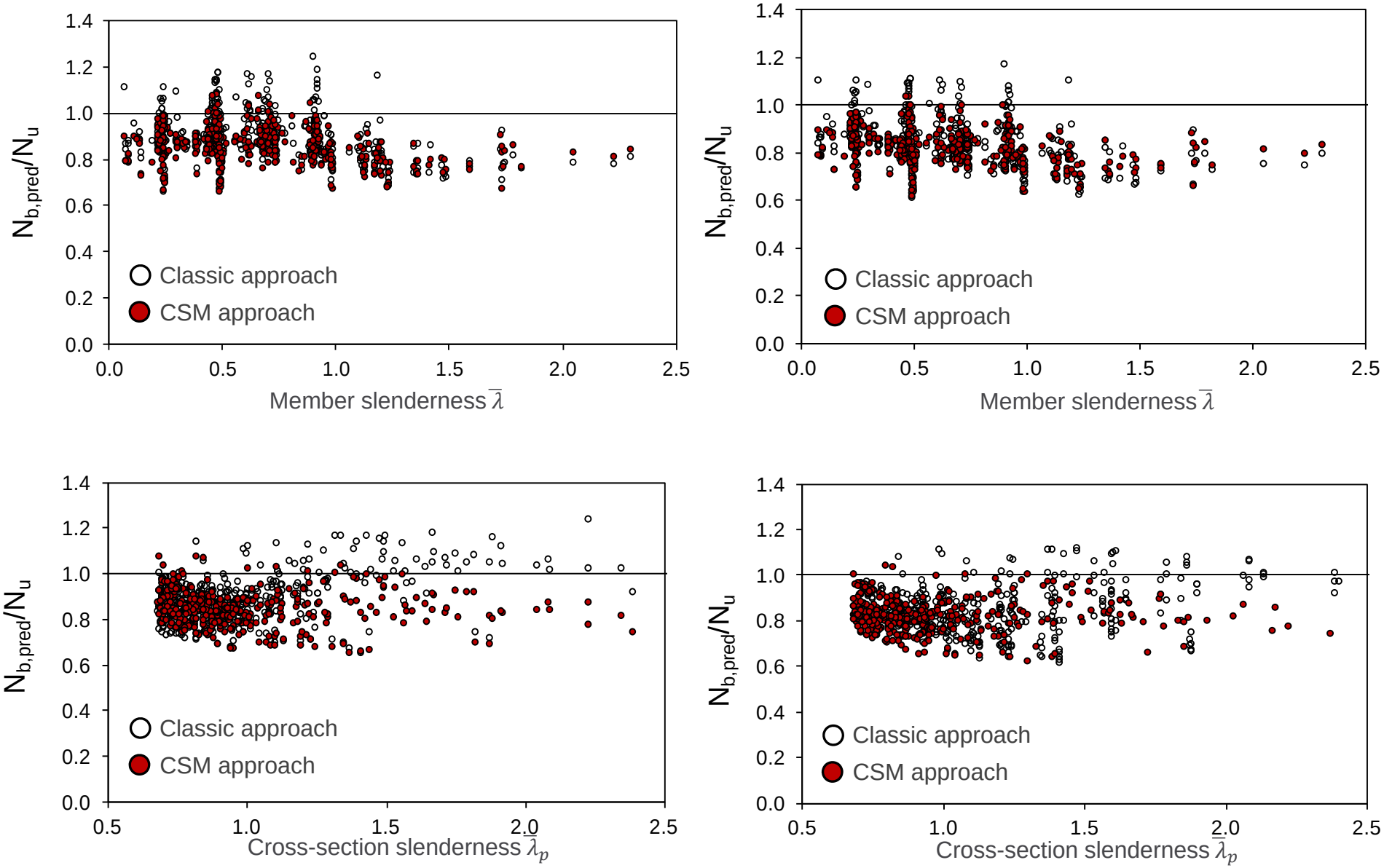
		CSM approach		No strain hardening	
		$N_{b,CSM,EN}/N_u$	$N_{b,CSM,rev}/N_u$	$N_{b,EN}/N_u$	$N_{b,rev}/N_u$
Austenitic	Mean	0.94	0.91	0.88	0.85
	COV	0.123	0.114	0.113	0.104
Ferritic	Mean	0.92	0.88	0.87	0.83
	COV	0.076	0.067	0.075	0.066
Duplex	Mean	0.91	0.88	0.87	0.84
	COV	0.066	0.065	0.064	0.062
All	Mean	0.92	0.89	0.87	0.83
	COV	0.083	0.075	0.080	0.072

CSM approach provides more accurate column resistance predictions.

Highest $N_{b,pred}/N_u$ ratios obtained for the buckling curve in EN1993-1-4.

EN1993-1-4 buckling curve

Revised curves



		CSM approach		Effective width method	
		$N_{b,CSM,EN}/N_u$	$N_{b,CSM,rev}/N_u$	$N_{b,EN}/N_u$	$N_{b,rev}/N_u$
Austenitic	Mean	0.88	0.86	0.94	0.91
	COV	0.094	0.090	0.114	0.107
Ferritic	Mean	0.84	0.80	0.87	0.81
	COV	0.092	0.093	0.114	0.125
Duplex	Mean	0.84	0.82	0.90	0.87
	COV	0.069	0.071	0.114	0.115
All	Mean	0.85	0.81	0.89	0.84
	COV	0.090	0.093	0.118	0.127

Similar accuracy for both methods.

CSM: simpler and easier, no effective width calculations.

EN1990, Annex D

EN1993-1-4 γ_{M1}=1.10

Stocky cross-sections (strain hardening)

	Grade	b	V_δ	V_r	γ_{M1}
EN1993-1-4 [1] buckling curve	Austenitic	1.113	0.122	0.145	1.08
	Ferritic	1.035	0.074	0.100	1.10
	Duplex	1.126	0.066	0.089	1.03
Revised buckling curves [31]	Austenitic	1.143	0.113	0.138	1.03
	Ferritic	1.101	0.066	0.094	1.01
	Duplex	1.178	0.066	0.088	0.99

Slender cross-sections (local buckling)

	Grade	b	V_δ	V_r	γ_{M1}
EN1993-1-4 [1] buckling curve	Austenitic	1.102	0.097	0.125	1.08
	Ferritic	1.205	0.091	0.113	1.02
	Duplex	1.194	0.069	0.090	0.99
Revised buckling curves [31]	Austenitic	1.136	0.092	0.121	1.03
	Ferritic	1.280	0.089	0.112	0.95
	Duplex	1.236	0.073	0.093	0.97

CSM approach for columns can be safely applied to stainless steel RHS and SHS

8. Conclusions and future research works

- New approach for stainless steel columns based on the Continuous Strength Method presented that incorporates strain hardening effects and avoids effective width calculations

- The method is equivalent to the traditional approach but considers a modified generalized imperfection factor (depends on cross-section slenderness and material)

$$N_{b,CSM} = \frac{\chi_{CSM} \cdot N_{CSM}}{\gamma_{M1}}$$

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

$$\phi_{CSM} = 0.5 \cdot \left[1 + \eta^* + \bar{\lambda}^2\right]$$

Modified generalized imperfection factor

$$\eta^* = \frac{1}{g}\alpha\left(\bar{\lambda} - \bar{\lambda}_0\right) = \frac{\sigma_{CSM} W_{el}}{M_{CSM}}\alpha\left(\bar{\lambda} - \bar{\lambda}_0\right)$$

- The assessment showed that the CSM approach improves the prediction of column resistances.

8. Conclusions and future research works

- The proposed approach is analytic: can be updated with changing buckling curves.
- The proposed approach is analytic: can be used for different materials (carbon steel, aluminium) and cross-sections (CHS, I-sections) for which the CSM is developed.
- Direct impact in beam-column checks (adoption of accurate end-points)
- Further research is needed to study the applicability of the method.

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