EN 1990: Parametric studies on reliability levels and implications for design

Dr Pal Chana, (British Cement Association) presents the latest research findings from the publication by CEN of the National Annex to standard EN 1990 Basis of Structural Design

Background

Publication by CEN of EN 1990 *Basis of Structural Design*[1] marks the start of availability of the long-awaited Eurocodes. This standard provides the framework for the whole suite of Eurocodes, which includes the design of concrete structures, as well as geotechnical and seismic design. Other standards published subsequently in the series are EN 1991-1-1 '*General actions – densities, self-weight, and imposed loads for buildings*' and EN 1991-1-2 '*Actions on structures exposed to fire*'.

The design standards for the main structural materials (EN 1992-1-1 for concrete, etc) have been sent for Formal Vote and, all being well, should be published in early 2005. This first generation of Eurocodes will contain some elements of choice for countries, although recommendations will usually be given for the choices.

One important exception lies in EN 1990, in which the criteria for choosing between three load combination expressions for structures are not specified. The choice should be given in the National Annex for EN 1990 and affects, among other things, the consistency in reliability over the range of potential designs.

Structural safety and materials

The objective of structural safety is to define methods and parameters for the evaluation of structures' reliability. Barring particular instances, in most cases the needs of users or occupiers do not discriminate between the different types of construction materials and/or methods of construction. Whatever the material and construction method adopted, the expectation is that the construction should be able, over a given period of time (its 'working lifetime'), to resist the actions to which it will be expected to be subject without breaking down or becoming unstable and to perform the functions for which it was designed and built.

Any system of standards and/or building regulations should therefore not discriminate between materials. That is to say, they should make possible alternative construction solutions that make use of different materials while having the same level of reliability – with the only limitations being each material's inherent properties.

*Subscript *k* indicates that both types of load are statistically calculated. In reality regulations define, for various loads, intensities that allow for a reduced probability (typically 5%) of being exceeded during the lifetime of the structure.

Panel 1

$$\sum_{j \geq 1} \gamma_{G,j} G_{k,j} \text{ '+' } \gamma_p P \text{ '+' } \gamma_{Q,1} Q_{k,1} \text{ '+' } \sum_{i > 1} \gamma_{Q,i} \psi_{0,i} Q_{k,i} \qquad \text{...(6.10)}$$

$$\left\{ \begin{array}{ll} \sum_{j \geq 1} \gamma_{G,j} G_{k,j} \text{ '+' } \gamma_p P \text{ '+' } \gamma_{Q,1} \psi_{0,1} Q_{k,1} \text{ '+' } \sum_{i > 1} \gamma_{Q,i} \psi_{0,i} Q_{k,i} & \text{....(6.10}a\text{)} \\ \sum_{j \geq 1} \xi_j \gamma_{G,j} G_{k,j} \text{ '+' } \gamma_p P \text{ '+' } \gamma_{Q,1} Q_{k,1} \text{ '+' } \sum_{i > 1} \gamma_{Q,i} \psi_{0,i} Q_{k,i} & \text{....(6.10}b\text{)} \end{array} \right.$$

'+' implies 'to be combined with'
Σ implies 'the combined effect of'§

Load combinations

A structure can be subject to a multiplicity of loads. In Eurocode terminology, loads considered to be always present over its lifetime (self-weight, finishes, etc.) are defined as 'permanent loads' and represented by the symbol G and expressed by a value evaluated on a statistical basis G_k. Service loads (people, machines, equipment, wind, snow, etc.) that can be present with a variable intensity and duration over a building's design lifetime are defined as 'variable loads' and represented by the symbols Q and Q_k*.

For different types of structures the ratio Q_k/G_k varies within a wide range of values. For assigned service loads – that is, the conditions for which a structure is actually designed and built - the ratio Q_k/G_k takes on reduced values when heavy materials such as concrete and masonry are used compared to when 'light' materials like steel, timber and aluminium are used†.

In design standards both permanent and variable loads are multiplied by coefficients (load safety factors) γ_G and γ_Q, greater than one, to take into account uncertainties specific to gathered statistical data and guarantee an adequate safety margin. The value of these coefficients depends:

- on the type of load: given that permanent loads G are relatively more controlled than variable loads Q, which depend on human decisions or atmospheric agents, in general $\gamma_G < \gamma_Q$;
- on the level of protection specific to each country, as defined by its National Authorities.

The probability of variable loads being greater than the characteristic value over the design lifetime of a building is relatively small (5% or less). The probability of different variable loads acting simultaneously on the same structure, with intensities greater than their characteristic values, is even smaller than the probability of each individual load being exceeded. This is taken into account by classifying variable loads in order of decreasing importance of the effect generated by each and by multiplying all loads except for the most important ones by reducing coefficients ψ_o.

Alternatives expressions for load combinations are given in EN 1990 [1 Annex A1.2], see 6.10 in Panel 1, or the most unfavourable of the expressions 6.10a and 6.10b (see Panel 1) may be used‡:

Expression (6.10) and (6.10b) are identical except for a reduction factor ξ for permanent loads introduced in the latter.

†The distinction is not based on the specific weight of each material, but on the volume occupied. The materials considered 'heavy' are those that, even not having the highest specific absolute weight, are used in volumes that represent an elevated structural weight – and therefore an elevated self-weight.
‡The standard also allows for a slightly modified version of 6.10a. As the major conclusions of the study are valid for the slightly modified expression also this one is not taken into consideration in the presentation, for the sake of simplicity.
§In the expression P denotes the relevant value of a prestressing action.

The standard allows the choice of which load combination expression(s) to use, via a National Annex. It gives recommended values for the coefficient of variation of permanent load, the reduction factor (ξ) and the partial (γ) and combination (ψ) factors for actions, which may be modified in the National Annex, to adjust the reliabilty level.

Cembureau/BIBM/ERMCO commissioned study

A preliminary study showed that the two load combination expressions give quite differing levels of reliability for different ratios of variable load to total load (χ).

For most practical cases, concrete structures have a value of χ between 0.2 and 0.6 whereas steel and timber have a value between 0.5 and 0.8. Hence, the choice of load combination expressions in the National Annex for EN 1990 is crucial in order to obtain a consistent level of safety.

Cembureau/BIBM/ERMCO are the representative organisations for the cement, precast and ready mix concrete industries in Europe respectively. In order to help members in their national discussions, Cembureau/BIBM/ERMCO commissioned Prof. Gulvanessian of BRE, as leader of the CEN TC 250 Project Team for Basis of Structural Design, to review the implications of the possible choices. The final report was reviewed independently and separately by Prof. Jensen, Prof. Spehl and Prof. Calgaro, members of the same CEN Project Team.

The findings

Basic results

In the aforementioned study the variation of the 'probability of failure', P_f , with χ was investigated. A series of diagrams were produced, based on assumptions present in EN 1990. A typical figure is represented below (Fig 1).

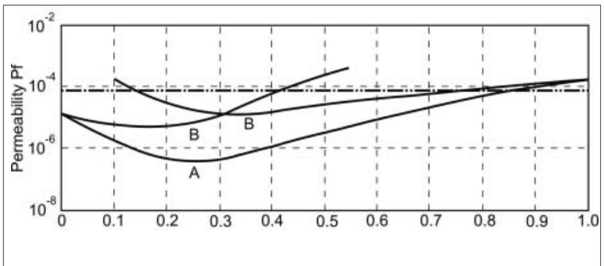
Curve A is based on expression (6.10) and curves B on expressions (6.10a – 6.10b).

Even if 'accepted' P_f values vary among Member States, a commonly agreed value of $P_f = 7.23 \times 10^{-5}$ is recommended for common structures in EN 1990**. This value is represented by the horizontal dotted line.

It can be observed that:

1. For all curves the variation of P_f is sensitive to the variation of χ, but this effect is more relevant for curve A.

Fig 1. Variation of P_f with χ [ref. 2]



Curve A is based on expression (6.10) and curves B on expression (6.10a - 6.10b)

Consideration	Case A (expression 6.10)	Case B (expressions 6.10a, 6.10b)
The level of reliability from use of national codes	Dependent on the country (e.g. same in UK)	Dependent on the country (e.g. same in Nordic countries and The Netherlands)
Consistency of reliability for range of χ	No Higher reliability for χ between 0.2 and 0.6	Yes
Usability	As for current National Codes that use the format of expression 6.10	Additional checks required compared to case A.
Economy Considering actions only for a given resistance	As for UK practice	Greater economy for χ between 0.15 and 0.6 As for Nordic countries and The Netherlands practice

2. When $\chi < 0.80$ all expressions are on the safe side.
3. When $\chi > 0.85$ neither expression is on the safer side. This corresponds to $G_k < 1/3 (Q_k + W_k)$, a case quite normal for light structures.
4. When $0 < \chi < 0.60$, expression 6.10 (curve A) gives P_f values in any case less than 10^{-5}, that is, about two order of magnitude more safe than required
5. When $0.15 < \chi < 0.40$, expression 6.10 (curve A) gives P_f values less than 10^{-6}, that is, about three order of magnitude more safe than required.

The diagram gives a 'visual' justification of why expressions (6.10a and 6.10b) are proposed in EN1990 as an alternative to expression 6.10. Structures have to be safe but not safer than required by current legislation and practices, or so safe that they may become uneconomical. Safety should also be as uniform as possible for a large range of χ load ratios. Both conditions are fulfilled by expressions (6.10a and 6.10b). It is also evident that a 'safety differential' (represented by the distance between curves A and B) exists. The differential is a maximum for χ values between 0.20 and 0.50 and a minimum for χ values higher than 0.80.

Taking into account the differentiation into 'heavy' and 'light' structures on the basis of their χ values, heavy structures designed in conformity with Eurocodes seem to be intrinsically safer than light ones – but this is at the cost of being less competitive on the construction market.

The problem described (uneven probability between heavy and light structures, intrinsically greater risk for light structures) may be solved partly by an appropriate choice of the combination expression(s) and of the partial factors on load γ_G and γ_Q. In EN 1990 values of $\gamma_G = 1.35$ and $\gamma_Q = 1.50$ are suggested. By adopting these values, both problems are addressed only if expressions 6.10a and 6.10b are used, as shown by the fig 1.

The choice of the loading expressions should be governed by the following considerations:

- The potential for achieving adequate consistency in reliability over the range of potential designs
- Ease of use for designers, considering both the superstructure and the substructure
- The use of the same load combination rules and partial and combination factors for actions for all the materials
- The reliability currently implied nationally, by using the appropriate National Codes of Practice
- Improved economy.

**Alternatively, value $\beta = 3.8$ for reliability index β may be used.

Owing to space constraints, the full parametric studies cannot be detailed in this note. The key findings of the study can be summarised in a table for the two expressions (Cases A & B) against four criteria of the criteria, assuming that the same expression would be used for design in all materials in a structure.

Conclusion

Each of these expressions is already in effective use in one country or another. Case B gives a greater consistency of reliability over the range of load ratios than Case A and is therefore more equitable to all materials. When used with appropriate partial and combination factors for all materials Case B would still achieve current target levels of reliability.

Cembureau/BIBM/ERMCO are very pleased to make the report available publicly. The Associations believe that the report will make a very valuable contribution to the practical implementation of the Eurocodes and in particular to the process of making choices by national competent authorities.

The full documentation is available on the Cembureau website (www.cembureau.be) in an easily accessible form, including an Executive Summary and reports from the independent reviewers. se

REFERENCES

1. EN 1990 – Eurocode 0 *Basis of structural design* – CEN 2002
2. 'Safety of structures' – An independent technical expert review of partial factors for actions and load combinations in EN1990 'Basis of Structural Design', *BRE Report no. 210297*, April-March 2003 – available on www.cembureau.be