Harmonization of the safety level of design rules for steel structures : from ductile to brittle failure modes

HARMONIZATION OF THE SAFETY LEVEL OF DESIGN RULES FOR STEEL STRUCTURES - FROM DUCTILE TO BRITTLE FAILURE MODES

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KEYWORDS: Safety Assessment, Eurocode 3, Ductile to Brittle Failure, Buckling

ABSTRACT

The design rules for steel structures in Eurocode 3 [1] cover a number of different failure modes and were developed considering a variety of methodologies and goals in terms of accuracy and safety. Accordingly, these design rules do not display a homogeneous level of safety (assessed in accordance with EN 1990 [2]) throughout their own, respective field of application and in comparison with other rules in the same code. Research work by the authors, carried out in the context of the European research project SAFEBRICTILE, aims at developing harmonized procedures for the assessment and development of design rules for steel structures for design verifications that cover *i.* ductile (e.g. cross-sectional resistances), *ii.* semi-ductile (e.g. buckling of members of low to intermediate slenderness) and *iii.* "structurally brittle" failure modes (e.g. local failure of welds). These modes are driven by plasticity, instability and fracture, respectively. The work plan of the research project is subdivided accordingly, see *Fig. 1.*

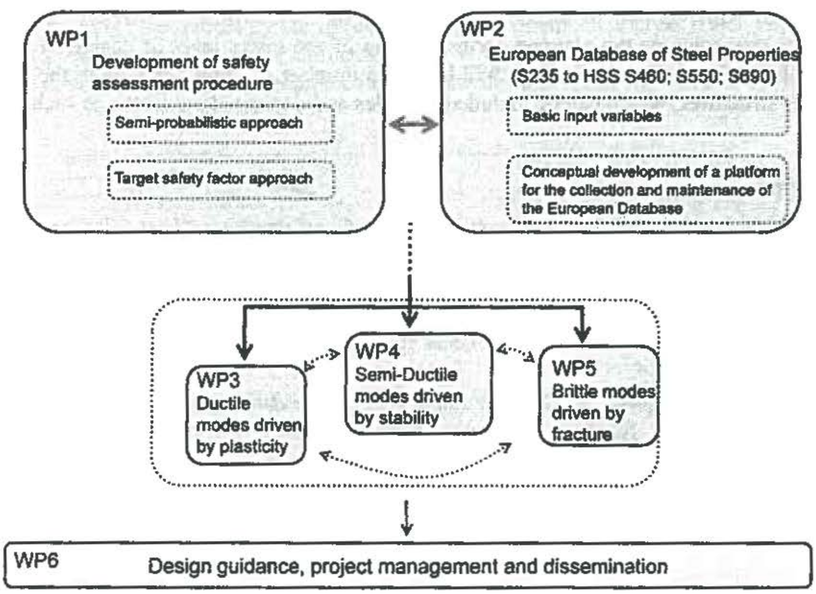

Fig. 1 Work plan of the RFCS-funded research project SAFEBRICTILE

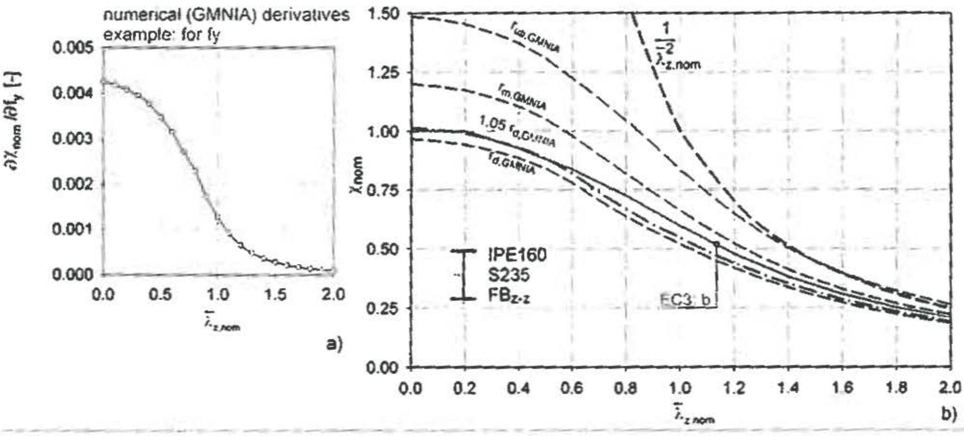

Fig. 2 Constant Reliability Curve (CRC) vs. current EC3 buckling curve for an IPE 160 section – S235 – $FB_{z\text{-}z}$

This paper gives an overview of the current safety level, describes the work plan and objectives of SAFEBRICTILE, and outlines a method that may be used to efficiently determine "target" values of reliability for any type of failure mode; see *Fig. 2* for an application example of the latter. Thereby, the focus is put on ductile and semi-ductile failure modes, as present in typical short- to medium-length structural members (tension bars, beams, columns, beam-columns). Numerical simulations of the (realistic) strength of steel structures are systematically used in the proposed procedure in order to reduce the need for both physical testing and computation runs to a minimum. At the same time, the procedures make extensive use of a new European Steel Products Database [3], which is also being developed in the project.

CONCLUSIONS

The procedure for the determination of "Constant Reliability Curves" with target values of safety describes in this paper is part of the developments of the SAFEBRICTILE research project and represents one step towards the planned harmonization of the safety level of design rules for steel structures in EC3. The project's findings will lead to a number of improvements in the design and safety of steel structures, which can be included in codes and dedicated publications such as [4].

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INTRODUCTION

The design rules for steel structures in Eurocode 3 [1] cover a number of different failure modes and were developed considering a variety of methodologies and goals in terms of accuracy and safety. Accordingly, these design rules do not display a homogeneous level of safety throughout their respective field of application, as well as in comparison with other rules in the same code. Research work by the authors, carried out in the context of the European research project SAFEBRICTILE, aims at developing harmonized procedures for the assessment and development of design rules for steel structures for design verifications that cover *i.* ductile (e.g. cross-sectional resistances), *ii.* semi-ductile (e.g. buckling of members of low to intermediate slenderness) and *iii.* "structurally brittle" failure modes (e.g. local failure of welds). These modes are driven by plasticity, instability and fracture, respectively. This paper gives an overview of the current safety level, describes the work plan and objectives of SAFEBRICTILE and outlines a method that may be used to efficiently determine "target" values of reliability for any type of failure mode. Thereby, the focus is put on ductile and semi-ductile failure modes, as present in typical short- to medium-length structural members (tension bars, beams, columns, beam-columns).

1 RELIABILITY MANAGEMENT AND SAFETY ASSESSMENT IN EN 1990

The reliability level of the Eurocode design rules is managed in EN 1990 [2] by means of the reliability index β (see EN 1990- Annex B and C). This index represents the main tool used in the code to obtain a reliability differentiation with respect to a set of "Reliability Classes" (RCs 1 to 3), which in turn are linked with "Consequence Classes" (CCs). It can be interpreted as the "distance" - in multiples of the standard deviation of the reliability function Z - between the "central" zone of reliability (where, simply stated, the mean values of resistance and action are located) and the design point (where low design values of resistance are compared with high values of action. Different values of β are given in EN 1990. For most structures, a reference period of 50 years and a reliability class of RC2 is assumed, leading to the value of **β=3.8** given in the code. In order to obtain a material- and location-independent codification of structural design rules, the *semi*-probabilistic design concept of the Eurocode further adds the following convention: *the total reliability index β is allocated in constant, material- and location-independent fractions to the resistance and the load side with the factors α_R=0.8 and α_E=0.7*, using the root of the sum of squares ($\sqrt{\alpha_R{}^2+\alpha_E{}^2}\approx 1$). This creates a clear separation between loads and resistances, and allows for a standardized evaluation of e.g. test data to determine the appropriate value of γ_M for the resistance side. For the purposes of this paper, this implies that the desired "distance" - in terms of standard deviations - between the mean and design strength values for a given failure mode shall be **$\alpha_R \cdot \beta = 0.8 \cdot 3.8 = 3.04$.** This value can be used for the determination of "target" values of the design resistance, as will be shown in this paper. EN 1990, Annex D contains the "standard" procedure for the assessment of a given design rule, termed "resistance function" in the code, (i.e. a mathematical

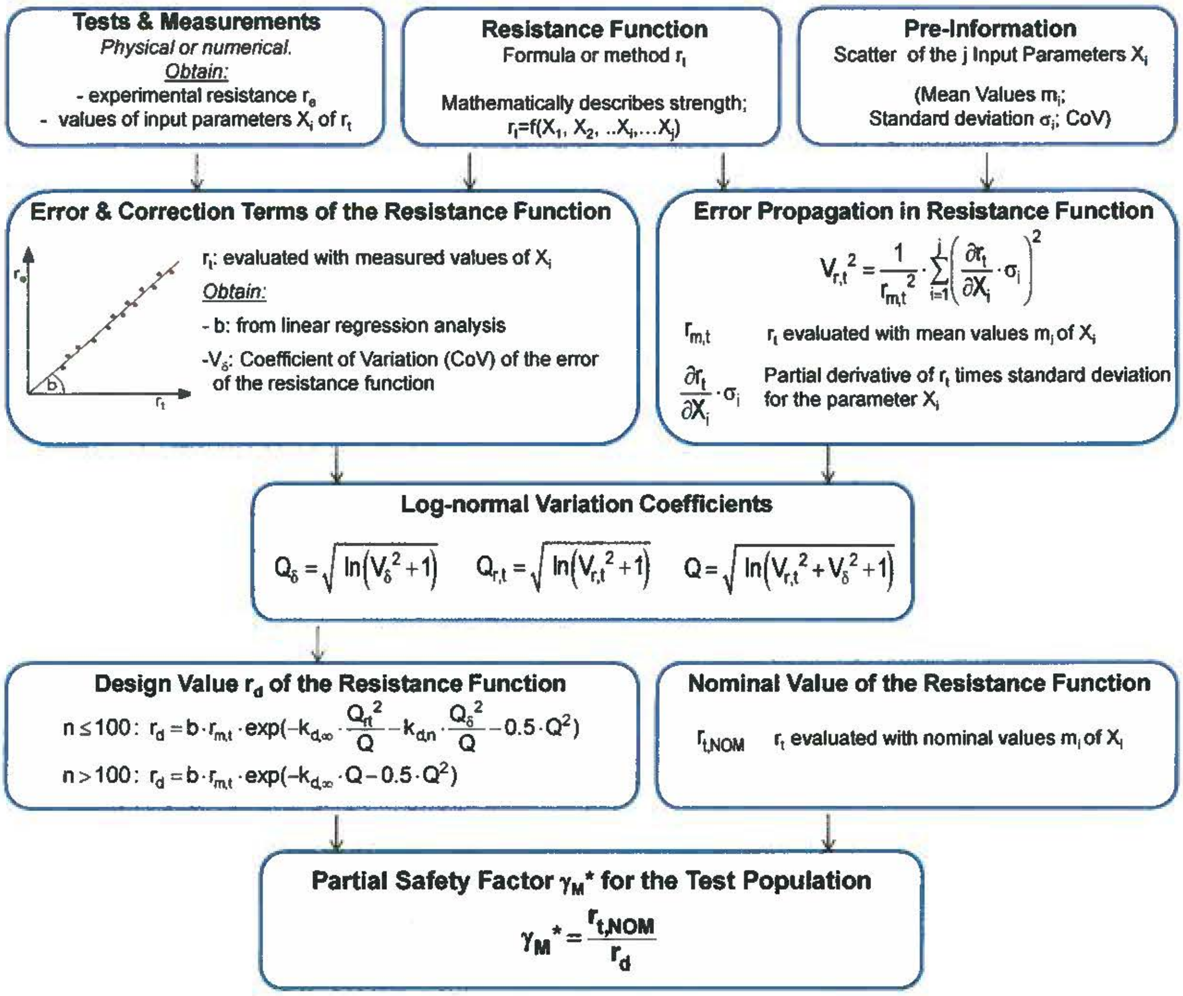

Fig. 1 Flow-chart of the statistical evaluation procedure in EN 1990- Annex D

representation of the strength of an element for a certain failure mode), as used in the past for the calculation of the "appropriate" values of the partial resistance factors γ_M. The method was developed specifically for the evaluation of physical test results and is summarized in *Fig. 1* in form of a flow chart. The main steps to be taken are *i.* The calculation of the coefficient of variation (CoV) associated with the "error" of the resistance function, V_δ; *ii.* The evaluation of the error propagation term for the resistance function, $V_{r,t}$; *iii.* The calculation of the design resistance values r_d, which depend on the sample size "n" (the value of $k_{d,n}$ converges to $k_{d,\infty}=\alpha_R\cdot\beta=3{,}04$ for an infinite sample size); *iv.* The "exact" necessary safety factor γ_M* (this notation is used to contrast it with the "codified" factors γ_{M0}, γ_{M1}, etc.) is determined as the ratio between the "nominal/characteristic" strength and the design strength. As stated in the introduction, the evaluation – using the above methodology - of the design rules for steel structures included in the current version of EN 1993 leads to an inconsistent, non-homogenous level of safety for different failure modes. *Fig. 2* shows the results of such evaluations of physical tests for members of different length/slenderness, loaded in compression (a) and bending (b). When instability becomes the dominant failure mode, flexural or lateral-torsional (LT) buckling becomes dominant, respectively. The results match evaluations previously performed by *Müller* [3]. The relatively large differences between the resulting "exact" safety factors, for cases covering one individual failure mode but determined for different member lengths, are evident. The representation shows a certain transition of the safety level occurring between the ductile (low slenderness) and semi-ductile (intermediate slenderness) failure modes, even though there is continuity between the EC3 nominal/characteristic resistance functions for these basic modes. An even larger divergence of the safety levels can be observed for design rules where this continuity is not present, e.g. at the transition between cross-sectional classes.

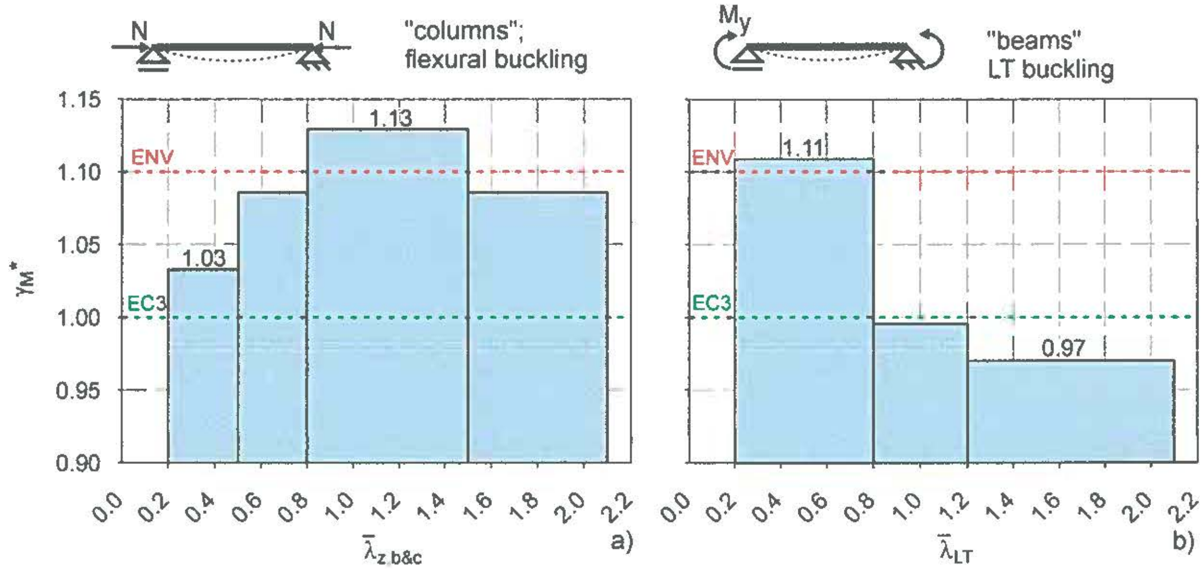

Fig. 2 Partial safety factors γ_M as indicated in the literature for different buckling cases; weak-axis flexural buckling, curves b & c (a); lateral-torsional buckling of hot-rolled beams (b)*

2 OUTLINE OF THE RESEARCH PROJECT "SAFEBRICTILE"

The non-homogeneous safety level in current design rules stems from the way these rules were and are currently developed: the main focus is put on developing design rules/functions which reflect the underlying mechanical behaviour of a failure mode with sufficient accuracy; thereby, usually nominal geometric and material parameters are used for the comparisons, and in this phase little attention is paid to the scatter of these basic input quantities or of the design resistances themselves. The safety evaluation follows as a last *validation step.* Whether or not the obtained "scatter" of the calculated safety values γ_M* is acceptable or not is usually determined in a qualitative way, and always retrospectively. The RFCS-funded research project SAFEBRICTILE, started in July 2013, set out to develop a more consistent approach for the development of design rules for steel structures, with the aim of harmonizing the safety levels in a methodic and rational way.

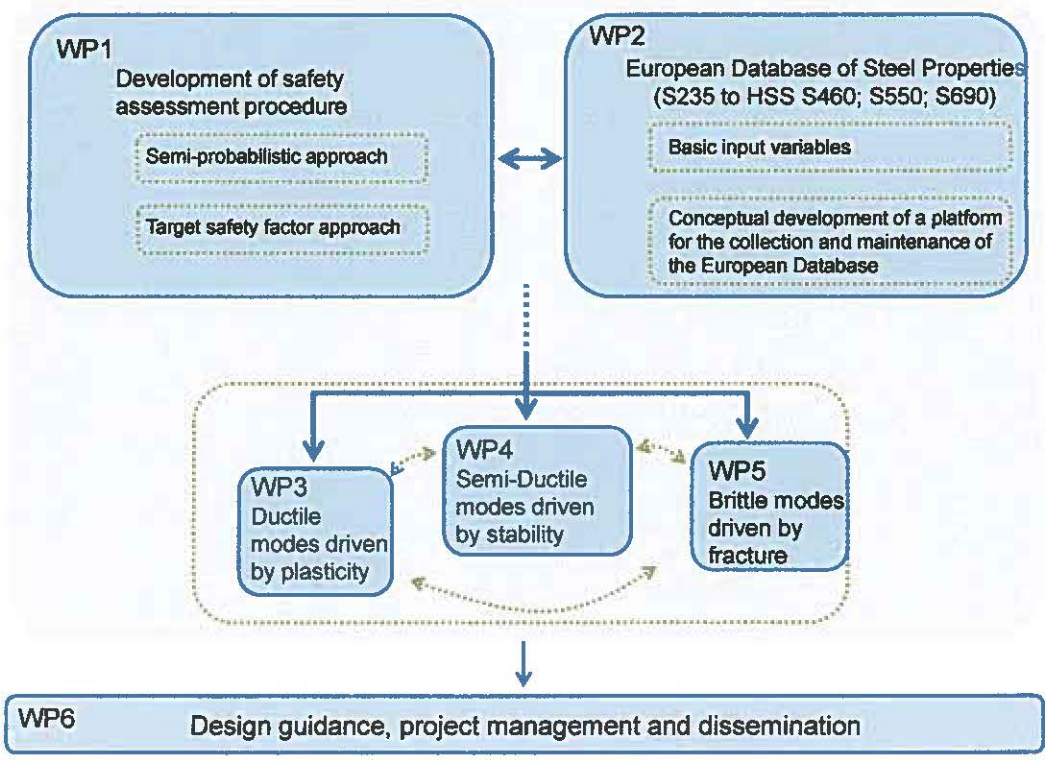

Fig. 3 Work plan of the RFCS-funded research project SAFEBRICTILE

The main work packages and fields of study of the project are shown in the flow chart in *Fig. 3*. In line with the project objective of covering failure modes ranging from ductile to brittle, individual work packages with corresponding experimental and numerical tasks are foreseen and carried out at the structural laboratories at the Technical University of Eindhoven (WP3), the University of Coimbra (WP4) and the University of Stuttgart (WP5). The more general work packages WP1 and WP2 are developed in cooperation between the European Convention for Constructional Steelwork (ECCS) and the University of Coimbra. Some aspects of this work, i.e. the development of a simplified version of the EN 1990 safety assessment procedure of *Fig. 1* and of a database of European steel product properties, are presented in two separate papers in these proceedings, see [4], [5]. The remainder of this paper will focus on the principal task of developing a tool that allows for a rational, efficient determination of the "target values" of the design resistances, thereby using numerical and analytical/statistical tools.

3 TARGET VALUES OF DESIGN STRENGTH - CONSTANT RELIABILITY CURVES

With the help of advanced numerical tools, it is nowadays possible to carry out a relatively large and mechanically and statistically representative number of "numerical tests", with arbitrary or even random distributions of the basic material and geometrical input parameters of the studied problem, thereby replacing the much more costly and time-consuming full-scale physical tests without much loss in accuracy. This is currently particularly true for problems related to ductile and semi-ductile failure modes, for which advanced geometrically and materially nonlinear analyses with structural and geometric imperfections (GMNIA) are well-known to be able to reproduce real "physical tests" with great accuracy. Any one GMNIA result of this type can be termed $r_{GMNIA,i}$, in contrast to a "real" experimental result $r_{e,i}$. These GMNIA calculations can thus be used to "invert" the methodology of EN 1990 (*Fig. 1*) and to calculate "design values" of the resistance (with associated "target values" of the safety factor γ_M) directly, by numerical and analytical means. This, in turn, allows one to calibrate any developed design equation ("resistance function") towards these "GMNIA design values", termed $r_{d,GMNIA}$ in the following. The following steps can be taken to obtain $r_{d,GMNIA}$:

i. Collect data for the main input parameters ("basic variables") of the studied problem, as well as data on existing physical test results $r_{e,i}$. The former will include the statistical parameters of the material and geometrical properties, as well as corresponding information regarding imperfections. See [5] for work in SAFEBRICTILE to expand the existing data pool. The latter should be used to account for the (ideally, and usually, small) error caused by the GMNIA calculation itself, $V_{\delta,GMNIA}$:

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

with $s_\Delta^2 = \frac{1}{n-1}\sum_{i=1}^{n}\left(\Delta_i - \bar{\Delta}\right)$; $\bar{\Delta} = \frac{1}{n}\sum_{i=1}^{n}\Delta_i$; $\Delta_i = \ln\left(\frac{r_{e,i}}{b \cdot r_{GMNIA,i}}\right)$; $b = \sum_{i=1}^{n} r_{e,i} \cdot r_{GMNIA,i} \Big/ \sum_{i=1}^{n}\left(r_{GMNIA,i}\right)^2$

ii. Calculate the adjusted, *mean value resistance* $r_{m,GMNIA}$ resulting from a GMNIA calculation carried out with mean values of the statistical input data. In agreement with the EN 1990 Annex D terminology, we can define that $g_{r,GMNIA}(\underline{X})$ represents the result of a GMNIA calculation for a row of j different, arbitrary values $\underline{X}$ of the basis variables. If $\underline{X}_m$ is the row of j variables where every value corresponds to its mean, we can write:

$$r_{m,GMNIA} = b \cdot g_{r,GMNIA}(\underline{X}_m) \tag{2}$$

This expression includes the linear regression correction factor b, which – for ductile and semi-ductile failure modes - should be very close to 1.00 if appropriate GMNIA models are used.

iii. Calculate the coefficient of variation $V_{r,GMNIA}$ of the GMNIA resistance function:

$$V_{r,GMNIA}{}^2 = \frac{VAR\left[g_{r,GMNIA}(\underline{X})\right]}{g_{r,GMNIA}(\underline{X}_m)^2} = \frac{1}{r_{m,GMNIA}{}^2} \cdot \sum_{i=1}^{j}\left(\frac{\partial g_{r,GMNIA}}{\partial X_i} \cdot \sigma_i\right)^2 \tag{3}$$

Equation (3) contains partial derivatives of the GMNIA resistance function. Since the procedure is numerical, these cannot be explicitly calculated, but must be calculated numerically, i.e. by carrying out (at least) one additional GMNIA calculation per variable at an increment ΔX_i:

$$\frac{\partial g_{r,GMNIA}}{\partial X_i} \approx \frac{g_{r,GMNIA}(X_{1m},\ldots,X_{im}+\Delta X_i,\ldots,X_{jm}) - g_{r,GMNIA}(\underline{X}_m)}{\Delta X_i} \quad (4)$$

It is proposed to carry out these partial derivatives at $g_{r,GMNIA}(\underline{X}_m)$, representing the result of a GMNIA calculation with mean values of the basis variables. This somewhat differs from the EN 1990 Annex D procedure, however the differences between (4) and the Annex D procedure are minimal. See [6] for more details. An example of a numerical derivative is given in *Fig 4a*.

iv. Calculate the lognormal variation coefficients $Q_{r,GMNIA}$, $Q_{\delta,GMNIA}$ and Q:

$$Q_{r,GMNIA} = \sqrt{\ln\left(V_{r,GMNIA}^{\ 2}+1\right)} \ ; \ Q_{\delta,GMNIA} = \sqrt{\ln\left(V_{\delta,GMNIA}^{\ 2}+1\right)} \ ; \ Q = \sqrt{\ln\left(V_r^{\ 2}+1\right)} \quad (5)$$

with $V_r^{\ 2} = V_{r,GMNIA}^{\ 2} + V_{\delta,GMNIA}^{\ 2}$

v. Calculate the design point $r_{d,GMNIA}$. If $V_{\delta,GMNIA}$ is calculated on the basis of many tests (n>100) or, more plausibly, if $V_{\delta,GMNIA}$ is kept small enough by using appropriate, realistic GMNIA calculations, r_d can be calculated as follows:

$$r_{d,GMNIA} = b \cdot r_{m,GMNIA} \cdot \exp(-k_{d,\infty} \cdot Q - 0.5 \cdot Q^2) \quad (6)$$

Through the value of $k_{d,\infty}$=0.8 · 3,8=3,04, this procedure leads to the strength which, *by definition*, is a resistance value that needs no further reduction (the "necessary" γ_M is 1.0). Any other desired value of $\gamma_M \neq 1.0$ can simply be obtained by multiplication with $r_{d,GMNIA}$. *Fig 4b* shows this for the case of weak-axis flexural buckling of an IPE section. Nominal slenderness and strength values ($\bar{\lambda}_{nom}$, χ_{nom}) are used to have a dimensionless representation. The 1.0 or 1,05 · $r_{d,GMNIA}$ curves in the plot can be compared with the currently valid EC3 buckling curve "b": As can be seen in the figure, the distance between the EC3 "b" curve and the $r_{d,GMNIA}$ curve changes over slenderness, following a pattern that is very similar to the γ_M* values for this same buckling case shown in *Fig 2a*. This confirms that the methodology presented here indeed delivers reliable estimates of the "true" r_d, with a hugely reduced experimental and computational effort (80 GMNIA runs were used in total).

4 CONCLUSIONS

The procedure shown in this paper is part of the developments of the SAFEBRICTILE research project and represents one step towards the planned harmonization of the safety level of design rules for steel structures in EC3. *Fig. 5* shows a compact, schematic representation of the proposed methodology for ductile and semi-ductile failure modes. A more in-depth description of this

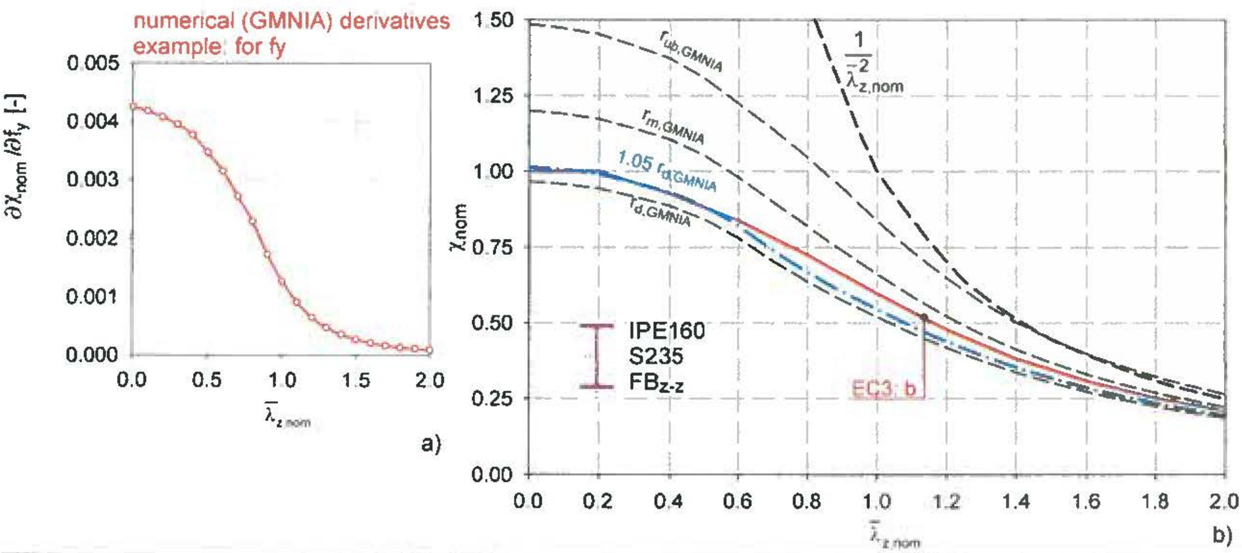

Fig. 4 Constant Reliability Curve (CRC) vs. current EC3 buckling curve for an IPE 160 section – S235 – $FB_{z\text{-}z}$.

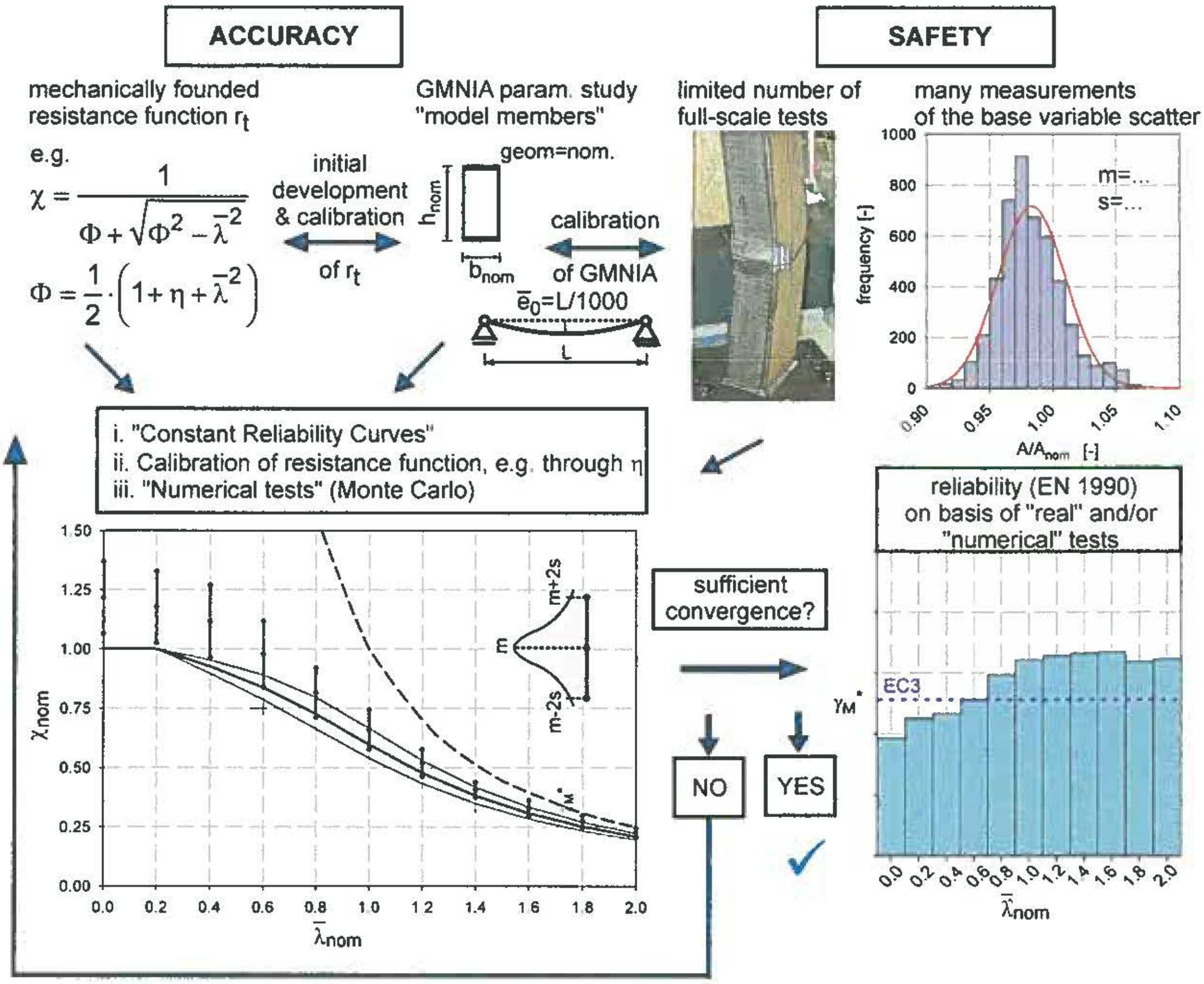

Fig. 5 Schematic representation of the proposed methodology.

methodology, a discussion of the necessary statistical input data, and a simplification of the evaluation procedure of EN 1990 Annex D to be used in conjunction with the above "constant reliability curves" determination, is given in [6], as well as [4] and [5].

5 ACKNOWLEDGEMENTS

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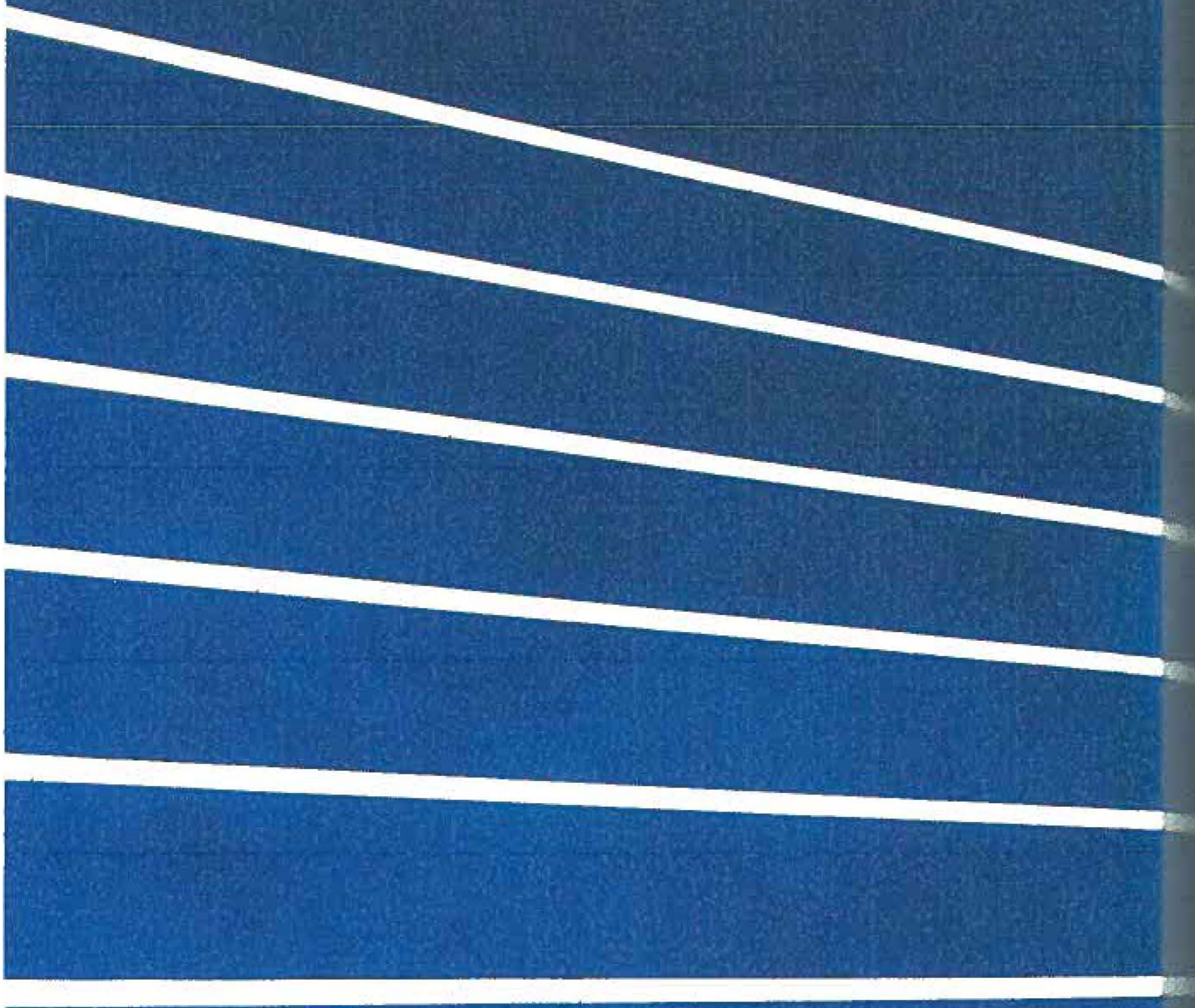

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