RELIABILITY OF CIVIL ENGINEERING STRUCTURES

Author :**Er. Monika Dadhwal**[1]
[1]MTech structure engineering and construction, Department of Civil Engineering, MRIEM,Rohtak, Haryana
Co-author :**Abhishek Arya**[2]
[2]Assistant Professor, Civil Engineering Department, MRIEM, Rohtak.

Abstract:

The structural reliability recommended in Eurocodes and other international documents vary within a broad range, while the regard to the failure consequences and style working life is mentioned only very vaguely. In some cases the target reliability indexes are indicated for one or two reference periods like 1 to 5-0 years, however no explicit link to the planning working life is typically provided. This text attempts to clarify the connection between the target reliability levels, failure consequences, the planning working life and therefore the discount rate. The theoretical study supported probabilistic optimization is supplemented by recommendations useful for code makers and required by practicing engineers. It appears that the optimum reliability indices depend totally on the ratio of the value of structural failure to the value per unit of structural parameter, and fewer significantly on the planning working life and on the discount rate.

1. Introduction

The target reliability levels recommended in various national and international documents for brand spanking new structures are inconsistent in terms of the values and therefore the criteria consistent with which the acceptable values are to be selected. Almost no recommendations are available for temporary structures. Generally, optimum reliability levels are often obtained by considering both the value of the structure and therefore the expected cost of failure over the planning working life.

The design working life is known as an assumed period of your time that a structure is to be used for its intended purpose with none major repair work being necessary. Indicative values of design working life (10 to 100 years for various sorts of new structures) are given in EN 1990 (2002) [2]. Recommended values of reliability indexes are given for 2 reference periods, 1 year and 50 years (see Table 1), with none explicit link to the planning working life that generally differs from the reference period, while no specific indicative values are available for temporary structures.

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

It should be recognized that the few βvalues (for 1 year and 50 years) given in Table 1 for every reliability class correspond to an equivalent reliability level. Application of those values, however, depends on the period of time considered within the verification, which can 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 fifty years is additionally accepted because the design working life for common structures (see the discussion by Diamantidis (2009) [1]).

Table1 :Reliabilitydistribution accordingtoEN1990(2002) [2].

Reliability classes	Consequencesof structural failure	Reliabilityindexβforreferenceperiod 1year	50years	Examplesofbuildingsand civilengineeringworks
RC3–high	High	5.2	4.3	Bridges,publicbuildings
RC2–normal	Medium	4.7	3.8	Residencesandoffices
RC1 –low	Low	4.2	3.3	Agriculturalbuildings

For example, considering a structure of reliability class 2 having a design working lifetime of 50 years, the reliability index β = 3.8 should be used, as long as probabilistic models of basic variables are available for this era. An equivalent reliability level is achieved when a reference period of 1 year, and a target of β = 4.7 are applied using the theoretical models for a reference period of 1 year. Thus, when designing a support, similar dimensions (reinforcement area) would be obtained considering ß = 4.7 and basic variables associated with 1 year or ß = 3.8 and basic variables associated with 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 entire design working life with none restriction concerning its length, and are related not only to the results, but also to the relative costs of safety measures (Table 2).

Table 2 : Life-time target reliability indexes β consistent with ISO 2394 (1998).

Relativecostsof safetymeasures	Consequencesoffailure 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

Similar recommendations are provided in the JCSS (2001) [8] Probabilistic Model Code (Table 3)based on the previous study. The recommended target reliability indexes arealso related to both the consequences and to the relative costs of safety measures, though for areference period of 1 year. The consequence classes in JCSS (2001) [8] (similar to EN 1990, 2002[2])are linked to the ratio ρ defined as the ratio $(C_{str} + C_f)/ C_{str}$ of the total cost induced by a failure (cost ofconstructionC_{str}plus directfailure costsC_f)totheconstructioncost C_{str}asfollows:

- Class 1 Minor Consequences: ρ is less than approximately 2; risk to life, given a failure, issmall to negligible and the economic consequences are small or negligible (e.g.

agriculturalstructures,silos, masts);

- Class 2 Moderate Consequences: ρ is between 2 and 5; risk to life, given a failure, is mediumand the economic consequences are considerable (e.g. office buildings, industrial buildings,apartment buildings);

- Class3LargeConsequences:ρisbetween5and10;risktolife,givenafailure,ishigh,andthe economic consequences are significant (e.g. main bridges, theatres, hospitals, high risebuildings).

However, it is not quite clear what is meant in JCSS (2001) [8] by "the direct failure costs". This termindicatesthattheremaybesomeother"indirectcosts"thatmayaffectthetotalexpectedcost.Hereit is assumed that the failure costs C_f cover all additional direct and indirect costs (except the structuralcosts C_{str}) induced by the failure. The structural costs are considered separately and related to the costsneededforanimprovementof safety(costs perunit ofdecisionparameterC_1).

Both the documents ISO 2394 (1998) [7] and JCSS (2001) [8] seem to recommend reliability indexes that are less than those given in EN 1990 (2002) [2] even for the "small relative costs" of safety measures. It should be noted that EN 1990 (2002) [2] gives the reliability indexes for 2 reference periods (1 and 50 years) which will be accepted because the design working life for common structures (see also the discussion provided by Diamantidis (2009) [1]). ISO 2394 (1998) [7] recommends indexes for "life-time, examples", thus associated with the planning working life, with none restrictions, while Probabilistic Model Code by JCSS (2001) [8] provides reliability indexes for the reference period of 1 year.

Table 3 : Tentative target reliability indexes β and associated with one year reference period and supreme limit states consistent with JCSS (2001) [8].

Relativecostsof safetymeasures	Minorconsequences offailure	Moderateconsequences offailure	Largeconsequencesof failure
Large	$\beta=3.1(p\approx10^{-3})$	$\beta=3.3(p\approx5\times10^{-4})$	$\beta=3.7(p\approx10^{-4})$
Normal	$\beta=3.7(p\approx10^{-4})$	$\beta=4.2(p\approx10^{-5})$	$\beta=4.4(p\approx5\times10^{-6})$
Small	$\beta=4.2(p\approx10^{-5})$	$\beta=4.4(p\approx5\times10^{-6})$	$\beta=4.7(p\approx10^{-6})$

However, a transparent link between the planning working life and therefore the target reliability level isn't apparent from any of the above-mentioned documents. Thus, it's not clear which target reliability index should be used for a given design working life different from 50 years (say 10 years).

A new promising approach to specify the target reliability supported the concept of Life Quality Index (Fischer et al., 2012) [3] is taken into account in an on-going revision of the International Standard ISO 2394 (1998) [7].

The basic aim of this contribution is to clarify the link between the planning working life and therefore the reliability index, and to supply guidance for specification of the target reliability level for a given design working life. The submitted theoretical study supported probabilistic optimization is supplemented by practical recommendations. This contribution is an extension of the previous study by Holicky and Retief (2011) [6], and Holicky [8].

2. Generalprinciplesof probabilisticoptimization

Probabilistic optimization may be based on a certain objective function adjusted to given condition ofheritage structure. A simplified form (not covering monitoring and maintenance) may be expressed asthepresentvalue of the totalexpected cost $C_{tot}(x,o,q,n)$

$$C_{tot}(x,o,q,n)=C_{str}\sum_{1}^{n}P_{f}(x,i)Q(o,i)+C_{f}\sum_{1}^{n}P_{f}(x,i)Q(q,i)+C_{0}+xC_{1} \quad (1)$$

The cost of construction C_{str} including artistic value is discounted as it is paid in the future afternumber of years i. Here x denotes the decision parameter of the optimization (a parameter of structuralresistance),o is the annual obsolescence (oldness) rate of heritage structure enhanced by annualdiscountrate q.

The cost of failure C_f including relevant artistic values is also discounted as it is paid after numberof years i, q is the annual discount rate (without obsolescence rate o), e.g. 0.03, an average long runvalue of the real annual discount rate in European countries, n is the number of years to the failure,whichmaydifferfromthedesign workinglife(specified usuallyas 50or100 years).

Further, $P_f(x,i)$ is the failure probability in year i, $Q(o,i)$ is the discount factor dependent on theannual obsolescence rate o, $Q(q,i)$ is the discount factor dependent on the annual discount rate q andthenumber of years$i$,C_0istheinitialcost ofintervention independentofthedecisionparameter $x$andfailure(aquantitynotaffectingtheoptimization),andC_1 isthecostper unit ofthedecisionparameter$x$(astructuralparameterquantityaffectingthestructuralresistanceandoptimization).

Note that the design working life may generally differ from the time to failure denoted by thenumber of years n and considered here as an independent variable affecting the probability of failure.Maintenance and possible repair of the structure is not included in the objective function (1), and theseaspects are to be considered in further studies. Assuming independent failure events in subsequentyears,theannualprobabilityoffailure$P_f(x,i)$inyear$i$maybeapproximatedbythegeometricsequence

$$P_f(x,i)=p(x)(1-p(x))^{i-1} \quad (2)$$

The initial annual probability of failure $p(x)$ is dependent on the decision parameter x. Note that annualfailureprobabilitiescanbeassumedtobeindependentwhenfailureprobabilitiesarechieflyinfluenced by time-variant loads (climatic actions, traffic loads, accidental loads). Then the failureprobability $P_{fn}(x)$ during n years can be estimated by the sum of the sequence $P_f(x,i)$, that can beexpressedas

$$P_{fn}(x,n) = 1 - (1 - p(x))^n \beta n\, p(x) \quad (3)$$

Note that the approximation indicated in equation(3)is fully acceptable for small annual probabilities$p(x)$<

10^{-3}.

Thediscountfactorofthepresentvalueoftheexpectedfuturecostsinyear*i*isconsideredintheusualformas

$$Q(q,i) = 1/ (1+q)^{i} \quad (4)$$

Thus,thecostofmalfunctioningC_f isdiscountedbythefactor$Q(q,i)$dependingonthediscountrate*q*andthe pointintime (yearnumberdefinedas *i*) whenthelossofstructuralutilityoccurs.

Consideringequations(2)and(4)thetotalcosts$C_{tot}(x,q,n)$describedbyequation(1)maybewrittenin asimplified formas

$$C_{tot}(x,o,q,n)=C_{str}PQ(x,o,n) + C_f p(x)\ PQ(x,q,n)+C_0+xC_1 \quad (5)$$

3. Failureprobabilityofagenericstructuralmember

Consideragenericstructural memberdescribedbythelimitstatefunction$Z(x)$ as

$$Z(x)= xf - (G+Q) \quad (10)$$

Here x denotes a deterministic structural parameter (e.g. the cross-section area), f the strength of thematerial,Gtheloadeffectduetopermanentloadand$Q$theloadeffectduetovariableload.Theoretical models of the random quantities f, G and Q considered in the following example are givenin Table 4 (adopted from the probability model code described in JCSS (2001) and Holicky (2009)[4]).

Table4 :Theoretical models oftherandomvariables*f*,*G*and*Q*(annualextremes).

Variables	Distribution	Mean	Standarddeviation	Coefficientofvariation
f	Lognormal	100	10	0.10
G	Normal	35	3,5	0.10
Q	Gumbel	10	5	0.50

ConsideringthetheoreticalmodelsgiveninTable4,thereliabilitymargin$Z(x)$maybewellapproximatedbythethr eeparameterlognormaldistribution$\beta_{Z(x)}$thatprovidessufficientaccuracy.

Theannualfailureprobability$p(x)$isthengivenas

$$p(x)=\beta_{Z(x)}(Z(x)=0) \quad (11)$$

Theannualfailureprobability$p(x)$inequation(11)isevaluatedforthereliabilitymargin$Z(x)$=0using three parameter for $Z(x)$; then for x = 1 and n = 50 the failure probability is $P_{fn}(1)$ β 6.7 $10^{\beta 5}$andcorrespondingreliabilityindexisβ3.8(common valueindicated inEN1990(2002)[2]).

4. Conclusion

Thetargetreliabilitylevelsrecommendedinvariousnationalandinternationaldocumentsareinconsistent in terms of the values and the criteria according to which the appropriate values are to beselected.Itisshownthatthetargetreliabilityofstructurescanbederivedfromtheoreticalprinciplesof probabilistic optimization considering the objective function as the total costs expressed as a sum ofthe initial costs C_0, the marginal costs x C_1 (where x denotes the decision parameter and C_1 theincrementalcostofdecisionparameter$x$),andthefailureconsequencesconsistingoftheconstruction costs C_{str} and failure costs C_f (the loss of structural utility at the time of failure), these being taken intoaccount bytherelevantcostratios C_{str}/C_1 and C_f/C_1.The construction costsC_{str} is discounted considering an annualobsolescence (oldness) rate$q$ andthe time to failure (numberofyears) n, the failure costs C_f is discounted considering an annualdiscount rate q and the time to failure (number of years) n. In such a way the total cost is affected(reduced) bytheobsolescence rate$o$anddiscountrate$q$, andthe numberofyears$n$.

References:

1. Diamantidis D 2009 “Reliability differentiation”, In.: Holický et al.: Guidebook 1, Load effects on Buildings, CTU in Prague, Klokner Institute, ISBN 978-80-01-04468-1, pp. 48-61, 2009
2. EN 1990 2002 Eurocode / Basis of structural design, CEN
3. Fischer K, Barnardo-Viljoen C, and Faber, M, H 2012. Deriving target reliabilities from the LQI,
4. LQI Symposium in Kgs. Lyngby, Denmark
5. Holický M and Schneider J (2001). “Structural Design and Reliability Benchmark Study”, In.: Safety, Risk and Reliability – Trends in Engineering c/o IABSE, ETH Zûrich, International Conference in Malta, ISBN 3-85748-102-4, pp. 929-938
6. Holický M 2009 Reliability analysis for structural design, SUN MeDIA Stellenbosch, ZA, ISBN 978-1-920338-11-4, 199 pages
7. Holický M and Retief J 2011 Theoretical Basis of the Target Reliability. In: 9th International Probabilistic Workshop. BraunschweigTechnischeUniversität, pp. 91-101. ISBN 978-3- 89288-201-5
8. Rackwitz R 2000 *Optimization — the basis of code-making and reliability verification.* Structural Safety, **22**(1), p. 27-60.
9. Holický M 2013 Introduction to Probability and Statistics for Engineers, Springer, Heidelberg, New York, London