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RELIABILITY AND RISK ACCEPTANCE CRITERIA FOR CIVIL ENGINEERING STRUCTURES

Abstract

The specification of risk and reliability acceptance criteria is a key issue of reliability verifications of new and existing structures. Current target reliability levels in standards appear to have considerable scatter. Critical review of risk acceptance approaches to societal, economic and environmental risk indicates that an optimal design strategy is mostly dominated by economic aspects while human safety aspects need to be verified only in special cases. It is recommended to specify the target levels considering economic optimisation and the marginal life-saving costs principle, as both these approaches take into account the failure consequences and costs of safety measures.

Keywords

Reliability, risk, risk acceptance, standards, structures, target reliability.

1 INTRODUCTION

The specification of target reliability levels is one of the key issues of structural design. The target values recommended in various prescriptive documents need further feedback and should be further analysed. *ISO 2394:2015* indicates procedures for estimating target reliability levels by optimisation of the total cost related to an assumed remaining working life of a structure. These approaches are critically compared with individual and societal risk acceptance criteria, with target levels based on a marginal life-saving costs principle, and with recommendations of present standards. Conclusions for future developments are drawn.

2 RISK ACCEPTANCE

This chapter provides the summary of risk acceptance criteria that were described in more details in [1]; references to other studies are provided.

2.1 Human risk

In general two types of human risk are distinguished: the individual and the societal risk. The annual probability of being harmed describes the risk to an individual due to a hazardous situation and is called the individual risk. In this contribution the risk to society as a whole is of prime interest and therefore this societal risk is considered herein. The societal risk is often represented in the form of a numerical *F*-*N*-curve [2, 3]. This curve (*N* represents the number of fatalities and *F* is the

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frequency of accidents with more than N fatalities) shows the probability of exceedance as a function of the number of fatalities N on a double logarithmic scale [4]:

$$1 - F_N(x) = P(N > x) = \int_x^{\infty} f_N(x)\,\mathrm{d}x \qquad (1)$$

where:

$f_N(x)$ – is the probability density function of number of fatalities per year and

$F_N(x)$ – the probability distribution function of the number of fatalities per year, representing the probability of less than x fatalities per year.

A simple measure for societal risk is the annual expected value of the number of fatalities, which is frequently used to compare alternative projects in terms of their inherent risk.

Typical F-N curves reported in the literature show different curves for the same industrial activity in various countries or for different industrial activities in the same country. The following general formula has been proposed to represent the societal human risk acceptance criterion:

$$F \leq aN^{-k} \qquad (2)$$

where:

a, k – are given constants.

The constants a and k can be related to statistical observations from natural and man-made hazards. Some natural hazards show relationships with k slightly smaller than unity while most manmade hazards are described by a relationship with $k > 1$. From statistical observations the constants a and k vary widely depending on the type of hazard and the type of technical activity. It has been proposed to set the constants such that the curve envelops the curves for most natural hazards and some more common man made hazards from below [12]. For acceptable risks in case of structural failures as an example the constant would be around $a = 10^{-6}$ and for marginally acceptable risks $a = 10^{-4}$; $k = 1$ represents risk-neutral curves, $k > 1$ describes curves with risk aversion and $k < 1$ curves with risk proneness. The case of $k < 1$ leads to infinitely large expected losses (in terms of lives or cost) and, therefore, is not acceptable. Based on the F-N curves the so-called ALARP (as low as reasonably possible) region can be defined by two limits [2]. The upper limit represents the risk that can be tolerated in any circumstances while below the lower limit the risk is of no practical interest. Such acceptability curves have been developed for various industrial fields including the chemical and the transportation industry [1].

In the ALARP principle the “width” between upper and lower bound curves is of importance. In many cases this width is two orders of magnitudes allowing for too much flexibility in practical cases. It is noted further here that human safety does not only involve fatalities but also injuries. In many studies injuries are related to fatalities by using a multiplicative factor as for example 0.1 for moderate injury and 0.5 for major injury. Based on this simple procedure weighted fatalities can be obtained.

Note that optimal values of the parameters a and k should be carefully specified taking into consideration a reference system – a group of buildings or an individual structural member - and other structure-specific and industry-specific parameters [18]. An example of fatality criteria (F-N curves) in various European countries is given in Fig. 1 [23].

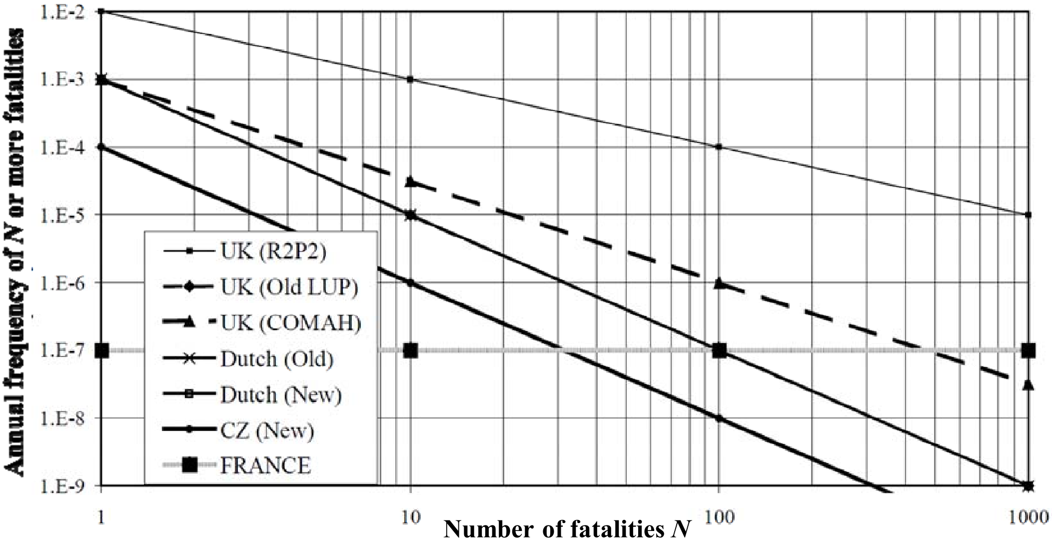

Fig. 1: *F-N* curves relating expected fatalities (*N*) from an accidental event or failure and the annual frequency of occurrence (*F*) of events with not less than *N* fatalities in various countries [23]

2.2 Environmental and economic risks

Besides human safety, environmental and economic risks play an important role in decision making. The environmental consequences can be presented in terms of permanent or long-term damage to terrestrial, freshwater, marine habitats and groundwater reservoir. Thereby the parameter of damage can be the damaged area. A different parameter has been selected by NORSOK [5] in which the recovery time from the accident defines the damage. The overall principle implies that recovery following environmental damage shall have an insignificant duration when compared to the expected period (return period) between such damages. For details see [1].

Economic consequences are direct consequences related for example to repair of initial damage and replacement of equipment/contents and indirect consequences such as loss of production, temporary relocation, rescue costs or loss of reputation. Analogous to the *F-N* curve and the expected number of fatalities *F-D* curves with *D* the economic damage can be established. Detailed discussion is provided in the following chapter.

3 DECISION CRITERIA BASED ON COST OPTIMIZATION

ISO 2394:1998 indicates that the target level of reliability should depend on a balance between the consequences of failure and costs of safety measures. From an economic point of view the objective is to minimize the total working-life cost. The expected total costs C_{tot} may be generally considered as the sum of the expected structural cost, costs of inspections and maintenance, and costs related to failure (malfunction) of a structure. The decision parameter(s) d to be optimised in structural design may influence resistance, serviceability, durability, maintenance, inspection strategies etc. Examples of d include shear or flexural resistances, stiffness of a girder to control deflections etc. In the present study the decision parameter is assumed to represent structural resistance affecting ultimate limit states. Moreover, the benefits related to use of the structure that in general should be considered in the optimisation are assumed to be independent of a value of the decision parameter.

According to *ISO 13822:2010* lower target reliability levels can be used if justified on the basis of societal, cultural, economical and sustainable considerations. *ISO 2394:2015* indicates that the target level of reliability should depend on a balance between the consequences of failure and costs of safety measures. From an economic point of view the objective is to minimize the total working-life cost.

The structural cost consists of:

- Cost C_0 independent of the decision parameter (surveys and design, temporary and assembly works, administration and management, etc.),
- Cost $C_1(d)$ dependent on the decision parameter; normally the linear relationship can be accepted, $C_1 \times d$.

In general the former cost exceeds significantly the latter i.e. $C_0 >> C_1 \times d$; see [6] and *ISO 15686-5:2008*.

The failure cost C_f - the cost related to consequences of structural failure may include (depending on a subject concerned, *ISO 2394:2015*):

- Cost of repair or replacement of the structure,
- Economic losses due to non-availability or malfunction of the structure, as discussed before,
- Societal consequences (costs of injuries and fatalities that can be expressed e.g. in terms of compensations or insurance cost),
- Unfavourable environmental effects (CO_2 emissions, energy use, release of dangerous substances, as related to the aforementioned environmental risk),
- Other (loss of reputation, introducing undesirable 'non-optimal' changes of design practice).

The estimation of the failure cost is a very important, but likely most difficult step in the cost optimisation. According to *ISO 2394:2015* not only direct consequences of failure (those resulting from the failures of individual components), but also follow-up consequences (related to malfunction of a whole structure) should be included.

For consistency, the structural and failure costs need to be expressed on a common basis. This is achieved by converting the expected failure costs, related to a working life t, to the present value [7]:

$$\mathrm{E}[C_f(t,d)] \approx C_f\, p_f(d)\, Q(t,d) \tag{3}$$

where:

C_f – is the present value of the failure cost,

$p_f(d)$ – failure probability related to a basic reference period [7, 24] and

Q – is a time factor.

The expected total costs are expressed as:

$$\mathrm{E}[C_{tot}(t;d)] = C_0 + C_1 \times d + C_f\, p_f(d)\, Q(t,d) \tag{4}$$

The optimum value of the decision parameter d_{opt} (optimum design strategy) is then obtained by minimising the total cost. Apparently d_{opt} is independent of C_0. Following the JCSS Probabilistic Model Code [12], Annex G of *ISO 2394:2015* indicates the target reliabilities based on economic (monetary) optimisation. More details are provided in the recent papers: [8, 9, 24] for structural design and [7, 13] for assessing existing structures.

The time factor Q is obtained for a sum of the geometric sequence [8, 9]:

$$Q(t_{ref}, d) = \frac{1 - \left[(1 - p_f(d))/(1+q)\right]^{\frac{t_{ref}}{t_0}}}{1 - \left[(1 - p_f(d))/(1+q)\right]} \tag{5}$$

where q = annual discount rate for which *ISO 15686-5:2008* assumes values between 0 and 0.04. *ISO 2394:2015* then suggests 0.01-0.03 for most Western economies and 0.05-0.08 for most Asian economies. Lentz [10] discussed in detail discounting for private and public sectors, indicating values around 0.05 for a long-term average of q while Lee and Ellingwood [14] suggested lower values for investments over multiple generations.

4 MARGINAL LIFE SAVING COSTS PRINCIPLE

The Life Quality Index LQI [15] and several other metrics were derived to support decisions related to allocations of available public resources between and within various societal sectors and industries. The LQI is an indicator of the societal preference and capacity for investments into life safety expressed as a function of GDP, life expectancy at birth and ratio between leisure to working time (*ISO 2394:2015*).

The ISO standard provides detailed guidance on how preferences of the society in regard to investments into health and life safety improvements can be described by the LQI concept. The target level is derived by considering the costs of safety measures, the monetary equivalent of societal willingness to save one life, and the expected number of fatalities in the event of structural failure. Essentially, this approach combines economic and human safety aspects. Compared with economic optimization, it should lead to lower target reliability indices, as only the human consequences of structural failure are taken into account, while other losses such as economic and environmental costs as briefly discussed in Section 2 are disregarded.

In principle, the LQI approach weighs the value of the expected casualties of a certain activity against the economic value of the activity. In such an analysis, the danger to which the people are subjected might vary on an individual basis within the group of people affected, which may be deemed unethical [13]. Examples of application of the LQI approach are provided in [7, 11, 16, 17].

5 DIFFERENCE BETWEEN DESIGN OF NEW AND ASSESSMENT OF EXISTING STRUCTURES

Risk acceptance criteria and related target reliabilities for structural design and assessment of existing structures are discussed in scientific literature. The recent contributions [7, 13, 19] revealed that the differences between the assessment of existing structures and structural design – considering higher costs of safety measures for existing structures as a key one – are often inadequately reflected. The following remarks may be useful when specifying target reliability levels for assessment of existing structures:

- The approaches discussed in previous sections apply for both new and existing structures.
- It is uneconomical to require the same target reliabilities for existing structures as for new structures [7, 20-22]. This requirement is consistent with regulations accepted in nuclear and offshore industry, for buildings in seismic regions, bridges in USA and Canada, etc.
- Minimum levels for human safety are commonly decisive for existing structures while economic optimisation dominates the criteria for design of new structures [7].
- Two target levels are needed for the assessment of existing structures – the minimum level below which a structure should be repaired and the optimum level for repair [7, 13].

6 IMPLEMENTATION OF TARGET RELIABILITY IN CODES

Target reliability criteria are implemented in various international and national standards. In *EN 1990:2002* and *ISO 2394:2015* the index β is generally used as a measure of the reliability. The reliability index is related to the failure probability through the inverse of the standardized normal cumulative distribution. It is noted that the target reliability levels in codes of practice provide criteria for limit states that do not account for human errors, i.e. the target levels should be compared with the so-called notional reliability indicators, *ISO 2394:2015*. The target levels are differentiated with respect to various parameters. It is shown here that the target reliability can be specified by taking into account:

1. *Costs of safety measures* that should reflect efforts needed to improve structural reliability considering properties of construction materials and characteristics of investigated failure modes. The relative cost of safety measures significantly depends on the variability of load effects and resistances [6].
2. *Failure consequences* are understood to cover all direct and indirect (follow-up) consequences related to failure including human, economical and environmental impacts. When specifying these costs the distinction between ductile or brittle failure (warning factor), redundancy and possibility of progressive failure (collapse) should be taken into account. In this way it would be possible to consider the system failure in component design. However such an implementation is in practice not always feasible and therefore consequence classes are specified with respect to use of the structure in *EN 1990:2002* and to the corresponding number of persons at risk in *ASCE 7-10:2010*. Detailed classification with respect to importance of a structure and expected failure consequences provides the Australian and New Zealand standard *AS/NZS 1170.0:2002*.
3. *Time parameters.* Target levels are commonly related to a reference period or a design working life. The reference period is understood as a chosen period of time used as a basis for statistically assessing time-variant basic variables, and the corresponding probability of failure. The design working life is considered here as an assumed period of time for which a structure is to be used for its intended purpose without any major repair work being necessary. The concept of reference period is therefore fundamentally different from the concept of design working life. Obviously target reliability should be always specified together with a reference period considered in reliability verification. *ISO 2394:2015* indicates the remaining working life can be considered as a reference period for the serviceability and fatigue limit states while a shorter reference period might be reasonable for the ultimate limit states. When related to failure consequences, it is proposed here to refer to lifetime probabilities if economic consequences are decisive. When human safety is endangered, other reference periods such as one year are commonly accepted.

EN 1990:2002 recommends the target reliability index β for two reference periods (1 and 50 years); see example for medium consequences of failure in Tab. 1. These target reliabilities are intended to be used primarily for the design of members of new structures. The two β-values given in Tab. 1 are provided for two reference periods used for reliability verification and should correspond approximately to the same reliability level:

- $\beta = 3.8$ should be thus used provided that probabilistic models of basic variables are related to the reference period of 50 years,
- The same reliability level should be approximately reached when $\beta = 4.7$ is applied using the related models for one year and failure probabilities in individual yearly intervals (basic reference periods for variable loads) are independent.

Tab. 1: Target reliability indices according to selected standards

Standard	Failure consequences	Reference period	β in standard
EN 1990:2002	medium	50 y. (1 y.)	3.8(4.7)
ISO 2394:1998	moderate	life-time	2.3/ 3.1/ 3.8*
ISO 2394:2015 (economic optimization)	Class 3	1 y.	3.3/ 4.2/ 4.4*
ISO 2394:2015 (LQI)	-	1 y.	3.1/ 3.7/ 4.2*
ISO 13822:2010	moderate	min. per. safety	3.8

*High/ moderate/ low relative costs of safety measures, respectively.

Considering an arbitrary reference period t_{ref}, the reliability level is derived from the annual target in accordance with *EN 1990:2002* as follows:

$$\beta_{tref} = \Phi^{-1}\{[\Phi(\beta_1)]^{tref}\} \qquad (6)$$

where:

$\Phi(\cdot)$ – the inverse cumulative distribution function of the standardized normal distribution (Φ^{-1} being its inverse) and

β_1 – is the target reliability index related to the reference period t_{ref} = 1 year.

Note that Equation (6) should be used with caution as the full independency of failure events in subsequent years (reference periods) is frequently not realistic.

When compared to *EN 1990:2002*, a more detailed and substantially different recommendation is provided by *ISO 2394:1998*. The target reliability index is given for the working life and related not only to the consequences but also to the relative costs of safety measures, as exemplified in Tab. 1. The consideration of costs of safety measures is particularly important for existing structures. According to *ISO 2394:1998* the target level for existing structures apparently decreases as it takes relatively more effort to increase the reliability level compared to a new structure. Consequently for an existing structure one may use the values of one category higher, i.e. instead of "moderate" consider "high" relative costs of safety measures [7].

Similar recommendations are provided in the JCSS Probabilistic Model Code [12] and *ISO 2394:2015*. Recommended target reliability indices are also related to both the consequences and to the relative costs of safety measures, however for the reference period of one year. *ISO 2394:2015* gives target levels based on economic optimization and acceptance criteria using the Life Quality Index LQI [6].

In *ASCE 7-10:2010* buildings and other structures are classified into four risk categories according to the number of persons at risk. Category I is associated with few persons at risk and category IV with tens of thousands. For all loads addressed by the standard except earthquake, *ASCE 7-10:2010* aims to reach target annual reliability ranging from 3.7 for category I up to 4.4 for category IV. The Canadian Standards Association uses for bridges a different and slightly more detailed approach than the documents presented above by including additional factors such as inspectability.

ISO 13822:2010 related to the assessment of existing structures indicates four target reliability levels for different consequences of failure (the ultimate limit states): small - 2.3, some - 3.1, moderate - 3.8 and high - 4.3. The related reference period is "a minimum standard period for safety (e.g. 50 years)". Recommendations on the target reliability levels are also provided in several national standards; some of these suggest reducing reliability levels for existing facilities while the same target reliabilities are required for existing and new structures in many others.

7 CONCLUSIONS

The parameters of risk acceptance criteria used in industrial applications appear to have considerable scatter. Comparison of selected approaches provided in Tab. 2 indicates that:

- Rational risk acceptance criteria are needed for human safety, economic and environment consequences of structural failure.
- The target reliability levels recommended in current documents are inconsistent in terms of the criteria and their parameters.
- In general the optimum reliability levels should be specified considering both the relative costs of safety measures and failure consequences over the design working life under the constraints imposed by human safety.

- An overall design strategy is mostly dominated by economic aspects while human safety aspects need to be verified only in special cases.
- It is recommended to specify the target reliability levels considering economic optimisation and the marginal life-saving costs principle, as both these approaches take into account the failure consequences and the costs of safety measures.

Tab. 2: Comparison of the discussed approaches

Approach	Advantages	Deficiencies	Applied in ISO
Human risk – *F-N* curve	- easy to apply - few input parameters needed - traditionally applied in many industries, comparisons amongst different activities possible	- in some cases risk averse decisions may be obtained favouring certain categories of lives - costs of safety measures are not directly taken into account (though they can be reflected by optimising procedure)	*ISO 2394:1998*
Cost optimisation	- enables to propose an optimal design strategy with respect to the whole life cycle costs - provides the optimum solution for an owner irrespective of other industrial sectors	- often difficult to specify failure consequences - discount rates are difficult to be specified for long-term design working lifetimes	*ISO 2394:1998* and *2015*, *ISO 13822:2010*
Marginal life saving costs principle – LQI	- combines human safety and economic optimisation - enables to compare life-saving investments in different industrial and societal sectors	- depends on socio-economic factors that may be difficult to assess in a long-term perspective - weighs the value of the expected casualties of a certain activity against the economic value of the activity; the danger to which the people are subjected might vary on an individual basis within the affected population	*ISO 2394:2015*

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