OPTIMIZATION OF STRUCTURAL DURABILITY

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Abstract

Principles of the probabilistic approach to structural durability will be soon provided in a newly developing international standard ISO „General Principles on the Design of Structures for Durability“. It is expected that after its completion the document will be implemented into the system of national standards in many countries. The operational use of the new procedures in practice would require additional studies focused on durability criteria, required reliability level, physical models of material deterioration, and theoretical models of basic variables.

An example of the durability limit state concerning reinforced concrete members illustrates the general optimization procedures. It appears that the optimum thickness of the concrete cover and the corresponding reliability level increases with the increasing cost of failure consequences and decreases with the increasing discount rate.

Further research into the target reliability levels considered in the limit states of structural durability should be based on advanced optimisation models, relevant economic data, physical models of material deterioration, and on theoretical models of basic variables.

1. INTRODUCTION

The technical committee TC 98 of the International organisation for Standardisation ISO has been preparing a new document on structural design ISO 13823 (2006) provisionally entitled „General Principles on the Design of Structures for Durability“. The document is based on the fundamental principles provided in recent international documents ISO 2394 (1998), ISO 19338 (2003) and CEN 1990 (2002). Materials of other international organisations as CEB (1997) and RILEM (1997) and other publications (for example Holický and Mihashi (2000), Holický and Holická (2006), Kasami et al. (1986), Norami (1996)) have also been taken into account. References to other ISO/IEC materials and to a number of particular studies are going to be provided in the upcoming document ISO 13823 (2006).

The experts participating in the development of the document ISO 13823 (2006) come from different countries of the whole world. The international discussions of methodical principles (including terminology) have therefore been complicated and time consuming. In spite of that, at present the document is in an advance stage of development and it is expected to be completed and agreed by the Technical Committee TC 98 within a year. Then the Committee Draft (CD) will be submitted to the secretariat of ISO for further processing. After its publication the document will be most likely implemented into national systems of standards in many countries.

However, the process of implementation of the document ISO 13823 (2006) and its effective use will not be easy and will definitely require additional research and development. The submitted contribution points out the most important aspects of the present version and draws attention to expected difficulties in operational use of the document. Topics required for further research and development are indicated.

2. VERIFICATION OF THE SERVICE LIFE

The fundamental durability requirement is represented by a simple condition that the predicted service life t_{SP} should be greater than the design service life t_D with a sufficient degree of reliability. Difficulties are obviously linked to the term „sufficient reliability". It is well recognised that the service life t_S is dependent on a number of basic variables and is consequently a random variable having a considerable scatter. The document ISO 13823 (2006) therefore provides a probabilistic formulation of this criterion in the form

$$\mathrm{P}\{t_S < t_D\} < P_{\mathrm{target}} \tag{1}$$

Here P_{target} denotes the target probability of the service life t_S being less than the design service life t_D. As a rule the design service life t_D is a deterministic quantity (for example 50 or 100 years) specified in advance.

3. VERIFICATION OF LIMIT STATES

Three different limit states are recognized in ISO 13823 (2006): ultimate limit state (ULS), serviceability limit state (SLS) and durability limit state (DLS). The probabilistic formulation of the ultimate limit states criterion is similar as in case of the service life. For an arbitrary point in time $t \leq t_D$ the following condition should be valid

$$\mathrm{P}_f(t) = \mathrm{P}\{R(t) - S(t) < 0\} < P_{\mathrm{target}} \tag{2}$$

where $R(t)$ denotes resistance and $S(t)$ action effect.

The basic probabilistic condition for the serviceability limit state is in ISO 13823 (2006) written analogously as

$$\mathrm{P}_f(t) = \mathrm{P}\{S_{\mathrm{lim}} - S(t) < 0\} < P_{\mathrm{target}} \tag{3}$$

Here S_{lim} denotes the limit value of the serviceability indicator (for example of the crack width or deflection). The durability limit state may be verified using Equations (2) or (3) depending on the particular conditions.

4. TARGET RELIABILITY LEVEL

Target reliability level, indicated by the target probability P_{target} or reliability index β_{target}, is not specified in ISO 13823 (2006). In general it should depend on the definition of the service life; whether the critical durability requirement concerns the ultimate limit state, serviceability limit state or durability limit state. As indicated in ISO 2394 (1998) the target reliability level should depend on the consequences of the limit states infringement and relative costs of safety measures (required for an increase of the reliability level). Obviously, in particular conditions the target reliability level may considerably vary. Table 1 provides indicative intervals for the target probability P_{target} and reliability index β_{target}, which are derived from the target values recommended in EN 1990 (2002) and ISO 2394 (1998). Note that $\beta = -\Phi^{-1}(P)$, where Φ denotes distribution function of the normal distribution.

Table 1: Indicative values of the target probability P_{target} and reliability index β_{target}

Limit state	P_{target}	β_{target}
Ultimate limit state – ULS	~ 10^{-4}	~ 3,7
Serviceability limit state – SLS	0,01 to 0,10	1,3 to 2,3
Durability limit state – DLS	0,05 to 0,20	0,8 to 1,6

The target probability P_{target} and reliability index β_{target} given in Table 1 represent indicative values only and specification of the appropriate reliability level remains therefore one of the most important open questions. In the following example of the durability limit state it is indicated that probabilistic optimization may provide some guidance.

5. DURABILITY LIMIT STATE

The durability limit state (DLS) can be well illustrated by the carbonation of concrete. The limit state is defined as a simple requirement that the carbonation depth $S(t)$ (action effect) is less than the concrete cover R (resistance). Failure probability can be then determined using Equation (2) from the integral

$$P_{\text{f}}(t) = P\{S(t) > R\} = \int_{-\infty}^{\infty} \varphi_S(x,t)\Phi_R(x)\text{d}x \qquad (5)$$

where $\varphi_S(x,t)$ denotes the probability density function of the action effect $S(t)$ and $\Phi_R(x)$ the distribution function of the resistance R.

Extensive measurements of the carbonation depth $S(t)$ on cooling towers (Holický and Mihashi 2000) (unprotected external concrete) provided the following expressions for the mean $\mu_S(t)$, coefficient of variation $w_S(t)$ and skewness $\alpha_S(t)$

$$\mu_S(t) = 5\ t^{0,2}\ \text{mm},\ w_S(t) = 0,1\ t^{0,2},\ \alpha_S(t) = 0,2\ t^{0,2} \qquad (6)$$

where t denotes time in years. Gamma distribution seems to be the most suitable theoretical model.

For a time-invariant concrete cover the following parameters have been obtained

$$\mu_R = 20,\ 25\ \text{a}\ 30\ \text{mm},\ w_R = 0,35\ \text{mm}, \alpha_R = 0,35 \qquad (7)$$

In that case Beta distribution having the lower bound at zero seems to be a suitable theoretical model. Note that in Annex A of ISO 13823 (2006) a normal distribution is assumed for both variables $S(t)$ and R; this assumption may provide a first approximation only as both basic variables have distribution with a significant asymmetry.

5. OPTIMIZATION

The total costs of execution and repair of the structure due to failure (infringement of the durability limit state) can be expressed as a function of the mean μ_R (decisive parameter)

$$C_{\text{tot}}(\mu_R,t,p) = C_0 + C_1\,\mu_R + P_f(\mu_R\,,t)\;C_f/(1+p)^{\,t} \tag{8}$$

where C_0 denotes the initial costs independent of μ_R, C_1 expenses for a unit of μ_R , C_f expenses for the durability failure at the service life t and p the discount rate (around 0,03). Standardised total costs are considered as

$$\kappa_{\text{tot}}(\mu_R,t,p) = [C_{\text{tot}}(\mu_R,t,p) - C_0] / C_1 = \mu_R + P_f(\mu_R\,,t)\;C_f/\,[(1+p)^{\,t}\,C_1] \tag{9}$$

The optimum mean μ_R may be then determined from

$$\frac{\partial \kappa_{\text{tot}}(\mu_R, t, p)}{\partial \mu_R} = 0 \tag{10}$$

Taking into account Equation (9) the following condition may be derived

$$\frac{\partial P_f(\mu_R, t)}{\partial \mu_R} = -\frac{(1+p)^t C_1}{C_f} \tag{11}$$

Note that within a realistic domain of μ_R from 20 do 60 mm Equation (11) may not have a practical solution and the minimum of the total costs may not be attained.

Considering the above described durability limit state, the standardised total costs $\kappa_{\text{tot}}(\mu_R,t,p)$ given by Equation (9) are shown in Figure 1 assuming the service life t = 50 years and the discount rate p = 0,03.

Figure 1 indicates that the optimum mean μ_R (in mm) increases with increasing the cost ratio C_f/C_1. For the cost ratio C_f/C_1 = 200 the optimum μ_R is about 20 mm, for the cost ratio C_f/C_1 = 1000 the optimum mean of the concrete cover is much greater, $\mu_R \sim$ 28 mm. Figure 1 also shows variation of the reliability index β with the mean μ_R The scale for β is on the right hand side of the graph. Thus for the mean μ_R = 40 mm (the optimum for C_f/C_1 = 5000) the reliability index β is about 2,3 for which the failure probability $P_f(40,50)$ = 0,01.

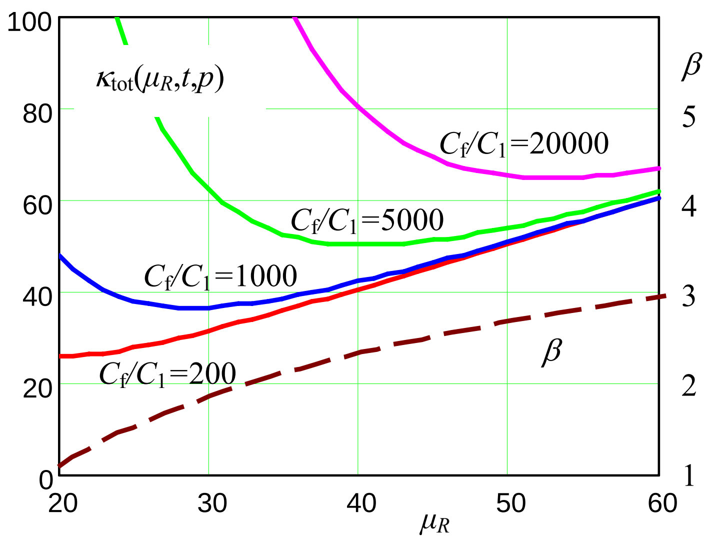

Figure 1: The total standardised costs $\kappa_{\text{tot}}(\mu_R, t, p)$ for t = 50 years and p = 0,03, the mean μ_R is given in mm

Variation of the standardized total costs $\kappa_{tot}(\mu_R, t, p)$ with both the mean μ_R (in mm) and discount rate p is shown in Figure 2 for the cost ratio $C_f/C_1 = 1000$ and the service life $t = 50$ years.

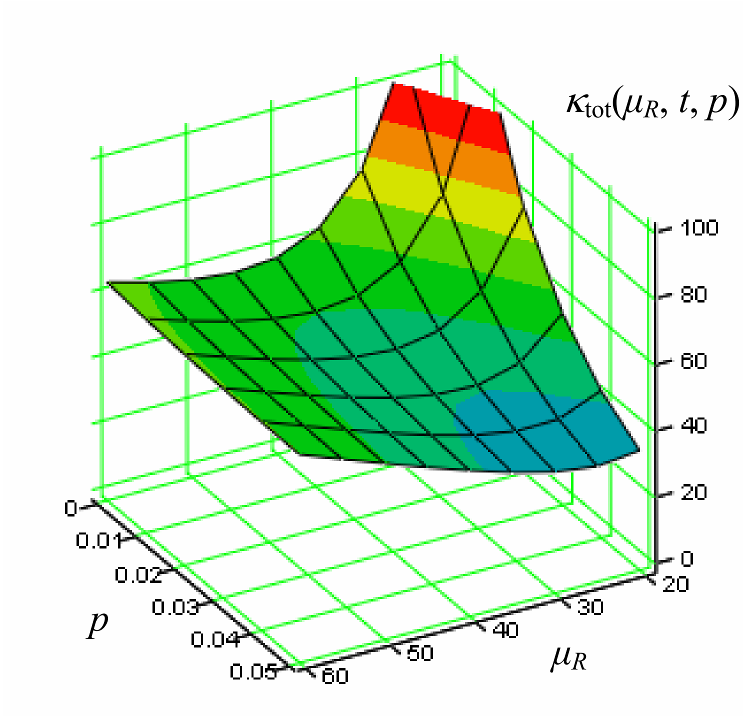

Figure 2: The total standardised costs $\kappa_{tot}(\mu_R, t, p)$ for $C_f/C_1 = 1000$, $t = 50$ years, the mean μ_R is given in mm

Figure 2 clearly indicates that the discount rate p may significantly affect the total costs and the optimum mean μ_R. Obviously, with increasing the discount rate p the total costs and the optimum mean μ_R decrease. In addition also the service life t may affect the optimum concrete cover.

7. CONCLUSIONS

Methods of probabilistic optimisation may provide rational background information for a specification of the target reliability level. In case of carbonation of a concrete cover the total costs depend on the thickness of the concrete cover, service life and discount rate. The optimum concrete cover increases with increasing the costs due to durability failure, and decreases with increasing the discount rate.

Operational use of the new procedures in practice requires further research that should be primarily focussed on the following topics:

- Appropriate physical models for material deterioration
- Suitable theoretical models for basic variables
- Differentiated probabilistic criteria for durability requirements.

The following particular conclusions may be drawn from the optimization study of a concrete cover.

- The optimum thickness of a concrete cover of reinforced concrete structures is significantly dependent on the cost ratio C_f/C_1, specified life and discount rate.
- Commonly used concrete covers of reinforced concrete structures correspond to relatively low cost ratios C_f/C_1 and seem to be uneconomical; however, this conclusion is relevant if all the costs are paid by one partner (e.g. final owner).
- For the service life of 50 years, discount rate 0,03 and the low cost ratio $C_f / C_1 = 200$, the optimum concrete cover is about 20 mm ($\beta = 1{,}2$), for $C_f / C_1 = 1000$ the optimum cover is about 28 mm ($\beta = 1{,}7$) and for $C_f / C_1 = 5000$ about 40 mm ($\beta = 2{,}3$).
- Further experimental data and appropriate theoretical models for the carbonation process including the description of wetting and drying effects in outdoor conditions are needed. And, for more realistic reliability conditions, expected corrosion of reinforcement is to be taken into account.
- Further studies on all the components of expected costs including marginal and costs due to protection failure are needed in order to formulate more realistic objective functions.

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REFERENCES

CEB. 1997. Bulletin d' Information No. 238 New Approach to Durability Design. An example for carbonation induced corrosion.

EN 1990. 2002. Eurocode – Basis of structural design. CEN 2002.

Fib. 2004. TG 5.6: Model Code for Service Life Design (SLD), working materials.

Holický M. and Mihashi H. 2000. Stochastic Optimisation of Concrete Cover Exposed to Carbonation. In: R.E. Melchers & Mark G. Steward (ed.), Application of Statistics and Probability. A. A. Balkema Rotterdam, pp. 279-284.

Holický M. and Holická N. 2006. Probabilistic optimisation of concrete cover exposed to carbonation. Proc. of the Internatioal RILEM-JCI Seminár. pp. 384-393.

ISO 13823. 2006. General Principles on the Design of Structures for Durability. ISO TC98/SC2, Draft 10. 2006.

ISO 2394. 1998. General principles on reliability for structures. ISO.

ISO 19338. 2003. Performance and assessment requirements for design on structural concrete. 2003.

Kasami, H., Izumi, I., Tomosawa, F. and Fukushi, I. 1986. Carbonation of concrete and corrosion of reinforcement in reinforced concrete, Proc. of First Australia-Japan Coordinated Workshop on Durability of Reinforced Concrete, Building Research Institute, Japan, C4, pp.1-13, October 1986.

Norami T. 1996. Service life design. Construction and Building Materials, vol.10, no 5, 1996, 403-406

RILEM. 1997. REPORT 14 Durability Design of Concrete Structures, Edited by Sarja A. and Vesikari E., E & FN SPON, London, pp 165.