Safety assessment across modes driven by plasticity, stability and fracture

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Safety Assessment across Modes Driven by Plasticity, Stability and Fracture

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ABSTRACT

The European design rules for steel structures in EN1993 cover various failure modes that were developed using different methodologies in terms of accuracy and safety. Consequently, the safety level of these design rules is not homogeneous throughout their own field of application, as well as in comparison between different rules. Safety is regulated by partial factors for the various loads and resistances, respectively. EN 1990 - Annex D offers a procedure for the reliability assessment of resistance functions, based on a semi-probabilistic approach. However, its application is not straightforward in many cases concerning steel design rules and several additional assumptions are necessary to ensure that a target probability failure is achieved. Moreover, the design rules are calibrated using certain variability values for the relevant parameters, such as material properties, geometric properties and imperfections. It is therefore required to appropriately characterize the statistical distributions of these basic variables in order to comply with the safety assessment procedure. The present research work, carried out in the context of the European research project SAFEBRITILE, had as a main objective the harmonization of the reliability level of design rules for steel structures covering modes driven by ductility, stability and fracture.

This paper gives an overview of the reliability assessment of the Eurocode design rules carried out within the project for the studied failure modes; presents the adjustments in these design rules proposed whenever it was necessary; it also transmits the project recommendation on the statistical distributions of the relevant basic variables for steel structures, summarized in the "European database of steel properties" that was also developed within the project framework.

Keywords: safety assessment, ductility, stability, fracture

1 INTRODUCTION

The SAFEBRITILE project (Ref. N° RFSR-CT-2013-00023) intended to contribute towards the harmonization of the reliability level of design rules for steel structures covering modes driven by ductility, stability and fracture. There were some inconsistencies regarding the design rules in the various parts of Eurocode 3, which were of major focus throughout the project, i.e. discontinuity in the safety levels due to the lack of guidance on how to perform safety assessments and to calibrate new design rules, as well as the lack of information on the distribution of the relevant basic variables such as the steel properties. Therefore, in SAFEBRITILE, an objective and consistent safety assessment procedure for the various failure modes that are relevant for steel structures was developed. The developed procedure makes use of statistical distributions of the relevant basic variables, which were collected continuously during the project in a database of steel properties. This collection allowed for final recommendations on the statistical distributions of the relevant

parameters. The unified procedure, being able to cover failure modes driven by plasticity, stability and fracture, was used to reassess and amend several design rules within the project. The results of this project led to major competitiveness gains: (1) faster time cycle in the development of new design procedures able to cope with innovation; (2) increased reliability in the accuracy of new design models; (3) major savings in R&D costs by avoidance of major duplication of work.

In the following paragraphs, firstly the developed safety assessment procedure is presented, followed by the recommendations about statistical distributions relevant to steel structures, which were finally used to assess design rules for modes driven by plasticity, stability and fracture.

2 SAFETY ASSESSMENT PROCEDURE

One of the main objectives of the SAFE BRICTILE research project consisted in the improvement of existing and the development of new procedures for the safety and reliability assessment of design rules for steel structures. For this purpose, the existing procedures for the safety assessment of design rules verified by testing, given in EN 1990 Annex D [1], were reanalysed, adapted and expanded for the purposes and applications of the project. The main, semi-probabilistic reliability approach adopted in EN 1990 and illustrated in Fig. 1 was kept as a reference framework for the developed safety assessment procedure. This means that the basic premise of the semi-probabilistic approach of the Eurocodes, i.e. the assumption that the resistance and action-sided components of the total reliability level (expressed by the reliability index β) are allocated with a fixed coefficient, was maintained.

Fig. 1. Design resistance R_d as a function of the reliability index β

The main clarifications, changes and additions made in the safety assessment procedure developed in the project to the existing regulations in EN 1990, and - in particular - to the assessment procedure for γ_M in EN 1990 – Annex D, are summarized in the following [2]:

- i. The reliability differentiation in EN 1990, as it may be applied to steel structures, was explained; the developed recommendation clearly states that the reliability differentiation for steel structures is not typically conducted at the level of resistance factor differentiation (with the exception of fatigue design). Instead, a common target reliability level, expressed by a value of $\beta=3.8$, was applied for all safety verifications.
- ii. The need for and the scope of the use of experimental data was clarified. The developed guideline to the safety assessment procedure shows how to use the experimental data in the

- context of the calculation of the error propagation term $V_{r,t}$ and in the averaging of the calculated values of γ_M^* for any given data pool.
- iii. Methods for the reduction of the calculated model error parameters b and V_δ , i.e. the division of the experimental data into subsets and the method of tail approximation, were explained in the developed guideline.
 - iv. “Acceptance levels” for deviations between the calculated values of γ_M^* and existing (or desired) “target” values of safety factors γ_{Mx} (γ_{M0} , γ_{M1} , $\gamma_{M2}\dots$) were given and justified on both the basis of non-exceedance probabilities and past practice and experience, see Fig. 2. As the plot in the figure shows, the values of “permissible” $\gamma_M^* = \gamma_{M,target}$ associated with certain failure probability multipliers are strongly dependent on the scatter of the resistance, specifically on V_r . A small scatter of the resistance function implies that using an “incorrect”, and too low, value of $\gamma_M^* = \gamma_{M,target}$ may lead to much higher than desired probabilities of non-exceedance of the strength used in design. High scatter – while usually not desirable – has the effect of making a precise choice of γ_M less relevant in terms of failure or non-exceedance probability.
 - v. The use of numerical experiments, in lieu or in addition to physical tests in the laboratory, was explained in detail in the guideline, and requirements and limits for their application were developed.
 - vi. The possibility of performing more advanced methods of reliability assessment in compliance with EN 1990, as well as the most important methods of this type, were described. These include Monte Carlo and response surface methods.
 - vii. The type and content of documentation reports needed for an independent evaluation (for example by code committees) were explained.
 - viii. Finally, a complete worked example was prepared for the guidelines, which illustrates the main aspects of the proposed procedure.

Fig. 2. Impact of the ratio $\gamma_M^* / \gamma_{M,target}$ on the implied notional failure probability as a function of the coefficient of variation V_r and recommended values of f_a (i.e. the acceptance limit for $\gamma_M^* / \gamma_{M,target}$)

3 STATISTICAL DISTRIBUTIONS OF BASIC VARIABLES

In the scope of the project a “European database of steel properties” was developed. Its aim was to collect the necessary data in order to obtain knowledge about the statistical distributions for the relevant basic variables such as steel properties. The database is available on the website of ECCS Fig. 3 (<http://www.steelconstruct.com/>). It was built to store material properties of steel and filler material (from tensile tests); geometrical properties (standard measurements of the various cross-section dimensions), and global geometrical imperfections and material imperfections (residual

stresses). During the project large amounts of data were collected by the project partners; then, the collected data were analysed and further combined with existing data from previous statistical characterizations.

Fig. 3 Website of ECCS with “European database of steel properties” (<http://www.steelconstruct.com/>)

This global collection allowed the project partners to recommend normalized distributions for the material and geometrical properties in *Table 2* and *Table 3*, respectively.

Table 1. Recommended distributions for steel properties

Steel	$f_{y,nom}$	$f_{y,m}/f_{y,nom}$	c.o.v.	$f_{u,nom}$	$f_{u,m}/f_{u,nom}$	c.o.v.
S235	235	1.25	5.5%	360	1.2	4.5%
S355	355	1.2	5%	470	1.125	3.25%
S460	460	1.15	4.5%	540	1.1	3.25%

Table 2. Distributions for geometrical dimensions of hot-rolled profiles

Dimension	b	h	t_w	t_f
mean/nom	1	1	1	0.975
c.o.v	0.9%	0.9%	2.5%	2.5%

These distributions are considered representative of the current steel production, and sufficient to guarantee the partial factors adopted in EC3-1-1 ($\gamma_{M0} = \gamma_{M1} = 1.0$). It is acknowledged that, today, due to technical advancement and well-defined quality control processes, some European steel producers can achieve better statistical distributions for the material and geometrical properties.

4 MODES DRIVEN BY PLASTICITY

4.1 Design rules considered

In this part of the project, design rules for the following failure modes were considered: net cross-section, moment-shear interaction of I-shaped sections, moment-normal force (M-N) interaction of I-shaped sections and M-N interaction of rectangular hollow sections (RHS). Except for the net cross-section failure mode, all other failure modes have design rules using the yield stress. The design rule for the net cross-section failure mode uses the tensile strength. However, it turned out that substantial yielding occurs when plates fail on their net cross-section [3]. So all considered cases have failure modes driven by plasticity.

For net cross-section resistance and for moment-shear interaction of I-shaped sections, the reader is referred to separate papers in this conference, [3] and [4] respectively. In this paper, moment-normal force interaction of I-shaped sections and moment-normal force interaction of RHS are treated briefly.

4.2 M-N interaction of I-shaped sections

The current design rules for M-N interaction of I-shaped sections bent around the strong axis are given in cl. 6.2.9.1 (4) and (5) of EN 1993-1-1 [5] and are not repeated here. It concerns the equations

(6.33), (6.34) and (6.36) in EN 1993-1-1. In these equations, also the normal force resistance $N_{pl,Rd}$ and the strong axis bending moment resistance $M_{pl,y,Rd}$ contain partial factors γ_{M0} . A statistical assessment of these design rules was performed against a database of numerical test results generated using material non-linear finite element analyses. The result of the statistical assessment was that $\gamma_{M0} = 1.00$ is sufficient for steel grades S235 and S355 but that $\gamma_{M0} = 1.05$ would be required for steel grade S460 when following the acceptance criterion mentioned in Fig. 2. For that reason, a new modified design rule was proposed by replacing equation (6.36) of EN 1993-1-1 by Eqs. (1-3):

$$M_{N,y,Rd} = M_{pl,y,Rd} - \frac{N_{Ed}^2}{4t_w f_y} \quad \text{for } N_{Ed} \leq N_{pl,w,Rd} = h_w t_w f_y \quad (1)$$

$$M_{N,y,Rd} = \frac{M_T}{N_{pl,Rd} - N_{pl,w,Rd}} (N_{pl,Rd} - N_{Ed}) \quad \text{for } N_{Ed} > N_{pl,w,Rd} \quad (2)$$

$$\text{with } M_T = M_{pl,y,Rd} - \frac{N_{pl,w,Rd}}{4t_w f_y} \quad (3)$$

Symbols used are in line with those in EN 1993-1-1 or explained in the equations themselves. For this modified design rule, $\gamma_{M0} = 1.00$ satisfies the acceptance criterion of Fig. 2. The modified design rule is better than the current one, which can also be concluded from Fig. 4, where r_e is the numerical test result and r_t the theoretical resistance obtained with the appropriate design rule. In an ideal situation, $r_e/r_t = 1$. The same is illustrated in Fig. 5a.

Fig. 4. Performance of design rules for M-N interaction of I-shaped sections bent around the strong axis: a) HEA240; b) IPE330

4.3 M-N interaction of RHS

The current design rule for M-N interaction of RHS bent around the strong axis is given in cl. 6.2.9.1 (5) of EN 1993-1-1 and is not repeated here. It concerns equation (6.39) in EN 1993-1-1. In this equation, the normal force resistance $N_{pl,Rd}$ and the strong axis bending moment resistance $M_{pl,y,Rd}$ contain partial factors γ_{M0} . A statistical assessment of these design rules was performed against a database of numerical test results generated using material non-linear finite element analyses. The result of the statistical assessment was that $\gamma_{M0} = 1.00$ is sufficient for steel grade S235, steel grade S355 needs $\gamma_{M0} = 1.04$ and that $\gamma_{M0} = 1.13$ is required for steel grade S460. For that reason, a new modified design rule was proposed [6], replacing equation (6.39) of EN 1993-1-1 by Eqs. (4, 5):

$$M_{N,y,Rd} = M_{pl,y,Rd} - \frac{N_{Ed}^2}{8t_w f_y} \quad \text{for } N_{Ed} \leq N_{pl,w,Rd} = 2h_w t_w f_y \quad (4)$$

$$M_{N,y,Rd} = \left(\frac{h}{2} - \frac{N_{pl,Rd} - N_{Ed}}{4b f_y} \right) (N_{pl,Rd} - N_{Ed}) \quad \text{for } N_{Ed} > N_{pl,w,Rd} \quad (5)$$

Symbols used are in line with those in EN 1993-1-1 or explained in the equations themselves. For this modified design rule, $\gamma_{M0} = 1.00$ is sufficient for steel grades S235, S355 and S460. Fig. 5b shows

a comparison of the current and the modified design rule with the exact solution, showing that the modified design rule is indeed better than the current design rule for M-N interaction of RHS bent around the strong axis.

Fig. 5. Comparison of the current and the modified design rule with the exact solution for strong axis M-N interaction: a) HEA240; b) RHS 200/100/10

5 MODES DRIVEN BY STABILITY

5.1 Overview

In this section, the modes driven by stability are tackled. The aim of this part of the project was to contribute towards the revision of EN 1993-1-1 [5], by achieving transparent, simple and straightforward unified stability verification procedures. For that, focus was firstly given to the application of the safety assessment procedure to the existing stability design rules in EN 1993-1-1 thus assessing the current safety level of uniform members in compression (cl. 6.3.1), bending (cl. 6.3.2), bending and compression (cl. 6.3.3) and the general method for lateral and lateral-torsional buckling of structural components (cl. 6.3.4). Based on the results obtained the stability verifications were extended to non-uniform members.

Table 3. New imperfection factors for steel grade S460, minor axis

Fabrication	Limits		Axis	EC3-1-1		[7]	
				S235 S355	S460 0	S235 S355	S460
Rolled	$h/b > 1.2$	$t_f \leq 40\text{mm}$	y-y z-z	0.21 0.34	0.13 0.21	-	-
		$40\text{mm} < t_f \leq 100\text{mm}$	y-y z-z	0.34 0.49	0.21 0.34	-	-
		$t_f > 100\text{mm}$	y-y z-z	-	-	0.34 0.49	0.21 0.34
	$h/b \leq 1.2$	$t_f \leq 100\text{mm}$	y-y z-z	0.34 0.49	0.21 0.34	-	-

* $h/b \leq 1.2$ and $t_f > 100\text{mm}$ is not included in the table, because no hot-rolled cross-sections were found

5.2 Safety assessment of stability design rules

The safety assessment was performed on the basis of the procedure described in Section 2. The assessment covered various hot-rolled cross-sectional shapes, loading conditions and buckling modes: flexural buckling about minor and major axes and lateral-torsional buckling. The assessment revealed some inconsistencies in the buckling curves for flexural buckling about minor axis and steel grade S460 [7]. As a result, a modification of these curves was proposed and new imperfection factors are given in Table 3. Regarding lateral-torsional buckling, the following design methods were assessed, namely the General and Special cases from EC3 and the new proposal from Taras and Greiner (2010) [8]. The latter method was found to give the most accurate estimations for the cases

analysed. This assessment, incorporating the changes indicated in *Tab. 3*, shows that $\gamma_{M1} = 1.0$ is satisfactory.

5.3 Stability design of non-uniform members

EN 1993-1-1 does not provide specific rules for non-uniform members. In SAFEBRICITILE, stability design rules were developed that address the specific difficulties in the verification of non-uniform members, such as critical location, choice of buckling curve, and cross-section properties.

The Eurocode 3 design rules for columns and beams make use of the Ayrton-Perry equations. In [9] it was found practical to have a similar format for the verification of web tapered columns and beams. Within the project, the Ayrton-Perry format for columns and beams was extended to the verification of web-tapered beam-columns loaded with major axis bending moment and axial force by adaptation of the interaction formulae in EN 1993-1-1 (Eqs. (6, 7)), by adjusting the interaction factors k_{yy} and k_{zy} as given in *Table 4*. The method was validated with a large number of numerical simulations, covering different cross-sectional shapes, bending moment distributions, several ratios of bending moment and axial force, and tapering [11].

$$\frac{N_{Ed}(x_{c,N}^I)}{\chi_y(x_{c,N}^I) N_{Rk}(x_{c,N}^I) / \gamma_{M1}} + k_{yy} \frac{M_{y,Ed}(x_{c,M}^I)}{\chi_{LT}(x_{c,M}^I) M_{y,Rk}(x_{c,M}^I) / \gamma_{M1}} \leq 1.0 \quad (6)$$

$$\frac{N_{Ed}(x_{c,N}^I)}{\chi_z(x_{c,N}^I) N_{Rk}(x_{c,N}^I) / \gamma_{M1}} + k_{zy} \frac{M_{y,Ed}(x_{c,M}^I)}{\chi_{LT}(x_{c,M}^I) M_{y,Rk}(x_{c,M}^I) / \gamma_{M1}} \leq 1.0 \quad (7)$$

Table 4. Interaction factors for web-tapered beam-columns according to Method 2

k_{yy}	$C_{my} \times \left(1 + \underbrace{\left(\bar{\lambda}_y(x_{c,N}^{II}) - 0.2 \right)}_{\leq 0.8 \geq 0} \frac{N_{Ed}(x_{c,N}^I)}{\chi_y(x_{c,N}^I) N_{Rk}(x_{c,N}^I) / \gamma_{M1}} \right)$
k_{zy}	$1 - \frac{\underbrace{0.1 \bar{\lambda}_z(x_{c,N}^{II})}_{\leq 0.1}}{C_{m,LT} - 0.25} \frac{N_{Ed}(x_{c,N}^I)}{\chi_z(x_{c,N}^I) N_{Rk}(x_{c,N}^I) / \gamma_{M1}} \text{ for } \bar{\lambda}_z(x_{c,N}^{II}) < 0.4 : 0.6 + \bar{\lambda}_z(x_{c,N}^{II}) \leq 1 - \frac{0.1 \bar{\lambda}_z(x_{c,N}^{II})}{C_{m,LT} - 0.25} \frac{N_{Ed}(x_{c,N}^I)}{\chi_z(x_{c,N}^I) N_{Rk}(x_{c,N}^I) / \gamma_{M1}}$

Fig. 6. Application of the method

Additionally, as nowadays the daily design process makes extensive use of numerical models based on linear elastic analyses complemented by linear eigenvalue calculations, a method was developed for columns and beams based on discretized cross sectional verifications, which is able to cope with members with various geometries and loading. The method requires first a linear buckling analysis for each member, which can be done using the free software *LTbeamN*, for example (<https://www.cticm.com/>). Then, the critical buckling mode is amplified with the imperfection factors

originally deducted for uniform members. Consistency with the existing design rules and mechanical background is maintained. An example of the application procedure is given in *Fig. 6*.

For both cases, the statistical assessment according to Section 2 shows a similar level of safety when compared to members with uniform cross-section.

6 MODES DRIVEN BY FRACTURE

One of the main objectives is to develop recommendations for the statistical evaluation of failure modes driven by fracture, based on experimental testing for design, exemplified for fillet welded connections. A second main objective is to give more detailed design rules for welded dual-steel connections composed of two different steel grades, Mild Carbon Steel and High Strength Steel and a range of different filler metals.

Fig. 7. Mixed connections between Mild Carbon Steel and High Strength Steel

Especially for the particular situation of joining high strength steel and mild carbon steel elements used in dual-steel structural configurations, the present design rules, e.g. in EN 1993-1-8 [12], are in many cases inadequate, as they always require that the weld metal should at least match the higher steel grade (overmatching) of base metal in terms of strength and toughness, but allow only the lower strength to be taken in to account for the design.

In fact, recent rules and safety margins according to EN 1993-1-8 were developed traditionally for standard steels and then transferred to high strength steels. The existing data, which have formed the basis for the Eurocode, clearly draw a dependency on the material strength f_u and not on f_y as some more traditional design rules assume. This is confirmed by more recent investigations on fillet welded connections of high strength steels [12], showing a possible improvement for S460 of the existing design rules in EN 1993-1-8, but the necessity of reduction for S690 [13]. Investigations focused on

automatically welded specimens of steel S690 indicate a much clearer picture on the influences. It became clear that the filler metal played an eminent role, so that [12] suggests a modified design resistance function in dependence on both the filler metal and the base metal strength. For the modified function it was necessary to determine new correlation coefficients of β_w depending on the strength of the filler metal, see *Eq. (8)* for the design resistance according to [12]:

$$f_{wd} = f_u / (\beta_w \gamma_{M2}) \quad (8)$$

Whereas the earlier research was on fillet welded connections of equal base metals on both sides, the SAFEBRIC TILE project investigated mixed dual-steel connections and systematically collected relevant data to feed the “European database of steel properties”. A number of 54 different specimens was tested and statistically evaluated in various lots in dependence on the different parameters such as type of welding (manual, automatically) and shape of weld. The aim was to review the applicability of the new design rules by [12] for mixed connections, but also to develop rules for an appropriate safety assessment procedure where fracture and tensile material strength f_u play the important role.

The evaluation of the load carrying capacity of mixed connections showed a clear influence of the filler metal. Comparing the experimental results of shear stresses and the design resistance according to EN 1993-1-8 taking into account the weaker base material, a clear safety margin can be observed. Therefore, the necessity is given for a new evaluation on the design rules taking into account mainly the filler metal in addition to a smaller contribution of the base material.

To determine correlation coefficients β_w for mixed connections, the safety assessment procedure according to EN 1990 Annex D [1] for design assisted by testing was used, see Section 2. The results of the safety assessment procedure were compared using the correlation coefficient β_w of [12] applied to mixed connections. For the determination of the correlation coefficients β_w , the tested connections were divided in different evaluation groups depending on the strength of the filler metal. On the basis

of discussion in the respective working group, the correlation coefficient β_w was determined for mixed connection for each strength of filler metal. An example is shown in *Table 5* for the results of connections with different base metals combined with the strength of filler metal G46. The comparison between [12] and the results of mixed connections showed a good agreement of the correlation coefficient β_w for each strength of filler metal. The applicability of the correlation coefficients β_w by [12] could thus be confirmed.

Table 5. Results of statistical evaluation for connections with the strength of filler metal $f_y = 460 \text{ N/mm}^2$

Research project	Number of test specimen	Safety assessment procedure according to Annex D				
		b	V_δ	V_r	γ_M^*	$\beta_{w,FM}^k$
		[-]	[%]	[-]	[-]	[-]
Rasche [12]		1,33	7,48	0,159	1,08	0,86
SAFEBRICITILE		1,32	7,82	0,153	1,06	0,85

Fig. 8 shows the characteristic shear resistance depending on the nominal tensile strength of the minimal base metal strength in the connection. The comparison between the design resistance for mixed connections determined by the new function of [12] (continuous black line, *Fig. 8*) and the design resistance determined with the slightly better correlation coefficient for mixed connection (continuous red line *Fig. 8*) shows a good agreement, too. And also a constant safety level between the experimental load carrying and the design resistance for mixed connections could be achieved.

Fig. 8. Comparison of exp. shear stress and design resistance (EN 1993-1-8 [12]) for mixed connections with strength of filler metal G46

7 CONCLUSIONS

The main achievements of the SAFEBRICITILE project were described in this paper and are in line with the project objectives. Firstly, a detailed and fully tested procedure for the safety assessment of design rules was developed that fully linked each design rule to the target probability of failure of the complete structure, in the framework of EN 1990, Annex D. This detailed procedure is now progressively adopted by researchers around Europe, allowing consistency across research and code developments with respect to their underlying safety. Specific but crucial application aspects such as ensuring homogeneity of safety levels across the range of application of design rules (sub-sets) and acceptance levels for the unavoidable scatter of safety across subsets were addressed, as well as the issue of quality control (documentation) and ease of use (through the supply of detailed examples). Secondly, the project collected a database of steel properties based on recent tests. Given that many steel properties are nominal properties, the project proposed statistical distributions that correspond to modern steel production in Europe for yield and ultimate stresses and geometric dimensions that are in line with the recommended partial factors γ_{M0} , γ_{M1} and γ_{M2} of Eurocode 3, part 1-1 in terms of satisfying the target failure probabilities. Finally, the project carried out a comprehensive safety assessment of most design rules in EN 1993-1-1 concerning cross sectional resistance and buckling

resistance of members (see sections 4 and 5) and the resistance of fillet welds in EN 1993-1-8 (section 6) that, in some cases, led to the adjustment of some rules and showed that the recommended partial factors of EN 1993-1-1 were acceptable. Additionally, for non-uniform members and mixed fillet welded connections, extended but compatible rules were proposed that present a similar level of safety.

The outcomes of the SAFEBRICKTILE project should provide objective and transparent guidance for the ongoing revision of Eurocode 3 and its future maintenance, while contributing to the competitiveness of the European steel sector.

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