New approaches in Eurocode 3 – efficient global structural design
Part 0: An explanatory introduction

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Abstract

The new versions of the EN 1993-1-1 (EC3-1-1) and the EN 1993-1-5 (EC3-1-5) standards have introduced the general method to design beam-column structures. This design method uses 3D geometric model and general finite element method. In a series of papers we present this general design approach. The parts of the series are the following:

- Part 0: An explanatory introduction
- Part 1: 3D model based analysis using general beam-column FEM
- Part 2: Resistances of cross-sections using generalized cross-sectional models
- Part 3: Resistances of structural members using the general method
- Part 4: Special issues of the 3D model based design method

In this paper the topic is reviewed briefly and placed into the field of interest of practicing engineers struggling for understanding the advantages of using the Structural Eurocodes.

1. Evolution of standardized structural design

The demand for uniform rules which are obligatory for all providers in the construction field arose in the early decades of the 20th century. This standardization process was generated unequivocally by the practice with the aim to have minimum criteria for safe design and on the other hand consistence methods for comparing different designs. Consequently the regulations were prepared mainly by engineers involved in practice and supported a clear, transparent and practical way of design. What is also important to see is that this birth of modern structural design regulated by codes was far before the appearance of numerical calculation methods and digital computers so the rules were simple and easy-to-use in conformity with the limitations of the usual hand calculation methods of this era. Practically the verification process was based on a 'bipolar' concept, where the structural design is dissolved into two sharply separated phases:

- *analysis* – calculation of structural response (deformations, forces, stresses etc.) to a certain loading
- *resistance* – calculations of structural limits (cross section, member checks etc.) to a certain response

Interaction between these two sides was generally not considered. The calculations on the analysis side were performed by simple tools yielding unambiguous results and the more complicated effects (for instance the geometrical nonlinearity or torsion) were neglected or simplified by approximate factors. The structural standards practically regularized only the resistance side. These rules were based on straightforward principles easy to calculate by hand and took into account the uncertainties of these simple models. An important consequence of the simplicity requirements is that the structural design formulae were developed only at cross section and structural member levels there were no appropriate methods for compound, global type structural levels considering such failure modes which cannot be dissolved into and covered by component failures. In this approach the global structural model should be isolated to separate members for which the resistance calculations can be evaluated. Apparently the methods of this era developed considerably through the years but the basic way and the bipolar philosophy of design did not change. The most significant achievement in the evolution of structural design process was the appearance of desktop computers in the engineering activities. The new structural software products and available numerical methods have suddenly changed the possibilities of engineering calculations and accordingly increased the potential efficiency and productivity of structural design. However it is important to see that these new opportunities influenced *qualitatively* only the structural *analysis* by widening the range of computable phenomena and speeding up the calculations. The whole design process was not really affected since the standard *resistance* calculations did not exploit the possibility in the increased computational capability. The newly developed standard formulae kept avoiding the field of structural analysis continuing the conventional bipolar design concept and were still trying to answer the requirements of simplicity using the member isolation approach. Accordingly the structural software packages developed more and more powerful and comprehensive analysis tools but were limited to simple implementation of the conventional hand oriented resistance calculations.

The research and development body behind the Structural Eurocodes started to realize this situation and as a first answer in the final version of Eurocode 3 new design approaches have been introduced seceding from the bipolar design concept and using 3D global structural analysis results for the resistance calculations. These innovative rules are poorly known and acknowledged by the practicing engineers because of two main reasons:

- the philosophy of global structural design is quite far from the usual working methods of engineers due to long practice in the conventional methods
- the new rules involve more serious requirements for modelling and analysis of structures these are not efficiently supported by the commonly used structural design software products.

Recognizing however the significant potential in these methods and knowing the continuous, comprehensive research in order to widen their applicability in a series of papers the general design approach is introduced showing the requirements for the appropriate calculations and the possibilities comparing to the conventional methods. This introductory paper is intended to attract attention by presenting the basic idea of the general method applied for stability design problems and summarizing the most important advantages and consequences of application. The subsequent articles contain detailed descriptions on the increased requirements for analysis of the structural model (Paper 1), calculation of the resistance of cross sections (Paper 2), application of general method for stability design (Paper 3) and some special issues from this field (Paper 4).

2. Basic idea of the general stability method

In order to clarify the basic idea of the general method for stability design (Section 6.3.4 in EC 3) let us examine first the two fundamental buckling cases belonging to a single member subjected to compression (pure flexural buckling) or strong axis bending (pure lateral-torsional buckling). The basic steps of checking this structural member against buckling according to the conventional method of EC3 6.3.1 and 6.3.2 are the following:

- *Step1*
  Calculation of the design values of internal forces (N_{Ed}, $M_{y,Ed}$) on the examined member according to appropriate analysis method (first or second order etc.)
- *Step2*
  Calculation of pure elastic critical forces (N_{cr}, $M_{y,cr}$) of the member belonging to the appropriate buckling mode (pure flexural buckling, pure lateral-torsional buckling)
- *Step3*
  Calculation of pure ultimate limit forces ($N_{c,Rk}$, $M_{y,Rk}$) of the most critical cross section of the member
- *Step4*
  Calculation of member slenderness and reduction factors for the pure buckling cases:
  $$\lambda = \sqrt{\frac{N_{c,Rk}}{N_{cr}}} \Rightarrow \chi(\lambda)$$
  $$\lambda_{LT} = \sqrt{\frac{M_{y,Rk}}{M_{y,cr}}} \Rightarrow \chi_{LT}(\lambda_{LT})$$
- *Step5*
  Code check for member stability design situation of pure cases:
  $$N_{Ed} \leq \frac{\chi N_{c,Rk}}{\gamma_{M1}}$$
  $$M_{y,Ed} \leq \frac{\chi_{LT} M_{y,Rk}}{\gamma_{M1}}$$

In case of interaction of buckling forms the pure cases should be calculated as described and additionally special interaction factors should be determined for the final code check (see EC3 6.3.3). The calculations of *Step1* are generally performed on suitable numerical model by some structural engineering software, for *Step3* the EC3 provides simple and clear formulae (see EC3 6.2), *Step4* and *Step5* are straightforward calculations. From the point of view of the practicing engineer the key step of this process is the calculation of critical forces (*Step2*). The EC3 does not contain regulations for this issue only general requirements are formulated. Usually these values are calculated by some analytical expressions which contain several parameters depending on the proper support and loading conditions (effective length, moment gradient factor etc.). Although there are a great number of technical books and articles providing proposals for the determination of these parameters for different kinds of problems in a general case the accuracy of these assumptions are highly influenced by the practical experience and knowledge of the engineer. Moreover the decisions in this field have usually a significant effect on the final result taking a substantial uncertainty into the design process increasing the possibility for an unsafe or uneconomic structure. This is the point where the general method represents a remarkable change in the design process generalizing the calculations of the critical forces utilizing the possibilities inherent in the numerical analysis methods.

In order to understand the theoretical basis of this generalization let us introduce the following relationships for the examined cases:

$$\alpha_{ult,k,N} = \frac{N_{c,Rk}}{N_{Ed}};\ \alpha_{cr,N} = \frac{N_{cr}}{N_{Ed}}$$

$$\alpha_{\text{ult,k,M}} = \frac{M_{\text{y,Rk}}}{M_{\text{y,Ed}}};\ \alpha_{\text{cr,M}} = \frac{M_{\text{y,cr}}}{M_{\text{y,Ed}}}$$

In these relationships the $\alpha_{ult,k}$ factors are multipliers of the internal forces to reach the characteristic resistance of the cross sections and the α_{cr} factors are multipliers of the internal forces to reach the buckling resistance of the member. The conversion leads to a new form of the member slenderness and code check (*Step4* and *Step5*):

$$\lambda = \sqrt{\frac{\alpha_{\text{ult,k,N}}}{\alpha_{\text{cr,N}}}};\ 1 \le \frac{\chi\alpha_{\text{ult,k,N}}}{\gamma_{\text{M1}}}$$

$$\lambda_{LT} = \sqrt{\frac{\alpha_{\text{ult,k,M}}}{\alpha_{\text{cr,M}}}};\ 1 \le \frac{\chi_{LT}\alpha_{\text{ult,k}}}{\gamma_{\text{M1}}}$$

Although these equations seem to describe only a formal conversion, but that is the basic form of the general method of EC3 6.3.4 representing a design process for stability checks at a higher structural level, the steps are the following (see Fig. 1 for comparison with the conventional approach):

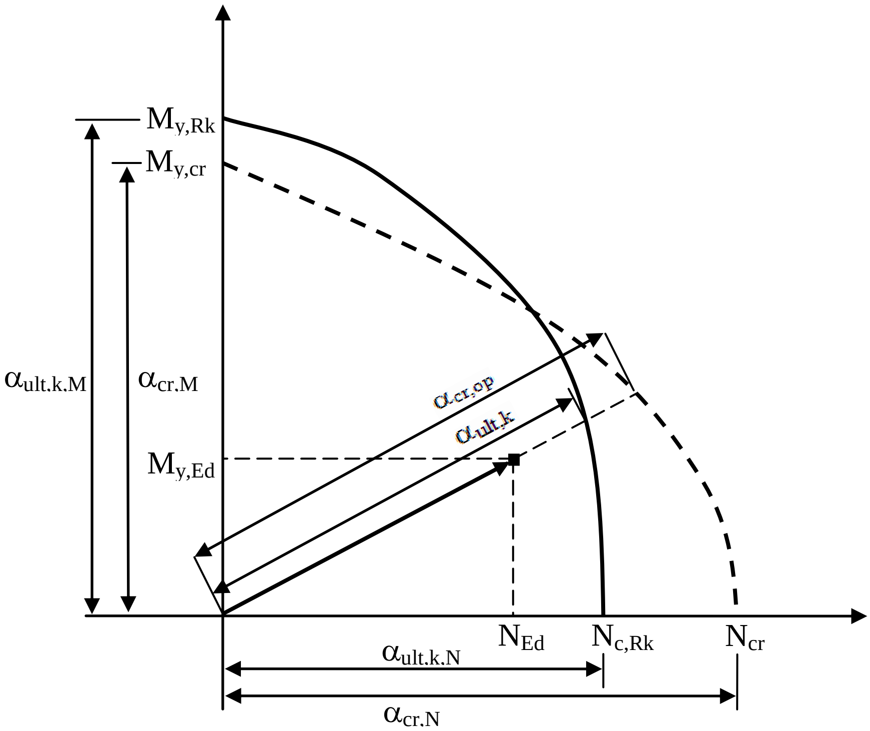

Figure 1. Load factors for the conventional and the general methods

- *Step1*
  Calculation of the design values of internal forces on the examined member according to appropriate analysis method (first or second order etc.)
- *Step2*
  Calculation of critical load level (α_{cr}) belonging to the complete loading case (instead of divided to pure cases)
- *Step3*

Calculation of ultimate load level ($\alpha_{ult,k}$) of the most critical cross section belonging to the complete loading case (instead of divided to pure cases)

- *Step4*
  Calculation of general slenderness and reduction factors:
  $$\lambda_{op} = \sqrt{\frac{\alpha_{\text{ult,k}}}{\alpha_{\text{cr}}}} \Rightarrow \chi(\lambda_{op}), \chi_{LT}(\lambda_{op})$$
- *Step5*
  Code check for member stability design situation of pure cases:
  $$1 \le \frac{\chi_{op}\alpha_{\text{ult,k}}}{\gamma_{\text{M1}}}$$
  where χ_{op} is determined from the values of χ and χ_{LT}

With taking the calculations of critical and ultimate values from the member force level to the applied load level this method generalizes the conventional approach in two main fields:

- it is applicable not only for single, isolated members but for certain structural parts or whole structural models where the governing buckling mode forms a consistent shape involving the whole examined part
- the buckling form should not be separated into pure cases but the real, complete loading and appropriate buckling situation is taken into the calculation (Fig. 1), accordingly the application of special interaction factors becomes unnecessary

Calculation of the values of α_{cr} and $\alpha_{ult,k}$ for the general slenderness – covering all possible global buckling modes – requires special analysis and cross section models and algorithms, these important issues are discussed in the subsequent Papers 2&3 of this series.

It is important to note that in the recent version of EC3 there are several restrictions on the application field and moreover the National Annexes are usually quite distrustful of this approach mainly because of the lack of enough knowledge and experience. However on the other hand there are heavy research and development efforts on extending its applicability and this method is expected to cover much larger area of practical problems then the isolated member based conventional procedures.

Another important issue which should be addressed is the efficient utilization of structural analysis software products in the design process. In the conventional design approach the isolation of members and the separation of pure buckling modes make the use of computer oriented numerical methods inconvenient (sometimes impossible) in the phase of calculation of elastic critical forces. That is the feature what was referred to as “bipolar” way of design since the structural analysis phase is still limited to the calculation of internal forces (*Step1*) and it is sharply separated from the structural design phases (*Step2* to *Step5*). This approach was evident when all the calculations were performed by hand or on tools with very limited calculation capacity. Nowadays however when the structural design software has dominant role in the design process containing several efficient calculation possibilities (including the determination of elastic critical forces) this bipolar design approach has become outworn. Due to its described extensions the general method is highly applicable for software implementation yielding numerical analysis based solution for the key phase of *Step2* in the design process.

3. Some application issues

This section is not intended to point out some important issues regarding the stability verification of steel structures. Three important topics are reviewed which can cause problems using the conventional methods and for which the introduced general approach gives solution. Each problem is revealed briefly from the point of view of elastic critical buckling analysis aiming only to attract attention; the subsequent articles of this series present more detailed examinations and examples.

3.1 Buckling parameters

The design procedures – buckling curves, interaction factors – used in the conventional stability verification were developed and calibrated for simply supported uniform members (mainly with doubly symmetric cross sections) the basic model of structural standards. In case of these types of members there are straightforward calculation formulae for the elastic critical forces however naturally in a practical structural model the members can rarely be considered as simply supported. In these general cases special buckling parameters should be introduced reducing the real problem to the standard model. For the basic buckling modes these parameters are the following:

- ν_y, ν_z - effective length factors for the in-plane and flexural buckling considering the rotational restraints in the plane of buckling at the member ends
- ν_z, ν_w - effective length factors for the lateral-torsional buckling considering the rotational restraint in the lateral plane; and torsional restraint at the member ends respectively
- C_1, C_2, C_3 – moment gradient factors for lateral-torsional buckling considering the distribution of bending moment along the member length

There are several problems with the appropriate determination of these factors; we collected the most important ones:

(1) all the proposals for these factors are usually based on certain members having some kind of support at both ends, solutions for general intermediate supports or cantilever-like behavior are very rare and incomplete
(2) for the effective torsional length factor (ν_w) there are no practical proposal even it can be very dominant in some cases where the dominant buckling mode includes torsion
(3) it was just recently realized that the moment gradient factors (C_1, C_2, C_3) can highly depend on the lateral and torsional effective length factors as well
(4) the determination of these factors can be very difficult and uncertain in the cases when the buckling of a certain member is only a part of a global type buckling mode involving a complete part of the structure

The last problem is of very high importance, because – from other reasons as well see Section 3.3 – it is usually recommended to develop the structural model so as to form a coherent mechanical system which generally has dominantly some kind of global buckling modes. These modes, by nature, cannot be handled appropriately by the conventional member isolation technique and this is the main issue where the general stability design approach can provide significant improvements for the reliability and efficiency of the structural design process.

3.2 Irregularities

As it was described in the previous section the stability design procedures were verified – experimentally and analytically as well – on simple standard models created specially for the examination of certain buckling modes these problems can be regarded as the regular cases. All deviations from these cases yield irregular problems and models these can be divided into two main categories:

- *structural irregularity*: deviation from the uniform, prismatic member model: tapered members, haunched members, built-up members etc.
- *behaviour irregularity*: deviation from the examined regular buckling modes (the previously discussed pure buckling cases): for instance buckling about an eccentric restraint axis caused by eccentric lateral supports

Originally these irregularities were one of the main reasons for the introduction of the general method into the EC3, because the conventional methods have no appropriate tools for the examination of these cases although they are very frequent in the steel structural design practice.

3.3 Variation of slenderness values

When using the conventional method and evaluating the critical forces and slenderness separately for the isolated members the usual result is that the values of member slenderness vary considerably within one coherent structural model. There is one main problem with this approach from reliability point of view: the higher critical forces and accordingly the lower member slenderness values are calculated with the assumption that the reminder elements of the complete structure are in a stable position which is obviously not true considering that their critical forces belong to a lower load level. This problem is in strong connection with the robustness criteria which becomes more and more important design requirement for structures, accordingly the EN 1991-1-7 proposes the following (among others) in the Section 3.3 (2b):

> "*designing the structure so that in the event of a localised failure (e.g. failure of a single member) the stability of the whole structure or of a significant part of it would not be endangered*"

Using the general stability design method these controversies can automatically be identified and an optimal distribution of member slenderness values can be reached by using one critical load factor for all the members.

4. Conclusions

An introduction is presented into the general stability method appeared in the EC3 as an alternative approach for stability design. Reviewing the history of structural standards the roots of the presently applied design approaches have been demonstrated and it is pointed out that the significantly increased capacity in the field of structural analysis provided the necessary facilities for more advanced design approaches. The new versions of the Structural Eurocodes for steel structures (EC3) contain several new approaches less known and accepted by the engineering practice. The strong opinion of the authors is that these new methods yield the real innovation of the Eurocodes and provide the main benefits compared to the national standards. However it is also important to see that the appropriate application of these approaches requires a deeper background and knowledge in certain fields of structural engineering sciences to reach the aimed advantages through a more efficient structural design process. This series of articles is intended to introduce these new approaches from this point of view.