Management of reliability and risk in the Eurocode System

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Summary

The art of Civil Engineering is to foresee the unforeseeable. Undesirable events are idealised by limit states, and design codes are calibrated in order to limit the probability of these events to below a threshold accepted by public opinion. In the Eurocode system, all Principles, Application Rules, assumptions and statements are deemed to ensure a safe and durable design. But the designer can freely exert his expertise to select the appropriate levels of reliability. EN 1990 Basis of Design is a very innovative code of practice, introducing the concept of reliability management and giving importance to the contribution of quality control in reducing risk and also recognising the importance of a safe but economic structure. This paper describes the concepts concerning risk and reliability management in the Eurocode system in general, and more precisely in EN 1990, and gives recommendations for further research in the field of structural safety and calibration of codes.

Keywords: risk, reliability, Eurocodes, failure, differentiation, safety, durability, partial factor design, limit states

1. Introduction

The Eurocodes, integrated set of international codes of practice for the design of buildings and civil engineering works which will ultimately replace the differing rules in the various Member States of the European Union, are intended to serve as reference documents for the following purposes :

- as a means of compliance of building and civil engineering works with Essential Requirement No. 1- Mechanical resistance and stability, and Essential Requirement No. 2 - Safety in case of fire – of the Construction Products Directive ;
- as a basis for specifying contracts for the execution of construction works and related engineering services in the area of public works ;
- as a framework for drawing up harmonised technical specifications for construction products.

EN 1990: Basis of Design [1], the head code, is an innovative document, being the first material-independent operational code of practice which establishes the principles and requirements for the safety, serviceability and durability of structures; in addition it describes the basis for their design and verification and gives guidance for related aspects of structural reliability.

The requirements defined in Section 2 of EN 1990 concerning safety, serviceability, robustness etc. are deemed to be met only if their Principles and Application Rules are complied with. In addition, various assumptions should be satisfied, including adequate supervision, quality control during the execution of the work and maintenance.

The objective of this paper is to discuss the following fundamental questions :

- How is it possible to characterise the reliability levels reached when applying Eurocodes to the design of construction works ?
- May these levels be differentiated depending on the nature of construction works ?

2. The concept of “ risk ” - Background

EN 1990 defines the concepts of Partial Factor Design (PFD), gives recommended values of partial factors applicable to actions and provides a general framework for the management, at national levels, of structural reliability. Embodied in the values of the partial factors there are implicit "acceptable” or “accepted” risk levels, but the word “risk” is not defined, probably because it also relates to the consequences of the hazard and the use of the structure.

Risk in civil engineering is a rather complex concept, at least two-dimensional, covering both the possible consequences of hazards and their associated probability. It may be defined as follows:

Prob(F)×C, where Prob(F) is the probability of the hazard occurring, and C is the consequence in magnitude or extent, expressed, for example, in numbers of deaths, time or monetary units [2].

PFD is based on the consideration of limit states which are, in most common cases, classified into ultimate and serviceability limit states idealising undesirable phenomena. The design is such that their probability of occurrence in 50 years is less than an “ acceptable ” value.

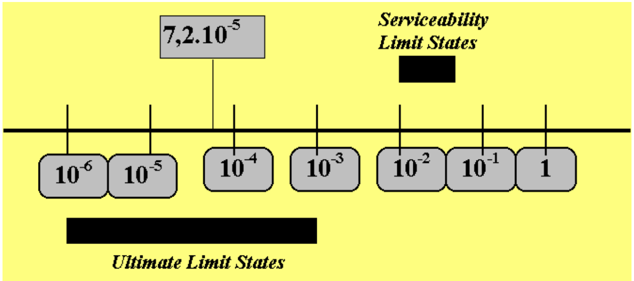

Fig. 1 Probabilities associated with limit states

Figure 1 shows the usual ranges of values for the ultimate and serviceability limit states.

CEB Bulletin 124/125 [3] proposes a tentative Table giving probability thresholds of structural failure in 50 years (Table 1). In addition it was stated that the target probability of failure should be less than the “acceptable” personal risk per year multiplied by the working life of the structure and divided by the average number of endangered people.

Table 1: Probability of structural failure in 50 years

Average number of endangered people	**Economic consequences**		
	Low	Medium	High
Low (< 0,1)	10^{-3}	10^{-4}	10^{-5}
Medium	10^{-4}	10^{-5}	10^{-6}
High (> 10)	10^{-5}	10^{-6}	10^{-7}

The “ acceptable ” individual risk for calibration purposes was operationally taken equal to 10^{-5}. Interestingly, the CEB Table reproduced here as Table 1 was considered too sensitive and consequently was not included in the CEB Model Code 90[4].

The concept of “acceptable” risk of human death resulting from structural failure raises very sensitive questions, concerned with public perception [5]. Fatalities due to accidents, taken from recent figures [6] given in Table 2 are considered to reflect the public perception of acceptability of fatalities for different types of accidents and exposure to serious hazards.

Death has a cost implication for Society, and it can be considered that the monetary value of a human life is dependent on social consensus as to the minimum value acceptable by public opinion. This monetary value for a fatality is dependant on local criteria. As an example, in France, it is currently 0,6M Euro, which the authors consider low.

This value must be considered an average figure, being actually dependent on the public reaction to an event. For example if the cost of a fatality of 0,6M Euro was considered as pertinent for a human life in the case of structural failure, then codified reliability levels currently used are very high. However, if reliability levels were reduced in order to bring them into line with the 0,6M Euro, then this would lead to increased fatalities due to many more structural failures: public opinion would definitely not accept this.

Table 2: "Accepted" risks of death due to exposure to various hazards

Hazard	**Risk** (× 10^{-6} p.a.)[a]	**Hazard**	**Risk** (× 10^{-6} p.a.)[a]
Building hazards		*Occupations (UK)*	
Structural failure (*UK*)	0,14	Chemical and allied industries	85
Building fires (*Australia*)	4	Ship building and marine engineering	105
		Agriculture	110
		Construction industries	150
		Railways	180
		Coal mining	210
		Quarrying	295
		Mining (non-coal)	750
		Offshore oil and gas *(1967-1976)*	1650
		Deep sea fishing (*1959-1978)*	2800
Natural hazards (U.S)		*Sports (U.S)*	
Hurricanes (1901-1972)	0,4	Cave exploration *(1970-1978*)	45
Tornadoes (1953-1971)	0,4	Glider flying (*1970-1978)*	400
Lightning (1969)	0,5	Scuba diving *(1970-1978)*	420
Earthquakes (California)	2	Hang gliding *(1977-1979)*	1500
		Parachuting (*1978)*	1900
General accidents (U.S 1969)		*All causes (U.K. 1977)*	
Poisoning	20	Whole population	12000
Drowning	30	Woman aged 30	600
Fires and burns	40	Man aged 30	1000
Falls	90	Woman aged 60	10000
Road accidents	300	Man aged 60	20000

[a] risk expressed as probability of death for typical exposed person per calendar year

EN 1990 recognises that risks associated with structural failure, related to the present time are reasonable and EN 1990's recommendations are based on this recognition.

3. Reliability levels in EN 1990

EN 1990 specifies that the levels of reliability applicable to a particular structure or structural member may be specified by the classification of the structure as a whole and/or the classification of its components.

The question of reliability levels is already invoked in particular ENV Eurocodes. For example ENV 1998 (Eurocode 8 : Design of structures for earthquake resistance) introduces an "importance" factor γ_I to be applied to the seismic action only (but not to the combination of actions for the seismic design situation) and is associated several classes of buildings and bridges : these classes are defined by considering the expected final consequences of damages due to earthquakes. Although guided by the Eurocode, the choice of the appropriate class for a particular project leaves some flexibility to the user for interpretation and judgement.

EN 1990 includes a very innovative operational Informative Annex B entitled "Management of Structural Reliability for Construction Works". It clarifies some concepts, (for example the distinction between reliability differentiation and compensating measures to preserve a given reliability level), and provides guidance on the methods which can be adopted at national levels to use these concepts.

Annex B recognises that, at the present time, the requirements for reliability are related to the structural members of the construction works only, and not to the whole structure. This also applies if a design is directly based on probabilistic methods, which is allowed by EN1990 provided an agreement is made with the relevant authority. The designer can also select different levels of reliability, e.g. for structural safety or for serviceability, taking into account

- the cause and /or mode of attaining a limit state ;
- the possible consequences of failure in terms of risk to life, injury, potential economic losses ;
- public aversion to failure ;

– the expense and procedures necessary to reduce the risk of failure.

Annex B defines qualitatively three consequences classes (CC) by considering the consequences of failure or malfunction of the structure. For example, residential and office buildings belong normally to the medium class (CC2). Three reliability classes (RC), which may be defined by the β reliability index concept, are associated to the three consequences classes, and are given in Table 3.

Table 3 : Reliability classes and recommended minimum values for reliability index β

Reliability Class	**Minimum values for β**					
	Ultimate limit states		Fatigue		Serviceability	
	1 year reference period	50 years reference period	1 year reference period	50 years reference period	1 year reference period	50 years reference period
RC3	5,2	4,3				
RC2	4,7	3,8		1,5 to 3,8	2,9	1,5
RC1	4,2	3,3				

In EN 1990, it is assumed that the values of β in Table 3 correspond, for ultimate limit states, to levels of safety for reliability class RC2 structural members. Nevertheless, a design using EN 1990 with the recommended values of partial factors given in Annex A1 (application for buildings) and the other design Eurocodes is generally considered to lead to a structure with a β value *greater than* 3,8 for a 50 year reference period. The probability of failure and its corresponding β index are only notional values that do not necessarily represent actual failure rates (which depend mainly on human errors). They are used as operational values for code calibration purposes and comparison of reliability levels of structures. This point is discussed in Para 5.

4. Design codes and risk management

A logical policy of risk management includes the two following steps,

- definition of objectives, i.e. levels beyond which foreseeable damages become unacceptable,
- adoption of a strategy, i.e. definition of the means to attain these objectives,

with choices based on a socio-economic optimisation.

It is very difficult to develop a codified system, including design, product, execution, and testing standards, giving homogeneous levels of reliability, in particular because public opinion is inconsistent : additional requirements in regulations and codes generally follow tragedies. For these reasons, most of the decisions in risk management taken by the relevant authorities are at present limited to nuclear safety, fire, explosions due to dust, gas, etc., earthquakes, road safety (provisions and resistance of barriers, parapets, etc.) and safety at work.

It should be understood that codified failure probability thresholds are only mathematical tools : they do not mean that some rates of tragedies are acceptable. For example, the fact that the characteristic value of a material strength is based on a 5% fractile does not prevent the designer adopting a conservative attitude if he believes that very low values can be expected.

For some applications, the Eurocodes provide a degree of flexibility and choice to establish design and verification rules in agreement with the relevant authority, in particular when :

- determining some basic calculation data (e.g. ground properties, or wind related data, or direct assessment of actions that are not codified ...) ;
- selecting design situations (especially the accidental ones) and measures intended for structural robustness ;
- refinement and precision of calculations (number of cross sections to be verified, definition and properties of finite elements ...).

As a consequence, engineering judgement in structural design remains, and will remain, necessary. This implies that design codes have to be necessarily flexible enough to allow engineers to exercise their judgement, whilst limiting the risk of voluntary or involuntary misinterpretation.

5. Reliability management in EN 1990

As stated in Para 3 of this paper, EN 1990 recognises that a design using the recommendations of the suite of the structural Eurocodes together with quality management and other measures is considered to lead to a structure with a β value *greater than* 3,8 for a 50 year reference period. Examples of such measures include preventative and protective measures; measures relating to design calculations; measures aimed to reduce errors in design and execution of the structure, and gross human errors, and the provision of adequate inspection and maintenance.

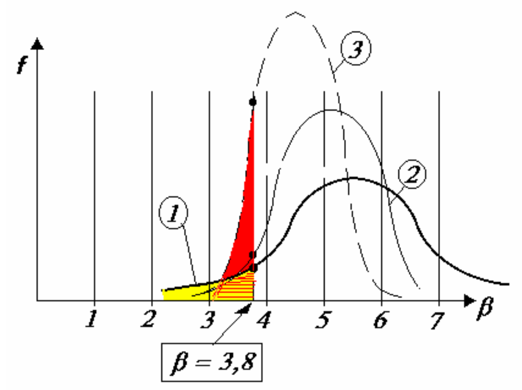

Fig. 2 : Histograms of β values for construction works (symbolic representation)

Many investigations have been performed in the past (for example CEB Bulletin 202) [7], consisting of the calculation of β factors, corresponding to ultimate limit states, for structures or structural elements designed with various standards on the basis of realistic data concerning actions and resistances. They consistently show a significant scatter of the β values. A comparable scatter would probably be found using the Eurocode suite. This is due to the fact that all codified models (models for actions, resistances, structural analysis, etc.), including numerical values, are unavoidably approximate in order to simplify design in the most common cases and be more or less appropriate for each particular case. Symbolically, Figure 2 shows a representation of histograms of relative frequency of β values for an assumed large number of calculations : curve 1) corresponds to buildings and curve 2) to bridges. The difference between bridges and buildings is due to the higher levels of design supervision, control of material quality and execution inspection given to the design and execution of bridges. This is an example of reliability differentiation by the requirements for quality levels.

A certain proportion of construction works may have a β value less that 3,8 in 50 years. Many engineers consider that this value should be considered as a target value for the calibration of the whole system actions-resistances-partial factors. Considering the case of buildings, it could be envisaged to lower the average value of the β factor (curve 3 in fig. 2), but with a corresponding reduction in the scatter, so that the proportion of construction works below $\beta = 3{,}8$ would remain approximately the same. Such lowering of the average β index value can be obtained by using expressions (6.10a) and (6.10b) of EN 1990 for combinations of actions applicable to ultimate limit states of resistance instead of the classical expression (6.10)[1].

As already stated, the normal reliability level can be maintained by the adoption of higher quality levels in design and execution. Other means have been used in the Eurocodes. For example, the adjusting factors α and β for traffic loads (ENV1991-3) are normally intended to keep constant reliability levels in different traffic conditions, but they might be used also to define reliability classes (to be applied, for example, for the assessment of existing bridges).

The main tools selected in EN1990 Annex B for the management of structural reliability of construction works are :

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[1] Expression (6.10) writes : $\sum_{j\geq1}\gamma_{G,j}G_{k,j}"+"\gamma_P P"+"\gamma_{Q,1}Q_{k,1}"+"\sum_{i>1}\gamma_{Q,i}\psi_{0,i}Q_{k,i}$. Expressions (6.10a) and (6.10b) are :

$$\sum_{j\geq1}\gamma_{G,j}G_{k,j}"+"\gamma_P P"+"\gamma_{Q,1}\psi_{0,1}Q_{k,1}"+"\sum_{i>1}\gamma_{Q,i}\psi_{0,i}Q_{k,i} \quad \text{and} \quad \sum_{j\geq1}\xi_j\gamma_{G,j}G_{k,j}"+"\gamma_P P"+"\gamma_{Q,1}Q_{k,1}"+"\sum_{i>1}\gamma_{Q,i}\psi_{0,i}Q_{k,i}$$

where ξ is a reduction factor for unfavourable permanent actions : its recommended value for buildings is 0,85.

- differentiation by β values (see Table 3) ; at this stage, this is a specialist activity ;
- modification of partial factors ;
- design supervision differentiation ;
- inspection during execution

A reliability differentiation can be envisaged by distinguishing classes of γ_F factors to be used in the fundamental combinations of actions for persistent design situations. EN1990 Annex B suggests the use of a multiplication factor K_{FI} applicable to γ factors of unfavourable actions : equal to 1,0 for the reliability class RC2 ($\beta \geq 3{,}8$), 0,9 for reliability class RC1 and 1,1 for reliability class RC3.

EN1990 Annex B allows the linking of the reliability classes to the requirements for quality levels of the design (DSL, design supervision level) and execution process (IL, inspection level).

With reference to design supervision levels, the Annex also envisages a classification of designers and/or design inspectors (checkers, controlling authorities etc) that depends on their competence and experience and their internal organisations, for the relevant type of construction works.

Annex B also recommends that a partial factor product property, or a member resistance can be reduced if an inspection class higher than that required according to Table 6 and/or more severe requirements are used.

6. Conclusion

The Eurocode system and in particular EN 1990 is very innovative in the field of reliability and risk management. For the first time an operational code (EN 1990) recognises the possibility of using an alternative probabilistic approach, and the use of tools, explained in this paper, for the management of structural reliability of construction works ; and that a design in accordance with the Eurocode system leads to an acceptable reliability level assuming normal design supervision and execution inspection levels. This statement is justified by the fact that the actual number of structural failures per year in the world with loss of human life is well below other commonly accepted risks. If this statement is recognised as correct, differentiation or preservation of reliability levels, with the objective of a socio-economic optimisation of the resources to be used to build construction works, taking into account the cost of construction, all consequences of failure, and public perception, can be envisaged at national levels and/or for particular projects.

To meet the above objectives, achieving safety with increased economy, research needs to be encouraged in risk and safety engineering, in particular in the determination of representative values of actions (imposed, climatic and accidental) ; homogeneity of reliability levels across various structural parts, products and materials ; ground-structure interaction ; and the refinement of measures intended for the preservation or the differentiation of reliability. This research is required for the maintenance of the remarkable international code system developed during the last 25 years, the Eurocodes.

7. References

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