LIÈGE université
Urban & Environmental Engineering

NORDIC STEEL 2024

Flexural buckling of mild and high-strength steel hot-rolled sections

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Improvement proposal for the flexural buckling design rules

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Column resistance – design procedure acc. to EC3

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

Where $\phi = 0.5 * [1 + \alpha * (\bar{\lambda} - 0.2) + \bar{\lambda}^2]$

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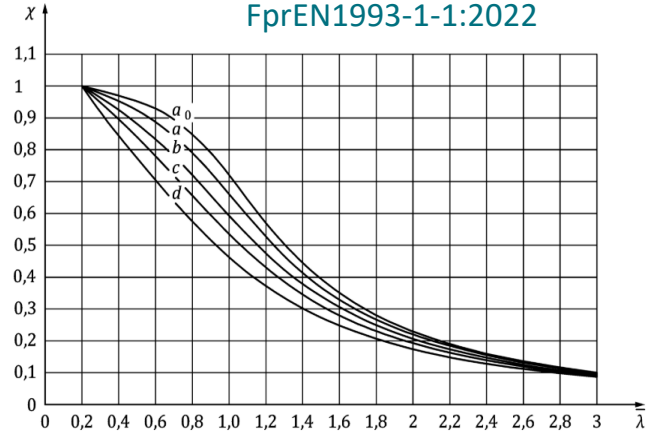
FprEN1993-1-1:2022



Key

Relative slenderness $\bar{\lambda}$

Reduction factor χ

Figure 8.5 — Buckling curves

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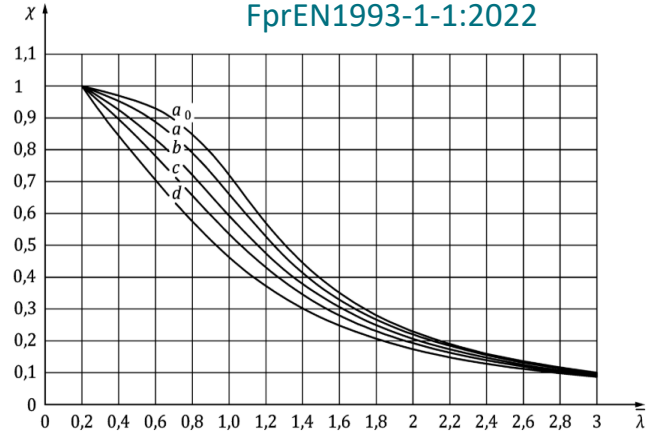
Imperfection parameter

FprEN1993-1-1:2022



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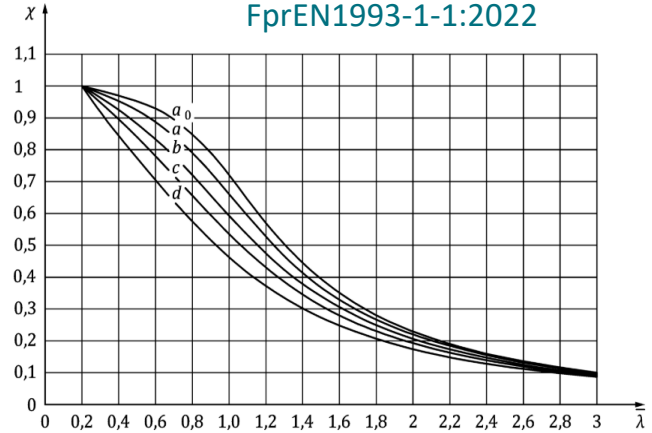

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Table 8.2 — Imperfection factors for buckling curves

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

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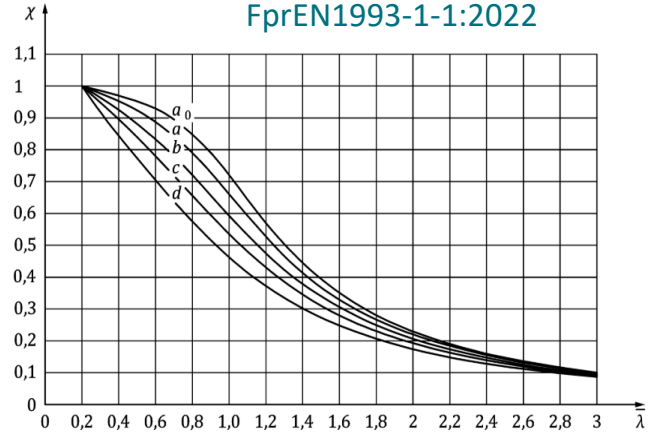

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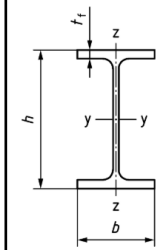
Cross-section		Limits		Buckling about axis	EN1993-1-1:2005		FprEN1993-1-1:2022	
					S235-S420	S460	S235-S420	S460 up to S700 inclusive
Rolled I- or H-sections		$h/b \leq 1.2$	$t_f \leq 40\ mm$	y-y	a	a_0	a	a_0
				z-z	b	**a_0**	b	**a**
			$t_f > 40\ mm$	y-y	b	a	b	a
				z-z	c	**a**	c	**b**
		$h/b > 1.2$	$t_f \leq 100\ mm$	y-y	b	a	b	a
				z-z	c	**a**	c	**b**
			$t_f > 100\ mm$	y-y	d	c	d	c
				z-z	d	c	d	c

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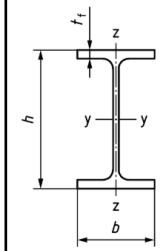
Rolled I- or H-sections		$h/b \leq 1.2$	$t_f \leq 40\ mm$	y-y	a	a_0	a	a_0
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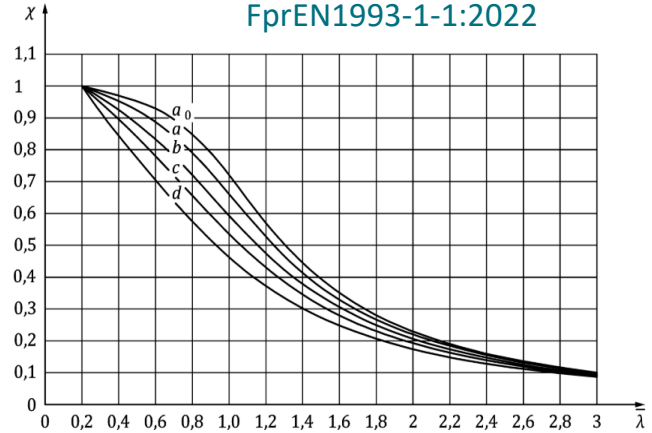

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Superior buckling resistance for HSS is still contemplated but, with few changes between the two standard versions

Literature review and research objective

Type of sections	Maquoi, 1982	Jönsson & Stan, 2016	Somodi & Kövesdi, 2017	Meng & Gardner, 2020
Hot-rolled (y-y)	$\boldsymbol{\alpha^* * (\bar{\lambda} - 0{,}2)}$ $\alpha^* = \alpha * \left(\frac{235}{f_y}\right)^n$ n=0.8, Maquoi, 1982 ; n=1.0, Johansson, 2005 ;	$\alpha * (\bar{\lambda}\varepsilon - 0{,}2)$ with; $\varepsilon = \sqrt{\frac{235}{f_y}}$ Class 4 neglected, only for strong axis buckling	/	/
Hot-rolled (z-z)		/	/	/
Welded I-sections		/	$\boldsymbol{\alpha^* * (\bar{\lambda} - 0{,}2)}$ $\alpha^* = \alpha * \left(\frac{235}{f_y}\right)^{0.6}$	/
Hot-finished tubes		/	/	$\boldsymbol{\alpha^* * (\bar{\lambda} - 0{,}1)}$ $\alpha^* = 0.24\varepsilon$ for hot-finished $\alpha^* = 0.56\varepsilon$ for cold-formed
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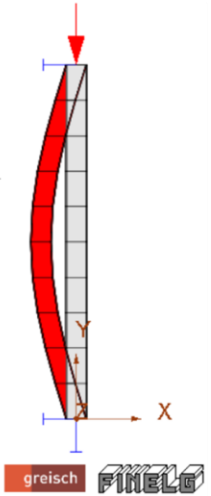
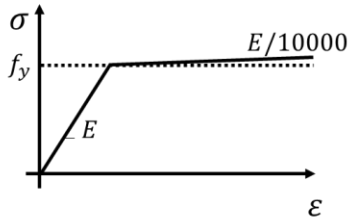
Numerical model description

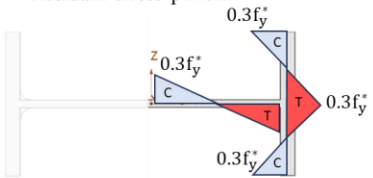
Support conditions &
Initial bow imperfection



Material law



Residual stress pattern



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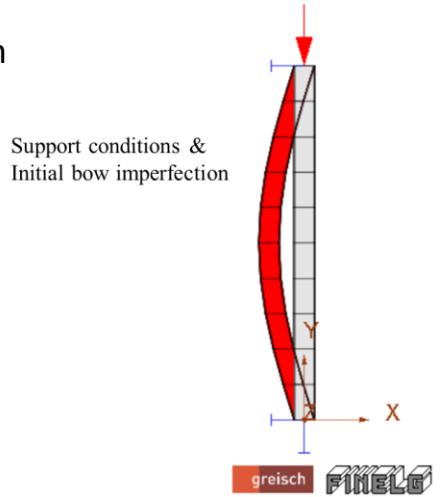

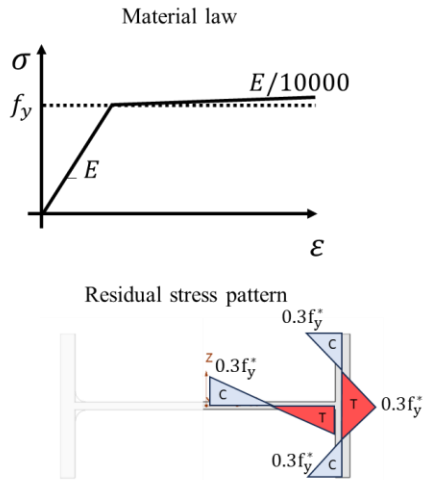

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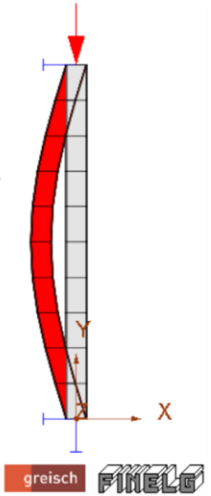

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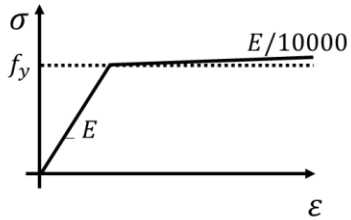

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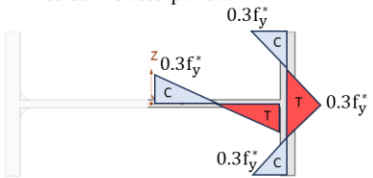

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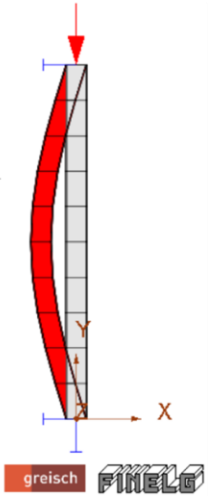

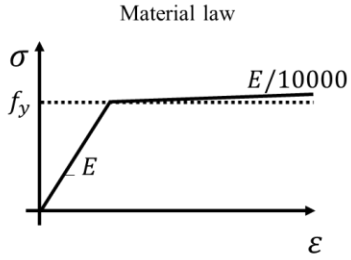

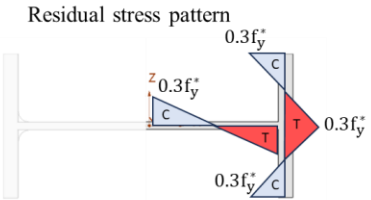

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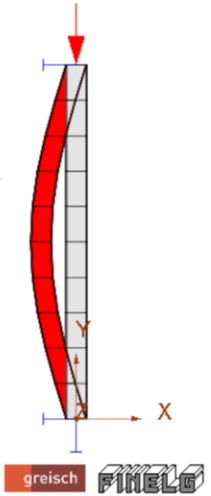

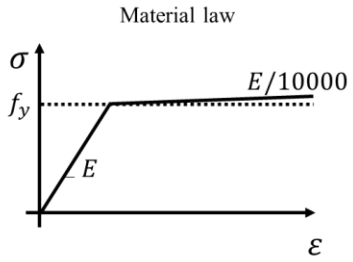

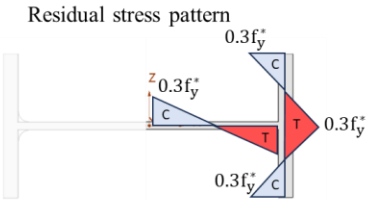

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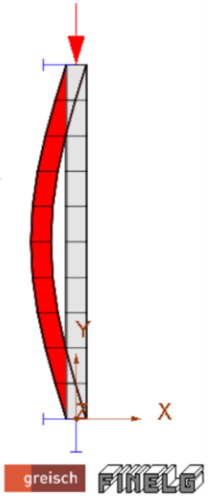

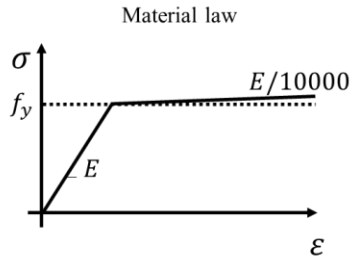

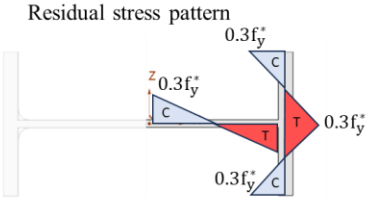

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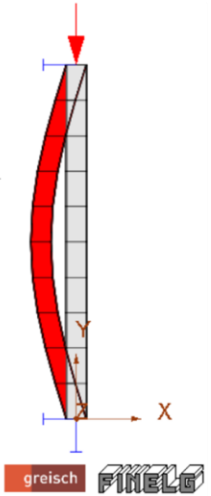

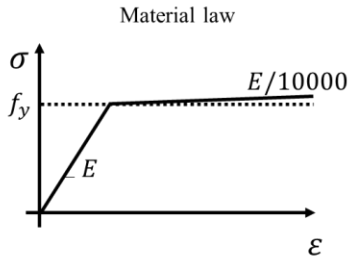

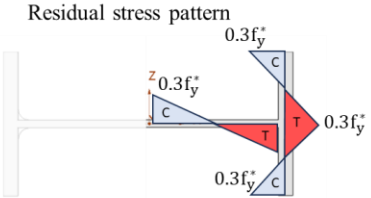

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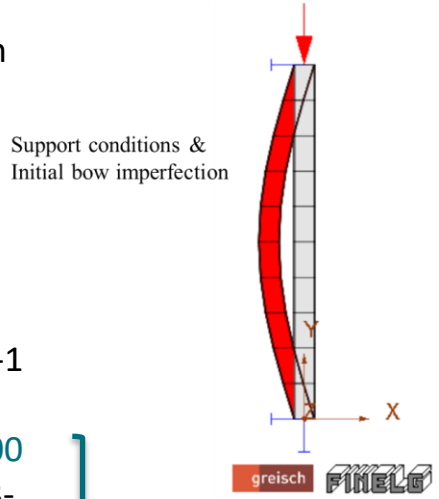

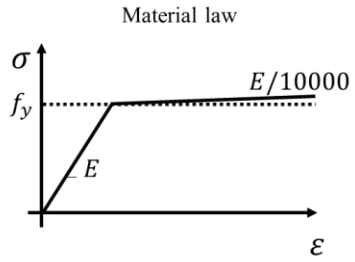

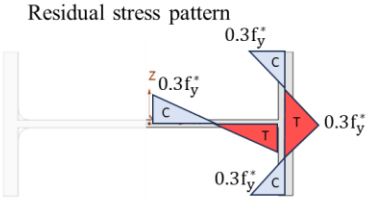

Unaffected by the yield strength

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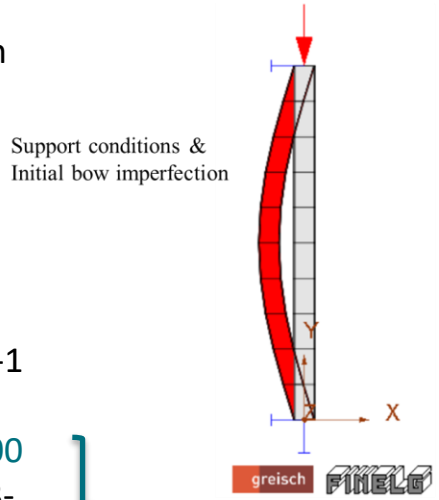

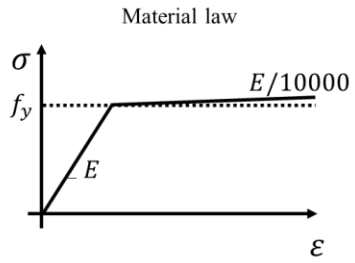

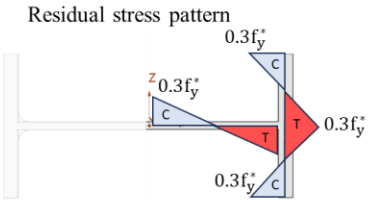

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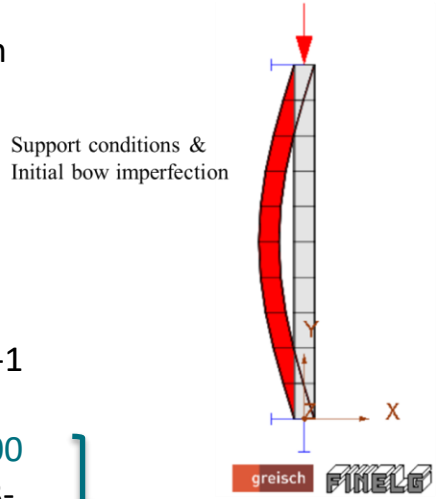
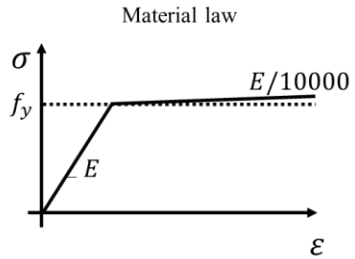
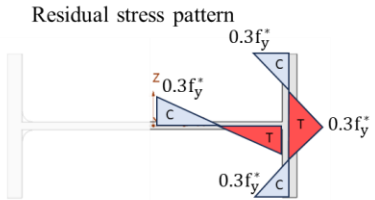
- Nominal yield strength prescribed in FprEN1993-1-1 and EN10025
- Initial geometrical imperfection amplified by L/1000
- Classical residual stress pattern (acc. to FprEN1993-1-14:2024)
- Weak-axis and strong-axis buckling
- The focus is made on profiles with height-to-width ratios above 1.2 and flange thickness below 40mm, i.e, HEM500 & HEB400







Unaffected by the yield strength

Numerical model description

- GMNIA analyses in the FINELG software with beam finite elements
- Stress-strain relationship : elastic perfectly plastic
- Class 1-2-3 cross-sections:

$$\bar{\lambda} = \sqrt{\frac{A * f_y}{N_{cr}}} \rightarrow L_{model} = \frac{i * \pi * \bar{\lambda}}{\sqrt{\frac{f_y}{E}}} \text{ and } \chi = \frac{N_{u,FEM}}{A_{FEM} * f_y}$$

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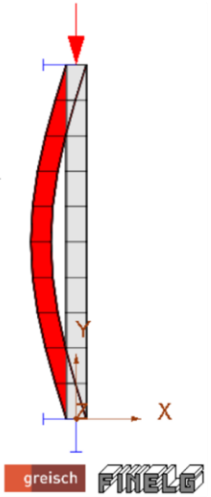
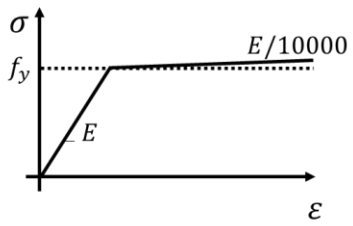
- The focus is made on profiles with height-to-width ratios above 1.2 and flange thickness below 40mm, i.e, HEM500 & HEB400

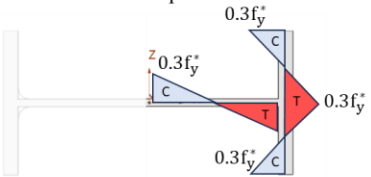
Support conditions & Initial bow imperfection



Material law



Residual stress pattern



Unaffected by the yield strength

Limits	Designation	h [mm]	b [mm]	t_w [mm]	t_f [mm]	r [mm]	Class in S460	Class in S690
h/b > 1.2	HEB400	400	300	13.5	24	27	2	3
/ t_f ≤ 40mm	HEM500	524	306	21	40	27	1	2

Validation on existing buckling tests

The validation was performed on the experimental tests carried out on heavy hot-rolled sections at the Fritz Engineering Laboratory in 1972

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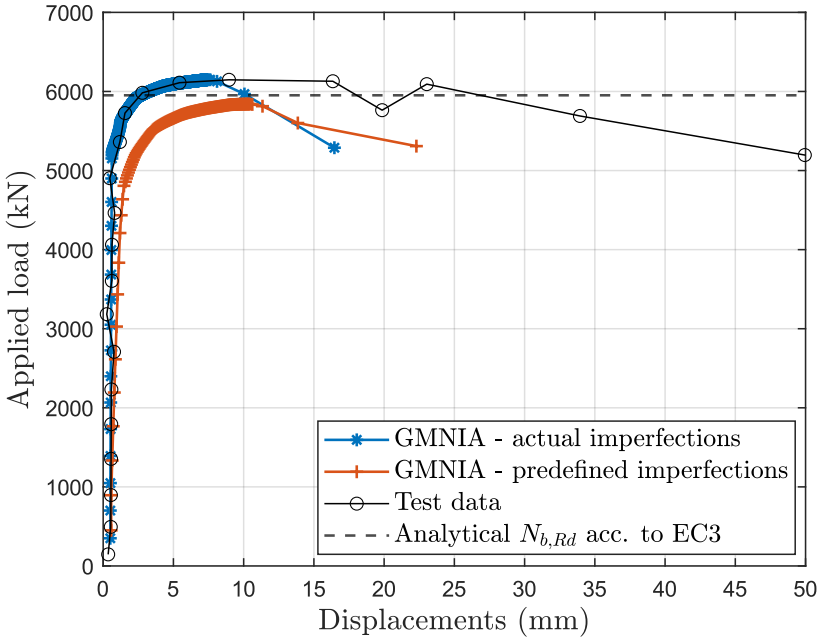

HEM340, Lcr=3.95m

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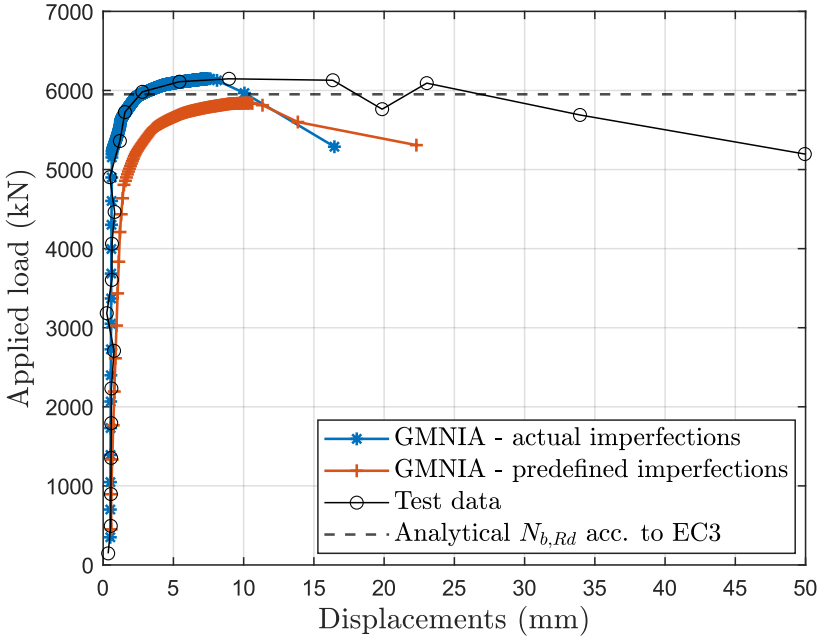
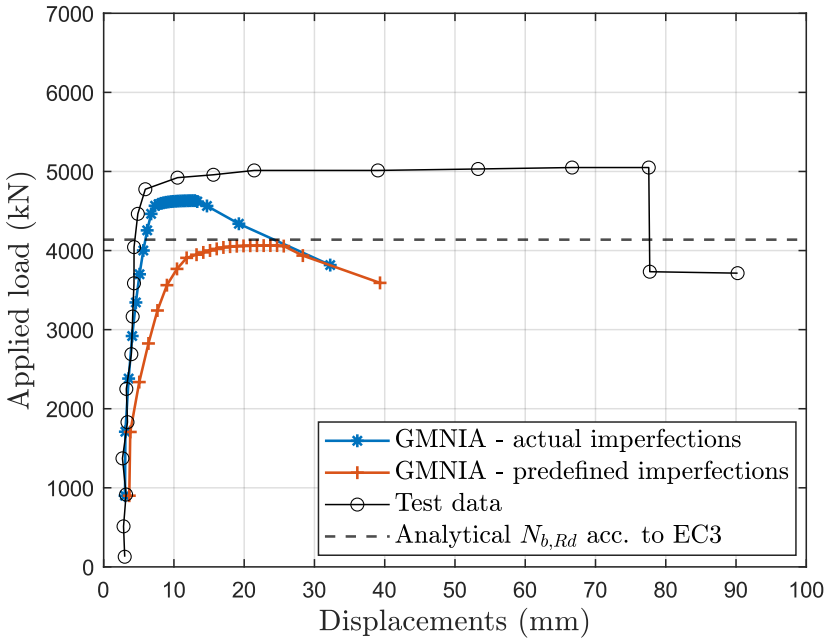


HEM340, Lcr=3.95m

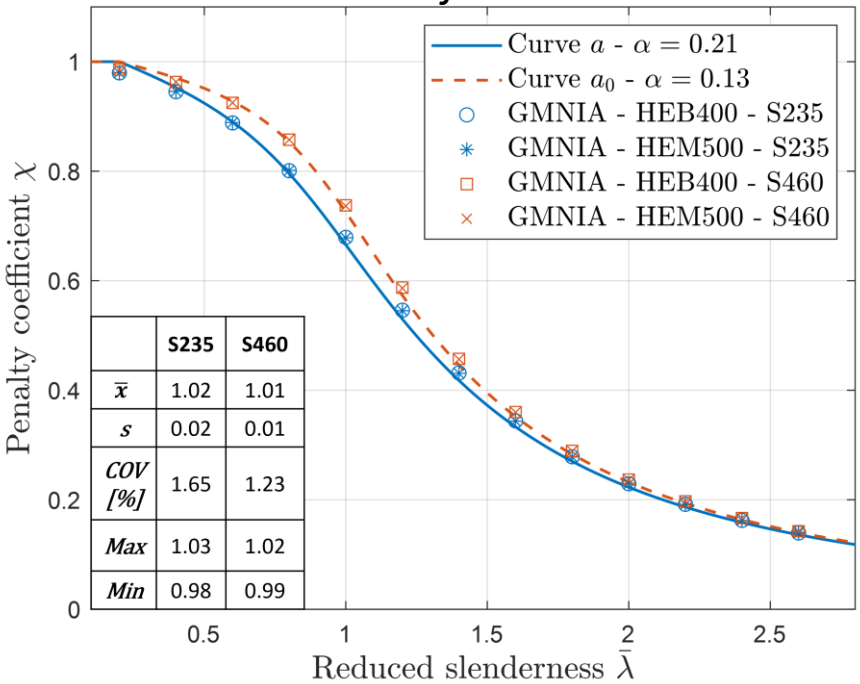


HEM340, Lcr=7.5m

Assessment of already covered grades (S235 – S460)

Assessment of already covered grades (S235 – S460)

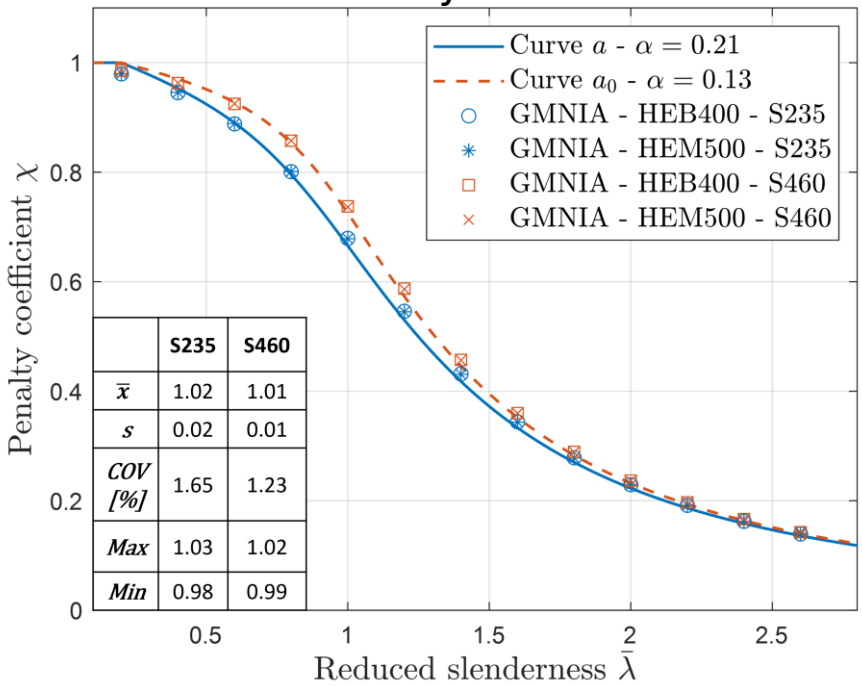
Major-axis



	S235	S460
$\bar{x}$	1.02	1.01
s	0.02	0.01
COV [%]	1.65	1.23
Max	1.03	1.02
Min	0.98	0.99

Assessment of already covered grades (S235 – S460)

Major-axis



	S235	S460
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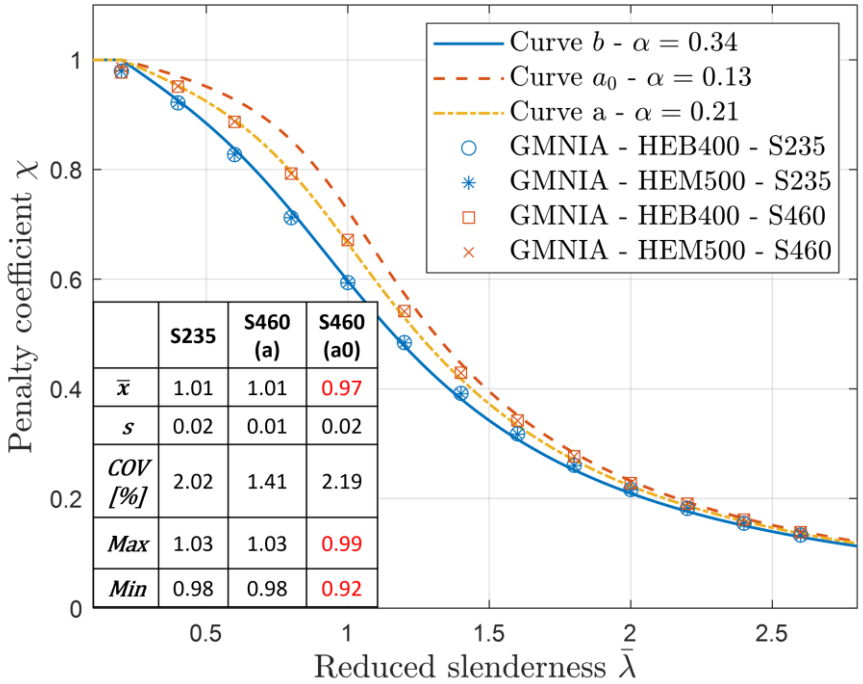
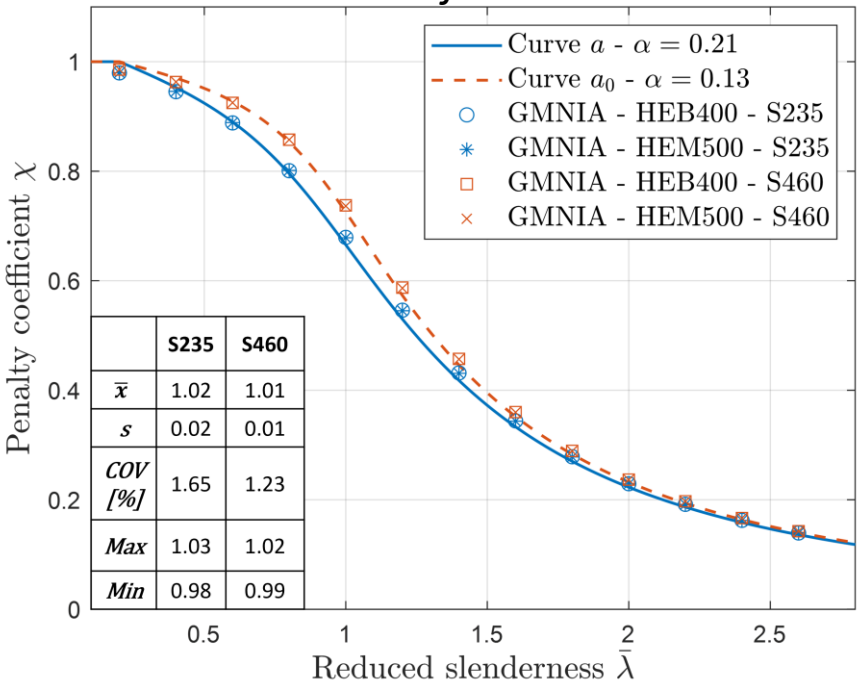


	S235	S460 (a)	S460 (a0)
$\bar{x}$	1.01	1.01	0.97
s	0.02	0.01	0.02
COV [%]	2.02	1.41	2.19
Max	1.03	1.03	0.99
Min	0.98	0.98	0.92

Assessment of already covered grades (S235 – S460)

Major-axis



	S235	S460
$\bar{x}$	1.02	1.01
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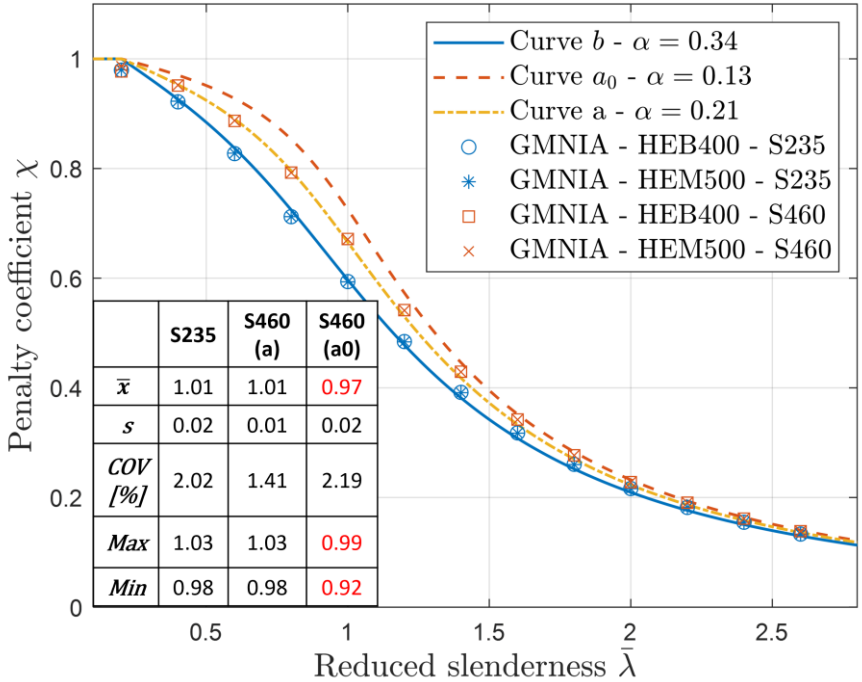
Minor-axis



	S235	S460 (a)	S460 (a0)
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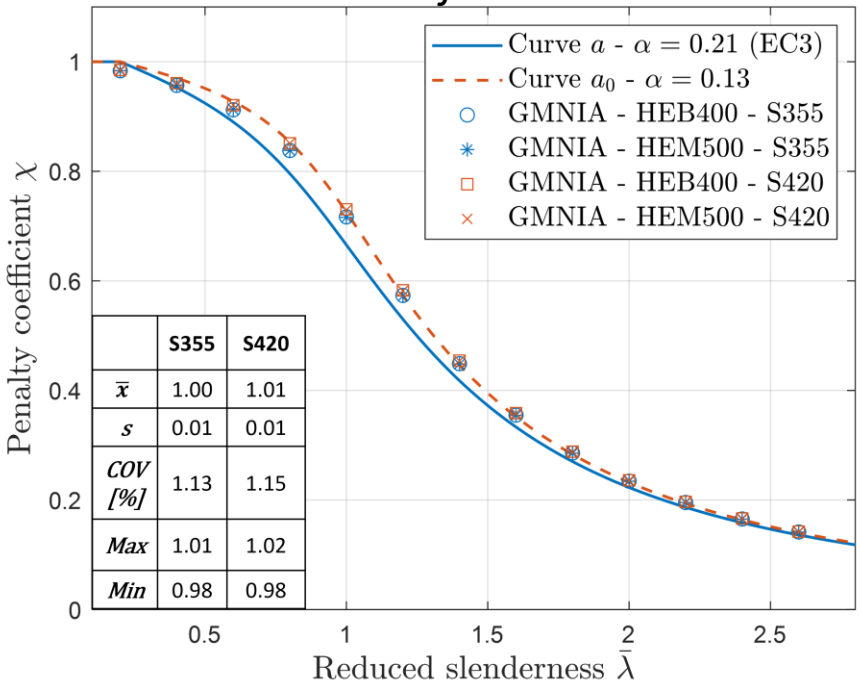
A good correspondence between numerical simulations and the new upcoming standard FprEN1993-1-1: 2022 has been contemplated.

Assessment of intermediate grades (S355 – S420)

Assessment of intermediate grades (S355 – S420)

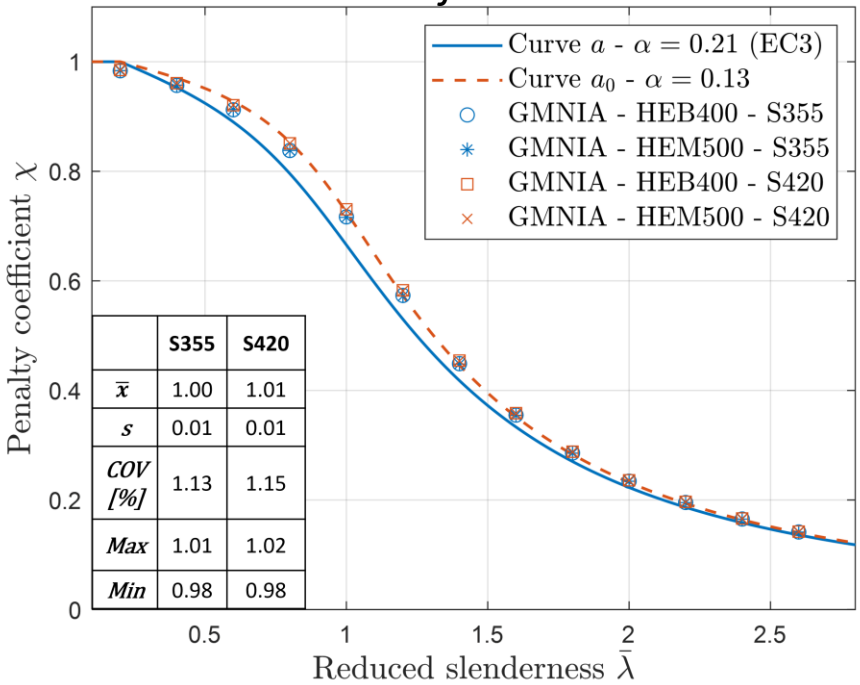
Major-axis



	S355	S420
$\bar{x}$	1.00	1.01
s	0.01	0.01
COV [%]	1.13	1.15
Max	1.01	1.02
Min	0.98	0.98

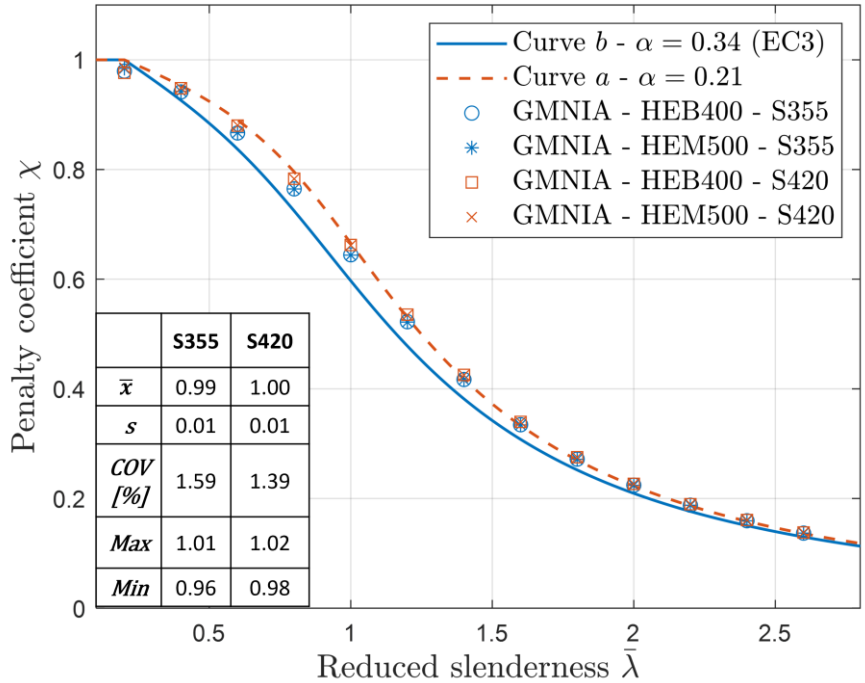
Assessment of intermediate grades (S355 – S420)

Major-axis



	S355	S420
$\bar{x}$	1.00	1.01
s	0.01	0.01
COV [%]	1.13	1.15
Max	1.01	1.02
Min	0.98	0.98

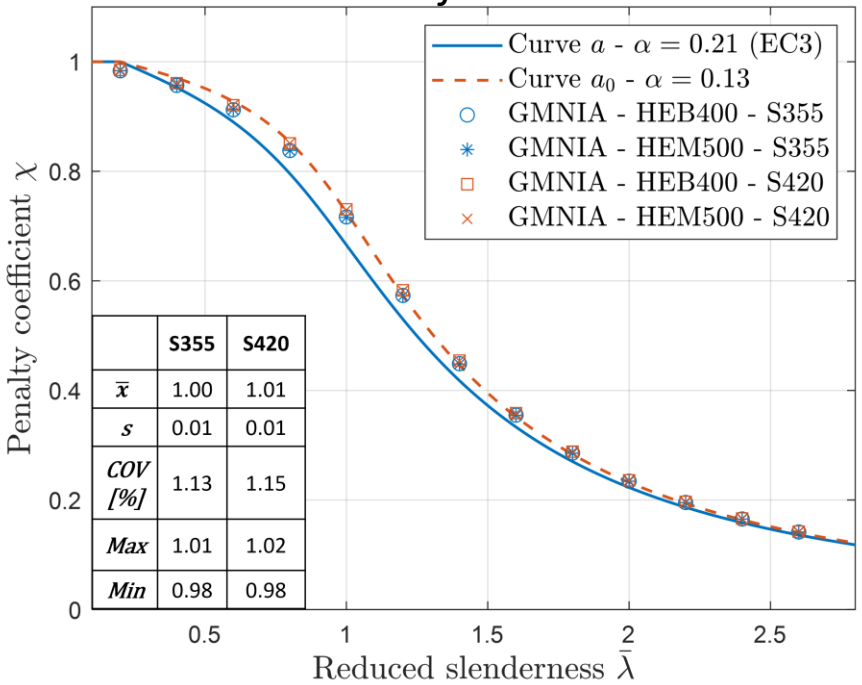
Minor-axis



	S355	S420
$\bar{x}$	0.99	1.00
s	0.01	0.01
COV [%]	1.59	1.39
Max	1.01	1.02
Min	0.96	0.98

Assessment of intermediate grades (S355 – S420)

Major-axis



	S355	S420
$\bar{x}$	1.00	1.01
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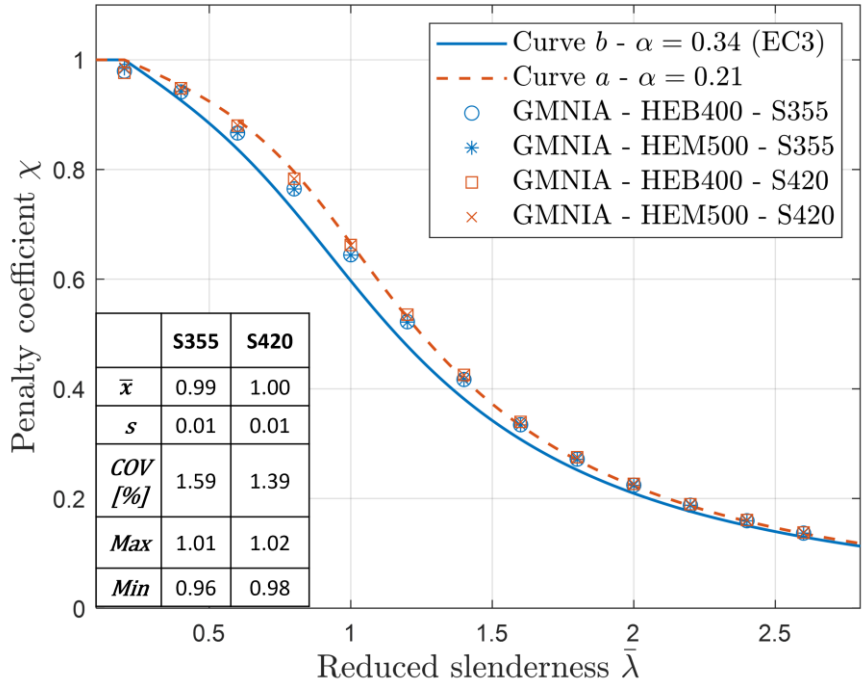

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s	0.01	0.01
COV [%]	1.59	1.39
Max	1.01	1.02
Min	0.96	0.98

Intermediate grades are categorized within the same buckling curve as S235, which has been evaluated as very conservative.

Proposal of a new modified imperfection factor

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$$\alpha^* * (\bar{\lambda} - 0{,}2) \Rightarrow \alpha^* = \alpha * \left(\frac{235}{f_y}\right)^{0.7}$$

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This exponent is chosen to respect the current recommended factors for S235 and S460

Proposal of a new modified imperfection factor

α_{FEM} evaluated for each f_y

$$\alpha^* * (\bar{\lambda} - 0{,}2) \Rightarrow \alpha^* = \alpha * \left(\frac{235}{f_y}\right)^{0.7}$$

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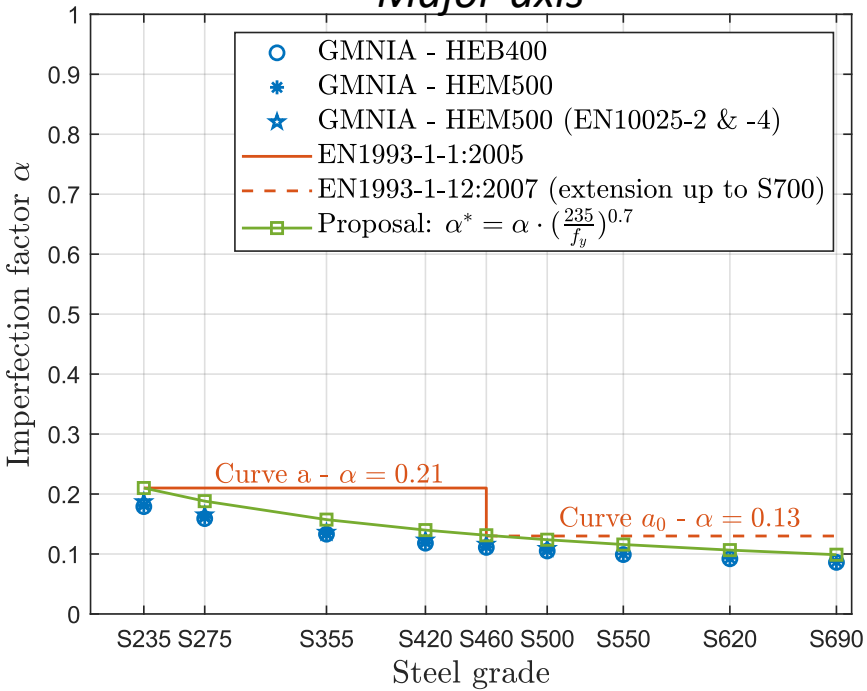
α_{FEM} evaluated for each f_y *Major-axis*



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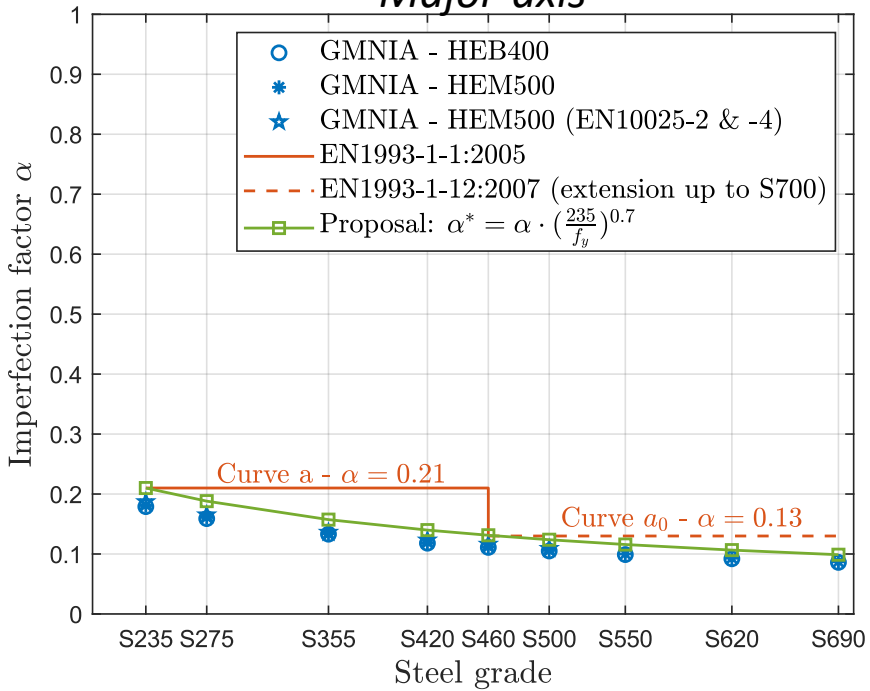
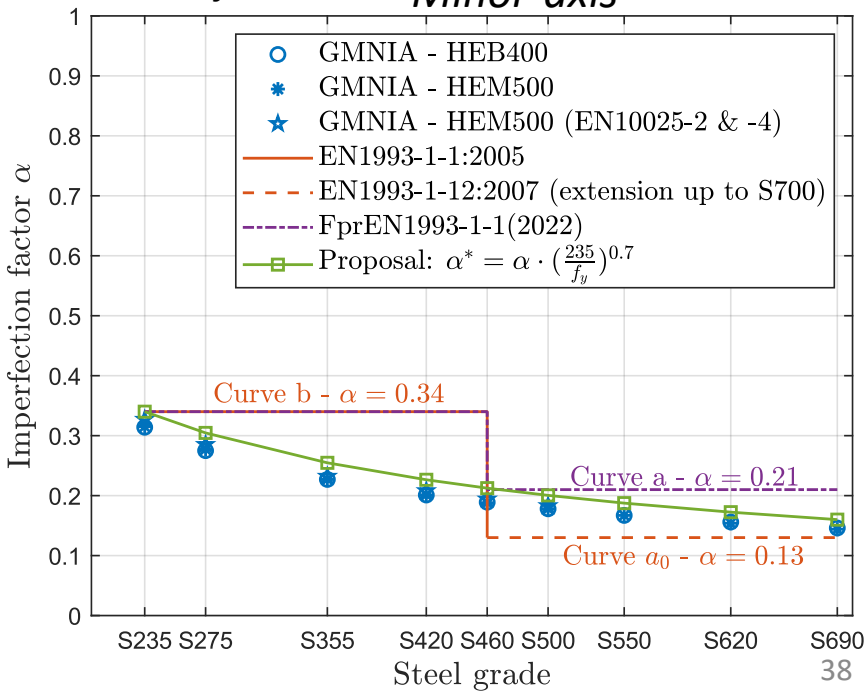
α_{FEM} evaluated for each f_y

Major-axis



Minor-axis



Benefit in terms of buckling resistance

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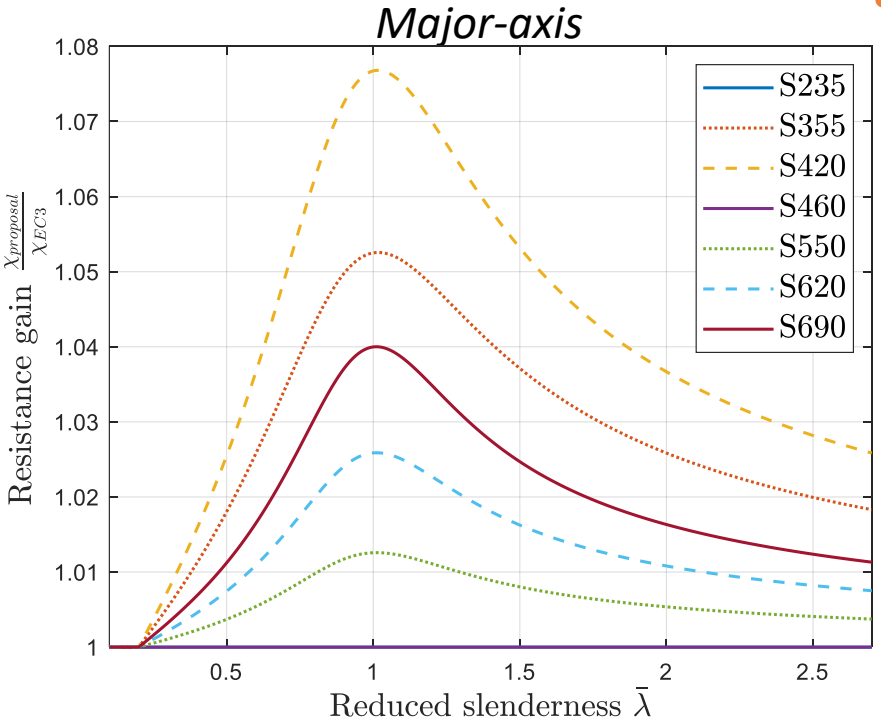
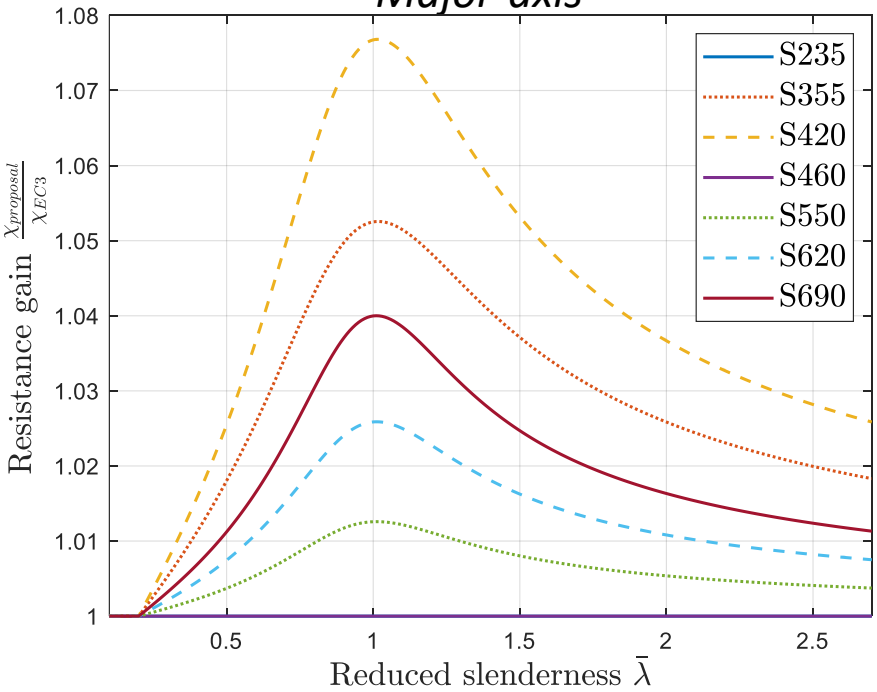
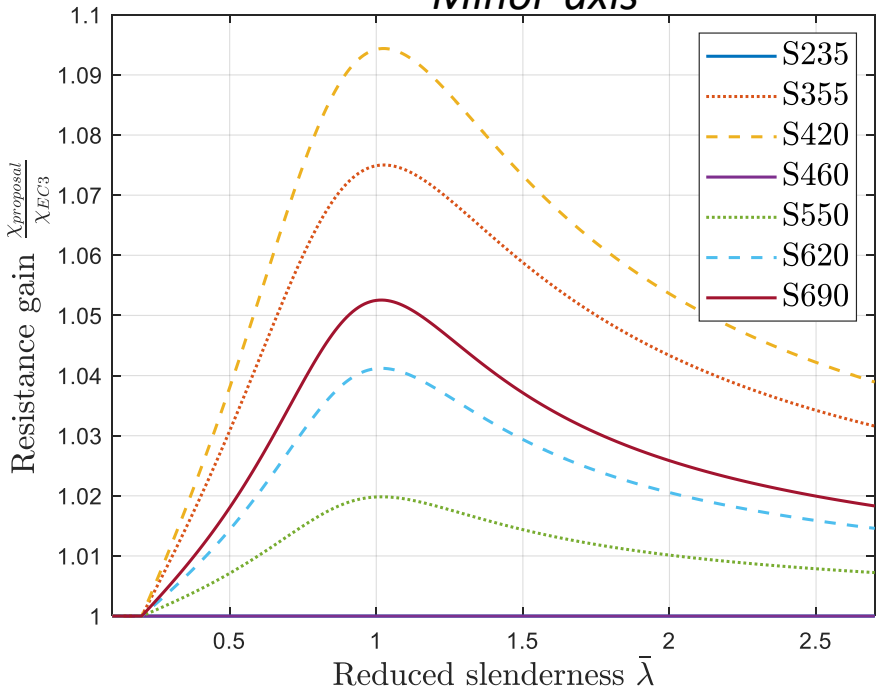


Benefit in terms of buckling resistance

Major-axis



Minor-axis



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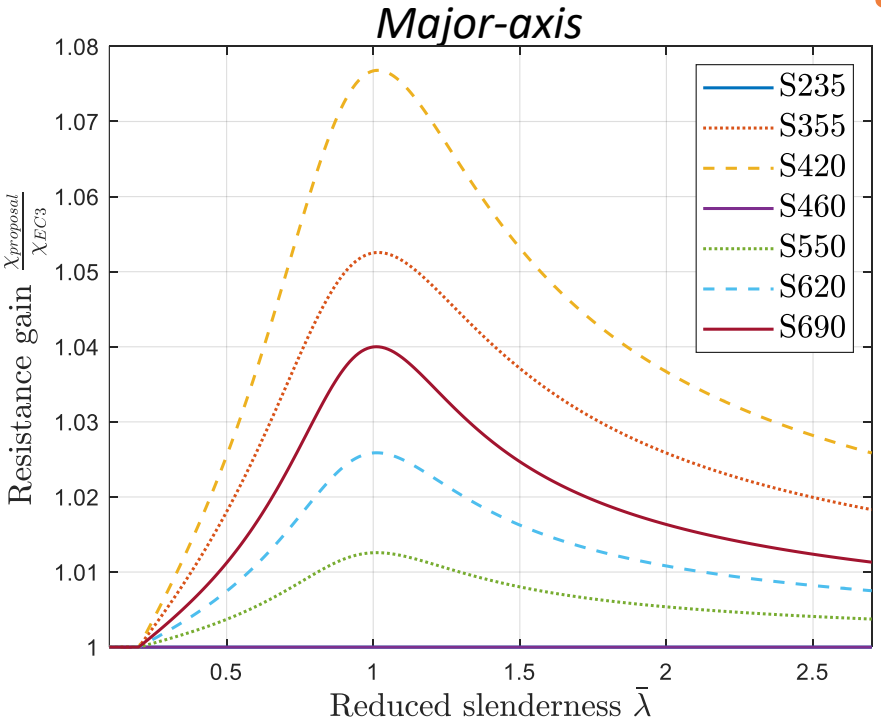

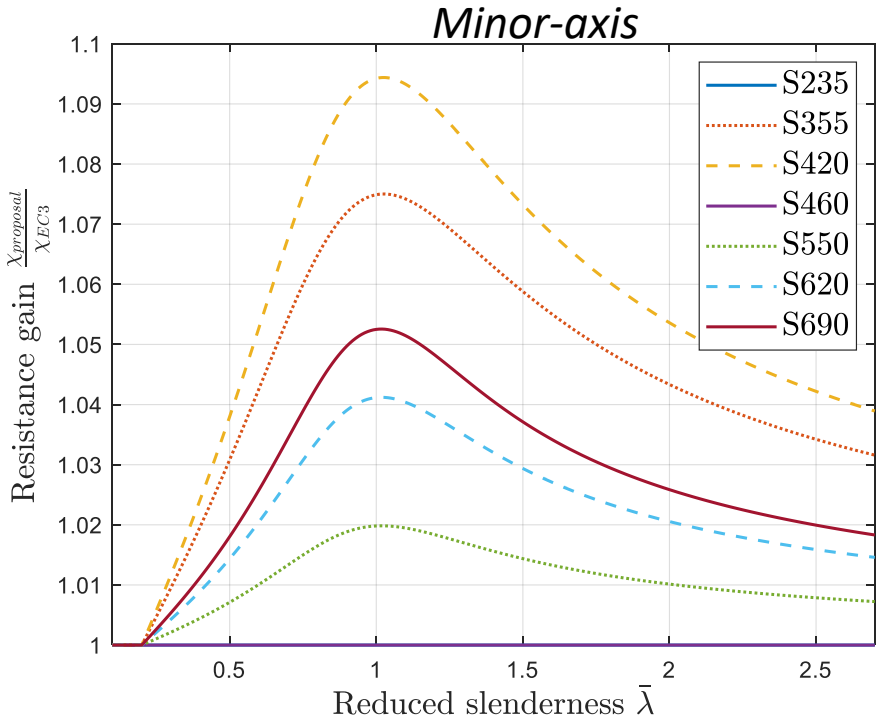

Advantage of this proposal: to keep the same buckling curve denomination for S235 ; to continuously account for the yield strength and thus to induce weight saving. Indeed, even a small increase of buckling resistance may lead to a gain of one or several profiles when designing a steel column.

Conclusions & perspectives

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$$\eta = \alpha * (\bar{\lambda} - 0.2)$$

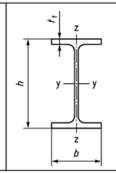
Cross-section		Limits		Buckling about axis	Buckling curves	
					S235 S275 S355 S420	S460 up to S700 inclusive
Rolled I- or H-sections		h/b>1.2	$t_f \leq 40\ mm$	y-y	a	a_0
				z-z	b	a
		h/b≤1.2	$t_f \leq 100\ mm$	y-y	b	a
				z-z	c	b

Table 8.3 of FprEN1993-1-1: 2022

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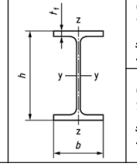
Cross-section		Limits		Buckling about axis	Buckling curves: S235 S275 S355 S420	Buckling curves: S460 up to S700 inclusive
Rolled I- or H-sections		h/b>1.2	$t_f \leq 40\ mm$	y-y	a	a_0
				z-z	b	a
		h/b≤1.2	$t_f \leq 100\ mm$	y-y	b	a
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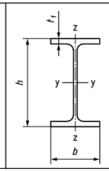
Table 8.3 of FprEN1993-1-1: 2022

$$\eta = \alpha^* * (\bar{\lambda} - 0.2), \text{ with } \alpha^* = \alpha * \left(\frac{235}{f_y}\right)^{0.7}$$

Cross-section		Limits		Buckling about axis	Buckling curve
Rolled I- or H-sections		h/b>1.2	$t_f \leq 40\ mm$	y-y	a
				z-z	b
		h/b≤1.2	$t_f \leq 100\ mm$	y-y	b
				z-z	c

Proposal of modification

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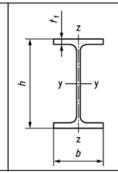
$$\eta = \alpha * (\bar{\lambda} - 0.2)$$

Cross-section		Limits		Buckling about axis	Buckling curves: S235 S275 S355 S420	Buckling curves: S460 up to S700 inclusive
Rolled I- or H-sections		h/b>1.2	$t_f \leq 40\ mm$	y-y	a	a_0
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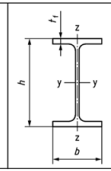
Cross-section		Limits		Buckling about axis	Buckling curve
Rolled I- or H-sections		h/b>1.2	$t_f \leq 40\ mm$	y-y	a
				z-z	b
		h/b≤1.2	$t_f \leq 100\ mm$	y-y	b
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- ✓ This proposal may lead to weight, carbon & cost savings.
- ❖ The approach can be applied to other section typologies in order to generalize the conclusions ;

$$\eta = \alpha * (\bar{\lambda} - 0.2)$$

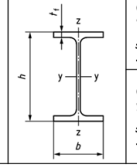
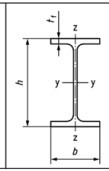
Cross-section		Limits		Buckling about axis	Buckling curves: S235 S275 S355 S420	Buckling curves: S460 up to S700 inclusive
Rolled I- or H-sections		h/b>1.2	$t_f \leq 40\ mm$	y-y	a	a_0
				z-z	b	a
		h/b≤1.2	$t_f \leq 100\ mm$	y-y	b	a
				z-z	c	b

Table 8.3 of FprEN1993-1-1: 2022

$$\eta = \alpha^* * (\bar{\lambda} - 0.2), \text{ with } \alpha^* = \alpha * \left(\frac{235}{f_y}\right)^{0.7}$$

Cross-section		Limits		Buckling about axis	Buckling curve
Rolled I- or H-sections		h/b>1.2	$t_f \leq 40\ mm$	y-y	a
				z-z	b
		h/b≤1.2	$t_f \leq 100\ mm$	y-y	b
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- ✓ A new modified imperfection factor has been proposed ;
- ✓ This proposal may lead to weight, carbon & cost savings.
- ❖ The approach can be applied to other section typologies in order to generalize the conclusions ;
- ❖ Buckling tests should be realised to confirm the numerical results and calibrate the partial safety coefficient.

$$\eta = \alpha * (\bar{\lambda} - 0.2)$$

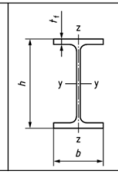
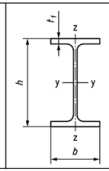
Cross-section		Limits		Buckling about axis	Buckling curves: S235 S275 S355 S420	Buckling curves: S460 up to S700 inclusive
Rolled I- or H-sections		h/b>1.2	$t_f \leq 40\ mm$	y-y	a	a_0
				z-z	b	a
		h/b≤1.2	$t_f \leq 100\ mm$	y-y	b	a
				z-z	c	b

Table 8.3 of FprEN1993-1-1: 2022

$$\eta = \alpha^* * (\bar{\lambda} - 0.2), \text{ with } \alpha^* = \alpha * \left(\frac{235}{f_y}\right)^{0.7}$$

Cross-section		Limits		Buckling about axis	Buckling curve
Rolled I- or H-sections		h/b>1.2	$t_f \leq 40\ mm$	y-y	a
				z-z	b
		h/b≤1.2	$t_f \leq 100\ mm$	y-y	b
				z-z	c

Proposal of modification

Conclusions & perspectives

- ✓ Existing design rules for flexural buckling have been assessed ;
- ✓ A literature review has been realised to determine existing continuous expressions ;
- ✓ A new modified imperfection factor has been proposed ;
- ✓ This proposal may lead to weight, carbon & cost savings.
- ❖ The approach can be applied to other section typologies in order to generalize the conclusions ;
- ❖ Buckling tests should be realised to confirm the numerical results and calibrate the partial safety coefficient.

Extended version

Journal paper: *L. Saufnay, J-P Jaspart and J.-F. Demonceau. "*Improvement of the prediction of the flexural buckling resistance of hot-rolled mild and high-strength steel members*"* Engineering Structures, Elsevier, 2024 *[Manuscript accepted – in production]*

$$\eta = \alpha * (\bar{\lambda} - 0.2)$$

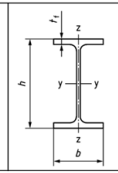
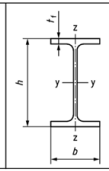
Cross-section		Limits		Buckling about axis	Buckling curves: S235 S275 S355 S420	Buckling curves: S460 up to S700 inclusive
Rolled I- or H-sections		h/b>1.2	$t_f \leq 40\ mm$	y-y	a	a_0
				z-z	b	a
		h/b≤1.2	$t_f \leq 100\ mm$	y-y	b	a
				z-z	c	b

Table 8.3 of FprEN1993-1-1: 2022

$$\eta = \alpha^* * (\bar{\lambda} - 0.2), \text{ with } \alpha^* = \alpha * \left(\frac{235}{f_y}\right)^{0.7}$$

Cross-section		Limits		Buckling about axis	Buckling curve
Rolled I- or H-sections		h/b>1.2	$t_f \leq 40\ mm$	y-y	a
				z-z	b
		h/b≤1.2	$t_f \leq 100\ mm$	y-y	b
				z-z	c

Proposal of modification

NORDIC STEEL 2024

LIÈGE université
Urban & Environmental Engineering

Thank you for your attendance !

Questions ?

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