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Safety philosophy of Eurocodes

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ABSTRACT: This paper examines how the Eurocodes deal with structural safety and risk management in civil engineering. The questions of responsibility of the designer and/or of the architect are underlying, but are not treated in detail. On one hand, the public aversion to failure and the societal desire of protection are increasing; on the other hand, the organization of the construction industry (research of profits, lower cost of construction processes, strategy of engineering companies, increasing of subcontracting) is a serious source of risks. What can be done in standards to invite engineers to exert their expertise in better conditions? The current format of verification of construction works is the semi-probabilistic format, called limit state design, and based on the partial factor method. Of course, it is possible to adjust the reliability levels by selecting the numerical values of the partial factors at the national levels, but, in reality, such a procedure is rather limited: changes of political nature are needed to reduce risks in civil engineering.

Keywords: Risk, Reliability, Safety, Structural Design, Accidental Actions, Eurocodes.

1 INTRODUCTION

Code of Hammurabi, Babylon, 1760 BC: if a builder builds a house for some one, and does not construct it properly, and the house which he built fall in and kill its owner, then that builder shall be put to death.

The concepts of safety, risk and hazard scenario are defined and mainly commented in two Eurocodes : EN 1990 "Basis of structural design" and EN 1991-1-7 "Eurocode 1 - Actions on structures – Part 1-7 : General actions - Accidental actions". The seismic risk is dealt with in EN 1998 "Eurocode 8 – Design of Structures for Earthquake Resistance" which gives the general performance requirements, the definition of the seismic action, structural analysis methods, and general concepts and rules applicable to civil engineering works.

From a general point of view, safety, risk and uncertainty are key features of most business and government problems and need to be understood to take rational decisions. A risk is an issue, item, event which may occur or not, and which may have a negative impact.

2 GENERAL REQUIREMENTS FOR CONSTRUCTION WORKS

From a general point of view, the main objective of Eurocodes remains the structural resistance to ensure safety of people. Section 2 of EN 1990 gives the general requirements for a structure. Of course, a structure shall be designed to have adequate structural resistance, serviceability, and durability (EN 1990, 2.1(2)P), and in the case of fire, the structural resistance shall be adequate for the required period of time (EN 1990, 2.1(3)P). But, moreover, a structure shall be designed and executed in such a way that it will not be damaged by events such as explosion, impact, and the consequences of human errors, to an extent disproportionate to the original cause (EN 1990, 2.1(4)P).

This last requirement is at the origin of the definition of structural robustness. It derives from Essential Requirement Nr. 1 of Council Directive 89/106/EEC of 21st December 1988 (CPD) on the approximation of laws, regulations and administrative provisions of the Member States relating to construction products (Annex I)[1] and its interpretation is not easy, in particular the "consequences of human errors".

In addition, potential damage shall be avoided or limited by appropriate choice of one or more design principles. Specific requirements are taken into account in case of fire.

In short, the first step of risk management is a good design to limit potential damage in case of undesired events. These events, taken into account through accidental design situations, shall be sufficiently severe and varied so as to encompass all conditions that can reasonably be foreseen to occur during the execution and use of the structure (EN 1990, 3.2(3)P).

In EN 1991-1-7, the global strategy concerning accidental actions distinguishes "identifiable" accidental actions (impact, explosions) and actions "resulting from an unspecified cause" (in clear, unidentified action origins). Of course, the selected design situations shall be sufficiently severe and varied so as to encompass all conditions that can reasonably be foreseen to occur during the execution and use of the structure (EN 1990, 3.2(3)P). Finally, it is the responsibility of the designer to define, for the client, possible reliability levels associated with risk levels (financial, economical, loss of human life, etc.).

3 APPROACH OF STRUCTURAL RELIABILITY IN THE EUROCODES

3.1 Reliability and reliability levels

Reliability is defined in EN 1990 (1.5.2.17) as the ability of a structure or a structural member to fulfil the specified requirements, including the design working life, for which it has been designed. Structural reliability covers in fact four aspects : safety, serviceability, durability and robustness of a structure.

Different levels of reliability may be adopted for structural resistance and for serviceability: they are selected by the designer who takes into account the possible cause and /or mode of attaining a limit state (i.e. an undesired phenomenon), the possible consequences of failure in terms of risk to life, injury, potential economical losses, public aversion to failure, the expense and procedures necessary to reduce the risk of failure.

3.2 How structural safety may be ensured?

The levels of reliability relating to structural resistance and serviceability can be achieved by various methods, or a combination of various methods, listed in EN 1990, like preventative and protective measures, measures relating to design calculations (representative values of actions, choice of partial factors), measures relating to quality management, measures aimed to reduce errors in design and execution of the structure, and gross human errors, other measures relating to the following other design matters: they are the basic requirements ; the degree of robustness (structural integrity) ; durability, including the choice of the design working life ; the extent and quality of preliminary investigations of soils and possible environmental influences ; the accuracy of the mechanical models used ; the detailing, efficient execution, *e.g.* in accordance with execution standards referred to in EN 1991 to EN 1999, adequate inspection and maintenance according to procedures specified in the project documentation.

Concerning design calculations, the first difficulty is that they are intended to establish models of a highly complex reality, following rules which are sufficiently simple to be used by designers. The simplifications do not have absolutely general validity, and any rule must have a clear field of application, and application of standards often necessitates a properly based appraisal (engineering judgment). Another difficulty arises from the fact that no universal measure of safety exists; *even a probability of failure is not invariant at the level of practical applications,* since it varies considerably depending on the information data and assumptions according to which it is calculated. For dealing with problems of structural safety there are three possible approaches : pragmatic (related to the past), dogmatic (related to the future), and progressive (related to the present).

[1] This requirement is kept in the "Construction Product Regulation" (CPR) of the European Parliament and of the Council, adopted on the 20th of January 2011, which will replace the CPD.

3.2.1 - Definition, choice and classification of phenomena to be avoided; limit-states.
It is usually considered that the phenomena to be avoided are modeled through limit-states, generally highly idealized and hence conventional. However the concept of performance criteria is more general (it can directly include the past history of the structure). For some limit-states (exceeding the bearing capacity), the first occurrence should be avoided; for other limit states (e.g. crack opening of a concrete structure), only numerous repetitions can cause damage; but many limit-states are of an intermediate nature (for example upheaval from a support).

Exceeding some limit-states involves immediate collapse (brittle fracture, loss of equilibrium) while other cases involve slow or progressive failure (ductile fracture, cracking). Exceeding limit-states involves consequences which may be more ore less dangerous. The most important of these consequences is the probability - higher or lower - of the loss of human lives. In most cases the risks for the persons are indirectly taken into account by considering the risks for the structure itself.

Taking account of the above distinctions, the limit-states are grouped in categories corresponding to probabilities of the same order of magnitude. One category includes the ultimate limit-states, another includes the serviceability limit-states. Each category should then be sub-divided, e.g. according to whether the limit-state can be reached by the occurrence, on one or more occasions, of certain values of the variable actions, in order to determine the probabilities or permissible frequencies of reaching the corresponding action-effects.

Only certain limit-states can, more or less exactly, be studied by comparing the action-effects applied to a cross-section with resistances. To enlarge the field of application of a numerical value by artificial modification of another factor (compensation) can lead to confusion.

3.2.2 - Nature of the choices of acceptable probabilities of occurrence of phenomena to be avoided.
The choices of degrees of structural safety are not simple technical operations but, between certain limits, the result of arbitrary options of a political nature. It may however be supposed that dimensions close to the lower envelope of those resulting from different national codes should give satisfaction to the competent authorities.

As a consequence of the relative nature of the probability of occurrence of a limit state, the acceptance of a certain value (whether or not stated explicitly) of this probability is linked with the knowledge available at the time of this acceptance; the probability often has to be re-evaluated later on, and the consequences drawn from its acceptance then have to be reconsidered.

3.2.3 - Criteria which may be taken into account when choosing the probabilities of phenomena to be avoided.
a) *Economic criteria*, when used for a simple optimization, have often led, for ultimate limit-states, to safety factors which are too low to be acceptable. This may be explained by the fact that aversion to the risk increases more than proportionally to the magnitude of the risk and the corresponding probability. These criteria do however permit useful analyses and lead, for example, to introduction of the concept of economic barrier (important for ultimate states) and the concept of lifetime of a structure (design working life, important for some serviceability states and for fatigue).

b) *Analogic criteria* are based on knowledge of the risks supported or accepted in circumstances where human life is not connected with the safety of structures. Their relevance is indicative only. In particular, the death rate due to traffic accidents is very much higher than the rate that could be accepted as a result of accidents connected with structural failure.

c) *Psychological criteria* intervene in appraisals by individuals or groups of persons. Appraisals by the widest and the most permanent group constitute the public opinion. This one is subjective, deterministic, variable, emotional, and thus far from rational. For example, it pays more attention to the number of victims in a particular accident than to the total number of victims. Broadly, its demands result from recorded accidents and hence depend on the number of existing structures of different types.

d) *Legal criteria*, at the present time, have remained essentially deterministic, and hence cannot be used for making the choice. Attention is drawn to the fact that the need for clarification of the legal aspects of safety is keenly felt in many countries. Moreover, certain legal practices which automatically link accidents with mistakes and faults, as far as penalties are involved, without drawing certain distinctions, should be reformed.

e) *Ethical criteria* make it possible to take account of the value of human life by determining it indirectly by reference to analogic criteria. But they require in addition that account should be taken of the evolution of probabilities in the course of time in each particular case.

f) *Risks acceptable during execution* should be subjected to a special analysis which should examine certain specific concepts (consequences for the completed construction, nature of the accident at work, safety concerning the contractors execution measures, possibility of influencing the risk, temporary nature of the risk).

3.2.4 - Modification of acceptable probabilities depending on different criteria.
Modifications of this kind (reliability differentiation) should not be confused with modifications of factors intended to maintain the probabilities constant.

In EN 1990 (Informative Annex B), the question of relating different levels of control (or, better, of quality) to different design rules has been introduced. This Annex will be developed and probably become normative in the revised version of EN 1990, in liaison with the classification adopted in EC7.

4 THE SEMI-PROBABILISTIC FORMAT (PARTIAL FACTOR DESIGN)

The basic principles of the semi-probabilistic format for the verification of construction works may be expressed as follows. The verification rules introduce safety:

- by selecting appropriate representative values of the various random variables (actions and resistances),
- through the application of a set of calibrated partial factors,
- through safety margins, more or less apparent, in the various models (models of actions, of effects of actions and of resistances).

In the most common cases, the verification of the safety of construction works is based on the verification of an equation of the following type:

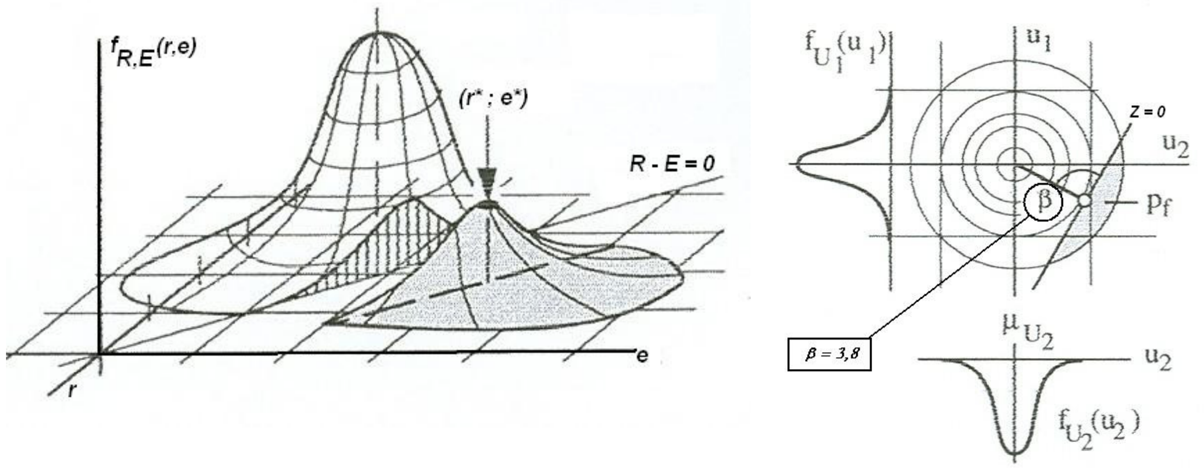
$E_d \leq R_d$

where E_d is the design value of the effect of actions such as internal force, moment or a vector representing several internal forces or moments, R_d is the design value of the corresponding resistance.

The general expressions for E_d and R_d are $E_d = E\{\gamma_{F,i} F_{rep,i} \; ; a_d\}$ and $R_d = R\left\{\eta_i \frac{X_{k,i}}{\gamma_{M,i}} ; a_d\right\}$

$F_{rep,i}$ is the relevant representative value of the action Nr. i (characteristic or other value), a_d is the design values of the geometrical data, X_{ki} is the characteristic value of the material or product property Nr. i, η_i is the mean value of the conversion factor taking into account volume and scale effects, effects of moisture and temperature, and any other relevant parameters, $\gamma_{F,i}$ and $\gamma_{M,i}$ are the global partial factors for action effects and resistances.

Their numerical values, which have been partially calibrated by using the structural reliability methods, are, in principle, based on a target value of the reliability index β equal to 3,8, which means a probability of failure of $7{,}2.10^{-5}$ in 50 years. The principles of the reliability theory (limited to the basic case of two random variables : E, effect of actions, and R, resistance) are summarized in figure 1.



Physical representation of the failure probability and coordinates of the design point

Reliability index in the normalised space

Figure 1. Principles of the reliability theory

Nevertheless, it is obvious that the partial factors cover “small errors”. But how can be defined the boundary between “small” and “gross” errors? Is it possible to compare a human error during execution and the misuse of an advanced software?

5 RISKS IN CIVIL ENGINEERING

Structural failures may happen during execution, immediately after execution or during normal use of construction works. Accidents are very frequent during execution. For example, there is probably one failure or collapse per week during construction of bridges in the World. In general, if the number of fatalities is low, information of the public is limited. The causes may be of various origins:

- human error (the most frequent) associated to a lack of supervision of execution,
- errors or underestimations in the design (inappropriate mechanical models, underestimation of actions –direction and magnitude – hazard scenarios not taken into account, construction processes, etc.);
- underestimation of problems due to an insufficient appraisal of scaling effects;
- excessively ambitious projects (architects, engineers, etc.).

Accidents arriving “immediately” after execution, i.e. after a few months or one or two years after the construction works are in use, are often difficult to explain. They may be due to an unforeseen short term behavior of the ground supporting the foundations.

Accidents during normal use of construction works may have many origins : scour effects due to exceptional flood, impacts and explosions, errors in dynamics (footbridges, football stands under crowd loading), errors in stability (in particular in case of structural modification of a building), lack of maintenance, etc.

The following non exhaustive list gives some hazards which may be encountered for construction works in use, or between uses and after use.

a) in use

to people in building

- stairs, floor finishes, glazing

to structure and people

- inadequate maintenance
- change of use

b) in maintenance

to people doing maintenance

- access, confined spaces
- hot materials, toxic materials
- falls from height, fragile roofs

c) in extension refurbishment and repair

- misunderstanding the original structure
- faults in the original structure
- earlier inappropriate modifications

d) in assessment

- incorrect assumptions (materials, structural form, loads)
- inadequate inspection

e) in demolition

- misunderstanding structure
- defects in structure
- inappropriate approach
- premature collapse, flying debris
- high risk elements; cantilevers, flat slabs, prestressed structures, retaining structures.

Of course, at any time, you may encounter risks like abnormal settlement, chemical attack in the ground, overload, misuse, terrorism, explosion, impact, instability, lack of redundancy or other robustness, novel materials and design concepts, corrosion and ageing, progressive/disproportionate collapse, risks to, or from, adjacent buildings, structures and other facilities.

Standards provide guidance to designers. Many of them recall that they must be used by qualified and experienced engineers like in the general assumptions of the Eurocodes. Indeed, the judgements which are common to most designs have been taken by the authors of the code, and the results set down in a manner which can be applied in design. When using a standard, the engineer implicitly accepts those judgements, in many cases without fully understanding the basis for them, or the limits on their application.

In particular, design standards assume that the structures they are applied to are 'normal' structures, and designers are not always able to recognise complexity. Complexity in the field of bridges may be more easily identified than complexity in the field of buildings. Outstanding structures are sometimes designed by architects who consider themselves as artists, and the problems of safety are to be dealt with by engineers, with poor fees !…

Should innovation be limited to avoid risks due to complexity? Of course, no. But for that reason the Eurocodes have introduced the principle, and some rules, of robustness.

Robustness is the ability of a system to resist damage but maintain its important functions. It is not limited to structures or even to physical systems; robustness principles can be applied to management systems. Robustness is somewhat different to other risk management systems in that it does not necessarily eliminate or reduce known risks, although it may do. Its primary value is in reducing the effect of unknown risks.

Strength and robustness are different. A single cantilever beam as a part of the main stability system should not be considered robust, however strong it might be, since its failure would lead to failure of the whole system. Although none of the design load cases could cause it to fail, it might be vulnerable to terrorist attack or a previously undiscovered form of brittle fracture.

EN 1990 proposes a classification of construction works, for the purpose of reliability differentiation, based on "consequences classes" (CC), i.e. by considering the consequences of failure or malfunction of the structure. This classification is described in Table 1 (EN 1990, Table B1).

Table 1. Definition of consequences classes

Consequences Class	Description	Examples of buildings and civil engineering works
CC3	**High** consequence for loss of human life, *or* economic, social or environmental consequences **very great**	Grandstands, public buildings where consequences of failure are high (e.g. a concert hall)
CC2	**Medium** consequence for loss of human life, economic, social or environmental consequences **considerable**	Residential and office buildings, public buildings where consequences of failure are medium (e.g. an office building)
CC1	**Low** consequence for loss of human life, *and* economic, social or environmental consequences **small or negligible**	Agricultural buildings where people do not normally enter (e.g. storage buildings), greenhouses

The criterion for classification of consequences is the importance, in terms of consequences of failure, of the structure or structural member concerned. Reliability classes are associated to these consequence classes. A refined classification for buildings is given in EN 1991-1-7 (Annex A).

For buildings in Consequences Class 3, a systematic risk assessment of the building should be undertaken taking into account both foreseeable and unforeseeable hazards.

6 CONCLUSIONS

Should design standards, and Eurocodes in particular, go beyond what is currently proposed? It is clear that the principles are good, but after, it is a matter of quality in the design, construction and maintenance processes. Lessons from accidents inspire the following additional list of design principles:

- Safety factors are not intended cover gross human errors.
- Foundations of civil engineering works have the same design working life as structures in general.
- Even if all individual parts of a structure are correctly designed, check the stability of the structure as a whole and ensure a minimum robustness.
- Avoid structures the stability of which is ensured by ties anchored in the ground and not protected against corrosion, exceptional or malicious actions.
- Avoid structures which are not damage-tolerant with regard to fatigue.
- Avoid structures with brittle members or sections: in case of rupture there is no pre-warning (the structure should be fault tolerant up to a certain degree).
- Avoid a too slender structure if a refined and pertinent dynamic analysis cannot be performed.
- Take into account structural effects of climatic changes.

Concerning the design process, risks are increasing for the following reasons:

- The societal needs are increasing.
- The cost of the structural part of construction works is decreasing (competition, global economy).
- As a consequence of the previous observation, engineering services are not correctly remunerated, time for design and construction is more and more shortened, the design is ensured by very small (and cheap) design offices without real technical competence, personnel on construction sites are not experienced, the control of quality by specialised companies is underpaid.

Finally, a system where all calculations made in a small design office are checked by the same person is not robust. Due to time constraints, the models may be inappropriate, the designer may have misunderstood the code, an important principle or a rule, or may fail to spot an error due to a particular combination of personal circumstances. Hopefully, for big projects, there is often a panel of experts following seriously the design process and give their opinion in reviews of the proposed approach. In some cases, sensitivity studies may be one way to judge the severity of a risk.

Finally, it is difficult to envisage an extension of the design codes to improve the situation concerning the management of risks in civil engineering : it is not a matter of partial factors or of probabilistic approach ; it is more a matter of education, in particular in engineering schools and universities and of organisation of the construction industry.

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