SAFETY ASSESSMENT OF EUROCODE 3 STABILITY DESIGN RULES FOR THE FLEXURAL BUCKLING OF COLUMNS

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ABSTRACT: This paper presents the safety assessment of Eurocode 3 – part 1-1 [1] rules for the flexural buckling columns using hot-rolled cross-sections (I and H cross-sections).

The safety assessment follows the procedure presented in Annex D of EN 1990 [2]. It is based on a large number (7332) of numerical simulations (GMNIA) covering various relevant parameters.
Firstly, it is concluded that the level of safety is consistent across the various types of I and H cross-sections and steel grades (maximum variation of 6.3%) except for S460 and minor axis buckling. It is therefore proposed to adjust the buckling curves for minor axis buckling for S460.

Secondly, the magnitude of the partial factor γ_{M1} is assessed. It is shown that depending on the random variables included in the analysis (just yield stress f_y; yield stress f_y and cross-section geometry; or yield stress f_y, cross-section geometry and modulus of elasticity E) the average value of γ_{M1} varies from 0.941 to 1.049 with c.o.v varying from 4.3% to 6.3%.

Keywords: Column, flexural buckling, safety assessment, design rules, steel, Eurocode 3, stability

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1. INTRODUCTION

A main purpose of modern design codes is to provide design principles and application rules that lead to appropriate safety levels. The safety margin reflects the risk society is willing to accept yet that maximises economical design. Nowadays, it is possible to link quantitatively a specific design rule and the corresponding failure probability [3]. However, because design codes combine a very large number of design rules that evolved over many decades of expensive research work and their semi-probabilistic implementation was only effectively started in the 1990's [4], the safety level is not uniform across the various design rules and also within single design rules. Eurocodes 3, part 1-1 [1] is no exception, despite the enormous work that was put in its development and the wide past proven experience that it incorporates. In this paper focus is given to the stability verification of columns.

The design verification of the flexural buckling resistance of columns in Eurocode 3 is based on the buckling curve approach and the underlying European buckling curves that were established in the 1970's. Their development was based on an extensive experimental programme carried out by the European Convention for Constructional Steelwork (ECCS) in several European countries [5]. The theoretical background was summarized by Beer and Schulz [6] by thorough analysis of the experimental programme presented in Sfintesco [5], assessing various imperfections that can possibly occur and affect the resistance of compressed members. Furthermore, the safety of one of the curves was evaluated by Monte Carlo simulation accounting for the variability of various parameters [7]. Finally, Maquoi and Rondal [8] derived the analytical Ayrton-Perry format of the design verification and the curves were put into equation.
Recently, within the scope of the stability rules for steel members, it was recognized that the

extensions, corrections and improvements that evolved over a long period of time since the establishment of the column buckling curves, coupled with the development of new structural steels with largely improved mechanical and geometrical properties and dramatically improved quality control procedures, required a reassessment of the current safety levels of the stability design rules of EC3-1-1 [1]. Thus, this paper addresses a systematic assessment of the safety levels of the fundamental case of flexural buckling of I-shaped hot-rolled steel columns. Firstly, the adopted assumptions for the safety assessment are summarized. A parametric study for the evaluation of rules for flexural buckling of prismatic columns in EC3-1-1 is subsequently carried out. It covers several slenderness ranges, level of residual stresses, yield stress, and cross-section shapes, such that a thorough evaluation of the several members covered by the analysed stability design rules is possible, using advanced nonlinear numerical simulations. Finally, a discussion on the value of the partial factor γ_{M1} to be adopted based on the obtained results is proposed, leading to the proposal of adjustments to the buckling curves.

2. SAFETY ASSESSMENT OF STABILITY DESIGN RULES

2.1 Scope and Assumptions

The assessment encompasses the design rules for flexural buckling of columns given in EC3-1-1, given in clause 6.3.1 for hot-rolled sections. The partial factor γ_{M1} is obtained based on the methodology given in Annex D of EN 1990. Following [2] the procedure is briefly summarized in Section 2.2. The buckling strength of the members is obtained using advanced numerical finite element simulations (GMNIA). Numerical models are detailed in Section 2.4.

For each case (in plane and out-of-plane buckling), a wide range of I-shaped cross sections covering several buckling curves are analysed across practical ranges of slenderness. The parametric study is organized by buckling mode and it is defined in Section 3.1 for the flexural buckling of columns.

In the safety assessment of the design rules carried out in Section 3, the following assumptions are considered:

- The variability of the input variables in the design model is not considered for the calculation of V_δ; the value is obtained from nominal properties since the "experimental" results are considered with nominal properties;
- The coefficient of variation of the basic variables, V_{rt}, considers only the variability of cross section dimensions, yield stress and modulus of elasticity; for these parameters more information is known and documented with recent data. The adopted distributions are summarized in Section 2.3.

2.2 Basis of Design

The framework for the statistical assessment of the steel members was presented and discussed in Tankova et al. [9]. The procedure proposed in Annex D of EN 1990 is summarized in Figure 1:

Step 1: Resistance function

$$r_t = g_{rt}(X_1, X_2 ... X_n)$$

Step 2: Compare experimental and theoretical values

Step 3: Estimate mean vale of correction factor b

$$b = \sum_{i=1}^{n} r_{e,i} r_{t,i} \Big/ \sum_{i=1}^{n} r_{t,i}^2$$

Step 4: Estimate CoV of the error:

$$\delta_i = r_{e,i} / b r_{t,i} \qquad \Delta_i = \ln(\delta_i)$$

$$s_\Delta^2 = \frac{1}{n-1} \sum_{i=1}^{n} \left(\Delta_i - \overline{\Delta}\right)^2$$

$$V_\delta = \sqrt{\exp(s_\Delta^2) - 1}$$

Step 5: Analyze compatibility – if the resistance function is acceptable

Step 6: Determine c.o.v $V_{rt,i}$ of the basic variables

Step 7: Determine design value of the resistance

$$Q_\delta = \sqrt{\ln(V_\delta^2 + 1)} \qquad Q_{rt} = \sqrt{\ln(V_{rt}^2 + 1)}$$

$$Q = \sqrt{\ln(V_\delta^2 + V_{rt}^2 + 1)}$$

$$r_d = \begin{cases} b g_{rt}(\underline{X_m}) \exp\left(-k_{d,\infty} \dfrac{Q_{rt}^2}{Q} - k_{d,n} \dfrac{Q_\delta^2}{Q} - 0.5Q^2\right) & n \leq 30 \\ b g_{rt}(\underline{X_m}) \exp\left(-k_{d,\infty} Q - 0.5Q^2\right) & n \to \infty \end{cases}$$

Figure 1. Flow Chart – Annex D

In Step 6, V_{rt} shall be determined as follows:

$$V_{rt}^2 = \frac{1}{g_{rt}\left(\underline{X_m}\right)^2} \sum_{j=1}^{k} \left(\frac{\partial g_{rt}\left(X_j\right)}{\partial X_j} \sigma_j \right)^2 \tag{1}$$

The partial derivatives are computed numerically using expression (2) adopting a sufficiently small increment "ΔX_i" for each test specimen separately, leading to $\gamma_{M,i}$ for each specimen; finally the mean value for the subset is considered.

$$\frac{\partial r_t}{\partial X_i} \approx \frac{r_t(X_1, ..., X_i + \Delta X_i, ...X_j) - r_t(X_1, ..., X_i, ...X_j)}{\Delta X_i} \tag{2}$$

2.3 Adopted Distributions

In Step 6 of the procedure given in *Figure 1*, information about the scatter of the basic input parameters is required. The distributions summarized in *Table 1* were considered as a reference for the variability of the yield stress. The data was obtained from (*Simões da Silva et al. 2009*) [10] for S235 and S355; and from OPUS [11] for S460, for which there was sufficient number of coupon tests to give reliable distributions (see Annex A for further detail).

The parametric study given in Section 3.1 was defined in order to cover various parameters. Regarding the material properties, a well-known phenomenon is the variation of yield stress with thickness; hence, in this assessment, the provisions of EN 10025[12] have been adopted. Since there was not sufficient information about the distributions of the material properties with the thickness variation, the distributions from *Table 1* were extrapolated from the nominal yield stress for $t_f \leq$ 16mm and the coefficient of variation was kept constant.

Table 1. Adopted Reference Yield Stress Distributions

Steel	$f_{y,nom}$	$f_{y,m}$	c.o.v	Source
	Mpa	MPa	-	-
S235	235	297.3	5.8%	Silva et al [10]
S355	355	419.4	4.8%	Silva et al [10]
S460	460	520.0	5.2%	OPUS [11]

It is noted that the extrapolated distributions were then considered for computation of the γ_{Mi} value of each column, according to its cross-section flange thickness irrespective of whether EN 10025 or EC3-1-1 were used for the choice of nominal yield stress.

Regarding cross-section geometrical properties, statistical indicators from Alpsten [13] and results reported in Taras [14] were adopted for H or I sections and are given in *Table 2*:

Table 2. Adopted Geometrical Distributions

	Mean	c.o.v	Source
b_m/b_{nom}	1	0.9%	Alpsten, G. (1972) [13], Taras A. (2010) [14]
h_m/h_{nom}	1	0.9%	
t_{fm}/t_{fnom}	0.975	3.0%	
t_{wm}/t_{wnom}	1.025	4.0%	

b_m denotes the mean value of the flange width, b_{nom} denotes the nominal value of the flange width, h_m is the mean value of the cross-section height, h_{nom} is the nominal value of the cross-section height, t_f is the mean value of the flange thickness, $t_{f,nom}$ denotes the nominal value of the flange thickness, t_w denotes the mean value of the web thickness and $t_{w,nom}$ denotes the nominal value of the web thickness. Although the reports by Alpsten [13] and Taras [14] are not recent, the statistical characterization of the cross-section dimensions is in line with the statistical indicators for area, moment of inertia and bending modulus as given in the report from the research project PROQUA [15], see *Table 3*. Considering a normal distribution, the computation of the distributions of area and moment of inertia from the distributions of the cross-section dimensions from *Table 2* leads to values of mean and standard deviation that fall within the range of Table 3. Hence, the statistical description of the cross-section dimensions of Table 2 are adopted in the calculation as input random variables.

Table 3. Statistical Distributions for Geometry (A, W, I) PROQUA [15]

	Mean, X_m	σ_x
A, W, I PROQUA *[15]*	$0.99X_{nom}$	$0.01 – 0.04\ X_m$

A distribution for the modulus of elasticity is adopted based on recommendations given in DNV [16] that reports $E_m = E_{nom}$ and a c.o.v. of 5%. It is noted that the statistical characterization of the modulus of elasticity is not so strongly supported by experimental evidence. Furthermore, the testing procedures are not often as reliable with respect to this property. Hence, in Section 3 a sensitivity study is carried out with respect to this property by also considering a c.o.v. of 3%.

2.4 Numerical Modelling

Advanced finite element simulations were carried out to obtain “experimental” results. In this “experimental” programme, finite element software product Abaqus 6.12 [17] was used. Each column is modelled with four-node linear shell elements (S4) with six degrees of freedom.

Advanced analyses were performed using geometrical and material nonlinearities with imperfections, also known as GMNIA. This type of analysis allows capturing the second order effects which are essential for stability problems.

Material nonlinearity is incorporated in the model by using elastic-plastic constitutive law with strain hardening, according to Figure 2, following the recommendations from ECCS [18].

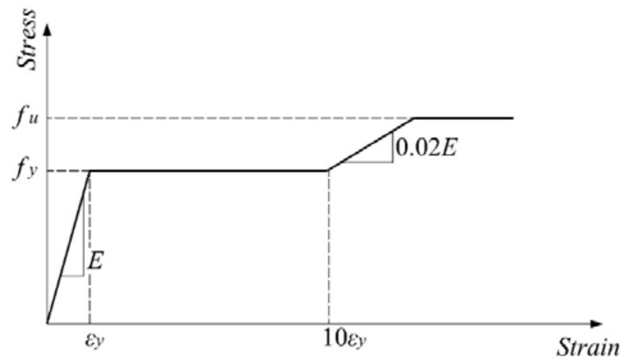


Figure 2, Constitutive Law

The yield stress, f_y, is considered either according to the provisions of the product standard EN 10025 [12], or from Table 3.1 of EC3-1-1. Since Table 3.1 of EC3-1-1 does not account for t>80 mm, for such cases, the same value of f_y as in EN 10025 was considered, see Figure 3.

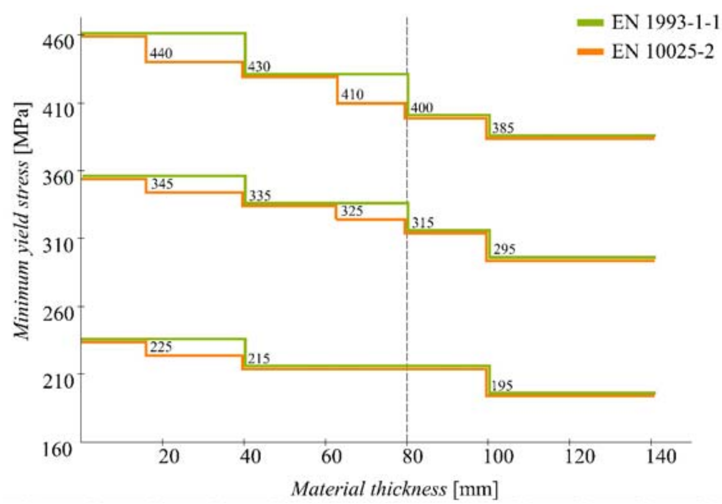
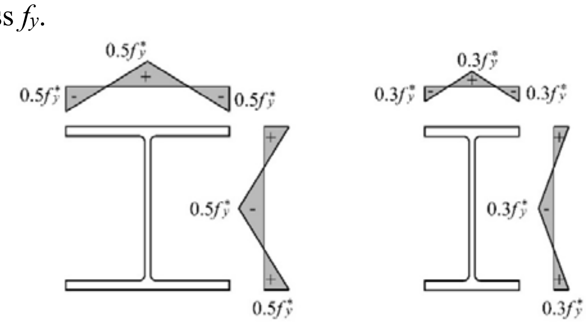


Figure 3. Variation of the Yield Stress with Thickness

Geometrical imperfections were modelled using an initial sinusoidal imperfection introduced in the weak or strong axis of the cross-section, with an amplitude $e_0=L/1000$ at mid span. Residual stresses were considered according to Figure 4. The adopted value of f_y* indicated in *Figure 4* was $f_{y,235}$=235 MPa. Nevertheless, for comparison, equivalent cases were included using the nominal value of the yield stress f_y.



(a) Hot-rolled, h/b<1.2 *(b) Hot-rolled, h/b>1.2*

Figure 4. Residual Stresses ("+" Tension and "–"Compression)

The load is applied using load stepping routine, in which the increment size is chosen in order to meet the accuracy and convergence criteria. The equilibrium equations are solved for each increment using Newton-Raphson iteration technique. The adopted mesh comprises 16 sub-divisions in the web and flanges and 100 divisions along the member's axis per 10 m length.

The boundary conditions are implemented as end fork conditions in the shell model. The following restraints are used - vertical (δz) and transverse (δy) displacements and rotation about the xx-axis (ϕx) are prevented at the supports. In addition, the longitudinal displacement (δx) is prevented in one end. End cross-sections are constrained to remain straight. Whenever major axis buckling behaviour is to be studied, minor axis displacements are restrained at the tip of both flanges and centre of the web.

3. FLEXURAL BUCKLING OF PRISMATIC COLUMNS

As the main purpose of this study is the assessment of existing rules for flexural buckling of prismatic columns from EC3-1-1, in order to cover all types of hot-rolled sections according to Table 6.2 of EC3-1-1, a wide range of I-shaped cross-sections was selected so that flange thickness and the ratio *h/b* would vary.

In this section, firstly, the scope of the parametric study is introduced; subsequently, the methodology for assessment of results is given and finally, the results are discussed.

3.1 Parametric Study: Definition

Table 4 illustrates the hot-rolled section selected for the study, organized according to *Table 6.2* of EC3-1-1. The selection includes 2 (two) American profiles.

Table 4. Sections of the Parametric Study for Columns

Fabrication	Limits		Sections		
			h/b	t_f [mm]	Profiles
Rolled	h/b>1.2	$t_f \leq$ 40mm	1.22	40	HEM340
			1.3	19	HEA400
			1.7	40	HEM500
			1.92	6.9	IPE140
			2.19	40	HEM650
			1.74	5.2	IPE80
			1.82	5.7	IPE100
			1.33	24	HEB400
			1.67	28	HEB500
			1.95	7.4	IPE160
			1.41	40	HEM400
			1.50	24	HEB450
			1.28	40	HEM360

Table 4. Sections of the Parametric Study for Columns (Continued)

Fabrication	**Limits**		**Sections**		
			h/b	**t_f [mm]**	**Profiles**
Rolled	**h/b>1.2**	**40mm<t_f≤100mm**	2.28	55.9	HL920x588
			2.29	62	HL920x656
			2.35	99.1	HL920x1077*
			3.36	64	HE1000x584
			2.31	73.9	HL920x787
			2.30	68.1	HL920x725
			3.08	65	W920x310x576
			2.56	70	HL1000x748
			2.05	69.1	W610x325x551
			2.06	54	HE600x399
			2.36	46	HE700x352
			2.69	54	HE800x444
			3.01	54	HE900x466
		t_f>100mm	1.231	130	HD400x1202*
			2.4	109	HL920x1194*
			1.201	106	HD400x900
			1.23	115	HD400x990
			2.37	115.1	HL920x1269*
			2.31	115.1	HL920x1377*
			1.25	125	HD400x1086
			1.26	140	HD400x1299
	h/b≤1.2	**t_f≤100mm**	1.2	22.5	HEB360
			1.17	97	HD400x818
			0.96	8	HEA100
			1.0	19	HEB300
			1.1	39	HEM300
			1.0	10	HEB100
			1.0	15	HEB200
			1.17	17.5	HE360A
			1.09	67.6	HD400x551
			1.12	77.1	HD400x634
			1.04	52.6	HD400x421
			1.10	72.30	HD400x592
			1.00	17	HEB240
		t_f>100mm	*No sections exist*		

*Heavy sections

The parametric study comprised 7332 numerical models, both for minor and major axis flexural buckling behaviour (3666 models for each mode). It includes several levels of slenderness, different steel grades, and two different levels of residual stresses, as given in Table 5.

Table 5. Parametric Study for Columns: Additional Parameters

Fabrication	$\overline{\lambda}$	Material and standard for f_y	Material imperfections
Rolled	0.5; 0.6; 0.7; 0.8 0.9; 1.0; 1.2; 1.4; 1.5 1.6; 1.8; 2.0; 2.5	**EN 10025:** S235 S355 S460	**h/b≤1.2:** $\frac{f_{y,235}}{f_y}$ **h/b>1.2:** $\frac{f_{y,235}}{f_y}$

For the evaluation of the flexural buckling resistance of steel columns, clause 6.3.1 in EC3-1-1 is considered to represent the theoretical result, r_{ti}, in the safety assessment procedure. The design procedure is summarized in Table 6 for simply supported members of length L, whereas the imperfection factors are summarized in Table 7 for the cross section shapes covered by the parametric study. The latter imperfection factors are considered from Table 6.1 and 6.2 of EC3-1-1 and from (Snijder et al. [19], [20]) for hot-rolled heavy cross-sections with t_f>100mm and h/b>1.2.

Table 6. Verification of Flexural Buckling of Columns, about Minor Axis (i=z) and Major Axis (i=y)

Parameter	Expression
N_{Rk}	$A \cdot f_y$ – class 1, 2 and 3 cross sections $A_{eff} \cdot f_y$ – class 4 cross sections
$N_{cr,z}$ **or** $N_{cr,y}$	$N_{cr,i} = \frac{\pi^2 EI_i}{L^2}$
$\overline{\lambda}_i$	$\overline{\lambda}_i = \sqrt{N_{Rk} / N_{CR,i}}$
α_i	See *Table 7*
η_i	$\alpha_i(\overline{\lambda}_i - 0.2)$
ϕ_i	$0.5 \times (1 + \eta_i + \overline{\lambda}_i^{\,2})$
χ_i	$1 / \left(\phi_i + \sqrt{\phi_i^2 - \overline{\lambda}_i^{\,2}}\right) \leq 1$
Verification	$N_{Ed} \leq N_{b,i,Rd} = \chi_i \times N_{Rk} / \gamma_{M1}$

Additionally, for $\overline{\lambda}_i \leq 0.2$ and $\frac{N_{Ed}}{N_{cr,i}} \leq 0.04$, flexural buckling about axis *i* does not need to be verified and only cross sectional checks apply ($\chi_i = 1$).

In Section 3.3 and Section 3.4 the partial factors γ_{M1} for several subsets are obtained respectively for minor and major axes flexural buckling. Selected input variables for safety assessment and subsets are described in the corresponding sub-sections.

Table 7. Imperfection Factors and Generalized Imperfection Limits for Flexural Buckling

Fabrication	Limits		Axis	Source: EC3-1-1 S235 S355	Source: EC3-1-1 S460	Source: (*Cajot et al. (2013)*) S235 S355	Source: (*Cajot et al. (2013)*) S460
Rolled	h/b>1,2	t_f≤40mm	y-y	0.21	0.13	-	-
			z-z	0.34	0.13		
		40mm<t_f≤100 mm	y-y	0.34	0.21	-	-
			z-z	0.49	0.21		
		t_f>100mm	y-y	-	-	0.34	0.21
			z-z			0.49	0.34
	h/b≤1,2	t_f≤100mm	y-y	0.34	0.21	-	-
			z-z	0.49	0.21		
		t_f>100mm	y-y	0.76	0.49	-	-
			z-z	0.76	0.49		

3.2 Parametric Study: Methodology

In the subsequent sections the results for minor and major axis flexural bucking of columns are detailed. The following main topics are discussed:

- Influence of the specification of the minimum yield stress according to EN 10025 and Eurocode 3;
- Influence of the magnitude of residual stresses used in the numerical analyses;
- Influence of imperfection factor α for steel grade S460;
- Validation of the buckling curves for heavy sections;
- Influence of the number of random variables;

Throughout the following paragraphs, charts and tables, the following methodology is adopted:

- The partial factors for different subsets are computed considering the *Annex D* procedure summarized in Section 2.2.
- The assessment is performed using normalized values of the partial factor. The normalization is done with respect to the average value of γ_{M1} obtained for *S235 and S355, t_f≤40mm, h/b>1.2* and *major axis of flexural buckling*, considering the yield stress f_y as the only random variable.
- Whenever a subset according to slenderness is analysed, the following division is adopted:
    - *Low* slenderness – normalized slenderness $\bar{\lambda} \in [0.5;0.8]$;
    - *Medium* slenderness– normalized slenderness $\bar{\lambda} \in (0.8;1.5]$;
    - *High* slenderness – normalized slenderness $\bar{\lambda} \in (1.5;2.5]$;
- For the first 4 topics listed above, only the variability of the yield stress is considered, as a relative assessment is sufficient to establish the influence of each parameter;
- In order to establish the influence of additional random variables, the following variables are considered: yield stress, geometrical dimensions of the cross-section and modulus of elasticity.

3.3 Results and Discussion – Minor axis Flexural Buckling

Hereby the results for minor axis flexural buckling are presented and discussed. Firstly, the reference cases for hot-rolled cross sections are analysed: the value of the yield stress both in r_e and r_t is considered according to EN 10025 and the level of the residual stresses is proportional to 0.3(0.5) x 235MPa for h/b>(≤1.2). Subsequently, the reference cases are analysed considering the value of the yield stress and r_t according to Table 3.1 of EC3-1-1, the experimental value r_e is computed according to the EN 10025, assuming it as the "reality". Finally, the reference cases are analysed considering the level of the residual stresses proportional to 0.3(0.5) x f_y for h/b>(≤1.2); More detailed results may be found in *Table B1* and *Table B2* of Annex B.

3.3.1 Results for hot-rolled cross sections

In the following all results are normalized (see Section 3.2). Partial factors are evaluated using the procedure from Annex D, as summarized in Section 2.2 and considering the variability of the yield stress only.

The parametric study was constructed aiming to cover all buckling curves for hot-rolled H and I sections and therefore, the sample includes members whose resistance is evaluated using different imperfection factors (α according to Table 7), different steel grades which are defined by different distributions, etc. Hence, further division into subsets is required, in order to avoid undesired bias of the results.
Since the reduction factor is mainly a function of slenderness, results should be assessed and organized by subsets of the slenderness ranges, as shown in Figure 5. The subsets are adopted according to Section 3.2: Low [0.5; 0.8]; Medium (0.8; 1.5]; and High (1.5; 2.5]. A larger partial factor is observed for S460 in *Figure 5* when compared to the other steel grades for all slenderness ranges. A possible explanation for this value is that the imperfection factors currently adopted for steel grade S460 may not be appropriate. This was independently confirmed by Lindner [21] and may thus require adjustment.

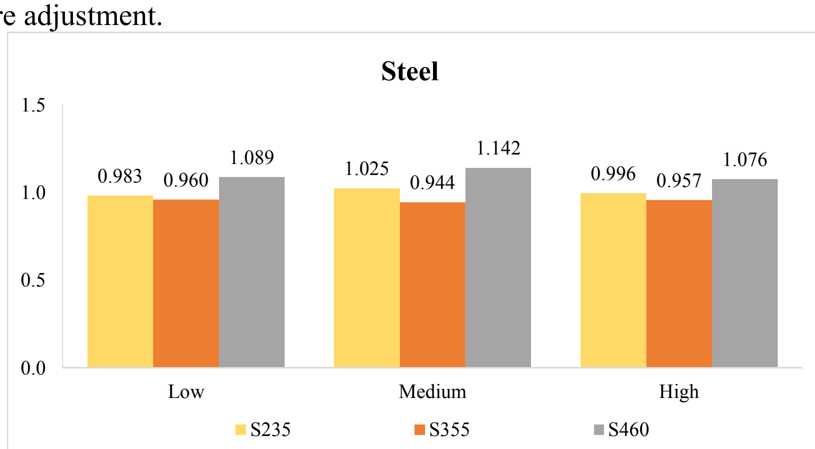


Figure 5. All Results Organized by Slenderness for Hot-rolled Cross Sections – f_y according to EN 10025 (Table B1, Annex B)

Figure 6 illustrates the results organized by the divisions given in Table 7, regardless of the slenderness range, thus allowing a direct comparison of the buckling curves in EC3-1-1. Firstly, it is clear that steel grade S355 leads to lower values of γ_{M1}. This is due to the relative amplitude of the residual stress with respect to the yield stress of the member when compared to S235 steel. Figure 6 again confirms that the imperfection factors for S460 may not be adequate, except for h/b>1.2, t_f>100mm because they were recently proposed and calibrated as this range was not available in the code (Snijder et al. [19], [20]). Finally, note that no cases with h/b≤1.2 and t_f>100mm are included in the parametric study since no sections with these characteristics were found in catalogues.

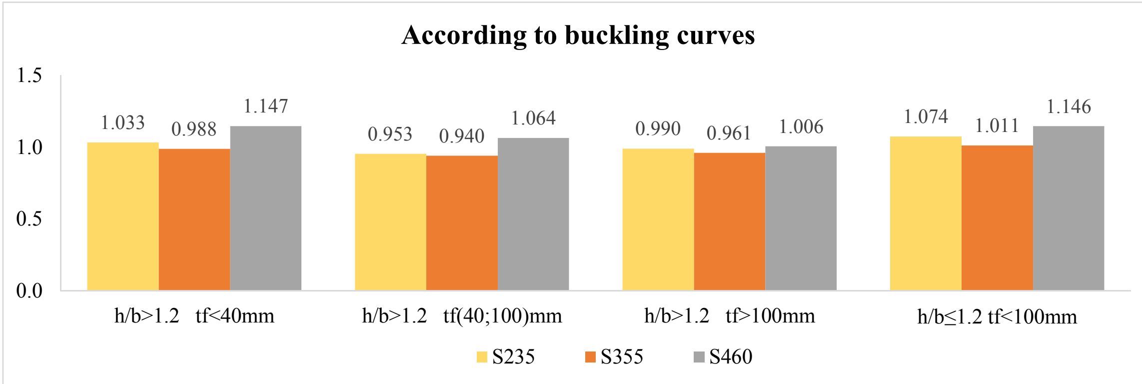


Figure 6. All Results organized by Buckling Curve Division for Hot-rolled Cross sections – f_y according to EN 10025 (Table B1, Annex B)

Additional subsets were considered for h/b≤1.2. The results are presented in Figure 7, the same trends being observed.

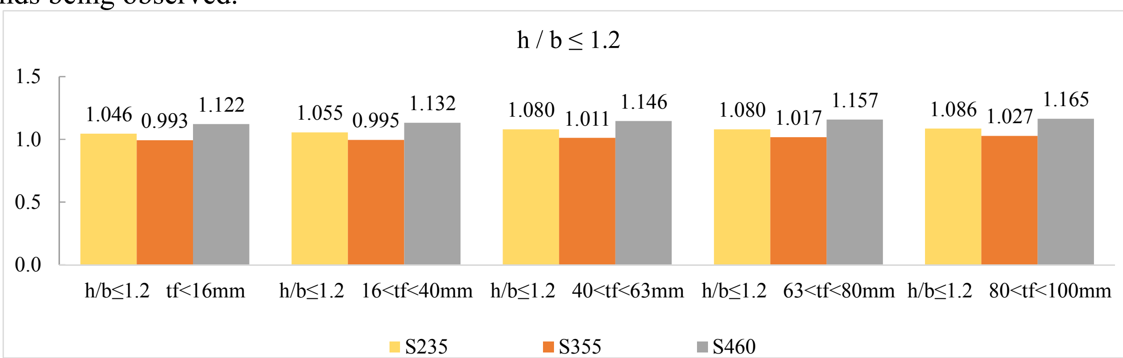


Figure 7. Subsets according to EN10025

3.3.2 Influence of the variation of the yield stress with thickness

The value of the yield stress in the theoretical value of the resistance r_t is now considered according to EC3-1-1, Table 3.1 and the "experimental" resistance r_e is computed considering the sub-divisions according to EN 10025, and presented in relative terms with respect to the results of EN 10025 (Figure 8). Results of Figure 8 are better interpreted together with Figure 3.

The second group for S235 and third group give the same values since the specifications of the yield stress in EN 10025 and EC3-1-1 are equal for the cross sections considered in the parametric study. On the other hand, for the first and fourth groups as well as second group for S355 and S460, differences are noted, for sections with thicknesses falling in the ranges (16; 40) and (63; 80), since the specifications in EC3-1-1 and EN 10025 are different in those ranges.

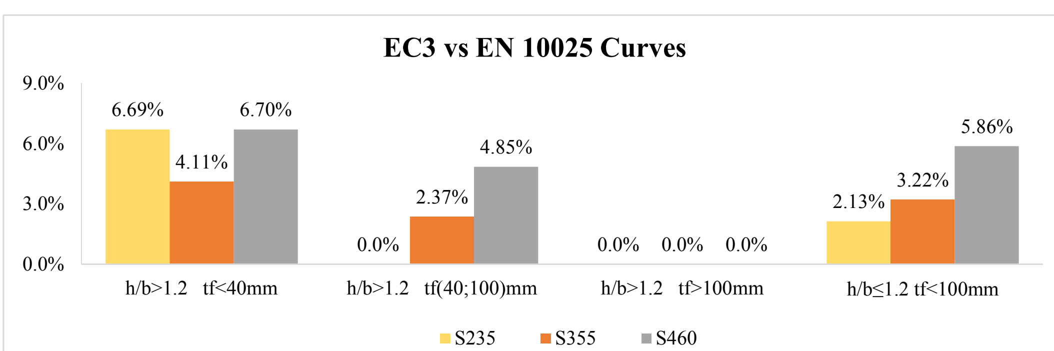


Figure 8. Percentage Difference for Normalized γ_{M1} between Yield Stress Calculated according to EC3-1-1 and EN 10025

The results in Figure 8 include thickness ranges that are different from the division according to EN 10025; hence, Figure 9 compares results between EN 10025 and EC3-1-1 for the intervals defined in EN 10025, highlighting maximum differences of about 8%.

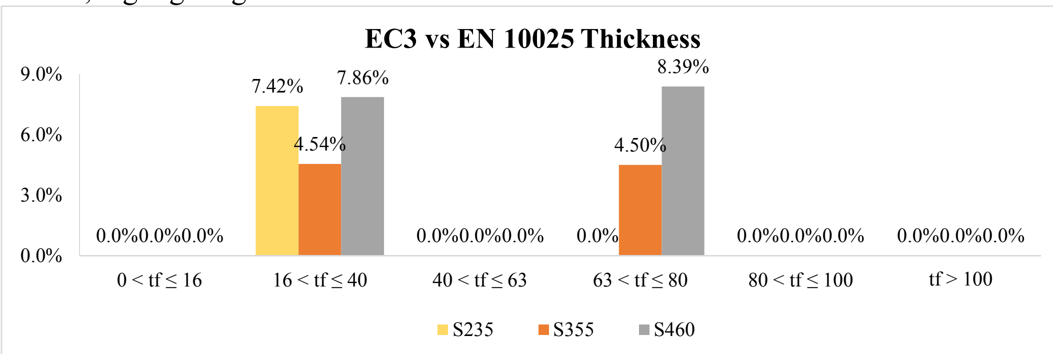


Figure 9. Percentage Difference for Normalized γ_{M1} between Yield Stress Calculated according to EC3-1-1 and EN 10025

3.3.3 Influence of the assumptions for the residual stress

Figure 10 and Figure 11 present relative results for the partial factor similarly to Figure 6, but assuming the conservative option that the level of the residual stresses is proportional to the yield stress 0.3(0.5) x f_y for h/b>(≤1.2). Since a higher level of the residual stresses is now considered (more conservative), the partial factor is expected to increase. This is observed both for steels S355 and S460, see Figure 10 and Figure 11 respectively. For steel grade S235, the analysis is not relevant.

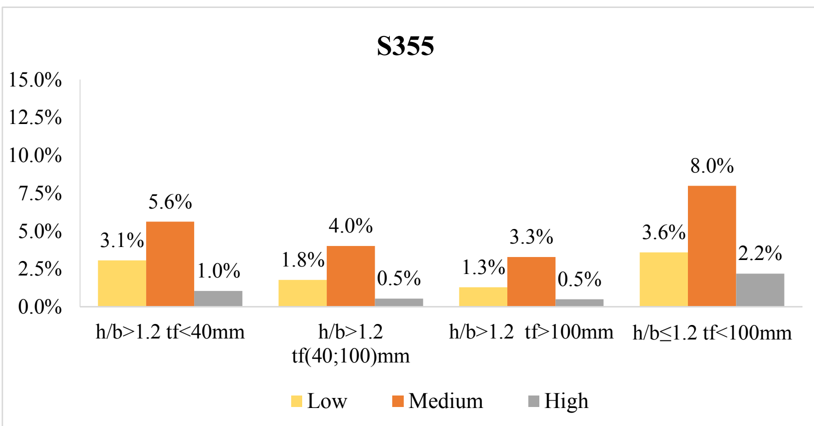


Figure 10. All Results organized by Buckling Curve and Slenderness Division for Hot-rolled Cross Sections and Steel Grade S355 – Residual Stress Proportional to the Actual Value of f_y (f_y according to EN 10025)

Figure 10 and Figure 11 represent the subsets by buckling curve, slenderness and steel grade. It is clearly seen that the influence of the residual stresses has higher impact in the medium slenderness range, as expected. Moreover, Figure 11 further shows that the adoption of residual stresses proportional to the yield stress 0.3(0.5) x f_y is too conservative.

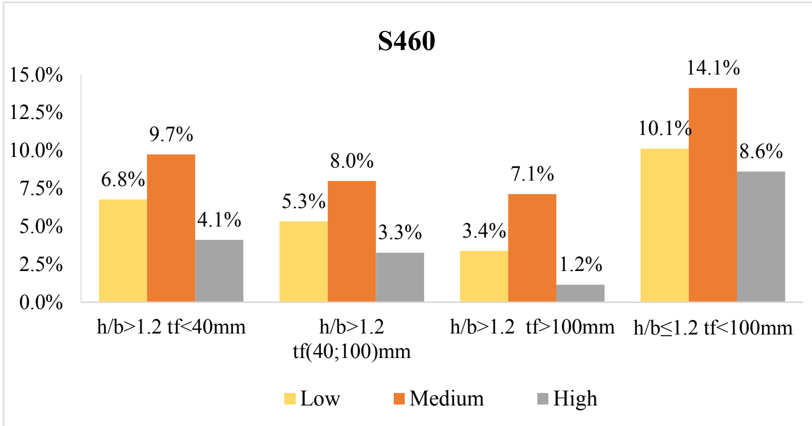


Figure 11. All Results organized by Buckling Curve and Slenderness Division for Hot-rolled Cross Sections and Steel Grade S460 – Residual Stress Proportional to the Actual Value of f_y (f_y according to EN 10025)

3.3.4 Evaluation of the partial factor considering new imperfection factors for S460

It was already seen that the results for steel grade S460 are significantly higher than those for the other steel grades. A possible improvement can be introduced by considering higher imperfection factors for minor axis flexural buckling as shown in Table 8 (values in bold).

Table 8. New Imperfection Factor for Steel Grade S460, Minor Axis

<table>
<tr><th rowspan="2">Fabrication</th><th rowspan="2" colspan="2">Limits</th><th rowspan="2">Axis</th><th colspan="2">EC3-1-1</th><th colspan="2">(Cajot et al. (2013))</th></tr>
<tr><th>S235
S355</th><th>S460</th><th>S235
S355</th><th>S460</th></tr>
<tr><td rowspan="4">Rolled</td><td rowspan="3">h/b>1,2</td><td>$t_f \leq 40$mm</td><td>y-y
z-z</td><td>0.21
0.34</td><td>0.13
0.21</td><td>-</td><td>-</td></tr>
<tr><td>40mm<$t_f \leq$100mm</td><td>y-y
z-z</td><td>0.34
0.49</td><td>0.21
0.34</td><td>-</td><td>-</td></tr>
<tr><td>t_f>100mm</td><td>y-y
z-z</td><td>-</td><td>-</td><td>0.34
0.49</td><td>0.21
0.34</td></tr>
<tr><td>h/b ≤1,</td><td>$t_f \leq 100$mm</td><td>y-y
z-z</td><td>0.34
0.49</td><td>0.21
0.34</td><td>-</td><td>-</td></tr>
</table>

*h/b≤1,2 and t_f>100mmn is not included in the table, because no cross-sections were found

Figure 12 and Figure 13, similarly to Figure 5 and Figure 6 show the results according to slenderness and buckling curve division, respectively. The improvement of using higher imperfection factors for steel grade S460 is clear.

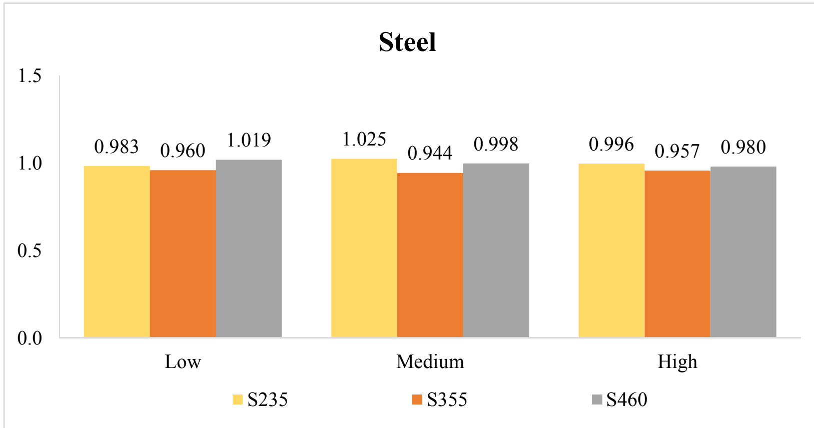


Figure 12. All Results organized by Slenderness for Hot-rolled Cross Sections – f_y according to EN 10025 (Table B1, Annex B)

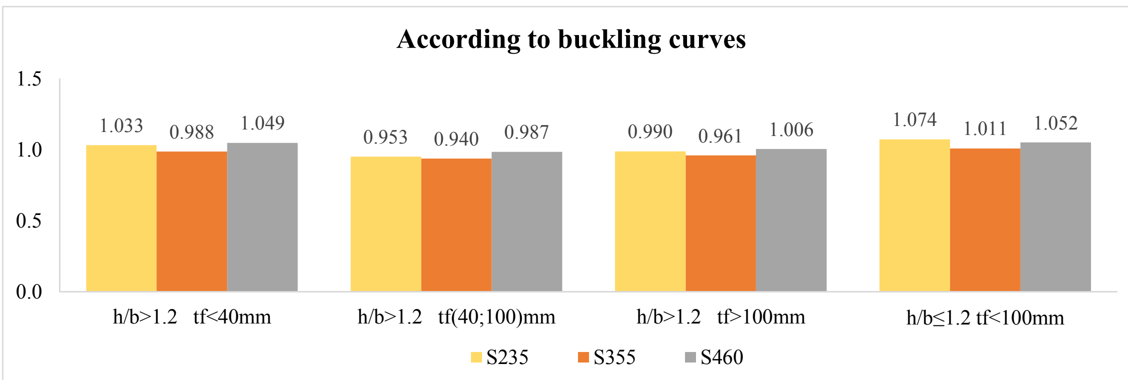


Figure 13. All Results organized by Buckling Curve Division for Hot-rolled Cross sections – f_y according to EN 10025 (Table B1, Annex B)

3.4 Results and Discussion – Major Axis Flexural Buckling

Identically to minor axis flexural buckling, the safety assessment is computed considering the Annex D procedure and variability of yield stress only, as stated in Section 3.2. The partial factors are also normalized with respect to the average value for *S235 and S355, t_f≤40mm, h/b>1.2* and *major axis of flexural buckling*. Firstly, the reference cases for hot-rolled cross sections are analysed: the yield stress both in r_e and r_t is considered according to EN 10025. Unlike minor axis flexural buckling, the relative values of the partial factor are more uniform for the different steel grades (Figure 14).

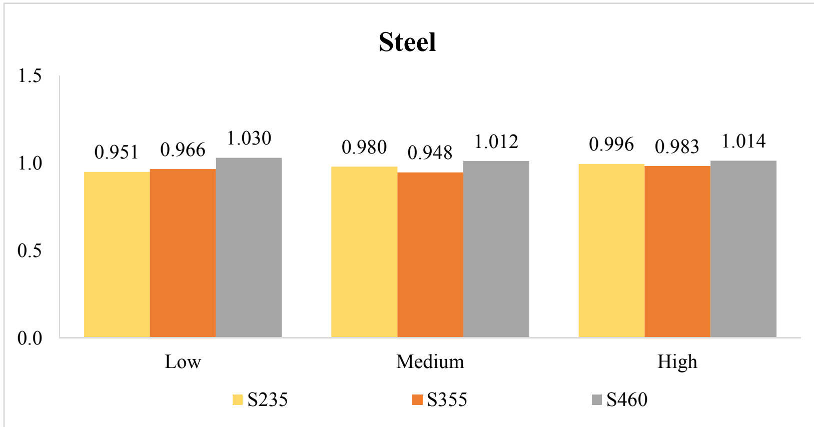


Figure 14. All Results organized by Slenderness for Hot-rolled Cross Sections – f_y according to EN 10025 (Table A1.1, Annex A1)

Similarly to Figure 6 for minor axis flexural buckling, Figure 15 illustrates the results organized according to the divisions presented in Table 7, regardless of the slenderness range, thus allowing a direct comparison of the buckling curves specified in EC3-1-1. All cases fall within an acceptable range of variation of the partial factor.

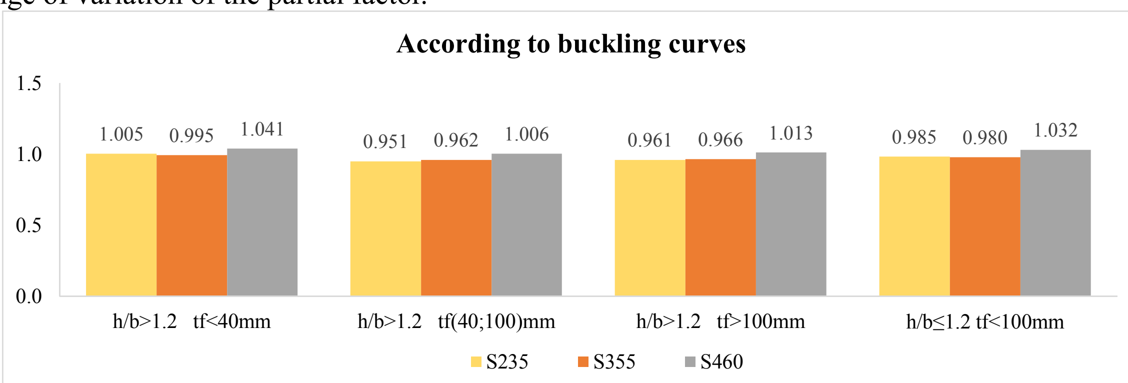


Figure 15. All Results organized by Buckling Curve Division for Hot-rolled Cross Sections – f_y according to EN 10025

Furthermore, when the influence of the variation of the yield stress with increasing flange thickness was analysed, similar conclusions were drawn. Identical results were found when the residual stresses were assumed proportional to the yield stress as in Section 3.3.3.

More detailed results are found in Table B1 and Table B2 in Annex B

3.5 Influence of the Number of Random Variables

In the previous sub-sections, only f_y was considered as a random variable. In reality, in the case on flexural buckling of columns, other basic variables also affect the behaviour of a column, such as the cross-section dimensions and the Young's modulus. It is noted that geometrical and material imperfections such as initial curvature and residual stresses are not included as basic random variables as they are included implicitly in the design model (Simões da Silva et al.) [22].

Hence, the following random variables are included in the analysis:

- Yield stress – f_y;
- Geometrical dimensions – b, h, t_w, t_f;
- Young's modulus – E;

The distributions of the basic variables are considered as previously presented in Section 2.3. The partial factor is obtained using the procedure proposed in Annex D as presented in Section 2.2 of this document. The influence of the number of basic variables is accounted as their number is gradually increased. The following cases are considered:

- **Annex D (fy)** – considers the yield stress as the only basic variable, the other parameters are assumed as deterministic quantities with no variability;
- **Annex D (fy+CS)** – considers the yield stress and the geometrical dimensions of the cross-section as random variables;
- **Annex D (fy+CS+E)** – considers the yield stress, the geometrical dimensions of the cross-section and the modulus of elasticity as random variables;

γ_{M1} is calculated for both major and minor axis flexural buckling for all three cases.

3.5.1 Minor axis flexural buckling

Figure 16 summarizes the normalized partial factors obtained for minor axis and considering the assumptions previously made. Firstly, as expected, higher values of γ_{M1} are obtained. Secondly, the rate of increase of γ_{M1} increases with increasing slenderness: 3.9%, 8.0% and 12.9% for low, medium and high slenderness, respectively, as Young's modulus and geometrical dimensions (moment of inertia) become more relevant in the medium and high slenderness ranges.

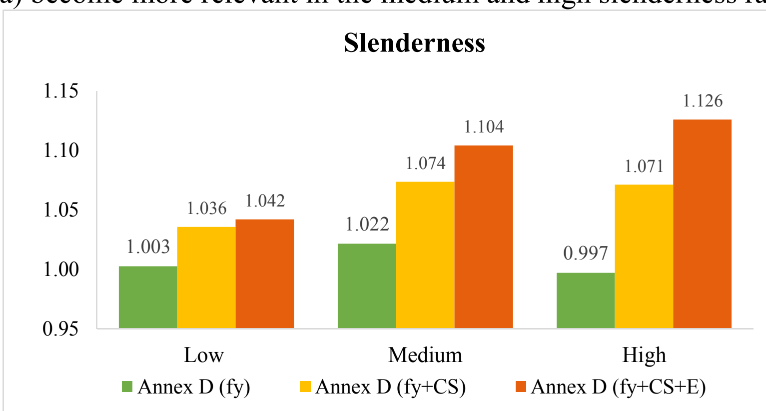


Figure 16. All Steels by Slenderness and using Different Number of Random Variables

Furthermore, results according to subsets of steel grade and slenderness are analysed in Figure 17 for Annex D (f_y + CS + E).

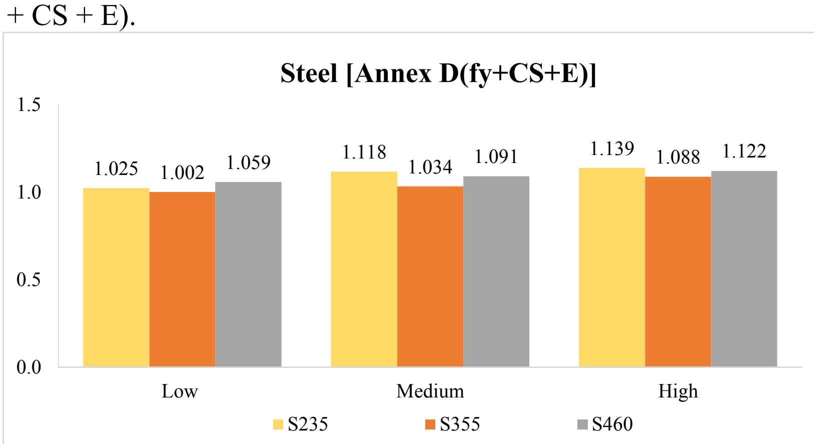


Figure 17. All Results organized by Slenderness and Steel Grade – using fy, Cross-section Dimensions and Modulus of Elasticity as Random Variables (Table B3, Annex B)

Similarly, results split according to buckling curve and steel grade are given in *Figure 18.* Detailed results for the intermediate case of Annex D (f_y + CS) are given in *Table B3* in Annex B.

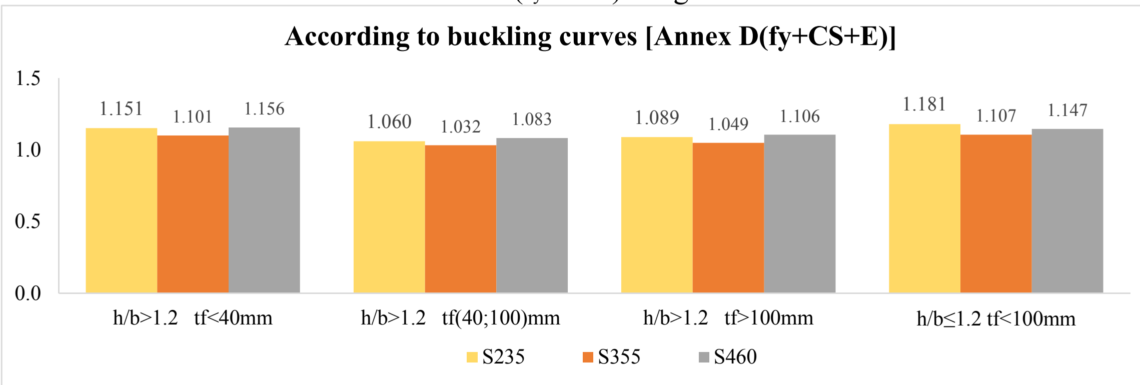


Figure 18. All Results organized by Buckling Curve for Hot-rolled Cross Sections – using fy, Cross-section Dimensions and Modulus of Elasticity as Random Variables (see also Table B3, Annex B)

Table B4 in Annex B summarizes the results divided according to steel grade, buckling curve and slenderness range.

While for the yield stress and geometrical dimensions there is certain knowledge about their distributions, it is not the case for the modulus of elasticity. It is a variable, which is very difficult to measure, and additional variability may be added simply because of the measurement method. Therefore, additional calculations were performed for a coefficient of variation of 3% for the modulus of elasticity (see also Table B3 and Table B4 in Annex B). Differences up to 4% can be found in the high slenderness range as illustrated on Figure 19 for subsets according to slenderness.

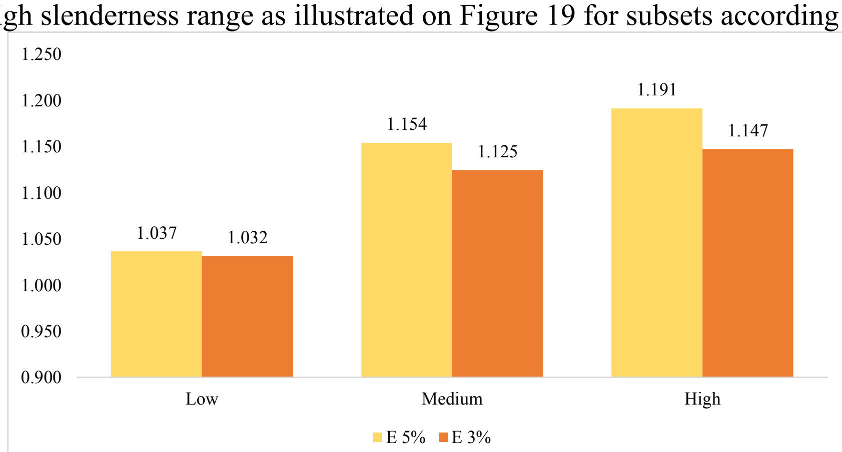


Figure 19. Difference between adopted Coefficients of Variation for E

3.5.2 Major axis flexural buckling

The same evaluation was performed for major axis of flexural buckling. The results are similar to the conclusions in the previous section, i.e. the presence of the modulus of elasticity leads to higher values for γ_{M1} (Figures 20 to 22). However, in general, the values of the γ_{M1} for major axis flexural buckling are lower than those for minor axis as presented in section 3.5.1 (3.1%, 7.1% and 11.4% for low, medium and high slenderness, respectively). Detailed results are given in *Table B3* and *Table B4* in Annex B.

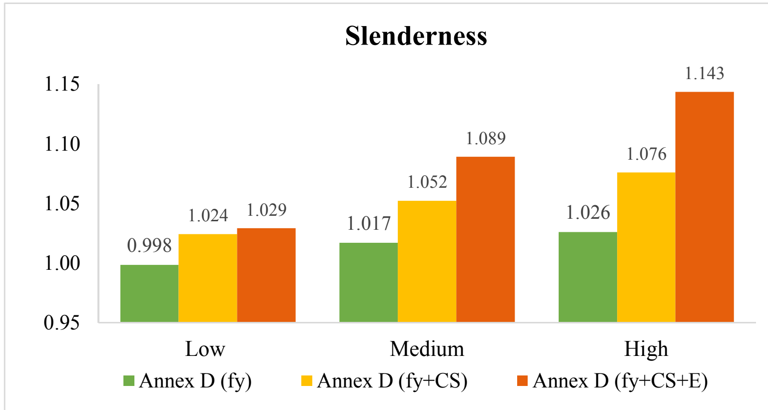


Figure 20. All Steels by Slenderness and using Different Number of Random Variables

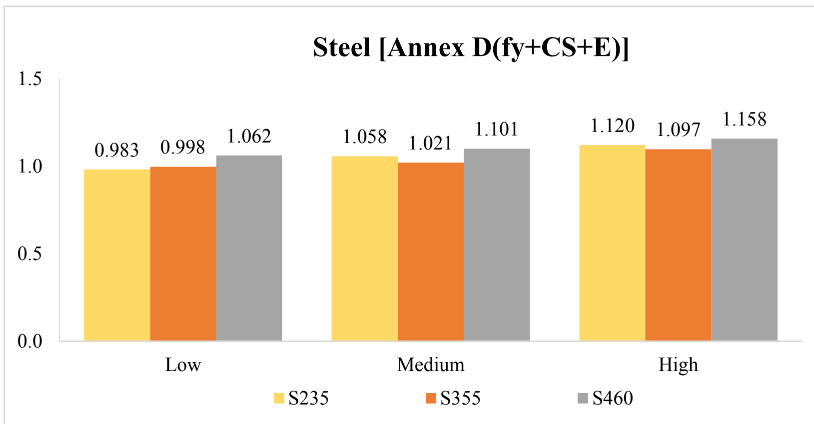


Figure 21. All Results organized by Slenderness and Steel Grade – using fy, Cross-section Dimensions and Modulus of Elasticity as Random Variables (Table A1.3, Annex A1)

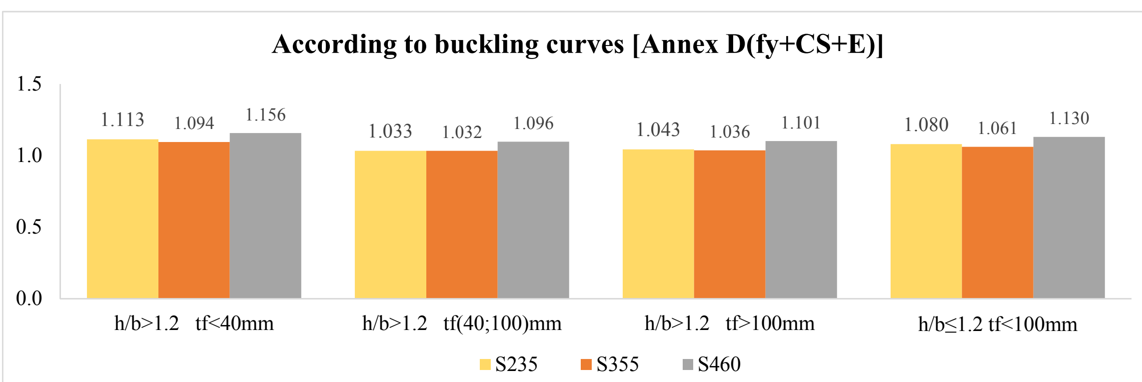


Figure 22. All Results organized by Buckling Curve for Hot-rolled Cross Sections – using fy, Cross-section Dimensions and Modulus of Elasticity as Random Variables

3.6 Summary

A parametric study to assess the safety of the code prescriptions of the flexural buckling of columns was presented. *Table 9* summarizes the relative values obtained per buckling curve, the results being presented as normalized factors with respect to a specific sub-group.

Table 9. Values of Normalized γ_{M1} for Flexural Buckling of Columns*

Fabrication	Limits		Axis	EC3-1-1 S235 S355	EC3-1-1 S460	[19], [20] S235 S355	[19], [20] S460
Rolled	h/b>1,2	$t_f \leq 40mm$	y-y z-z	1.000 1.011	1.041 **1.147**	-	-
		$40mm < t_f \leq 100mm$	y-y z-z	0.956 0.946	1.006 **1.064**	-	-
		$t_f > 100mm$	y-y z-z	-	-	0.963 0.975	1.013 1.006
	h/b≤1,2	$t_f \leq 100mm$	y-y z-z	0.983 1.042	1.032 **1.146**	-	-

* The relative value for the partial factor for S235 and S355 is determined as the mean value obtained for S235 and S355

**h/b≤1,2 and t_f>100mmn is not included in the table, because no cross-sections were found

The results were analysed in various subsets. The study revealed that the variation in the relative values of the partial factor is not high, except for steel grade S460 and minor axis of flexural buckling (the numbers in bold in *Table 9*). New imperfection factors were analysed and the results showed good agreement with the ones obtained for S235 and S355. *Table 10* summarizes the corresponding normalized partial factors.

Table 10. Values of Normalized γ_{M1} for Flexural Buckling of Columns*

Fabrication	Limits		Axis	EC3-1-1 S235 S355	EC3-1-1 S460	[19], [20] S235 S355	[19], [20] S460
Rolled	h/b>1,2	$t_f \leq 40mm$	y-y z-z	1.000 1.011	1.041 **1.049**	-	-
		$40mm < t_f \leq 100mm$	y-y z-z	0.956 0.946	1.006 **0.987**	-	-
		$t_f > 100mm$	y-y z-z	-	-	0.963 0.975	1.013 1.006
	h/b≤1,2	$t_f \leq 100mm$	y-y z-z	0.983 1.042	1.032 **1.052**	-	-

* The relative value for the partial factor for S235 and S355 is determined as the mean value obtained for S235 and S355

**h/b≤1,2 and t_f>100mmn is not included in the table, because no cross-sections were found

Finally based on the analysis performed in Section 3.5, the normalized values of the partial factor, considering different random variables, is summarized in *Table 11*. The increase γ_{M1} in varies from 7.9% to 11.4%.

Table 11. Values of Normalized γ_{M1} for Flexural Buckling of Columns*

Fabrication	**Limits**		**Axis**	**Annex D (fy)**		**Annex D (fy+CS)**		**Annex D (fy+CS+E)**	
				S235 S355	**S460**	**S235 S355**	**S460**	**S235 S355**	**S460**
Rolled	h/b>1,2	$t_f \leq 40$mm	y-y z-z	1.000 1.011	1.041 1.049	1.055 1.084	1.104 1.117	1.103 1.126	1.156 1.156
		40mm< $t_f \leq 100$mm	y-y z-z	0.956 0.946	1.006 0.987	0.994 1.009	1.052 1.047	1.033 1.046	1.096 1.083
		$t_f > 100$mm	y-y z-z	0.963 0.975	1.013 1.006	0.999 1.034	1.055 1.069	1.039 1.069	1.101 1.106
	h/b≤1,2	$t_f \leq 100$mm	y-y z-z	0.983 1.042	1.032 1.052	1.029 1.108	1.084 1.114	1.071 1.144	1.130 1.147

* The relative value for the partial factor for S235 and S355 is determined as the mean value obtained for S235 and S355

**h/b≤1,2 and t_f>100mmn is not included in the table, because no cross-sections were found

4. ASSESSMENT OF THE PARTIAL FACTOR

Section 3 analysed the design rules for the flexural buckling of columns in terms of the required value of the partial factors γ_{M1} to match the target probability of failure specified in EN 1990 [2]. The analysis was carried out by normalizing all values with respect to a reference case (major axis flexural buckling of I-section profiles in S235 to S355 with maximum flange thickness of 40 mm and h/b>1.2) because the quality of the design rules is very dependent on the scatter of the γ_{M1} values for the various subsets that may be considered. It was shown that the design rules provide consistent results across the various possible subsets, with small scatter on the value of γ_{M1}.

In this section it is proposed to discuss the adoption of a single global γ_{M1} for flexural buckling of columns that is in line with the failure probability in EN 1990 and incorporates all the viewpoints that support code drafting and the choice of safety factors [23],[9].

Table 12 summarizes the partial factors obtained for minor and major axis, now given as absolute values instead of normalized values. It is noted that all values are smaller, since the normalizing γ_{M1} for the reference case is equal to 0.979. The results are presented according to subsets of steel grade and buckling curve.

Table 12. Values of γ_{M1} obtained using Different Random Variables for Major and Minor Axes Flexural Buckling

Fabrication	**Limits**		**Axis**	**Annex D (fy)**		**Annex D (fy+CS)**		**Annex D (fy+CS+E)**	
				S235 S355	**S460**	**S235 S355**	**S460**	**S235 S355**	**S460**
Rolled	h/b>1,2	$t_f \le 40$mm	y-y	0.979	1.020	1.033	1.081	1.081	1.132
			z-z	0.990	1.028	1.062	1.094	1.103	1.133
		40mm<$t_f \le$100mm	y-y	0.937	0.985	0.974	1.030	1.011	1.074
			z-z	0.927	0.967	0.989	1.025	1.025	1.060
		t_f>100mm	y-y	0.944	0.992	0.979	1.034	1.018	1.078
			z-z	0.955	0.985	1.013	1.047	1.047	1.084
	h/b ≤1,2	$t_f \le 100$mm	y-y	0.962	1.011	1.008	1.062	1.049	1.107
			z-z	1.021	1.030	1.085	1.091	1.120	1.124

In Annex B, Table B5 and Table B6, a further division into subsets according to slenderness is performed in order to be able to compare the different slenderness ranges. Even though finer subsets into slenderness, steel grade and buckling curve are adopted, the partial factors higher than unity are mostly only observed when the Young's modulus is included.

Table 13. Average γ_{M1} for Minor and Major Axis Flexural Buckling, according to Buckling Curves and Slenderness

	Axis	**Annex D(fy)**	**Annex D(fy+CS)**	**Annex D(fy+CS+E)**
Mean value	y-y	0.943	0.995	1.040
	z-z	0.941	1.012	1.049
Coefficient of variation	y-y	4.28%	4.79%	6.31%
	z-z	4.33%	4.46%	5.54%

Table 13 summarizes the mean and standard deviation of γ_{M1} for the three different sets of random variable that were considered. It is concluded that depending on the random variables included in the analysis (just f_y; f_y and cross-section geometry; or f_y, cross-section geometry and modulus of elasticity E) the average value of γ_{M1} varies from 0.941 to 1.049 with the c.o.v varying from 4.3% to 6.3%. The mean value is lower than 1.05 for the more unfavourable case and the c.o.v. is low. Additionally, in general, the values of the γ_{M1} for major axis flexural buckling are similar to those for minor axis.

Recalling that the currently recommended value of γ_{M1} in Eurocode 3, part 1, is 1.0, and comparing with available data from the literature that led to the choice of $\gamma_{M1} = 1.0$, the results presented in this report for γ_{M1} are lower. In Muller (2003), a study on the flexural buckling resistance of hot-rolled sections was done and the corresponding partial factors were assessed, see Figure 23, corresponding to an average value of γ_{M1} for minor axis flexural buckling of 1.097 (cf. 0.941 as these results only considered the variability of f_y).

It is interesting to note that the observed trend (also in Muller (2003) [24]) of an increasing value of γ_{M1} in the intermediate slenderness range disappears when variability in cross-section and Young's modulus is included: in this case the value of γ_{M1} increases monotonically with slenderness. It is noted that the higher value of γ_{M1} for high slenderness is not so relevant because of practical reasons (practical range of column slenderness), as the parametric study included normalised slenderness ($\bar{\lambda}$) up to 2.5. It is therefore recommended to keep γ_{M1}=1.0 for columns.

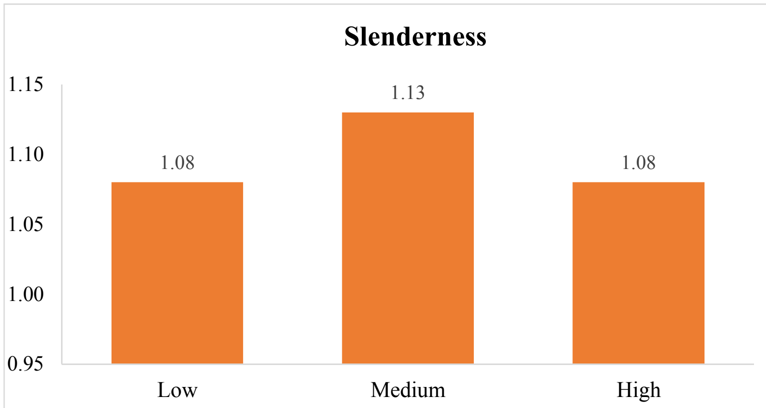


Figure 23. Results by Muller [24]

5. CONCLUSIONS

In this paper, the safety assessment of EC3-1-1 rules for flexural buckling of columns with hot-rolled I-shaped cross sections was performed and the partial factor was evaluated considering several subsets, including slenderness ranges, level of yield stress, EC3-1-1 buckling curves; flange thickness and respective variation of the yield stress; buckling axis.
The following conclusions were achieved:

- Influence of the adopted minimum yield stress using EN 10025 or Table 3.1 of Eurocode3;
  The level of the minimum yield stress was assessed for both minor and major axis of flexural buckling of hot-rolled columns. It was shown that in both cases the values proposed in EC3 can be up to 8% non-conservative, which itself is not a negligible difference.
- Influence of the level of the residual stresses adopted in the numerical models;
  The buckling curves are currently calibrated for level of residual stresses proportional to the yield stress f_y, which was shown to be conservative. When the results were divided into slenderness – in the medium slenderness range, where the residual stresses are actually important, high differences were obtained. These variations are relevant for the group of buckling curves S235-S420, with increasing difference as the steel grade increases; about 8% were noticed for S355.
- Imperfection factor for flexural-buckling of columns about minor axis which are made of steel grade S460;
  It was shown that the imperfection factor currently prescribed for flexural buckling of steel columns made of S460 about the minor axis is not adequate. Alternative analysis was performed in order to check if other curves are more suitable and the results are summarized in *Table 14*:

Table 14. New Imperfection Factor for Steel Grade S460, Minor Axis

Fabrication	**Limits**		**Axis**	**EC3-1-1**		[19], [20]	
				S235 S355	**S460**	**S235 S355**	**S460**
Rolled	h/b>1,2	$t_f \leq 40mm$	y-y z-z	0.21 0.34	0.13 **0.21**	-	-
	h/b>1,2	$40mm < t_f \leq 100mm$	y-y z-z	0.34 0.49	0.21 **0.34**	-	-
	h/b>1,2	$t_f > 100mm$	y-y z-z	-	-	0.34 0.49	0.21 0.34
	h/b≤1,2	$t_f \leq 100mm$	y-y z-z	0.34 0.49	0.21 **0.34**	-	-

- The recent study presented in [19], [20] about buckling curves for heavy sections was confirmed – the buckling curves chosen for sections with h/b>1,2 and t_f>100mm are found suitable;

Finally, the value of the partial factor was discussed. With the proposed modifications, it is recommended to keep γ_{M1}=1.0 for columns.

ACKNOWLEDGMENTS

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- the Portuguese Foundation for Science and Technology (FCT) under grant agreement SFRH/BD/99702/2014.

NOTATIONS

Latin upper case letters

A	is the gross cross sectional area;
A_{eff}	is the effective cross sectional area;
$N_{b,i,Rd}$	is the design buckling resistance about *i* axis of the compression member;
$N_{cr,i}$	is the critical compressive axial force for buckling about *i* axis;
N_{Ed}	is the design value of the axial force;
N_{Rk}	is the characteristic resistant axial force;
V_δ	Estimator for the coefficient of variation of the error term
V_X	Coefficient of variation
$\underline{X}_m$	Array of mean values of basic variables

Latin lower case letters

b	Correction factor
$g_{rt}(\underline{X})$	Resistance function used as a design model
$k_{d,n}$	Design fractile factor
n	Number of experiments or numerical results
r_d	Design value of the resistance
r_e	Experimental resistance value
r_n	Nominal value of the resistance
r_t	Theoretical resistance determined with $g_{rt}(\underline{X})$
s	Estimated value for the standard deviation σ
s_Δ	Estimated value for the standard deviation σ_Δ

Greek upper case letters

Δ	Logarithm of the error term δ
$\overline{\Delta}$	Estimated value for E(Δ)

Greek lower case letters

α_i	is the imperfection factor for flexural buckling about *i* axis;
δ	Error term
δ_i	Observed error term for test specimen i
η_i	is the generalized imperfection for flexural buckling about *i* axis;
$\bar{\lambda}_i$	is the non-dimensional slenderness for flexural buckling about *i* axis;
χ_i	is the reduction factor for flexural buckling about *i* axis.
σ	Standard deviation
σ_Δ^2	Variance of the term Δ

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Annex A – Statistical Distributions for the Yield Stress

The statistical distributions of the yield stress were chosen based on real experiments. The variation adopted for S235 and S355 is based on a previously performed study at the University of Coimbra [10]. It is summarized in Table A1:

Table A1. Results from

Steel Grade	tf (mm)	fy (MPa)	n	Mean (MPa)	St. Dev (MPa)	CoV	Minimum Value (MPa)	Quantile for the nominal value	Value for 99.9% quantile
S235	≤16	235	837	310.03	31.29	10.09%	239.2	99.17	*213.32*
			347	279.78	18.79	6.72%	239.2	99.14	*221.70*
			342	**297.30**	**17.11**	5.76%	**258**	**99.99**	***244.41***
S275 (n=3625)	≤16	275	1991	327.93	18.96	5.78%	-	99.74	269.35
	>16 ≤40	265	2342	306.28	15.63	5.10%	-	99.59	257.97
	>40 ≤63	255	71	299.23	14.07	4.70%	-	99.92	255.74
	>63 ≤80	245	21	290.38	9.68	3.33%	-	100.00	260.46
S355 (n=1979)	≤16	355	**733**	**419.38**	**20.25**	4.83%	**-**	**99.93**	**356.80**
	>16 ≤40	345	1146	395.82	15.16	3.83%	-	99.96	348.96
	>40 ≤63	335	77	380.51	10.01	2.63%	-	100.00	349.58
	>63 ≤80	325	23	361.87	10.25	2.83%	-	99.98	330.20

For S460, recent results from OPUS [15] were used. They are summarized in *Table A2.*

Table A2. Results from OPUS

Steel Grade	tf (mm)	fy (MPa)	n	Mean (MPa)	St. Dev (MPa)	CoV	Minimum Value (MPa)	Quantile for the nominal value	Value for 99.9% quantile
S460 (n=982)	<16	460	113	495.26	17.2	3.47%	not available	97.98	442.11
	>16 ≤40	**440**	**778**	**520.88**	**26.8**	**5.15%**		**99.87**	**438.06**
	>40 ≤63	430	91	486.4	43.5	8.94%		90.26	351.97

Annex B - Results

Table B1. All Results for Minor and Major Axis of Hot-rolled Sections, Normalized γ_{M1} with respect to the Average Value for S235/S355 $t_f \leq 40$mm, h/b>1.2 and Major Axis of Flexural Buckling (the Values in Green)

Sub-set		Minor axis					Major axis		
		n	EN10025	EN10025(S460)	EN10025 f_{yi}	EC3	EN10025	EN10025 f_{yi}	EC3
Total		1833	1.113	1.039	1.198	1.146	1.033	1.055	1.062
Low		564	1.056	1.003	-	-	0.993	-	-
Medium		705	1.127	1.022	-	-	1.012	-	-
High		564	1.075	0.997	-	-	1.021	-	-
S235		611	1.032	1.032	1.032	1.058	0.995	0.995	1.020
S355		611	0.988	0.988	1.033	1.010	0.993	1.001	1.013
S460		611	1.127	1.034	1.247	1.174	1.034	1.062	1.073
S235	Low	188	0.983	0.983	0.983	1.016	0.951	0.951	0.985
	Medium	235	1.025	1.025	1.025	1.045	0.980	0.980	0.999
	High	188	0.996	0.996	0.996	1.003	0.996	0.996	1.000
S355	Low	188	0.960	0.960	0.997	0.988	0.966	0.973	0.995
	Medium	235	0.944	0.944	1.008	0.960	0.948	0.970	0.960
	High	188	0.957	0.957	0.975	0.961	0.983	0.986	0.986
S460	Low	188	1.089	1.019	1.183	1.153	1.030	1.051	1.082
	Medium	235	1.142	0.998	1.275	1.175	1.012	1.057	1.035
	High	188	1.076	0.980	1.126	1.082	1.014	1.022	1.017
S235	h/b>1.2 t_f<40mm	169	1.033	1.033	1.033	1.102	1.005	1.005	1.077
	h/b>1.2t_f(40;100)mm	169	0.953	0.953	0.953	0.953	0.951	0.951	0.951
	h/b>1.2 t_f>100mm	104	0.990	0.990	0.990	0.990	0.961	0.961	0.961
	h/b≤1.2 t_f<100mm	169	1.074	1.074	1.074	1.097	0.985	0.985	1.006
S355	h/b>1.2 t_f<40mm	169	0.988	0.988	1.034	1.029	0.995	1.009	1.036
	h/b>1.2t_f(40;100)mm	169	0.940	0.940	0.962	0.962	0.962	0.965	0.982
	h/b>1.2 t_f>100mm	104	0.961	0.961	0.981	0.961	0.966	0.968	0.966
	h/b≤1.2 t_f<100mm	169	1.011	1.011	1.070	1.043	0.980	0.985	1.009
S460	h/b>1.2 t_f<40mm	169	1.147	1.049	1.270	1.223	1.041	1.084	1.120
	h/b>1.2t_f(40;100)mm	169	1.064	0.987	1.155	1.115	1.006	1.017	1.048
	h/b>1.2 t_f>100mm	104	1.006	1.006	1.064	1.006	1.013	1.027	1.013
	h/b≤1.2 t_f<100mm	169	1.146	1.052	1.332	1.213	1.032	1.074	1.090
S235	$0 < t_f \leq 16$	91	1.032	1.032	1.032	1.032	0.996	0.996	0.996
	$16 < t_f \leq 40$	182	1.043	1.043	1.043	1.120	1.026	1.026	1.099
	$40 < t_f \leq 63$	91	1.004	1.004	1.004	1.004	0.965	0.965	0.965
	$63 < t_f \leq 80$	117	1.042	1.042	1.042	1.042	0.977	0.977	0.977
	$80 < t_f \leq 100$	26	1.061	1.061	1.061	1.061	0.982	0.982	0.982
	$t_f > 100$	104	0.990	0.990	0.990	0.990	0.961	0.961	0.961
S355	$0 < t_f \leq 16$	91	0.995	0.995	1.044	0.995	0.998	1.002	0.998
	$16 < t_f \leq 40$	182	1.012	1.012	1.047	1.058	1.032	1.031	1.076
	$40 < t_f \leq 63$	91	0.955	0.955	1.000	0.955	0.964	0.972	0.964
	$63 < t_f \leq 80$	117	0.977	0.977	1.034	1.020	0.971	0.985	1.012
	$80 < t_f \leq 100$	26	0.993	0.993	1.051	0.993	0.972	0.986	0.972
	$t_f > 100$	104	0.961	0.961	0.981	0.961	0.966	0.968	0.966
S460	$0 < t_f \leq 16$	91	1.137	1.060	1.305	1.137	1.041	1.071	1.041
	$16 < t_f \leq 40$	182	1.152	1.066	1.287	1.243	1.067	1.091	1.148
	$40 < t_f \leq 63$	91	1.077	1.000	1.202	1.077	1.009	1.035	1.009
	$63 < t_f \leq 80$	117	1.105	1.000	1.250	1.197	1.016	1.053	1.095
	$80 < t_f \leq 100$	26	1.121	1.035	1.278	1.121	1.021	1.063	1.021
	$t_f > 100$	104	1.006	1.006	1.064	1.006	1.013	1.027	1.013

Notations:

- EN 10025 – minimum yield stress according to EN 10025
- EN 10025 (S460) - minimum yield stress according to EN 10025 and new bucking curves for S460;
- EN 10025 f_{yi} – yield stress proportional to f_y;
- EC3 - minimum yield stress according to EN 10025;

Table B2 All Results for Minor and Major Axis of Hot-rolled Sections, normalized γ_{M1} with the Average Value for S235/S355 t_f≤40mm, h/b>1.2 and Major Axis of Flexural Buckling (the Values in Green in Table B1)

Sub-set				Minor axis		Major axis	
			n	EN10025	EN10025 f_{yi}	EN10025	EN10025 f_{yi}
S355	h/b>1.2 t_f<40mm	Low	52	0.971	1.001	0.981	0.992
		Medium	65	0.950	1.007	0.949	0.974
		High	52	0.960	0.970	0.980	0.984
	h/b>1.2 t_f(40;100)mm	Low	52	0.925	0.942	0.949	0.950
		Medium	65	0.874	0.910	0.874	0.886
		High	52	0.917	0.922	0.942	0.946
	h/b>1.2 t_f>100mm	Low	32	0.937	0.949	0.949	0.951
		Medium	40	0.881	0.911	0.879	0.889
		High	32	0.912	0.917	0.944	0.945
	h/b≤1.2 t_f<100mm	Low	52	0.975	1.011	0.958	0.964
		Medium	65	0.940	1.022	0.906	0.943
		High	52	0.923	0.943	0.947	0.954
S460	h/b>1.2 t_f<40mm	Low	52	1.123	1.204	1.054	1.080
		Medium	65	1.147	1.271	1.022	1.074
		High	52	1.067	1.113	1.009	1.022
	h/b>1.2 t_f(40;100)mm	Low	52	1.061	1.121	1.014	1.026
		Medium	65	1.058	1.150	0.953	0.978
		High	52	1.012	1.047	0.983	0.987
	h/b>1.2 t_f>100mm	Low	32	1.000	1.035	1.019	1.031
		Medium	40	0.945	1.018	0.962	0.989
		High	32	0.954	0.965	0.983	0.986
	h/b≤1.2 t_f<100mm	Low	52	1.116	1.241	1.033	1.062
		Medium	65	1.126	1.312	0.987	1.067
		High	52	1.022	1.118	0.988	1.002

Notations:

- EN 10025 – minimum yield stress according to EN 10025
- EN 10025 f_{yi} – yield stress proportional to f_y;

Table B3. Normalized Partial Safety Factors, Minor and Major Axis Flexural Buckling, according to Buckling Curves

Sub-set		n	Minor axis Annex D (fy)	Minor axis Annex D (fy+CS)	Minor axis Annex D (fy+CS+$E_{5\%}$)	Minor axis Annex D (fy+CS+$E_{3\%}$)	Major axis Annex D (fy)	Major axis Annex D (fy+CS)	Major axis Annex D (fy+CS+E)
Total		1833	1.039	1.091	1.121	1.102	1.033	1.069	1.104
Low		564	1.003	1.036	1.042	1.038	0.998	1.024	1.029
Medium		705	1.022	1.074	1.104	1.085	1.017	1.052	1.089
High		564	0.997	1.071	1.126	1.092	1.026	1.076	1.143
S235		611	1.032	1.089	1.123	1.102	0.995	1.033	1.071
S355		611	0.988	1.041	1.072	1.053	0.993	1.028	1.062
S460		611	1.033	1.090	1.122	1.102	1.034	1.077	1.120
S235	Low	188	0.983	1.017	1.025	1.020	0.951	0.976	0.983
	Medium	235	1.025	1.083	1.118	1.096	0.980	1.018	1.058
	High	188	0.996	1.080	1.139	1.103	0.996	1.050	1.120
S355	Low	188	0.960	0.995	1.002	0.997	0.966	0.992	0.998
	Medium	235	0.944	1.001	1.034	1.013	0.948	0.984	1.021
	High	188	0.957	1.033	1.088	1.055	0.983	1.032	1.097
S460	Low	188	1.019	1.054	1.059	1.055	1.030	1.058	1.062
	Medium	235	0.998	1.056	1.091	1.070	1.012	1.055	1.101
	High	188	0.980	1.062	1.122	1.086	1.014	1.078	1.158
S235	h/b>1.2 t_f<40mm	169	1.033	1.108	1.151	1.125	1.005	1.062	1.113
	h/b>1.2 t_f(40;100)mm	169	0.953	1.021	1.060	1.037	0.951	0.992	1.033
	h/b>1.2 t_f>100mm	104	0.990	1.052	1.089	1.066	0.961	1.000	1.043
	h/b≤1.2 t_f<100mm	169	1.074	1.143	1.181	1.157	0.985	1.035	1.080
S355	h/b>1.2 t_f<40mm	169	0.988	1.061	1.101	1.077	0.995	1.047	1.094
	h/b>1.2 t_f(40;100)mm	169	0.940	0.997	1.032	1.011	0.962	0.997	1.032
	h/b>1.2 t_f>100mm	104	0.961	1.017	1.049	1.029	0.966	0.999	1.036
	h/b≤1.2 t_f<100mm	169	1.011	1.073	1.107	1.086	0.980	1.023	1.061
S460	h/b>1.2 t_f<40mm	169	1.049	1.117	1.156	1.132	1.041	1.104	1.156
	h/b>1.2 t_f(40;100)mm	169	0.987	1.047	1.083	1.061	1.006	1.052	1.096
	h/b>1.2 t_f>100mm	104	1.006	1.069	1.106	1.084	1.013	1.055	1.101
	h/b≤1.2 t_f<100mm	169	1.052	1.114	1.147	1.126	1.032	1.084	1.130

Table B4. Normalized Partial Safety Factors, Minor Axis Flexural Buckling, according to Buckling Curves and Slenderness

Sub-set			Minor axis					Major axis		
			n	Annex D (fy)	Annex D (fy+CS)	Annex D (fy+CS+E5%)	Annex D (fy+CS+E3%)	Annex D (fy)	Annex D (fy+CS)	Annex D (fy+CS+E)
S235	h/b>1.2 t_f<40mm	Low	52	0.990	1.029	1.037	1.032	0.972	1.001	1.007
		Medium	65	1.023	1.106	1.154	1.125	0.988	1.053	1.111
		High	52	0.991	1.118	1.191	1.147	0.993	1.087	1.175
	h/b>1.2 t_f(40;100)mm	Low	52	0.926	0.961	0.971	0.964	0.924	0.948	0.955
		Medium	65	0.931	1.005	1.049	1.022	0.894	0.947	0.996
		High	52	0.936	1.043	1.108	1.069	0.949	1.017	1.092
	h/b>1.2 t_f>100mm	Low	32	0.944	0.982	0.992	0.986	0.933	0.957	0.965
		Medium	40	0.950	1.022	1.063	1.038	0.909	0.958	1.010
		High	32	0.940	1.041	1.105	1.067	0.952	1.014	1.093
	h/b≤1.2 t_f<100mm	Low	52	1.011	1.058	1.068	1.061	0.949	0.982	0.990
		Medium	65	1.049	1.126	1.170	1.143	0.964	1.019	1.070
		High	52	0.985	1.101	1.169	1.128	0.970	1.046	1.125
S355	h/b>1.2 t_f<40mm	Low	52	0.971	1.010	1.018	1.013	0.981	1.012	1.017
		Medium	65	0.950	1.034	1.079	1.052	0.949	1.015	1.070
		High	52	0.960	1.074	1.144	1.102	0.980	1.064	1.149
	h/b>1.2 t_f(40;100)mm	Low	52	0.925	0.959	0.967	0.962	0.949	0.972	0.978
		Medium	65	0.874	0.946	0.987	0.962	0.874	0.922	0.967
		High	52	0.917	1.007	1.067	1.031	0.942	1.001	1.072
	h/b>1.2 t_f>100mm	Low	32	0.937	0.973	0.982	0.976	0.949	0.974	0.980
		Medium	40	0.881	0.952	0.991	0.967	0.879	0.925	0.972
		High	32	0.912	1.001	1.060	1.024	0.944	0.997	1.070
	h/b≤1.2 t_f<100mm	Low	52	0.975	1.020	1.029	1.023	0.958	0.991	0.998
		Medium	65	0.940	1.014	1.053	1.029	0.906	0.961	1.009
		High	52	0.923	1.023	1.085	1.048	0.947	1.012	1.085
S460	h/b>1.2 t_f<40mm	Low	52	1.041	1.079	1.083	1.080	1.054	1.084	1.087
		Medium	65	1.017	1.092	1.136	1.109	1.022	1.092	1.152
		High	52	0.982	1.080	1.149	1.107	1.009	1.109	1.202
	h/b>1.2 t_f(40;100)mm	Low	52	0.984	1.017	1.024	1.020	1.014	1.040	1.044
		Medium	65	0.934	1.004	1.045	1.020	0.953	1.011	1.063
		High	52	0.952	1.039	1.101	1.064	0.983	1.060	1.144
	h/b>1.2 t_f>100mm	Low	32	1.000	1.037	1.043	1.039	1.019	1.045	1.050
		Medium	40	0.945	1.021	1.063	1.037	0.962	1.013	1.067
		High	32	0.954	1.057	1.124	1.084	0.983	1.054	1.140
	h/b≤1.2 t_f<100mm	Low	52	1.028	1.072	1.079	1.075	1.033	1.068	1.073
		Medium	65	0.979	1.050	1.090	1.065	0.987	1.048	1.102
		High	52	0.944	1.037	1.099	1.062	0.988	1.070	1.155

Table B5. Partial Safety Factors, Minor Axis Flexural Buckling, according to Buckling Curves

Sub-set		Minor axis n	Minor axis Annex D (fy)	Minor axis Annex D (fy+CS)	Minor axis Annex D (fy+CS+E)	Major axis Annex D (fy)	Major axis Annex D (fy+CS)	Major axis Annex D (fy+CS+E)
S235	h/b>1.2 t_f<40mm	169	1.012	1.085	1.127	0.984	1.040	1.090
	h/b>1.2 t_f(40;100)mm	169	0.934	1.000	1.039	0.932	0.972	1.012
	h/b>1.2 t_f>100mm	104	0.969	1.031	1.067	0.942	0.979	1.022
	h/b≤1.2 t_f<100mm	169	1.052	1.119	1.157	0.965	1.014	1.058
S355	h/b>1.2 t_f<40mm	169	0.968	1.039	1.079	0.975	1.026	1.072
	h/b>1.2 t_f(40;100)mm	169	0.920	0.977	1.011	0.942	0.976	1.011
	h/b>1.2 t_f>100mm	104	0.941	0.996	1.028	0.946	0.978	1.015
	h/b≤1.2 t_f<100mm	169	0.990	1.051	1.084	0.960	1.002	1.040
S460	h/b>1.2 t_f<40mm	169	1.028	1.094	1.133	1.020	1.081	1.132
	h/b>1.2 t_f(40;100)mm	169	0.967	1.025	1.060	0.985	1.030	1.074
	h/b>1.2 t_f>100mm	104	0.985	1.047	1.084	0.992	1.034	1.078
	h/b≤1.2 t_f<100mm	169	1.030	1.091	1.124	1.011	1.062	1.107

Table B6. Partial Safety Factors, Minor Axis Flexural Buckling, according to Buckling Curves and Slenderness, c.o.v. of Modulus of Elasticity 5%

Sub-set			Minor axis n	Minor axis Annex D (fy)	Minor axis Annex D (fy+CS)	Minor axis Annex D (fy+CS+E)	Major axis Annex D (fy)	Major axis Annex D (fy+CS)	Major axis Annex D (fy+CS+E)
S235	h/b>1.2 t_f<40mm	Low	52	0.970	1.008	1.015	0.952	0.981	0.987
		Medium	65	1.002	1.083	1.131	0.967	1.031	1.088
		High	52	0.970	1.095	1.167	0.972	1.064	1.151
	h/b>1.2 t_f(40;100)mm	Low	52	0.907	0.941	0.951	0.905	0.929	0.936
		Medium	65	0.912	0.985	1.027	0.875	0.927	0.976
		High	52	0.917	1.021	1.086	0.930	0.996	1.070
	h/b>1.2 t_f>100mm	Low	32	0.925	0.962	0.972	0.913	0.938	0.945
		Medium	40	0.931	1.001	1.041	0.890	0.938	0.989
		High	32	0.921	1.020	1.083	0.932	0.993	1.070
	h/b≤1.2 t_f<100mm	Low	52	0.990	1.036	1.046	0.929	0.962	0.969
		Medium	65	1.027	1.103	1.146	0.944	0.998	1.048
		High	52	0.965	1.078	1.145	0.950	1.024	1.102
S355	h/b>1.2 t_f<40mm	Low	52	0.951	0.990	0.997	0.961	0.991	0.996
		Medium	65	0.930	1.013	1.057	0.930	0.994	1.048
		High	52	0.940	1.052	1.120	0.960	1.042	1.125
	h/b>1.2 t_f(40;100)mm	Low	52	0.906	0.939	0.947	0.929	0.952	0.958
		Medium	65	0.856	0.927	0.966	0.856	0.903	0.947
		High	52	0.898	0.987	1.045	0.923	0.981	1.050
	h/b>1.2 t_f>100mm	Low	32	0.917	0.953	0.962	0.930	0.954	0.960
		Medium	40	0.863	0.932	0.970	0.860	0.906	0.952
		High	32	0.894	0.980	1.038	0.924	0.977	1.048
	h/b≤1.2 t_f<100mm	Low	52	0.955	0.999	1.008	0.939	0.971	0.978
		Medium	65	0.921	0.993	1.032	0.888	0.942	0.988
		High	52	0.904	1.002	1.063	0.927	0.991	1.063
S460	h/b>1.2 t_f<40mm	Low	52	1.020	1.056	1.061	1.032	1.062	1.065
		Medium	65	0.996	1.069	1.113	1.001	1.069	1.128
		High	52	0.962	1.058	1.125	0.988	1.087	1.177
	h/b>1.2 t_f(40;100)mm	Low	52	0.964	0.996	1.003	0.993	1.018	1.022
		Medium	65	0.915	0.983	1.023	0.933	0.990	1.041
		High	52	0.933	1.018	1.079	0.962	1.038	1.120
	h/b>1.2 t_f>100mm	Low	32	0.980	1.016	1.022	0.998	1.024	1.028
		Medium	40	0.926	1.000	1.041	0.942	0.992	1.045
		High	32	0.934	1.035	1.101	0.962	1.032	1.116
	h/b≤1.2 t_f<100mm	Low	52	1.007	1.050	1.057	1.012	1.046	1.051
		Medium	65	0.959	1.029	1.067	0.967	1.027	1.079
		High	52	0.924	1.016	1.077	0.967	1.048	1.131