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Determination of Target Safety for Structures

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ABSTRACT: Codes of practice aim at guaranteeing structures having the risks acceptable to the public and the minimum total costs over a design working life. However, current criteria for structural design provide a broad range of target reliability indices, specified often for different reference periods even though their recalculation for different reference periods is indeterminate due to mutual dependence of failure events. General approaches for selecting target reliability levels are discussed in view of cost-benefit optimisation and human safety aspects. Design strategies seem to be driven by economic arguments rather than by human safety criteria.

1. INTRODUCTION

The target reliability levels recommended in various national and international documents for new structures are inconsistent in terms of the values and the criteria according to which the appropriate levels are to be specified. In general, optimum reliability levels can be obtained by considering both the relative costs of safety measures and the expected consequences of failure over the design working life as indicated e.g. in *ISO 2394:1998* for the general principles on structural reliability and approved draft *ISO/FDIS 2394:2015*. In accordance with this standard the minimum reliability for human safety should also be considered when people may lose their life or may be injured due to structural failure.

In this study procedures and current codified criteria for new buildings and bridges are critically reviewed, focusing on ultimate limit states. General approaches for selecting target and acceptable reliability levels include cost-benefit optimisation and human safety criteria. These approaches are discussed considering different consequence classes; obtained results are compared with the recommendations given in present standards.

2. TARGET RELIABILITY LEVELS IN CODES

As a measure of safety the reliability index β is related to the failure probability through the inverse of the standardised normal cumulative distribution (*EN 1990:2002*, *ISO/FDIS 2394:2015*). The target levels are differentiated in view of various aspects. It is shown here that the target reliability can be specified by taking into account:

2.1. Costs of safety measures

These costs 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 (Vrouwenvelder 2002).

2.2. Failure consequences

Herein failure consequences are understood to cover all direct and indirect (follow-up) consequences related to failure; see Section 4.

When specifying these costs the distinction between ductile or brittle failure (warning factor), redundancy and possibility of progressive 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 usually specified as a function of the use of the structure (*EN 1990:2002*) and the corresponding number of persons at risk (*ASCE 7-10:2010*).

2.3. Time aspects

Target levels are commonly related to a reference period or a design working life. The reference period is understood as a period of time used to specify time-variant basic variables, and to assess 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, the target reliability should be always specified together with a reference period considered in reliability verification.

2.4. Recommended values

EN 1990:2002 recommends the target reliability index β for the two reference periods - 1 and 50 years; see example for medium consequences of failure in Table 1. The two β-values given in Table 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 is approximately reached when $\beta = 4.7$ is applied using statistical models and parameters related to one year, and when failure probabilities in individual years are independent (basic reference periods for variable loads t_0; see Section 3).

Table 1: Target reliability indices for different reference periods and comparable failure consequences according to selected standards.

Standard	*Failure conseq.*	*Refer. Period*	β
EN 1990:2002	*medium*	*50 years* *(1 year)*	*3.8* *(4.7)*
ISO 2394:1998	*moderate*	*life-time*	*3.1*[*]
ISO/ FDIS 2394:2015	*moderate*	*1 year*	*4.2*[**]

[*] For moderate relative cost of safety measures. [**] For normal relative cost of safety measures.

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

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

where $\Phi(\cdot)$ = inverse cumulative distribution function of the standardised normal distribution (Φ^{-1} being its inverse); and β_1 = target reliability index taken for a reference period t_{ref} of one year.

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 (Table 1). Note that the consideration of costs of safety measures is particularly important for existing structures.

Similar recommendations are provided in (JCSS 2001) and in *ISO/FDIS 2394:2015* using economic optimisation (termed also as monetary optimisation). Recommended target reliability indices are again related to both consequences and relative costs of safety measures, however for the reference period of one year (Table 1). In addition *ISO 2394:1998* and *ISO/FDIS 2394:2015* include acceptance criteria for human safety, see Section 5.

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 from 3.7 for category I up to 4.4 for category IV (Hamburger 2013). *CAN/CSA-S6-00:1981* proposes a slightly more detailed approach for bridges by including additional factors such as inspectability.

2.5. Application

Application of the target reliability indices indicated in Table 1 is demonstrated by an example of a moderately important bridge with reasonable possibilities of detours in the case of malfunction of the bridge. The following classification can be expected.

- In accordance with *EN 1990: 2002* medium failure consequences are relevant for designing a key component (pier, main girder) of the bridge.
- In accordance with *ISO/FDIS 2394: 2015* moderate consequences and normal relative cost of safety measures can be accepted for structural design.

For the reference period $t_{\text{ref}} = 1$ year, Table 1 indicates two different reliability indices:

- $\beta_1 = 4.7$ for *EN 1990:2002* and
- $\beta_1 = 4.2$ for *ISO/ FDIS 2394:2015*.

ISO 2394:1998 indicates $\beta = 3.1$ for the working life of 100 years. This value would then be accepted for $t_{\text{ref}} = 100$ years, for $t_{\text{ref}} = 1$ year Eq. (1) leads to $\beta_1 = 4.3$. The range of β-values is relatively broad; *EN 1990:2002* specifies levels by about 0.5 greater than the ISO standards.

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/FDIS 2394:2015*).

3. EFFECT OF REFERENCE PERIOD

Eq. (1) is based on the assumption of independent failure events in subsequent years. The target level $\beta = 3.8$ in Table 1 could better be interpreted as corresponding to $\beta_1 = 4.5$ (and not to 4.7) as full independency of failure events in subsequent years is hardly realistic (Vrouwenvelder 2002).

To illustrate this let us assume that basic periods t_0 can be identified in such a way that failure events are independent during amongst the basic periods. Eq. (1) can then be reformulated as follows:

$$\beta_{\text{tref},t0} = \Phi^{-1}\{[\Phi(\beta_1)]^{\text{tref} / t_0}\} \qquad (2)$$

where $t_{\text{ref}} / t_0 \geq 1$. The following indications regarding t_0 can be useful:

- One year can be accepted in many cases (e.g. when climatic or traffic actions govern structural reliability),
- 5-10 years for office buildings for which reliability is dominated by a sustained component of the imposed load (JCSS 2001),
- $t_0 = t_{\text{ref}}$ for the cases in which the reliability is insignificantly affected by time-variant phenomena (e.g. structures subjected mainly to permanent actions, masonry or geotechnical structures).

Variation of the reliability index $\beta_{\text{tref},t0}$ with t_0 is shown in Figure 1. It can be observed from the figure that for $t_{\text{ref}} = 50$ years and $\beta_1 = 4.7$ the following target values should be considered:

- $\beta_{50} = 3.8$ for $t_0 = 1$ years,
- $\beta_{50} = 4.4$ for $t_0 = 10$ years,
- $\beta_{50} = 4.7$ for $t_0 = 50$ years.

Apparently the assumption of independent failure events needs to be carefully verified before selecting appropriate target levels.

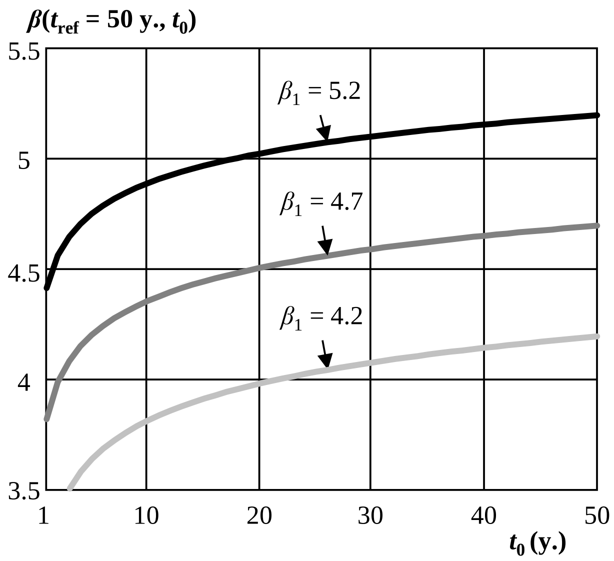

Figure 1: Variation of $\beta_{tref,t0}$ with t_0 for t_{ref} = 50 years and selected β_1-values (failures during t_0 basic periods mutually independent).

4. COST OPTIMISATION

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 while inspection and maintenance strategies are influenced marginally. 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. These are reasonable assumptions in many practical cases.

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, $C_0 >> C_1 \times d$ (Rackwitz 2000). For more details see *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/ FDIS 2394:2015*):

- Cost of repair or replacement of the structure,
- Economic losses due to non-availability or malfunction of the structure,
- 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),
- 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. 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 (Holicky 2013):

$$\mathrm{E}[C_\mathrm{f}(t,d)] \approx C_\mathrm{f}\, p_\mathrm{f}(d)\, Q(t,d) \tag{3}$$

where C_f = present value of the failure cost; $p_\mathrm{f}(d)$ = failure probability related to a basic reference period t_0; and Q = time factor. The time factor Q should include the effect of discounting and can be obtained for a sum of the geometric sequence (Holicky 2013; Holicky 2014).

The expected total costs are expressed as:

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

The optimum value of the decision parameter d_opt (optimum design strategy) is then obtained by minimising the total cost, $\min._d\, c_\mathrm{tot}(t;d) = c_\mathrm{tot}(t;d_\mathrm{opt})$. Apparently d_opt is independent of C_0. Following (JCSS 2001), Annex G of *ISO/ FDIS 2394:2015* indicates the target reliabilities based on economic (monetary) optimisation. More details are provided in the recent papers (Holicky 2013 and Holicky 2014).

5. REQUIREMENTS ON HUMAN SAFETY

ISO/ FDIS 2394:2015 indicates that the target failure probabilities may be selected solely on the basis of an economic optimization only if no risk of loss of human lives is associated with structural failures. Otherwise individual or societal risk criteria or the Life Quality Index (LQI) approach can be used to assure acceptable risks of occupants or users of the structure when compared to other daily-life activities. Such criteria essentially represent requirements of the society whereas economic optimisation reflects preferences of the owner of a structure.

General guidelines for assessment of the target reliabilities with respect to human safety are provided in *ISO 2394:1998*. Based on the concept of individual risk, the annual target failure probability $p_\mathrm{ft,hs}$ depends on the conditional probability of an occupant fatality p_1 given structural failure:

$$p_\mathrm{ft,hs}\text{ (per year)} \leq 10^{-6}\text{ (per year)} / p_1 \tag{5}$$

With respect to the loss of human life, *EN 1990:2002* distinguishes among low, medium, or high consequences (Consequence Classes CC1-CC3, respectively). Based on the study by (Steenbergen and Vrouwenvelder 2010) and limited statistical data, (Sykora et al. 2014) tentatively proposed that the probabilities p_1 can be approximated by the values 0.0025, 0.025 and 0.05-0.25 for CC1 to CC3, respectively. The annual target levels become from Eq. (5):

$$\begin{aligned}&\text{CC1:}\quad p_\mathrm{ft,hs} \leq 4 \times 10^{-4}\ (\beta_\mathrm{hs} \geq 3.4)\\ &\text{CC2:}\quad p_\mathrm{ft,hs} \leq 4 \times 10^{-5}\ (\beta_\mathrm{hs} \geq 3.9)\\ &\text{CC3 } (p_1 = 0.05)\text{:}\ p_\mathrm{ft,hs} \leq 2 \times 10^{-5}\ (\beta_\mathrm{hs} \geq 4.1)\\ &\text{CC3 } (p_1 = 0.25)\text{:}\ p_\mathrm{ft,hs} \leq 4 \times 10^{-6}\ (\beta_\mathrm{hs} \geq 4.5)\end{aligned} \tag{6}$$

ISO 2394:1998 indicates that in many cases authorities explicitly want to avoid accidents where large numbers of people may be killed. The additional societal risk criterion may thus be applied:

$$p_\mathrm{ft,hs} \leq A\, N_F^{-\alpha} \tag{7}$$

where N_F = expected number of fatalities given structural failure; and A and α = constants (*ISO 2394:1998* provides examples A = 0.01 or 0.1 and α = 2).

The number of fatalities should be estimated for a failure mode for which the target level is to be provided, considering possibility of progressive collapse and its consequences. In general the number of fatalities depends on numerous factors including number of occupants, probability of exposure, warning factor, probability of self- or assisted rescue, etc.

The analysis of more than one hundred structural collapses provided empirical relationships for the number of fatalities N_F and a collapsed area A_col (Tanner and Hingorani 2010):

$$\begin{aligned}&\text{CC1:}\quad \text{no recommendation}\\ &\text{CC2:}\quad N_F = 0.27 A_\mathrm{col}^{0.5} - 1 \geq 0\\ &\text{CC3:}\quad N_F = 0.59 A_\mathrm{col}^{0.56} - 1 \geq 0\end{aligned} \tag{8}$$

Apparently this must be understood as a first indication of the expected number of fatalities that should be always assessed on a case-specific basis; for guidance see (FEMA 2009; Janssens et al. 2012; Smit and Barnardo-Vijloen 2013).

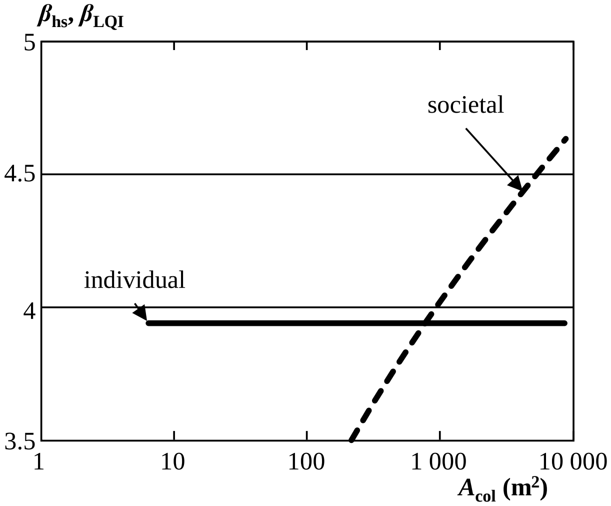

Figure 2: Annual target reliability index based on the individual and societal risk criteria as a function of the collapsed area for CC2.

Considering $A = 0.01$ and $\alpha = 2$, annual target reliability indices based on the individual (Eq. (6)) and societal (Eqs. (7) and (8)) risk criteria are shown as a function of the collapsed area in Figure 2 for CC2. Here the conditional probability p_1 is assumed to be independent of A_{col}; their mutual relationship should be investigated within further studies. It follows from the figure that the individual risk criterion is dominating over the societal risk criterion for, approximately, $A_{col} <$ 1 000 m^2. Similar curves are obtained for CC3 with β-levels increasing by about 0.5; for instance $\beta_{hs,ind.}$ = 4.1-4.5 assuming p_1 = 0.05-0.25.

The parameters $A = 0.01$ and $\alpha = 2$ should be considered as mere indications and should be carefully specified considering a reference system (group of buildings or individual structural member) and other structure- and industry-specific parameters (Hingorani and Tanner 2014). It is worth noting that $\alpha > 1$ represents a risk-averse decision making which is understood as an essential source of conservatism in structural reliability-related decisions (Cha and Ellingwood 2012).

ISO/ FDIS 2394:2015 indicates how preferences of the society in regard to investments into health and life safety improvements can be described by the LQI concept. The example given in Annex G of *ISO/ FDIS 2394:2015* is used here to compare the LQI target levels with the other considered approaches. The annual values β_{LQI} are obtained considering:

- Moderate relative cost of risk reduction measure, $(C_1 \times d) / C_0 = 0.01$;
- N_F / m^2 (input parameter, per m^2 of floor area of the building A_{floor}) derived from N_F given in Eq. (8):

$$\text{CC2: } N_F / A_{floor} = D(0.27A_{col}^{0.5} - 1) / A_{col} \geq 0 \quad (9)$$

assuming a known damage extent $D = A_{col} / A_{floor}$ that may depend on:

- A type of exposure – for earthquake it is likely greater than for local impact,
- Type of structural member subjected to damage,
- Structural robustness and its size as e.g. total collapse may be less likely for larger systems with more redundancies and alternative load paths, etc.

Detailed discussion on the damage extent for different exposures and structural systems is beyond the scope of this study.

As an example the following values of β_{LQI} are obtained from Annex G in *ISO/ FDIS 2394:2015* considering $A_{col} <$ 20 000 m^2 and D = 0.1 or 1:

- β_{LQI}(CC2) = 4.2 for D = 1,
- β_{LQI}(CC2) = 3.7 for D = 0.1.

It appears that β_{LQI} corresponds relatively well to the target level based on the individual risk criterion. Similar observations are made for CC3; for instance β_{LQI}(CC3) = 4.2 for D = 0.1 and $A_{col} <$ 2 000 m^2.

Considering the societal criterion being conservative due to risk aversion, recommendations concerning the target levels for human safety may be derived from the individual risk criterion and the LQI approach. The following annual target reliabilities could be accepted as a first approximation:

- $\beta_1 \approx 3.9$ for CC2;
- $\beta_1 \approx 4.3$ for CC3.

(Sykora et al. 2014) obtained $\beta_1 \approx 3.4$ for CC1.

These values are lower than those given in *EN 1990:2002*; for instance $\beta_1 \approx 4.7$ for CC2. This is indicating that a design strategy (represented by the EN 1990 values) is mostly driven by economic arguments as it is affordable and economically optimal to design for higher reliability than that required by human safety criteria. Furthermore, it appears that the difference of 0.5 is appropriate to distinguish between subsequent consequence classes. This is consistent with *EN 1990:2002*.

6. PRACTICAL IMPLICATIONS FOR MEMBER AND SYSTEM DESIGN

Since designers are mainly applying safety formats at a component (structural member) level, the definition of targets for members and associated limit states is preferred, *EN 1990:2002* and *ISO 2394:1998*. Structural members designed by such a procedure may have sufficient reliability beyond these local failure conditions due to section and internal redundancies, possible alternative load paths and/ or formation of plastic hinges. Therefore, failures of single members often have significantly lower consequences compared to the failure of the main part of the structure (system failure). It thus appears important to distinguish between member failure and structural collapse (Bhattacharya et al. 2001).

When deriving target safety levels by considering failures resulting to large collapsed areas and many fatalities it is obvious that these levels are more related to system failure i.e. global failure or failure of the main part of the structure. This distinction has been implemented in standards reflecting performance objectives of structures; see (Diamantidis 2008) for a review.

For instance *ASCE 7-10:2010* requires target reliability index by about 0.5 greater for progressive collapse than for a member or connection failure (Hamburger 2013). This difference was also proposed for bridges to distinguish between single- or multiple path failures (Kaszynska and Nowak 2005). A difference of 0.4 reflects practically the fact that in the case of system failure an order of magnitude more fatalities is expected compared to member failure (Allen 1981; Rackwitz 2002).

It thus seems appropriate to increase the target reliability index by 0.5 when reliability of a system or its key component is verified (as compared to design of a member). This corresponds to shifting one consequence class higher as discussed in the previous section.

This recommendation relates to ductile systems with alternative load paths (parallel systems) as relevant to many civil engineering structures. For a series system, target level for components is higher than a system target. As system behaviour of structures can hardly be classified into idealised types of systems such as series, parallel ductile or parallel brittle, detailed discussion on system targets is beyond the scope of this study.

7. CONCLUSIONS

The target reliability levels recommended in various documents are inconsistent in terms of the values and the criteria according to which the appropriate values are to be specified. In general optimum reliability levels can be obtained by considering both the relative costs of safety measures and failure consequences over the design working life; the minimum reliability for human safety should also be considered if relevant. The following conclusions are drawn:

- The recalculation of targets for different reference periods is undetermined due to mutual dependence of failure events.
- When specifying failure consequences warning factor and possibility of progressive collapse should be taken into account.
- The design strategy and respective codified target reliability levels (e.g.

annual reliability index $\beta_1 = 4.7$ in *EN 1990* for medium failure consequences) are mostly driven by economic arguments as it is affordable and economically optimal to design for higher reliability than that required by human safety criteria ($\beta_1 \approx 3.9$).

- The difference of 0.5 in the target reliability index is appropriate to distinguish between subsequent consequence classes.
- When reliability of a system or its key component is verified (as compared to design of a member), the target reliability index should be increased by about 0.5.

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