DECISION-SUPPORT TOOLS FOR LIFE CYCLE ASSESSMENT AND MANAGEMENT OF CONCRETE STRUCTURES

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Summary

The combined impact of the service life and relevant reliability level of structures on the financial and environmental aspects of concrete infrastructure building is discussed. An approach and tools for advanced design, assessment and decision-making utilizing modeling of degradation phenomena and relevant reliability of concrete structures, taking into account uncertainties involved are presented. The decision of the client regarding the optimal service life and associated level of reliability is crucial in this respect. The suitable methodology utilizes limit states associated with durability; the reliability assessment is effectively performed by employing the full probabilistic safety format. Degradation aspects, as carbonation of concrete, chloride ions ingress and corrosion of reinforcement, enable reliability prediction in time and the estimation of lifetime. Different mathematical models are mentioned for both the initiation as well as the propagation period which may enable to verify the SLS and/or ULS for concrete structure in different time steps considering the change of performance in time due to degradation. This may bring positive economical and sustainability impacts as the resulting software management tool will allow a cost efficient risk based decision support according to lifetime performance during design and maintenance of structures.

Keywords: concrete structures, degradation models, service life, reliability, limit states

1 Introduction

When attempting to achieve an optimal allocation of available economic resources for infrastructure building, the ability to make a reliable comparison of the life-cycle costs for different construction, technological and material scenarios is needed. In this context the important topics are e.g. the probabilistic vulnerability assessment of civil infrastructure systems, life cycle costing (LCC), life cycle assessment (LCA) and life cycle management (LCM). Naturally, cost-benefit issues are considered together with sustainability and environmentally friendly policies – see e.g. (Frangopol et al. 2012, Thoft-Christensen 2012). The durability issue has gained considerable attention together with performance-based approaches, sustainability and *cradle-to-grave* thinking.

The cost reduction in the overall value chain in construction industry may result in the increased competitiveness of building firms. This creates the need for performance and consequence-based design and also the modeling and realistic prediction of the deterioration of aging structures with the relevant consideration of uncertainties – these are the prerequisites for an effective decision-making process. Several consequences may be stressed: reliability and durability are crucial performance characteristics of a structure; the service life of a structure may be considerably influenced by the target reliability level, and, LCC, LCA and LCM are hence also influenced by the level of reliability.

2 Reliability and durability

2.1 Structural reliability

A general definition of structural reliability is introduced in (ISO 1998) and (EN 2002). The verification of a structure with respect to its reliability, i.e. to a particular limit state (LS), is carried out via estimation of the probability of the occurrence of failure in a specified reference period. This probability is usually expressed as:

$$P_f = \text{Prob}\ \{B \le A\} \tag{1}$$

A is the effect of action and B is the barrier or the resistance; both are random variables (or, in a more general sense, random fields). The general limit condition for both the ultimate and serviceability limit states (ULS and SLS) reads:

$$P_f \le P_d \tag{2}$$

where P_d is the design (acceptable, target) probability value. The index of reliability β is alternatively utilized instead of P_f in practice; the target value then becomes β_d. The formula for the transformation reads:

$$\beta = -\Phi^{-1}(P_f) \tag{3}$$

where $\Phi(.)$ is the standard normal probability distribution function. Generally, both A and B may change in the course of time and hence P_f and β are time dependent. This should be stressed especially in the context of limit states associated with durability (ISO 13823 2008) and (*fib* Draft Model Code 2010) and the probability condition (2) may be written as:

$$P_f(t_D) = P\left\{B\left(t_D\right) - A\left(t_D\right) \le 0\right\} \le P_d \tag{4}$$

where t_D = design service life.

Thus, for the reliability assessment of newly designed as well as existing structures the full probabilistic safety format has to be employed. Moreover, this approach is the only one which provides quantitative information about the safety level. The development of applications using stochastic methods is inevitable, and the considerable uncertainties associated with parameters governing deterioration processes highlight the need for the use of probabilistic methods.

It should be also noted that reliability level, limit state definition, service life, environmental load consequences and cost-saving results are mutually related – some elements of whole life costs are service-life dependant, e.g. inspection and maintenance costs change with service life length. Durability and its reliability implications therefore need to be addressed during the design process due to their pronounced economic and sustainability impacts; the agreement or decision of the client should be a fundamental part of that process. This is not yet a view commonly held by engineers, even though these ideas are clearly expressed in Section 3 of the (*fib* Draft Model Code 2010): "*Specifying performance requirements and the associated constraints of service life and reliability creates an initial bridge between the needs of the stakeholders and the design or the assessment. ... The specified (design) service life or the residual service life are related to the required service life as given by the stakeholders and to other implications of the service criteria agreement e.g. with regard to structural analysis, maintenance and quality management*".

It follows that the target level of reliability in the context of durability should be discussed with the client or left to his/her decision as it should depend on a balance between the consequences of failure and the costs of safety measures – see (ISO 1998, EN 2002).

2.2 Durability of concrete structures and limit states

Reinforced concrete (RC) is the most widely used building material and its durability features have to be understood and assessed. Concrete is composed of cement, water, sand and aggregates – cement being the most pollutive element as its production is responsible for about 80 % of the concrete industry's CO_2 emissions (Habert 2012). The most effective way to reduce environmental impact is to replace Portland cement with supplementary cementitious materials (SCM), which may have considerable durability implications (Chromá et al. 2007).

Owing to either carbonation of reinforced concrete or the ingress of chlorides into such concrete, the depassivation of reinforcing steel occurs (the initiation period); this may be followed by steel corrosion (the propagation period) – see (Tuutti 1982). With the focus on these periods, the modelling of relevant limit states (LS) within the probabilistic approach for the RC durability issue is described briefly below.

Eq. (4) may also be expressed by means of the service life format as:

$$P_f = P(t_S \le t_D) \le P_d \tag{5}$$

where t_D is the design life and the service life t_S can be determined as the sum of two service-life predictors:

$$t_S = t_i + t_p$$

where t_i is the time of the initiation of reinforcement corrosion and t_p is the time period after corrosion initiation (the propagation period).

Considering the durability issue, a special category of LS has been introduced which is intended to prevent the onset of deterioration or allow only a limited range of degradation effects. This category represents a set of limit states which may be called Durability Limit States (DLS) – see (ISO 2008, *fib*-Model Code 2010). DLS may be formally regarded as belonging in the SLS category as usually the depassivation of reinforcement, i.e. the initiation period, is considered to be a limit.

Being random quantities, the relevant values of variables *A, B* and t_S used in Eq. (1), (4) or (5) have to be assessed via the utilization of a suitable degradation model or by field or laboratory investigations. In the former case effective probabilistic software tools should be utilized.

Let us summarize the possible basic actions and barriers usable for the DLS of concrete structures – Equation (4):

Considering the initiation period, i.e. depassivation of reinforcement generally, the dominant degradation effects are

(i) Carbonation: in this case B is represented by concrete cover a and for A stands x_c – the depth of carbonation at time t_D. Analytical models of this action effect are based on the diffusion of CO_2 in the concrete pore system and have been discussed e.g. in (*fib* Bulletin, 2006, Teplý et al., 2007, Teplý et al., 20010a). Note that the carbonation of concretes from Portland Cement (OPC) and from blended cements should be distinguished from each other; more details about the latter case can be found e.g. in (Chromá et al., 2006) including the discussion of the *k*-value concept.

(ii) Chloride ingress: in this case $B = C_{cr}$ is the critical concentration of dissolved Cl^- (a prerequisite of steel depassivation) and $A = C_a$ is the concentration of Cl^- at the reinforcement at time t_D.

Weil considering the propagation period, i.e. the period when the corrosion of reinforcement is initiated, the damage to the structure proceeds as:

(iii) Concrete cracking due to corrosion: $B = \sigma_{cr}$ is a critical tensile stress that initiates a crack in the concrete on the interface with reinforcing bars; $A = \sigma$ is the tensile strength of the concrete. Also, a consecutive stage may be assessed, where $B = w_{cr}$ is the critical crack width on the concrete surface and $A = w_a$ is the current crack width on the concrete surface at time t_D.

(iv) A decrease in the effective reinforcement cross-section due to corrosion; then for action effect stands the effective reinforcement cross-sectional area at time t_D and the barrier is represented by the minimum acceptable reinforcement cross-sectional area with regard to the relevant SLS or ULS.

A great many works have been published in last two decades about the durability modelling and assessment of RC structures; see e.g. (Stewart and Rosowski 1997, DuraCrete 1998, Biondini and Frangopol 2008, Vořechovská et al. 2010 and Teplý et al. 2012).

3 Effect of reliability

3.1 Reliability index and costs

As stated in the basic codes for structural design (ISO 1998, EN 2002), the recommended reliability index value for an SLS (irreversible state) is 1.5, which is relevant to a 50-year design service life. It should be noted that the values of $0.8 < \beta_d \leq 1.8$ for the DLS are still under discussion – e.g. the recommendation of the (*fib* Model Code 2010) for the β_d is the value 1.3.

It should be noted that reliability level, limit state definition, target service life and cost-saving results are mutually related – some elements of whole life costs and benefits are service-life dependent. Those costs are especially:

(i) operating costs (such as insurance, energy, water, sewage, facility management) – all during the designed service life t_D;

(ii) maintenance costs (including inspections, i.e. actions planned during the designed service life t_D);

(iii) repair and/or degraded element replacement costs, including any possible loss due to the discontinuation of operations. These effects come with a certain probability (associated with the relevant limit state and target value of the reliability index) – this should be taken into account when making decisions;

(iv) expected benefits (for the owner, user and society) – all during the designed service life t_D.

To summarize: the interdependence of service life, reliability level, costs, benefits and environmental stress should be recognized and balanced well/optimized – i.e. the target is the inclusion of long-term financial implications in the evaluation of design, construction and real estate decisions.

As mentioned above, the agreement or decision of the client regarding the demanded/optimal service life and associated level of reliability (i.e. maximum failure probability or corresponding reliability index) are needed. Regarding this point, he/she also has to agree with chosen serviceability criteria in the context of the deterioration process. The designer performs the modeling and the assessment of the relevant limit states, related reliability indexes and consequently the service life.

3.2 Parametric approach

The parametric approach may be a tool used to gain a better understanding of the mutual correspondence of different variables influencing the performance of a structure as represented by computational models, to guide the design process and simplify decision making. In this respect a parametric study may be organized in a simple way as a series of analyses by gradual changes to a certain input parameter (say X_i) in each calculation step j (j = 1, 2, …, m) within a realistic range. By comparing the set of m results one can decide on an "optimal" solution within the context of the performance criteria in question. It has to be stressed that for the sake of correctness the probabilistic approach should be adopted for such a procedure. Considerable labour savings may be gained by making such a process automated. In the following paragraph the features of two software tools are described, both being equipped with such capabilities for parametric studies (developed by the authors and co-workers).

4 Applications

4.1 Software tools

Qualified decision making with consideration given to all the consequences and uncertainties discussed above is rather a complex task, and one which is strongly case dependent, so it is not feasible to provide a complete realistic example in the present paper. Instead, some parametric studies showing the effect of reliability level on service life or other implications for concrete structures are detailed below.

Firstly, here is a brief introduction to the software tools:

(i) The *RC LifeTime* web page is a user-friendly tool which utilizes three models of the concrete carbonation process. It considers input data as random variables and performs stochastic analysis. It is freely accessible at internet link (Rovnaník 2008) offering two options: (a) "Service Life Assessment", which provides the statistical evaluation of initiation period (considered to be equal to service life) and optionally provides the service life corresponding to the target value of the reliability index β_d; and (b) "Concrete Cover Assessment", which provides the statistical evaluation of concrete cover. The reliability index β relevant to the required value of concrete cover can be gained.

(ii) *FReET-D* software (Feasible Reliability Engineering Tool – Degradation) is a module for the statistical, sensitivity and reliability assessment of degradation effects in reinforced and pre-stressed concrete structures, currently encompassing 39 models and their modifications. It serves for assessing the potential degradation of newly designed as well as existing concrete structures in tasks such as the assessment of service life and the level of relevant reliability. The user may create different limit conditions. For more details see (Novák et. al 2013, Teplý et. al 2007). Having a broader choice of models is useful, e.g. due to problems with the availability of statistical data for the input variables of some models. The comparison and verification of several models of concrete carbonation and chloride ingress into concrete utilized in *FReeT-D* are presented in (Teplý et. al 2012). *FreET-D* is actually a specialized module of *FReeT* software (iii).

(iii) *FReeT* software (Feasible Reliability Engineering Tool represents a multipurpose simulation and reliability package enabling efficient statistical, sensitivity and reliability assessment (Novák at al. 2003, 2013). State-of-the-art probabilistic algorithms are implemented in *FReeT* to compute the probabilistic response and reliability. The attention is given to those techniques that are developed for analyses of computationally intensive problems; nonlinear FEM analysis being a typical example. Stratified simulation technique Latin hypercube sampling is used, in order to keep the number of required simulations at an acceptable level. The technique is used for both random variables' and random fields' levels. Sensitivity analysis is based on nonparametric rank-order correlation coefficients. Statistical correlation is imposed by the stochastic optimization technique – the simulated annealing (Vořechovský & Novák, 2009). Window of user-friendly environment of *FReeT* and *FReeT-D* is shown in Figure 1.

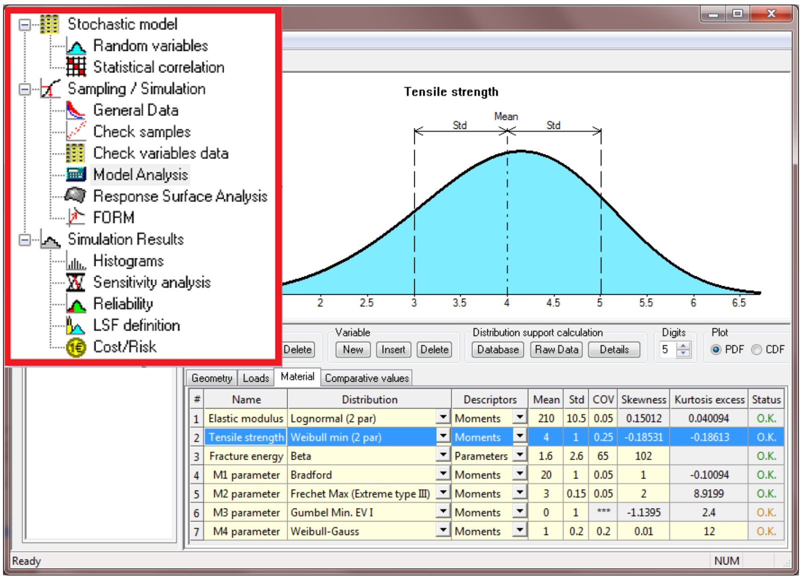

Fig. 1 FReeT software window.

4.2 Examples – parametric studies

4.2.1 Study 1

To present the effect of material quality an example of a concrete structure exposed to deicing salts or the effect of a coastal environment is analyzed for different concrete qualities – represented here by the diffusion coefficient D of concrete. According to (Duprat 2007), the values D = 1x10^{-12} and 2x10^{-12} represent excellent and good quality concretes, D = 4x10^{-12} is for ordinary quality concrete and D = 7x10^{-12} [m^2/s] is for poor quality concrete with a lognormal probability distribution and a coefficient of variation of 0.7 (high uncertainty). The mean concentration of Cl^- on the nearest surface C_S = 2 [wt.-%/c] is considered (one-bounded normal distribution with a coefficient of variation of 0.75). Using the critical Cl^- concentration C_{cr} = 0.6 [wt.-%/c] (Duprat 2007) Eq. (4) was assessed for concrete cover a = 50 mm. The most frequently referenced model, applied e.g. by (Collepardi et. al 1972), see also (Tikalsky 2005), was employed using *FReET-D*.

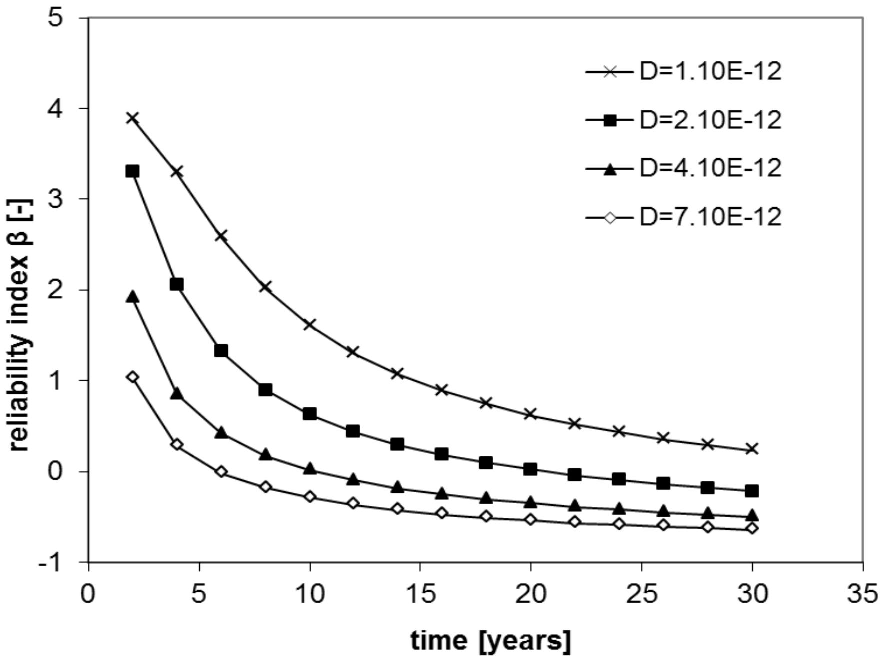

Fig. 2 *Service life vs. reliability index, influenced by chloride ion ingress for concretes of different diffusion coefficient values*

Fig. 2 presents the results of the stochastic analysis – the dependence of service life vs. the reliability index. It may be observed that e.g. for β = 0.8 the t_S ranges from 2 to 18 years depending on concrete quality; for the higher reliability requirement $\beta = 1.8$ the corresponding service life is predicted to be much lower. It may be expected that the chosen variant will have relevant consequences in terms of costs and benefits; these are not specified here because of case-specific dependences on many factors (structure type, loading and exposure conditions, maintenance, and others).

4.2.2 Study 2

Critical crack width on the concrete surface. A parametric study utilizing a suitable model employed in *FReET-D* is demonstrated in this example. The limit state condition (4) is constructed in this case in the form:

$$P_f(t_D) = P\left\{w_{cr} - w_a\left(t_D\right) \leq 0\right\} \leq P_d \tag{7}$$

where w_{cr} is the limit value of a crack width equal to 0.3 mm – one of the essential limits for the serviceability assessment of corrosion-affected RC structures recommended in CEN (2003), the actual corrosion-induced crack width w_a over time is analyzed by the model. In this example, time t_D represents the propagation period only; to gain a service life prediction the appropriate initiation period must be added. More details about this study may be found in Teplý and Vořechovská 2012.

In Fig. 3 the results of statistical analysis are depicted, i.e. the values of crack width on the concrete surface after 15 years of steel corrosion development as the function of concrete cover *a*.

Again, it is expected that the chosen variant will have relevant consequences in terms of costs and benefits.

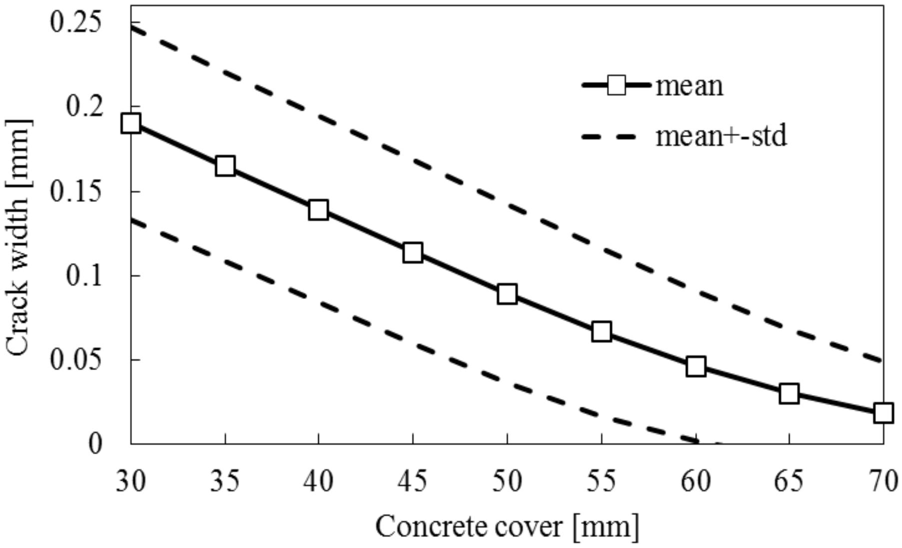

Fig. 3 *Crack widths on the concrete surface after 15 years of steel corrosion development.*

5 Conclusions

The present paper discusses the effect of and compromise between the service life and the time-varying reliability level of deteriorating concrete structures on whole-life costs and benefits. Due to the large uncertainties associated with the prediction of deterioration processes the application of stochastic methods and the employment of analytical models are recommended.

The presented approach for the assessment of a degrading concrete structure is formed by the following steps for each of the relevant design variants: the gathering and sorting of information about the structure – decision making regarding the exposure condition – choice of limit state – choice of model – the obtaining of relevant input data values (including their statistical parameters) – statistical and reliability analysis – service life and reliability index assessment – the evaluation of results and related costs – appropriate decision making. Final decision making follows in cases when there is more than one design variant.

The prerequisite for such a decision-making process is that the demanded reliability level and required service life should be agreed on or decided by the client. This choice may have pronounced financial and sustainability impacts.

Two studies focused on concrete structures are presented showing the mutual impacts of service life and reliability level.

The presented approach may be applied when searching for optimum life-cycle cost solutions, in the advanced design of structures (making decisions about alternatives) or in cost-effective decision-making processes concerning maintenance planning (including inspection planning). It may also be of use e.g. in the drafting or assessment of Public Procurements and Public Private Partnership Projects.

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