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EC3: A Eurocode for Reliable Steel Structures

EC3: Un Eurocode fiable pour les structures en acier

EC3: Ein Eurocode für sichere Stahlbauten

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SUMMARY

After having recalled in which context the background information particular to Eurocode 3 were made, this paper presents the basic studies which have been carried out to justify the choice of strength formulae, and in certain cases, when experimental data were sufficient enough, to determine the values of the partial safety factors assigned to the limite state functions. The evaluation of the partial safety factors depends upon some assumptions concerning the choice of the reliability level adopted which are given within the framework of this paper. At last the paper describes, in general terms, the calibration procedure which was set out within the study framework of the Editorial Group of the Eurocode 3.

RESUME

Après avoir rappelé dans quel contexte se situe le développement des études particulières à l'Eurocode 3, cet article présente les études de bases qui ont servi à justifier du choix des formules de résistance, et dans certains cas, lorsque les données expérimentales étaient en nombre suffisant, à déterminer les valeurs des coefficients partiels de sécurité affectés aux modèles de fonctions d'états limites. La détermination des valeurs des coefficients partiels de sécurité relève d'hypothèses et de certains choix sur les niveaux de sécurité qui sont précisés dans le cadre de cet article. Enfin on décrit, dans ses grandes lignes, la procédure de calibration qui a été mise au point dans le cadre des études du Groupe de rédaction de l'Eurocode 3.

ZUSAMMENFASSUNG

Nach Hinweis auf die Gründe und Zielsetzungen für die Ausarbeitung von Hintergrundberichten zu den Eurocode 3-Regeln wird auf die Grundlagenuntersuchungen eingegangen, die zu der Wahl der Bemessungsformeln für die verschiedenen Grenzzustände und soweit genügend Versuchsdaten vorhanden, auch zur Festlegung der Sicherheitsbeiwerte geführt haben. Die Teilsicherheitsbeiwerte hängen vom angestrebten Zuverlässigkeitsniveau ab; die Annahmen dazu werden in diesem Bericht angegeben. Schliesslich wird ein Überblick über das verwendete Versuchsauswerteverfahren gegeben, das von der Redaktionsgruppe für den Eurocode 3 für die Hintergrundberichte benutzt wurde.

1. INTRODUCTION

Eurocode 3 claims to be based on the best scientific and professional information available today. EC3 adopts modern principles in matter of structural safety based on probabilistic concepts of safety within the framework of a level 1 reliability code format through the use of partial safety factors applied to the load effects derived from a proper structural analysis and to the design resistance. The method of checking structural safety envisaged in EC3 refers to limit states and does not anymore refers to the traditional allowable stresses concept.

Adopting these main principles it results a major change for European countries, where codes are still based on the method of allowable stress design, and it requires a substantiated assessment of the safety.

National codes of the European Economical Communities member countries reflect various level of experiences or knowledges and various design practices which make difficult to reach a final consensus on the best safe and economical design formulae to be adopted for Eurocode 3.

Although recognizing the intrinsic value of the ECCS Recommendations, which represents the principal source document, they were incomplete on certain items and did not present a sound consistency between the single chapters.

From the Eurocode 3 first draft revision period it was clear that the conflicting ideas on particular design requirements or strength design model could only be solved by background appraisal studies.

At last, few knowledge and experience existed on newly developed high strength steel material elaborated by the steel industry such as the FeE 460 TM. The applicability of the design rules derived for normal steel grades needed to be proved for this new material and partial safety factors had to be adequately determined.

These were the main reasons which led the Editorial Group to undertake such detailed studies. These background information studies were carried out to fulfil various objectives :

- to assess the background information on the choice which led the Editorial Group to adopt particular design requirements when experimental data were insufficient to perform a sound statistical analysis, in such case, the objective was purely informative ;

- to choose the best "qualified" strength function, suitable model factors, and related partial safety coefficients. The statistical procedure required for such development could only be performed if a sound experimental basis already existed ;

- to achieve a coherent and an uniform safety level through the entire Eurocode 3 design code.

This paper presents an overview to the scientific background studies which have been carried out under the supervision of the Editorial Group to support basic provisions and reliability levels of design formulae of Eurocode 3. A special attention is brought to the definition of the partial safety factors which were considered in the studies of various strength formulae and particularly for the fatigue design strength.

2. STRENGTH FUNCTIONS

When designing a structure and its components parts an appropriate structural model has to be chosen and this choice concerns the analysis of the structure and the design check. A model implies the use of a method of global analysis (elastic or plastic) combined to a method of cross section or member resistance design check. Eurocode 3 provides the necessary requirements for such a choice as the best "qualified" strength functions (members in tension, bending or compression, connections design, fatigue assessment of structural details ...).

Using the agreed evaluations procedure described hereafter a uniform safety level was sought for all the proposed strength formulae and design rules throughout the Code.

3. GENERAL PRINCIPLES ADOPTED ON THE RELIABILITY LEVEL 1 CODE FORMAT

3.1 Design and safety checking format

In many background studies (see the list given in reference [3]) proposed strength formulae (strength functions) and design rules were compared with available tests results. The adoption of the limit state methods and the use of partial safety factors was adopted as the general checking and reliability design format through the entire Eurocode 3.

With this concept in mind, safety analysis is carried out comparing the effects of the actions (s) with the material or structural element strengths (r). Both variables are random and belong to a limit state function of the type :

$$z = r - s \tag{1}$$

where the random variables R and S denote, on the one hand, the effects of the material strength and geometrical uncertainties of the structural element and, on the other hand, the action effect variations.

In the context of a reliability analysis it is necessary to assess the probability of the failure event, i. e., the risk appreciation that the limit state expressed by the equation (1) will be reached, and to check that this probability is lower than a predefined value p_f :

$$\text{Prob}\,\{ Z < 0 \} < p_f \tag{2}$$

Under particular assumptions, knowing the mean value $(\bar{z})$ and the standard deviation σZ of the random variable Z, this probabilistic failure criterion may be replaced by the following condition :

$$\bar{z} - \beta . \sigma_Z > 0 \tag{3}$$

where β is denoted as the "design safety index".

For the case where R and S (the respective random variables of r and s are both normal, it can be demonstrated that :

$$\beta = -\Phi^{-1}(p_f) \tag{4}$$

where $\Phi^{-1}(.)$ stands for the inverse function of the standardized cumulative normal distribution.

With reference to a fixed limit state function as expressed by equ. (1), the reliability of the partial safety concept level 1 method as shown in equ. (5) can be made strictly identical to level 2 safety concept method as represented by the equ. (2) if the partial safety factors γ_f and γ_m are expressed by means of a proper functional relationship in terms of β.

$$\gamma_f \cdot s - r/\gamma_m > 0 \tag{5}$$

3.2 Choice of the reliability level

The reliability level is expressed by the safety index β. For the design rules of Eurocodes 3 the following failure probability were proposed [2] :

Safety classes	ULS		SLS	
	p_f	β	p_f	β
reduced	$\sim 5.\ 10^{-4}$	3.3	$\sim 16.\ 10^{-2}$	1.0
normal	$\sim 7.\ 10^{-5}$	3.8	$\sim 7.\ 10^{-2}$	1.5
high	$\sim 8.\ 10^{-6}$	4.3	$\sim 2.3\ 10^{-2}$	2.0

The safety requirements are defined by three safety classes. The various levels of target values of reliability indices take into account the possible consequences of failure in terms of risk to human life or injury and economic losses resulting from failure. The above table was established under particular assumptions with a reference to a 50 years design life of the construction. The conversion of β from the reference period of T= 50 years to an another reference period T' can by obtained from the following transformation :

$$\beta' = \Phi^{-1}\{ [\Phi(\beta)]^{T'/T}\} \tag{6}$$

The characteristic and design values of strengths (r_k , r_d) in Eurocode 3 have been evaluated on the basis of the normal safety class with β =3.8 as target value for ultimate limit state (ULS) and β = 1.5 for serviceability limit states (SLS).

4. GENERAL PROCEDURE FOR THE DETERMINATION OF CHARACTERISTIC STRENGTHS FROM TESTS AND FROM GIVEN STRENGTH FUNCTIONS

Many background studies deal with the comparison of strength formulae with available experimental tests results. The resistance of structures or part of structures in Eurocode 3 is check against a number of ultimate limit states which can be reached. These limited number of ultimate limit states are taken into account by suitable strength functions, specific for each limit state considered, which allow the definition of a set of safety domains.

These strength functions were checked against tests results in order to obtain the characteristic strength functions and their corresponding partial safety factors complying with the target safety value given in § 3. The main aspects of this statistical calibration procedure, developed specially to have a common reference for the background studies of Eurocode 3, are presented in the following [see ref. 3, Doc. 7.01].

4.1 Main steps of the calibration procedure

Lets have a strength function denoted by $g_R(X)$, where X are the basic random variables (geometrical, resistance) assumed to follow a lognormal a probability density function, the calibration procedure proceeds from the following main steps :

- STEP 1 : Check the correlation between experimental and calculated values :
  The strength function $g_R(X)$ compared with the tests results will be corrected if necessary by an additional factor $\overline{b}$ (mean value corrective factor) ; an another factor δ (an error term) gives an information on the scatter of the results from the mean value of the strength function. If the coefficient of correlation is greater than 0.9 then no correction is brought to the model function.
  The strength function must be established on a sound mechanical or physical interpretative model of the mode of failure considered or observed during the experiment. It should also include all relevant basic variables which affect the resistance.

- STEP 2 : Evaluation of the statistical characteristics of the basic variables and of the error term.
  In this step the determination of the mean value and the standard deviation of the basic variables may be obtained from the statistical analysis of the test data, if their representative values have been measured, if not they may be assumed from preknowledge or from an initial guess of the coefficient of variation.

- STEP 3 : Determination of the characteristic strength function and of the design strength function (or the partial safety factor) :

  The characteristic strength function is evaluated from the basic stastistical information on all variables as established in step 2. Two assumptions are made concerning the calculation of the value of the characteristic strength function :

  - The number of test specimens is such that it can be considered as infinite. In such case, their is no statistical uncertainty, and the characteristic value of the strength function can be determined in a straightforward manner.

  - The number of test specimens is limited, therefore a statistical uncertainty is taken into consideration.

  The fractile factor k_s is determined according to the relevant number of test results. k_s is established for a estimating 5% fractile and a level of confidence of 75%.

  The same derivation applies for the design strength function which must satisfy the requirement of a given value (target value) of the design safety index β. Depending upon also the number of test results, a table gives the corresponding design fractile factor k_d.

Then the partial safety factor applied to the characteristic strength function can be calculated from the following relation :

$$\gamma_M = r_k / r_d \qquad (7)$$

4.1 Remarks concerning the calibration procedure

The calibration procedure for the determination of the characteristic strength function and for the associated partial safety factor can be adapted to take into account for particular cases.

The incompleteness of available statistical data does not always allow the rigorous characterization of all the basic random variables. Particular considerations have been developed when some of the variables are defined by their nominal values (which are related in most cases to their mean values) instead of their characteristic values. Then the calibration procedure introduces a distinction between variables which have been measured within the course of the experimental investigation and variables for which preknowledge exists on their coefficient of variation.

The calibration procedure has been fully described when the strength functions are of particular formats such as the followings :

$$g_R(x) = X_1 * X_2 * .....* X_n$$

$$g_R(x) = X_1^{\alpha} * X_2^{\beta} * .....* X_n^{\nu}$$

$$g_R(x) = g_R(x_i) + g_R(x_j) + ...$$

For more complicated strength functions a more general iterative treatment is needed to determine the minimum distance of the limit state surface boundary from the origin of the standardized variables.

5. FATIGUE STRENGTH RELIABILITY IN EUROCODE 3

Several uncertainties affect a structural element subjected to fatigue loading. The variability of the parameters governing the fatigue strength life (i. e. fatigue loading and fatigue resistance) needs to be studied with careful attention.

A level 2 reliability model has been implemented (see ref. 3, Doc. 9.02) for the derivation of recommended partial safety factors in relation with the following fatigue strength assessment equation :

$$\gamma_F \cdot \Delta\sigma_{equ} = \Delta\sigma_R / \gamma_R$$

Where :

$\Delta\sigma_{equ}$ is the equivalent constant applied stress range which, for the given number of cycles, leads to the same cumulative damage as the design spectrum.

$\Delta\sigma_R$ is the fatigue strength as defined by the S-N curve of the relevant detail category.

γ_F and γ_R are the partial safety factors applied respectively to the spectrum loading and the resistance.

The partial safety factors depend upon the required safety index for which recommended values have been proposed on the basis of an appreciation of a risk appraisal which may be expressed in terms of two main parameters :

- The notional concept of "non fail-safe" and "fail-safe" of a structural element whose fracture may potentially gives rise (or not) to a catastrophic failure of the whole structure.

- The periodic inspection and maintenance of the construction in conjunction with the more or less accessibility of the structural detail for inspection and repair. Difficulties to access may be such as to make the detection or the repair unpractical, and in such a case particular measures to perform inspection should be taken.

It must be understood that the safety indices which were proposed (see following Table) are mainly based on an engineering judgement of what may be called a potential risk of acceptance of losses or damages. It belongs to each concerned authorities to make the decision on the proper choice of these values on the basis of a realistic risk assessment.

	"fail-safe" structural detail	"non fail-safe" structural detail
Periodic inspection and maintenance. Accessible joint detail.	$\beta = 2$	$\beta = 3$
Periodic inspection and maintenance. Poor accessibility.	$\beta = 2.5$	$\beta = 3.5$

The fatigue strength curve for each appropriate detail category has been determined on the basis of a statistical analysis of fatigue test data. The value of the "statistical" stress range $\Delta\sigma_{R,stat}$ correponding to a value of N of two million cycles, has been calculated for a 75% confidence interval of a 95% probability of survival for log N, taking into account the standard deviation and the sample size. Then the detail has been tabled to the closest appropriate conventional safe fatigue S-N curve.

Discontinuities play a major role in the fatigue strength, particularly for welded detail, and a careful consideration must be given to the weld quality which affects deeply the fatigue strength variation. About 6000 experimental fatigue test results were analysed altogether, and standard deviations of fatigue strength varied from $S_{\log\Delta\sigma R} = 0.1$ to $S_{\log\Delta\sigma R} = 0.2$.

In Chapter 9 of Eurocode 3 values of the product $\gamma_F.\gamma_R$ have been proposed on the assumption that $\gamma_F = 1.0$. There is few information concerning the fatigue loadings, and their characteristic strength and associated partial safety factors have to be evaluated from special statistical studies of recorded fatigue loading spectra, and the value of γ_F may thus be adjusted. Eurocode 3 does not give information on the fatigue loading ; this will be given in Eurocode 1.

6. CONCLUSIONS

The statistical evaluation procedure proposed in the former Annex Z of Eurocode 3 (which will be implemented in Eurocode 1) is fully independent of the variation of the load effects, the primary objective of the procedure is to calibrate selected strength functions versus a set of reference tests in order to obtain consistent values of partial safety factors.

Normally each strength function should have its own specific value of γ_M, however in order to avoid a large variety of partial safety factors on the resistance two reference values of γ_M were selected :

- γ_{M1} = 1.1 to be applied to all resistance formulae related to the yield strength f_y.

- γ_{M2} = 1.25 to be applied to all resistance formulae related to the tensile strength f_u (generally for bolt and weld resistances or net section and bearing strength).

However, for the particular case of hot-rolled sections of classe 1 that are bent about the strong axis bending and not subjected to any instability phenomena (except local buckling in the plastic domain) it has been found, from calibration studies using data (geometrical dimensions and yield strengths) from some modern European mill plant, that it would be justified to reduce γ_{M1} factor to the value of γ_{M0} = 1.0. However it is thought that this rule needs to comply with production control and quality assurance system requirements.

The calibration procedure has been developed mainly to propose a consistent methodology to evaluate the partial safety factors on strength. The γ_{M1} values which have been proposed by the Editorial Group are indicative and are identified through the Eurocode 3 document by a border frame ("boxed values"). The national Authorities in each member country are free to assign alternative values to these partial safety factors on due account of their own experience.

The main objective of a code is presumed to the achiement of structures which are optimal with regards to the state of economy and development and general values and experiences of the nation. Moreover, the measures that can be taken to achieve the required degree of structural reliability include not only the justification of relevant design rules and choice of associated partial safety factors, but also it requires an appropriate level of execution quality and proper standards for workmanship. Execution of steel constructions is covered partly in chapter 7 of Eurocode 3, which gives generally the minimum requirements. Rules related to execution and workmanship are further developed under the auspices of CEN TC/135.

7 . BACKGROUND DOCUMENTS REFERENCES FOR EUROCODE 3

[1] CECM-ECCS
Recommendations for steel structures.
European Convention for Constructional Steelwork, Bruxelles, 1978.

[2] CEB Bulletin n° 116-E
Volume 1, Paris, 1976

[3] List of the Background Documents :

References to volume 1 - Chapter 1 to 9

Doc. 2.01 Background document for chapter 2 of Eurocode 3.

Doc. 3.01 Design against brittle fracture.

Doc. 3.02 The relation between the nominal value of the yield strength in EC3 and the specifications in material standards

Doc. 4.01 Background document for chapter 4 of Eurocode 3

Doc. 5.01 Background document for the justification of safety factor γ_{M0} = 1,0 for rolled beams in bending about the strong axis.

Doc. 5.02 The b/t ratios controlling the applicability of analysis models in Eurocode 3

Doc. 5.03(1) Evaluation of test results on columns, beams and beam-columns with cross-sectional classes 1 to 3 in order to obtain strength functions and suitable model factors.

Doc. 5.03(2) Evaluation of test results on columns, beams and beam-columns with cross-sectional classe 4 in order to obtain strength functions and suitable model factors.

Doc. 5.04 Evaluation of test results on columnsand beam-columns with cross-sectional class IV in order to obtain strength functions and suitable model factors

Doc. 5.05 Evaluation of tests results on shear buckling in order to obtain suitable model factors.

Doc. 5.06 Evaluation of test results on web crippling in order to obtain suitable model factors.

Doc. 5.07 Evaluation of test results on hollow section lattice girder connections.

Doc. 5.08 Imperfections for compressed members.

Doc. 6.01 Evaluation of tests results on bolted connections in order to obtain strength functions and suitable model factors - PART A : Results.

Doc. 6.02 Evaluation of tests results on bolted connections in order to obtain strength functions and suitable model factors - PART B : Evaluation.

Doc. 6.03 Evaluation of tests results on bolted connections in order to obtain strength functions and suitable model factors - PART C : Test Data.

Doc. 6.05 Evaluation of tests results on welded connections in order to obtain strength functions and suitable model factors - PART A : Results.

Doc. 6.06 Evaluation of tests results on welded connections in order to obtain strength functions and suitable model factors - PART B : Evaluation.

Doc. 6.07 Evaluation of tests results on welded connections in order to obtain strength functions and suitable model factors - PART C : Test Data.

Doc. 6.08 Comparison of weld strength according to Eurocode 3 with weld strength according to national standards.

Doc. 6.09 Beam to column connection.

Doc. 6.10 Evaluation of test results on beam to column connections in order to obtain strength functions and suitable model factors.

Doc. 7.01 Procedure for the determination of design resistance from tests.

Doc. 9.01 Background document for chapter 9 of Eurocode 3.

Doc. 9.02 Report on the comparison of classification tables in existing national codes for fatigue in Europe and statistical evaluation of test data for large and small scale specimen.

Doc. 9.03 Background information on fatigue design rules for hollow sections ; statistical evaluation - Part A : Classification method

References to Volume 2 : Annexes

Doc. A.01 Evaluation of test results on connections in thin walled sheetings and members in order to obtain strength functions and suitable model factors
Part A : Evaluation and Results.

Doc. A.02 Part B : Test Data

Doc. D.01 Bakground document for design rules for high strength steels according to EN 10113.

Doc. D.02 Statistical evaluations of the results of bolted connections.

Doc. D.03 Evaluations of test results on welded connections made from FeE 460 in order to obtain strength functions and suitable model factors.

Doc. D.04 Statistical analysis of strength functions for welded H section joints with respect to available experimental data.