Target reliability levels – needs for harmonisation in present standards

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Abstract

The target reliability levels recommended in various national and international documents for new structures are inconsistent in terms of the values of reliability indices and recommendations for their applications. In general, optimum reliability levels should be specified taking into accounts both the relative costs of safety measures and the expected consequences of failure over the design working life. The minimum reliability for human safety should also be considered when people may be killed or injured as a result of failure. Submitted contribution attempts to clarify the link between the design working life and the reliability index, and to provide guidance for specification of the target reliability level for a given design working life. It is shown that the target reliability levels in the present normative documents are specified for different reference periods. A simple recalculation of targets to a given reference period (say 50 years) is proposed taking into account mutual dependence of failure events. The target reliabilities indicated in available documents are within a broad range and should be carefully revised.

Keywords: target reliability, construction costs, failure consequences, reference period, design working life.

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 values are to be selected. 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. In accordance with this standard the minimum reliability for human safety should also be considered when people may be killed or injured as a result of failure.

The basic aim of this contribution is to clarify the link between the design working life and the reliability index, and to provide guidance for specification of the target reliability level for a given design working life. This contribution is an extension of the previous study by Holicky (2013).

2. Target Reliabilities in Normative Documents

The design working life is understood as an assumed period of time for which a structure is to be used for its intended purpose without any major repair being necessary. Indicative values of design working life (10 to 100 years for different types of new structures) are given in *EN 1990:2002* for basis of structural design. Recommended values of reliability indexes are given for two reference periods, 1 year and 50 years (see Table I), without any explicit link to the design working life that generally differs from the reference period.

Table I: Reliability classification in accordance with *EN 1990*.

Reliability classes	Failure consequences	β for reference period		Examples of structures
		1 y.	50 y.	
RC3 – high	High	5.2	4.3	Grandstands, public buildings
RC2 – normal	Medium	4.7	3.8	Residences and offices
RC1 – low	Low	4.2	3.3	Agricultural buildings

It should be emphasized that the reference period is understood as a chosen period of time used as a basis for statistically assessing the time variant basic random variables, and the corresponding probability of failure. The concept of reference period is therefore fundamentally different from the concept of design working life. Confusion is often caused when the difference between these two concepts is not recognized.

The couple of β-values (for 1 and 50 years) given in Table I for each reliability class corresponds to the same reliability level. Practical application of these values, however, depends on the time period considered in the verification, which may be linked to available probabilistic information concerning time variant basic variables (imposed load, wind, earthquake, etc.). Holicky et al. (2009) noted that the reference period of 50 years is also accepted as the design working life for common structures.

For example, considering a structure of RC2 having a design working life of 50 years, the reliability index $\beta = 3.8$ should be used provided that probabilistic models of basic variables are available for this period. The same reliability level is achieved when a reference period of 1 year and $\beta = 4.7$ are applied using the theoretical models for a reference period of one year. Thus, when designing a structural member, similar dimensions (e.g. reinforcement area) would be obtained considering $\beta = 4.7$ and basic variables related to 1 year or $\beta = 3.8$ and basic variables related to 50 years.

A more detailed recommendation concerning the target reliability is provided by *ISO 2394:1998* where the target reliability indexes are indicated for the whole design working life without any restriction concerning its length, and are related not only to the consequences, but also to the relative costs of safety measures (Table II).

Table II: Examples of life-time target reliability indexes β in accordance with *ISO 2394:1998*.

Relative costs of safety measures	**Failure**		**consequences**	
	small	**some**	**moderate**	**great**
High	0	1.5	2.3	3.1
Moderate	1.3	2.3	3.1	3.8
Low	2.3	3.1	3.8	4.3

Note that Table II indicates reliability indexes related to life-time of a structure and not to one year reference period; $\beta = 0$ is recommended for reversible serviceability limit state, $\beta = 1.5$ for irreversible serviceability limit state. Values $\beta = 2.3$ to 3.1 are considered for fatigue limit state depending on the possibility of inspection and $\beta =$ 3.1, 3.8 and 4.3 (given in the last column of Table II for great consequences) are recommended for the ultimate limit states.

Similar recommendations are provided in the Joint Committee on Structural Safety Probabilistic Model Code by JCSS (2001) based on the study by Rackwitz (2000) (Table III); see also Vrouwenvelder (1997). These reliability indices are also adopted in the draft of the revision ISO 2394 - *ISO/DIS 2394:2013*. The recommended target reliability indexes are also related to both the consequences and to the relative costs of safety measures, though for a reference period of 1 year.

Table III: Tentative target reliability indexes β (and associated target failure rates) related to one year reference period and ultimate limit states in accordance with JCSS (2001) and *ISO/DIS 2394:2013*.

Relative costs of safety measures	**Failure**	**consequences**	
	minor	**moderate**	**large**
Large	$\beta = 3.1$ ($p \approx 10^{-3}$)	$\beta = 3.3$ ($p \approx 5\times10^{-4}$)	$\beta = 3.7$ ($p \approx 10^{-4}$)
Normal	$\beta = 3.7$ ($p \approx 10^{-4}$)	$\beta = 4.2$ ($p \approx 10^{-5}$)	$\beta = 4.4$ ($p \approx 5\times10^{-6}$)
Small	$\beta = 4.2$ ($p \approx 10^{-5}$)	$\beta = 4.4$ ($p \approx 5\times10^{-6}$)	$\beta = 4.7$ ($p \approx 10^{-6}$)

The consequence classes in JCSS (2001) (similar to those in *EN 1990*) are linked to the ratio ρ defined as the ratio $(C_{str} + C_f) / C_{str}$ of the cost induced by a failure (cost of construction C_{str} plus direct failure costs C_f) to the construction cost C_{str}:

- Class 1 Minor Consequences: ρ is less than approximately 2; risk to life, given a failure, is small to negligible and the economic consequences are small or negligible (e.g. agricultural structures, silos, masts);
- Class 2 Moderate Consequences: ρ is between 2 and 5; risk to life, given a failure, is medium and the economic consequences are considerable (e.g. office buildings, industrial buildings, apartment buildings);
- Class 3 Large Consequences: ρ is between 5 and 10; risk to life, given a failure, is high, and the economic consequences are significant (e.g. main bridges, theatres, hospitals, high rise buildings).

However, it is not quite clear what is meant by "the direct failure costs". This term indicates that there may be some other "indirect costs" that may affect the total expected cost. Here it is assumed that the failure costs C_f cover all additional direct and indirect costs (except the structural costs C_{str}) induced by the failure. The structural costs are considered separately and related to the costs needed for an improvement of safety.

ISO 2394:1998, *ISO/DIS 2394:2013* and JCSS (2001) seem to recommend reliability indexes lower than those given in *EN 1990* even for the "small relative costs" of safety measures. It should be noted that *EN 1990* gives the reliability indexes for two reference periods (1 and 50 years); the latter may be accepted as the design working life for common structures. *ISO 2394:1998* recommends indexes for "life-time, examples", thus related to the design working life, without any restrictions while JCSS (2001) and *ISO/DIS 2394:2013* provide reliability indexes for the reference period of 1 year.

A new promising approach to specify the target reliability based on the concept of Life Quality Index (Nathwani et al. (2009), Pandey & Nathwani (2004), Pandey et al. (2006)) is considered in an ongoing revision of ISO 2394. The target annual failure probabilities are dependent on the parameter K_1 (Table IV) that is derived from the marginal costs of a safety measure, expected number of fatalities given structural failure and several socio-economic parameters.

Table IV: Tentative minimum target reliability indexes β (and associated target failure rates) related to one year reference period and ultimate limit states, based on the LQI acceptance criterion (*ISO/DIS 2394:2013*).

Relative life saving costs	K_1	**LQI target reliability**
Large	10^{-3}-10^{-2}	$\beta = 3.1$ ($p \approx 10^{-3}$)
Medium	10^{-4}-10^{-3}	$\beta = 3.7$ ($p \approx 10^{-4}$)
Small	10^{-5}-10^{-4}	$\beta = 4.2$ ($p \approx 10^{-5}$)

3. Target Reliability for Various Reference Periods

The target reliability levels provided in various documents are related to different reference periods. Typically one year, 50 years or simply life-time are considered. Assume that the failure probability related to one year $p_1(\beta_1)$ corresponds to the reliability index β_1, thus

$$p_1(\beta_1) = \Phi(-\beta_1) \tag{1}$$

Here $\Phi(\cdot)$ denotes the cumulative distribution function of standardised normal distribution. An approximation of the failure probability p_{nk} within n basic periods assuming that the failures during each k reference periods are mutually independent is

$$p_{nk}(\beta_1,n,k) = 1 - [1 - p_1(\beta_1)]^{n/k} \tag{2}$$

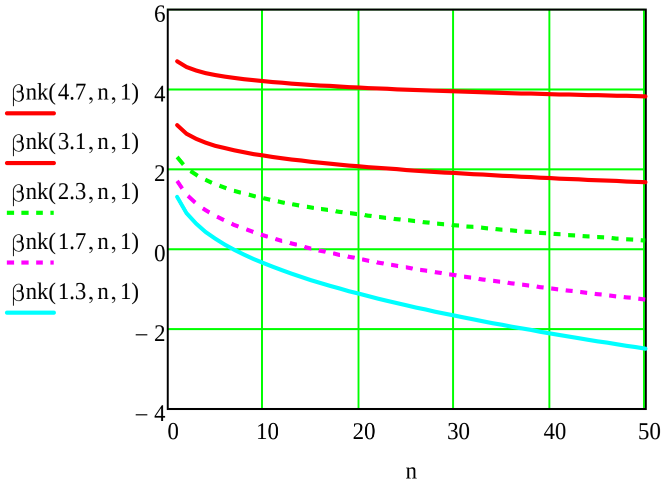

Figure 1. Variation of β_{nk} with n for k = 1 and selected β_1-values (failures during all basic (one year) reference periods are mutually independent).

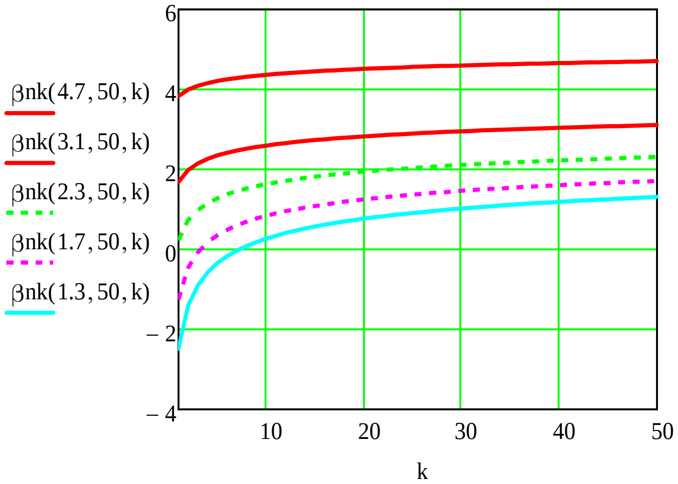

Figure 2. Variation of β_{nk} with k for n = 50 and selected β_1-values (failures during k reference periods are mutually independent).

where $n / k \geq 1$. For instance k = 5-10 years might be accepted when the reliability of a structure is dominated by the sustained (long-term) part of an imposed load. The reliability index β_{nk} corresponding to p_{nk} is then obtained using $\Phi(\cdot)$ in the same way as in eq. (1). Variation of the reliability index β_{nk} with n and k is shown in Figures 1 and 2. Note that k = 1 corresponds to the full independence of failures in the reference periods and

$$\beta_{n1}(\beta_1,n,1) = -\Phi^{-1}(p_{n1}(\beta_1,n,1)) \qquad (3)$$

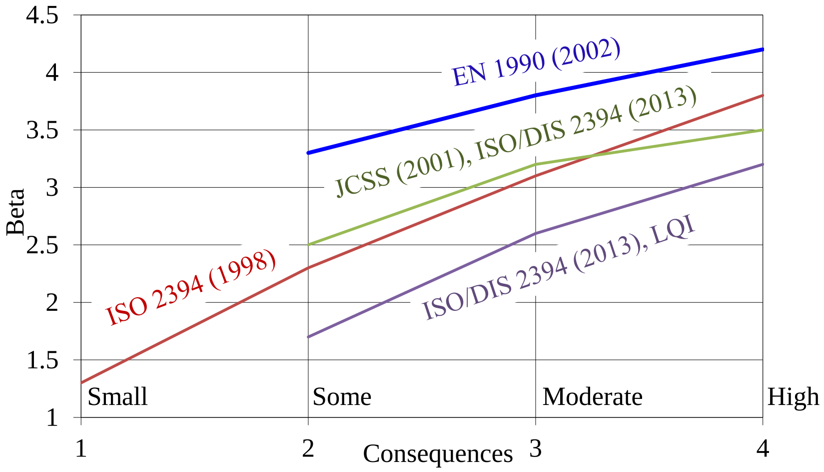

Figure 3. Variation of $\beta_{50,1}$ for the ultimate limit states with a degree of failure consequences.

When $k = n$ then the failures in all the reference periods are fully dependent, $p_{nn} = p_{11}$. This is relevant for the cases when structural reliability is dominated by time-invariant variables (resistance and geometry parameters, permanent actions, model uncertainties); examples might include masonry and geotechnical structures, sub-structures of bridges, underground structures etc. The reliability index is then

$$\beta_{n1}(\beta_1,n,n) = \beta_1 \tag{4}$$

These relationships together with in Figures 1 and 2 are helpful to compare the target reliabilities indicated in the above mentioned documents.

4. Comparison of Target Reliabilities

The target reliability indices indicated in Tables I to IV are recalculated for the reference period of 50 years (considered as life-time now) using eqs. (1) to (3). Considering ultimate limit states, Figure 3 shows variation of target reliability index $\beta_{50,1}$ (basic reference period $n = 50$) with a degree of consequences. Comparable relative costs of safety measures are taken into account, i.e. normal reliability class for *EN 1990*, moderate for *ISO 2394:1998*, normal for JCSS (2001) and *ISO/DIS 2394:2013* or medium for *ISO/DIS 2394:2013* - LQI approach.

It follows from Figure 3 that the target reliability indices indicated in various documents are within a relatively broad range. Obviously it may affect design or specification of partial factors and more detailed instructions how to apply the available recommendations should be provided.

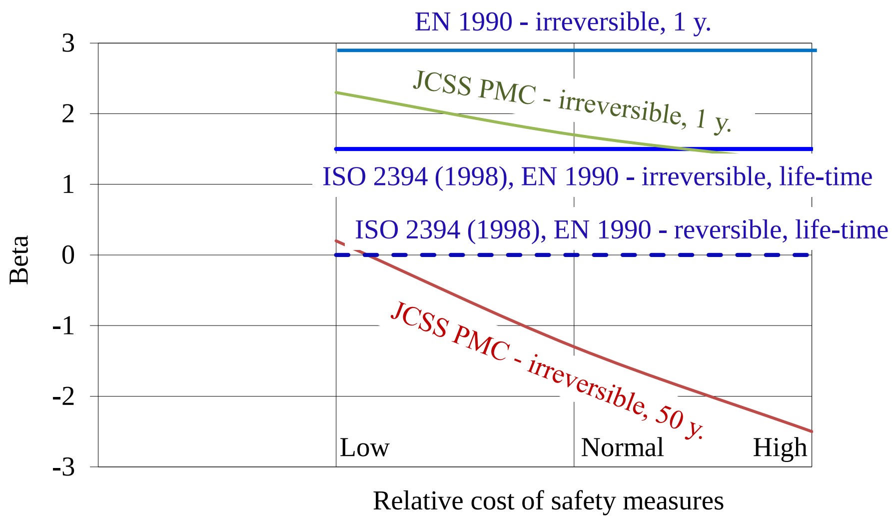

Figure 4. Variation of the reliability index β for serviceasbility limit states with a degree of relative costs of safety measures.

Somehow similar situation is observed for serviceability limit states for which three documents are considered here: *EN 1990*, *ISO 2394:1998* and JCSS (2001). Variation of the reliability index β with relative costs of safety measures is shown in Figure 4. *ISO 2394:1998* specifies the target values irrespective of safety measures and the recommended limits are represented in Figure 4 by horizontal lines. The targets in JCSS (2001) for irreversible limit states are related to one year reference period and the corresponding 50 years targets are recalculated assuming the full independence of failures.

It should be noted that the assumption of full independence is, particularly in the case of serviceability limit states, questionable and should be reconsidered. The assumption of a partial or full dependence of failures would obviously lead to more reasonable (greater) target betas, definitely closer to those related to one year reference period. As already suggested by Vrouwenvelder (2002) the target level β = 3.8 could better be interpreted as corresponding to β_1 = 4.5 for one year as complete independency of resistance and loads in subsequent years is not realistic.

5. Target Reliabilities for Existing Structures

In the presented study it is tacitly assumed that the target reliabilities are to be applied at a design phase. Vrouwenvelder & Scholten (2010) and Zwicky (2010) suggested that for some existing structures it is uneconomical to require the same reliability levels as for new structures. With reference to Tables II to IV that the target level for existing structures usually decreases as it takes relatively more effort to increase the reliability level then for a new structure. So for an existing structure one may for instance move from “moderate” to “large” relative costs of safety measures according to Vrouwenvelder (2002).

Two reliability levels are needed in the assessment of existing structures - the minimum level below which the structure is unreliable and should be upgraded, and the target level indicating an optimum upgrade strategy; for details see Steenbergen & Vrouwenvelder (2010), Sykora & Holicky (2012), Vrouwenvelder & Scholten (2010). Both these levels should be lower than the target reliabilities for structural design. It is noted that recently revised *ISO 13822:2010* for the assessment of existing structures does not provide further information for reduction of target reliabilities e.g. for shorter residual life-times. However, detailed discussion concerning the target reliabilities for existing structures is out of the scope of this contribution.

6. Recommendations for Practical Applications

Based on authors' experience the following recommendations are suggested for practical structural design for reference period equal design working life (considering the guidance in *EN 1990* and *ISO 2394:1998*):

- Ultimate limit state: β = 3.3 (RC1), β = 3.8 (RC2), β = 4.3 (RC3);
- Fatigue: β = 1.5-3.8 (RC2) depending on the degree of inspectability, reparability and damage tolerance;
- Serviceability limit state: β = 1.5 (irreversible), β = 0 (reversible).

As mentioned above these values are to be considered for reference periods equal to design working life of structures; e.g. commonly 50 years for buildings and 100 years for bridges. Shorter periods may be relevant for less important structures such as agricultural structures.

However, similar recommendations need to be provided in normative documents for engineering practice. It is recommended to consult appropriate target reliabilities with experts when:

- The independence of failure events in nearby reference periods is dubious (e.g. when structural reliability is expected to be dominated by time-invariant variables);
- The design situation is not covered by the above recommendations, e.g. fatigue for RC3 structures or reliability of temporary structures.

7. Conclusions

The following concluding remarks are drawn from the present study:

- In the present normative documents the target reliability levels are specified for different reference periods - typically one year, fifty years and life-time.
- Recalculation of targets to uniform reference period (say 50 years) is complicated by mutual dependence of failure events.
- With increasing mutual dependence the target reliabilities approach values related to one year (basic) reference period.
- The target reliabilities indicated in available documents are within a broad range and should be carefully revised.
- Target reliabilities in standards should be supplemented by clear recommendation on how to use them in practice.

- For ultimate limit states of common buildings and bridges (RC2), reliability index 3.8 can be considered for a reference period equal to the design working life (50-100 years).
- For fatigue the target reliabilities are currently specified in EN 1990 within a broad range and should be further analysed for different types of structures (e.g. high-rise buildings, road and railway bridges).

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