UDC 006.032:658.518.3

TARGET RELIABILITY LEVELS IN EUROCODES AND ISO STANDARDS

M. HOLICKÝ, J. MARKOVÁ, M. SÝKORA
(Czech Technical University, Prague, Klokner Institute)

The target reliability levels recommended in national and international documents vary within a broad range, while the reference to relevant costs and failure consequences is vague only. In some documents the target reliability index is indicated for one or two reference periods (1 year, 50 years or life-time) without providing appropriate links to the design working life. This contribution attempts to clarify the relationship between the target reliability levels, costs of safety measures, failure consequences, reference periods and the design working life. For ultimate limit states of common buildings and bridges (RC2), it is recommended to consider reliability index of 3.8 for a reference period equal to the design working life (50 years for buildings, 100 for bridges).

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 (ISO 2394:1998 for the general principles on structural reliability and its approved revision ISO/FDIS 2394:2015). 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 [1].

1 Factors affecting target reliabilities

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 commonly differentiated taking into account various aspects:

- Costs of safety measures – These costs should reflect efforts needed to improve structural reliability considering properties of construction materials and characteristics of failure modes. The relative cost of safety measures significantly depends on the variability of load effects and resistances [2];

- Failure consequences – Herein failure consequences are understood to cover all direct and indirect (follow-up) consequences related to failure [3]. 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 related to the use of the structure (EN 1990:2002) or to a number of persons at risk (ASCE 7-10:2010);

- 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 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 linked to a reference period considered in reliability verification.

2 Target reliabilities in normative documents

Indicative values of design working life (10 to 100 years for different types of structures) are given in EN 1990:2002 for basis of structural design. Recommended values of reliability indices are given for two reference periods, 1 year and 50 years (Tab. 1), without any explicit link to the design working life that generally differs from the reference period.

The couple of β-values (for 1 and 50 years) given in Table 1 for each reliability class corresponds to the same reliability level. Practical application of these values, however, depends on the time period considered in the structural verification, which may be linked to available probabilistic information concerning time variant basic variables (imposed load, wind, earthquake, etc.). It should be noted that the reference period of 50 years is also accepted as the design working life for common structures [4].

Table 1

Reliability classification in accordance with EN 1990

Reliability classes	Failure consequences – for loss of human life / economic, social or environmental consequences	β for reference period		Examples of structures
		1 y.	50 y.	
RC3	High or very great	5.2	4.3	Grandstands, public buildings
RC2	Medium, considerable	4.7	3.8	Residences and offices
RC1	Low and small or negligible	4.2	3.3	Agricultural buildings

For example, considering a structure in 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 indices are indicated for the whole design working life without any restriction concerning its length, and they are related not only to the consequences, but also to the relative costs of safety measures (Tab. 2).

Table 2

Examples of life-time target reliability indices 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 2 indicates reliability indices 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 2 for great consequences) are recommended for the ultimate limit states.

Similar recommendations are provided in the Joint Committee on Structural Safety Probabilistic Model Code-JCSS PMC [5], overview is given in [6] – based on the study by Rackwitz [7] (Tab. 3). These reliability indices are adopted in ISO/FDIS 2394:2015. The recommended target reliability indices are also related to both the consequences and to the relative costs of safety measures, though for a reference period of 1 year.

Table 3

Tentative target reliability indices β (and associated target failure rates) related to one year reference period and ultimate limit states in accordance with JCSS PMC [5] and ISO/FDIS 2394:2015

Relative costs of safety measures	Minor consequences of failure	Moderate consequences of failure	Large consequences of failure
Large	$\beta = 3.1$ ($p \approx 10^{-3}$)	$\beta = 3.3$ ($p \approx 5{\cdot}10^{-4}$)	$\beta = 3.7$ ($p \approx 10^{-4}$)
Normal	$\beta = 3.7$ ($p \approx 10^{-4}$)	$\beta = 4.2$ ($p \approx 10^{-5}$)	$\beta = 4.4$ ($p \approx 5{\cdot}10^{-6}$)
Small	$\beta = 4.2$ ($p \approx 10^{-5}$)	$\beta = 4.4$ ($p \approx 5{\cdot}10^{-6}$)	$\beta = 4.7$ ($p \approx 10^{-6}$)

The consequence classes in JCSS PMC [5] (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/FDIS 2394:2015 and JCSS PMC [5] seem to recommend reliability indices 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 indices 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 indices for "life-time, examples", thus related to the design working life, without any restrictions while JCSS PMC [5] and ISO/FDIS 2394:2015 provide reliability indices for the reference period of 1 year.

A new promising approach to specify the target reliability based on the concept of Life Quality Index [8–10] is considered in ISO/FDIS 2394:2015. The target annual failure probabilities are dependent on the parameter K_1 (Tab. 4) that is derived from the marginal costs of a safety measure, expected number of fatalities given structural failure and several socio-economic parameters.

Table 4

Tentative minimum target reliability indices β (and associated target failure rates) related to one year reference period and ultimate limit states, based on the LQI acceptance criterion (ISO/FDIS 2394:2015)

Relative life saving costs	K_1	LQI target reliability
Large	$10^{-3}\ldots10^{-2}$	$\beta = 3.1$ ($p \approx 10^{-3}$)
Medium	$10^{-4}\ldots10^{-3}$	$\beta = 3.7$ ($p \approx 10^{-4}$)
Small	$10^{-5}\ldots10^{-4}$	$\beta = 4.2$ ($p \approx 10^{-5}$)

It is noted that the target reliabilities given in standards are commonly derived considering typical failure modes and probabilistic models; see for instance ISO/FDIS 2394:2015. These considerations should be always clearly indicated to allow for comparing target levels among standards and to provide basis for further developments.

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

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

$\Phi(\cdot)$ 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

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

where $n / k \geq 1$. The following values of k may be taken into account:

- $k = 1$ year in many cases; for instance when climatic or traffic actions govern structural reliability,
- $k = 5\ldots10$ years for office buildings for which reliability is dominated by a sustained component of the imposed load [5], $k = n$ 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).

The reliability index β_{nk} corresponding to p_{nk} is then obtained using $\Phi(\cdot)$ in the same way as in Equation (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

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

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.

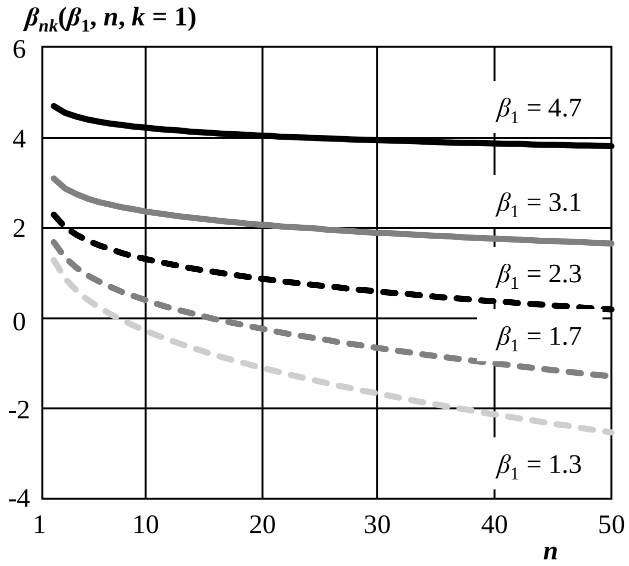

Fig. 1. Variation of β_{nk} with n for k = 1 and selected β_1-values
(failures during all basic (one year) reference periods are mutually independent)

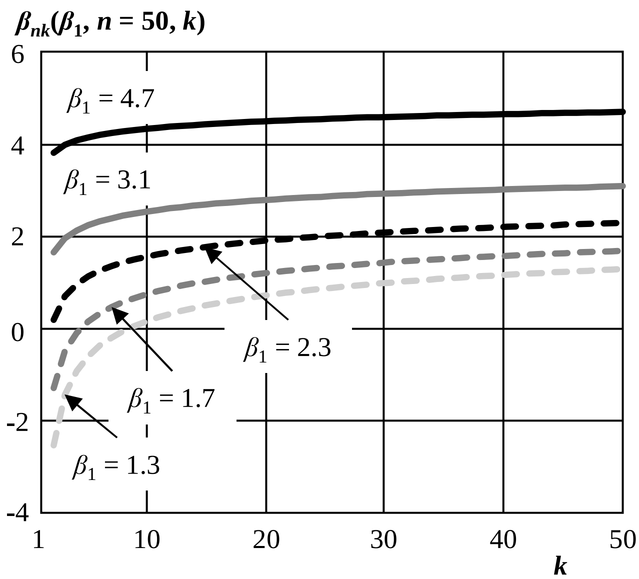

Fig. 2. Variation of β_{nk} with k for n = 50 and selected β_1-values
(failures during k reference periods are mutually independent)

4 Comparison of target reliabilities

The target reliability indices indicated in Tables 1 to 4 are recalculated for the reference period of 50 years (considered as life-time now) using Equations (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 PMC [5] and ISO/FDIS 2394:2015 or medium for ISO/FDIS 2394:2015-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.

Somehow similar situation is observed for serviceability limit states for which three documents are considered here: EN 1990, ISO 2394:1998 and JCSS PMC [5]. 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. JCSS PMC [5] targets 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 reliability indices, definitely closer to those related to one year reference period. As already suggested in [2] the target level β = 3.8 could better be interpreted as corresponding to $\beta_1 = 4.5$ for one year as complete independency of resistance and loads in subsequent years is not realistic.

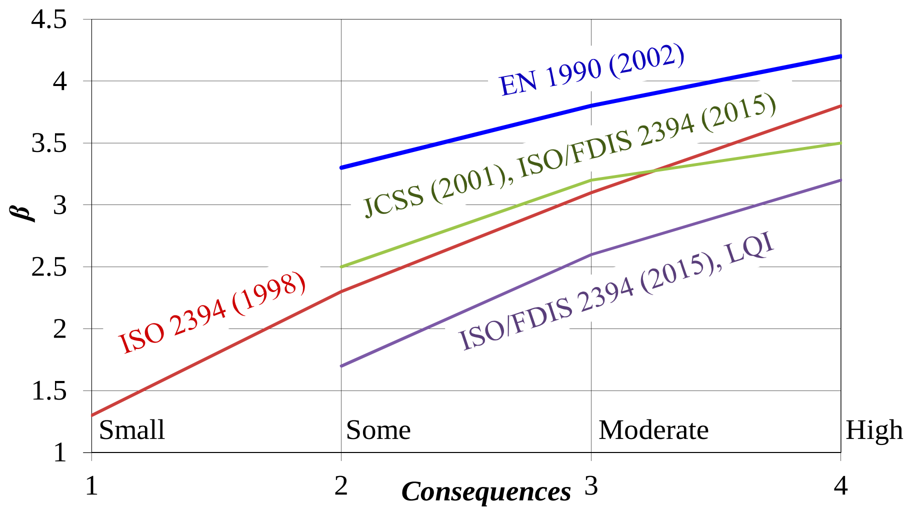

Fig. 3. Variation of $\beta_{50,1}$ for the ultimate limit states
with a degree of failure consequences

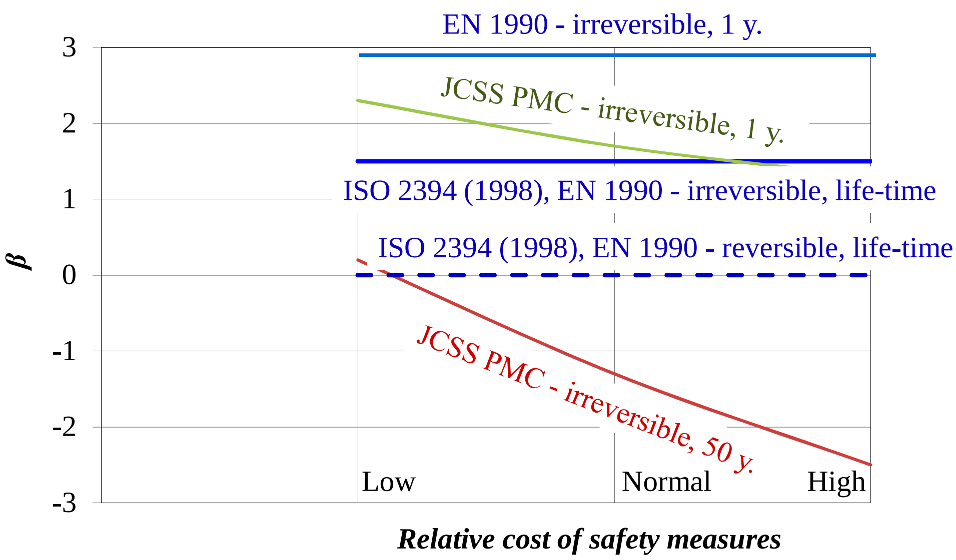

Fig. 4. Variation of the reliability index β for serviceability limit states
with a degree of relative costs of safety measures

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. For existing structures it is in some cases uneconomical to require the same reliability levels as for new structures [11; 12]. The target level for existing structures usually decreases as it takes relatively more effort to increase the reliability level then for a new structure; see Tables 2 to 4. So for an existing structure one may for instance move from "moderate" to "large" relative costs of safety measures [2].

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 [12–14]. Available experience indicates that the minimum level is often dominated by the human safety criteria whilst the optimum repair level is close to the target level accepted 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 provided elsewhere [15].

6 Recommendations for practical applications

Based on authors' experience the following recommendations are suggested for practical structural design for the reference period equal to a 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 revised, carefully considering failure modes and probabilistic models accepted when specifying target levels;
- 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).

Acknowledgements

The contribution is a part of the research project LG14012 supported by the Ministry of Education, Youth and Sports of the Czech Republic. Outcomes of CZ/13/LLP-LdV/TOI/134014 supported by the European Commission have been utilised; the contribution reflects the views of the authors, and the Commission cannot be held responsible for any use of the information contained therein.

REFERENCES

1. Holicky, M. Target Reliability Levels in Present Standards. Transactions of the VSB – Technical University of Ostrava / M. Holicky, J. Markova & M. Sykora // Civil Engineering Series. – 2014. – Vol. 14, Nr. 2. – P. 46–53.
2. Vrouwenvelder, A.C.W.M. Developments towards full probabilistic design codes / A.C.W.M. Vrouwenvelder // Struct Saf. – 2002. – Vol. 24, Nr. 2–4. – P. 417–432.
3. Holicky, M. Determination of Target Safety for Structures (submitted for publication) / M. Holicky, D. Diamantidis, & M. Sykora // In Proc. ICASP15. – Leiden: CRC Press/Balkema, 2015.
4. Load effects on buildings (Guidebook 1) / M. Holicky [et al.]. – Prague: CTU in Prague, 2009. – 214 p.

5. JCSS. JCSS Probabilistic Model Code. Joint Committee on Structural Safety, 2001.
6. Vrouwenvelder, A.C.W.M. The JCSS probabilistic model code / A.C.W.M. Vrouwenvelder // Struct. Saf. – 1997. – Vol. 19, Nr. 3. – P. 245–251.
7. Rackwitz, R. Optimization – the basis of code-making and reliability verification / R. Rackwitz // Struct. Saf. – 2000. – Vol. 22, Nr. 1. – P. 27–60.
8. Nathwani, J.S. Engineering Decisions for Life Quality: How Safe is Safe Enough? / J.S. Nathwani, M.D. Pandey & N.C. Lind. – London: Springer-Verlag, 2009. – 189 p.
9. Pandey, M.D. Life quality index for the estimation of societal willingness-to-pay for safety / M.D. Pandey & J.S. Nathwani // Struct.Saf. – 2004. – Vol. 26, Nr. 2. – P. 181–199.
10. Pandey, M.D., Nathwani, J.S. & Lind, N.C. The derivation and calibration of the life-quality index (LQI) from economic principles / M.D. Pandey, J.S. Nathwani & N.C. Lind // Struct. Saf. – 2006. – Vol. 28, Nr. 4. – P. 341–360.
11. Zwicky, D. SIA 269/2 – A New Swiss Code for the Conservation of Concrete Structures / D. Zwicky // In Proc. 3 rd fib International Congress. – Chicago: Precast/Prestressed Concrete Institute, 2010. – P. 13.
12. Vrouwenvelder, A.C.W.M. Assessment Criteria for Existing Structures / A.C.W.M. Vrouwenvelder & N. Scholten // Struct Eng Int. – 2010. – Vol. 20, Nr. 1. – P. 62–65.
13. Steenbergen, R.D.J.M. Safety philosophy for existing structures and partial factors for traffic loads on bridges / R.D.J.M. Steenbergen & A.C.W.M. VROUWENVELDER // Heron. – 2010. – Vol. 55, Nr. 2. – P. 123–139.
14. Sykora, M. Target reliability levels for the assessment of existing structures – case study / M. Sykora & M. HOLICKY // In Proc. IALCCE 2012. Leiden: CRC Press/Balkema, 2012. – P. 813–820.
15. Target reliability levels for assessment of existing structures based on economic optimisation and human safety criteria (invited contribution, submitted for review) / R.D.J.M. Steenbergen // Struct Concrete. – 2015.

Поступила 09.06.2015

УРОВНИ ЦЕЛЕВОЙ НАДЕЖНОСТИ В ЕВРОКОДАХ И ISO СТАНДАРТАХ

М. ХОЛИЦКИЙ, Я. МАРКОВА, М. СИКОРА
(Чешский технический университет, Прага, Институт имени Клокнера)

Рассматриваются условные уровни надежности, рекомендованные в национальных и международных документах. Показано, что эти уровни варьируются в широком диапазоне, в то время как ссылки на соответствующие затраты и последовательность отказов недостаточно изучена. В некоторых документах индекс целевой надежности определяется для одного или двух базовых периодов (1 год, 50 лет или в течение всего жизненного цикла) без предоставления соответствующих ссылок на проекты. В данной работе делается попытка прояснить отношения между уровнями целевой надежности, затратами на обеспечение безопасности, последовательностью отказов, базовыми периодами и сроком эксплуатации. Для предельных уровней состояния общественных зданий и мостов (RC2) рекомендовано использовать целевой индекс 3.8 для периода, равного проектному сроку службы: 50 лет – для зданий, 100 лет – для мостов.