STOCHASTIC DEGRADATION MODELS FOR DURABILITY LIMIT STATE EVALUATION: SARA – PART VI

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Abstract

Durability and reliability are decisive structural performance characteristics. While assessing the reliability level, the residual service life and making relevant conclusions and decisions and carrying out optimization concerning the structure under consideration, an appropriate limit state has to be defined and assessed.

Within this context, Durability Limit States (DLS) are recognized as a new category of limit states – see also some new international documents which are currently under development. DLS are now being considered in addition to the traditionally distinguished Ultimate Limit States (ULS) and Serviceability Limit States (SLS).

The utilization of design for durability may bring pronounced economical and sustainability impacts. However, broad application is still prevented by the insufficient dissemination of basic ideas, relevant knowledge or experimental evidence and by a lack of simple, user friendly and efficient design instruments (software and other) based on well-recognized models.

For such purposes the FReET-D code is introduced, which can serve for such tasks as a user-friendly tool. It is a deterioration module for statistical, sensitivity and reliability assessment of degradation effects in reinforced and pre-stressed concrete structures, currently encompassing 26 models for the description of degradation processes in materials. The models can be "chained" thus enabling the reflection of different types of DLS. Several examples of applications are presented.

INTRODUCTION

Generally, durability and reliability are decisive structural performance characteristics; to assess them the relevant processes deal with: (i) assessment of the reliability level of the particular limit state; (ii) residual service life assessment; (iii) the conclusions and decisions to be made, and optimization to be carried out for the structure under consideration.

The utilization of design for durability may bring pronounced economical and sustainability impacts. The prescriptive approach of current standards (e.g. Eurocodes [1, 2]) does not directly allow a design focused on a specific (target) service life and/or a specific level of reliability – this would require the inherent uncertainties in material and technological and environmental characteristics to be dealt with while assessing the service life of a structure. Such tasks necessarily require the utilization of stochastic approaches, analytical models of degradation effects and also simulation techniques, all based on the experimental evidence and relevant observations of structures under real conditions.

Within this context Durability Limit States (DLS) are recognized as a new issue when dealing with limit states (LS) by some new documents which are currently under development (ISO, fib Model Code [3, 4]). Both these documents are based on probabilistic approaches, are currently under development by international bodies and will introduce (or enhance) the *design of structures for durability* – i.e. the time-dependent limit state approach, and consideration of service life. DLS may be viewed either as a new category of LS (ISO) or are supposed to belong among the currently established Serviceability Limit States (SLS) – (fib). Less frequently, Ultimate Limit States (ULS) are involved too.

However, broad application is still prevented by the insufficient dissemination of basic ideas and by a lack of simple and efficient design tools (software and other) based on verified numerical models. In this context the FReET-D software is introduced which can serve for such purposes as a user-friendly tool to assess degradation phenomena effects. It is a deterioration module for statistical, sensitivity and reliability assessment of degradation effects in reinforced and pre-stressed concrete structures, currently encompassing 19 models and 7 modifications. The present paper informatively describes these models (for carbonation of concrete, chloride ingress and corrosion of reinforcement) and software feasibility is shown. Some examples of applications are briefly presented.

DURABILITY LIMIT STATES

Definition

The service life of a building or structure is determined by its design, construction, ageing and maintenance during use. While assessing service life, the combined effect of both structural performance and ageing should be considered, wherever relevant.

Structural design based on current building codes deals with limit states (LS), of both ultimate and serviceability type – ULS and SLS. As mentioned above there is a new category of limit states which precede the occurrence of other SLS or ULS, i.e. they describe the onset of deterioration (or allow a limited range of degradation only). They represent certain simplified limit states and are called Durability Limit States (DLS). Note that this kind of LS has not yet been introduced in current standards – deterioration states are (if assessed) considered as falling into the category of SLS mostly, sometimes ULS.

Generally, DLS may be described by the probability condition

$$P_f = P(t_S \leq t_D) \leq P_d \quad (1)$$

where the theoretical value of failure probability P_f is compared to the design (acceptable, target) probability value P_d. The predicted (modeled) service life t_S should be less or equal to design service life t_D. Alternatively, the limit conditions may be of a general form

$$P_f = P(A(t) \geq B(t)) < P_d \quad (2)$$

where A = action effect, B = barrier; both A and B (and hence the P_f) are time dependent; this has not been considered for common cases of ULS or SLS in design practice very frequently up to now. The time t_S and the deteriorating effect A are assessed by utilization of the appropriate degradation model (or chain of models) and the relevant LS, making use of a probabilistic approach.

Note: Instead of the probability of failure P_f, the index of reliability β is alternatively (and rather frequently) utilized in practice; both these quantities are interconnected by the transformation rule

$$\beta = -\phi^{-1}\left(P_f\right) \quad (3)$$

where Φ is the cumulative distribution function of the standardized Normal distribution. As stated in the basic design code [1], the recommended value of the reliability index for SLS (irreversible state) is = 1.5, which is relevant to a 50-year design service life. It should be noted that the design values of $0.8 < \beta_d \leq 1.5$ for the DLS are currently under discussion (e.g. the recommendation of the fib Model Code reads $\beta_d = 1.3$; the level of reliability in the context of durability should be left to the client's decision together with the target service life (as indicated in both future documents [3, 4]).

Concrete structures; degradation models

When considering the LS caused by the degradation of reinforced concrete structures, four kinds of attack may be distinguished:

(i) mechanical (mechanical load – static or dynamic),
(ii) chemical (carbonation, acid attack),
(iii) electrochemical (corrosion of reinforcement) and
(iv) physical (freeze-thaw, abrasion, fire and others).

The present text focuses on cases (ii) and (iii); for such purposes usually the initiation period (depassivation of reinforcement surface) and propagation period of corrosion process are distinguished/assessed.

Modeling of degradation processes may be based on models of different levels of sophistication:

a) macro-level;
b) simplified models, probabilistic approach;
c) micro-level.

The *a-level* is the most simple, often called a "deemed-to-satisfy" set of rules (mostly according to current codes) and does not allow for the design/assessment of a specified service life with a specified reliability level. The *b-level* comprises simple models (often semi-empirical), verified by comparisons with testing under experimental and real-conditions; the variables are treated as random quantities, so the outputs are also capable of expressing statistical and probabilistic quality with respect to time evolution (service life assessment). In the present work this level is dealt with. The *c-level* is the most refined one where the models are complex and are developed making use of basic physical laws and often constitutive laws of mechanics, thus leading to the problem of needing to solve partial differential equations. This level of sophistication is too high for everyday design practice. Note that *levels b* and *c* may be viewed as performance-design types.

SOFTWARE

Options

In the frame of the *b-level* mentioned above, the FReET-D software (see [7] or www.freet.cz) has been developed. The utilization of stochastic approaches (a combination of analytical models and simulation techniques) was involved in the creation of specialized software for assessing newly-designed as well as existing concrete structures.

FReET-D is an associated product of the multipurpose probabilistic software for statistical, sensitivity and reliability analysis of engineering problems, FReET (Feasible Reliability Engineering Tool), which is based on efficient reliability techniques [5, 6]. FReET can be utilized in two modes: as a stand-alone multipurpose program for any user-defined problem, and as a module integrated with ATENA software (Červenka Consulting) [8]; this integration has been developed within the SARA project [9].

FReET-D provides:

(i) modeling of degradation phenomena in concrete structures, statistical and sensitivity analyses;
(ii) assessment of service life;
(iii) assessment of reliability measures.

For the purposes of options (ii) and (iii) the user may create different simple limit conditions of types (1) or (2).

The FReET-D module has been developed by implementing a number of degradation models for reinforced concrete structures. Degradation models are time dependent mathematical functions that show the average increase of cumulative degradation with time. These models are parameterized with several material, structural and environmental parameters which are considered to be random variables. For all models, the factor ψ (the general multiplier) of model uncertainty is provided to compensate for the possible inexactness or incompleteness of results. In common cases the recommendation of the JCSS (Joint Committee for Structural Safety) may be used: the factor ψ may be represented by a two-parametric lognormal PDF with a mean equal to 1.0 and a standard deviation of 0.15.

The main criteria in selecting the degradation model for each specific use are e.g.:

- type of relevant degradation mechanism, definition of appropriate limit state and given exposure conditions;
- availability of statistical data or the testing method for the input variables of each model;
- accuracy of the model when using the available data in relation to the required accuracy/strategy level.

The list of models currently implemented in FReET-D is specified in table 1. The implementation of additional models is still in process. The original literature sources for all models that are predominantly deterministic are referenced in the FReET-D manuals [7].

The single models listed in table 1 can be used to construct different LS. Other types of DLS have to be described by more then one model: a series of two or more models must be used – such composition may be called a "chained" model. E.g. A Limit State based on reinforcement corrosion necessitates the existence of depassivation. In such cases one output of the preceding model is time, which serves subsequently as an input (random variable) for the following model.

Inputs

Input parameters for the computational model are defined as random variables. Random variables can be divided into categories in order to make the handling of a large number of random variables easier and more transparent. Variables are described by their probability density functions (PDF) and statistical definition, which includes statistical characteristics, statistical parameters or their combination. The user can select an appropriate PDF from the set of 29 theoretical models in a user-friendly manner. The shape of the probability distribution of a particular random variable is displayed in graphic form. Random variables can also be described by user-defined raw data.

A mutual statistical dependence between input variables can be prescribed and is arranged by a simulated annealing method.

Some models may be highly input-demanding; in order to simplify the handling of inputs their statistical sensitivity is provided by means of Spearman rank-order correlation coefficients, i.e. the user may easily gain measurements of the relative effect of each basic variable. The sensitivity analysis used in FReET-D is based on the assumption that the randomly generated input variables which significantly influence the output (both positively and negatively) have a high absolute value of correlation coefficient. In the opposite way, a low correlation coefficient will signalize a low influence. The sensitivity coefficients (their value being within the range from –1 to +1) thus provide information on the relative influence of the change in input random variables on the change in output values.

Table 1: Models implemented in FReET-D

Degradation mechanism	Model notation	Output	Note
Carbonation	Carb1a Carb1b	Carbonation depth at time *t*; time to depassivation	Concretes from Portland cement; model b differs by RH function
	Carb2a Carb2b		Ditto; simplified model
	Carb3		Concretes from Portland cement; influence of temperature
	Carb4a Carb4b		Concretes from blended cements; model b differs by RH function
	Carb5a Carb5b		Concretes from blended cements; model b is for HVFA concretes
	Carb6 Carb7		Concretes from blended cements; type of cement considered
	Carb8		Concretes from blended cements; *fib*-Model Code 2008 model
	Carb9		Concrete from Portland cement with lime-cement mortar coating
Chloride ingress	Chlor1a Chlor1b	Depth of chlorination at time *t*; time to depassivation	Model b provides calculation of saturation concentration of Cl^- by analytical formula
	Chlor2a Chlor2b	Concentration of chlorides at depth *x* and time *t*	Model b provides calculation of diffusion coefficient by experimentally derived formula
	Chlor3a Chlor3b		*fib*-Model Code 2008 model; model b provides calculation of surface Cl^- conc. for specific conditions by analytical formula
Reinforcement corrosion	Corr1	Net rebar diameter at time *t*	Uniform type of corrosion
	Corr2	Pit depth at time *t*	Pitting type of corrosion
	Corr3	Net cross sectional area of rebar at time *t*	Pitting type of corrosion
	Corr4	Time to cracking due to corrosion	Crack initiation on the steel-concrete interface; uniform corrosion
	Corr5	Crack width due to corrosion at time *t*	Crack width on concrete surface; uniform corrosion
	Scc1a Scc1b	Stress intensity factor at the pit tip at time *t*	Prestressed reinforcement, pitting corrosion; fracture mechanics approach

There are two main benefits from understanding the sensitivity of individual input parameters for a model:

(i) The "dominancy" of an individual input parameter is assessed by the value of the sensitivity coefficient: for less sensitive parameters less effort can be devoted to investigating the input values. Consequently such input variables may also be considered to be deterministic ones within a similar computation.

(ii) The most sensitive input quantities should be determined and verified more carefully in technological or constructional processes.

The user can also automatically perform a simple parametric study of the dependence of an output parameter on a selected input variable. For a definition of a type (2) limit state function, the user may create an appropriate value for barrier B – called the comparative value within FReET. It is possible (and in many cases even desirable) to regard the comparative value as a random variable.

Outputs

According to the user-defined type of analysis FReET-D provides the following type of outputs:

- after performing the statistical analysis (by the Monte Carlo method or Latin Hypercube sampling method), the statistical moments of output variables are shown in a numerical and graphical way; also the values of the sensitivity coefficients for individual inputs are provided;
- reliability analysis provides the probability of failure value or reliability index relevant to a user-designed limit condition. For this purpose the FORM technique may also optionally be utilized;
- for the output quantity the best-fitted PDF may be automatically found.

ILLUSTRATIVE EXAMPLES

Example 1: Reinforcement depassivation (Carb1b and Chlor1a)

This example illustrates the calculation of time to reinforcement depassivation, t_i, due to carbonation and/or chloride ingress dependent on the concrete cover thickness (this quantity being set as a "parameter" in the range from 25 to 75 mm). The full description of all input values is not within the scope of this paper; let us list the most important ones only. For carbonation it is the CO_2 content in the atmosphere: N (820, 98.4) mg/m^3 and relative humidity: Beta (70, a = 0, b = 100) %. For chloride ingress it is the concentration of chlorides on the concrete surface: the deterministic value of 50 mol/m^3 and critical concentration of Cl^- in liquid: the deterministic value of 13.4 mol/m^3 (see also Fig. 1 where the input variables for chloride ingress calculations are displayed in the input window of FReET-D software). The results of statistical analysis are shown in Fig. 2 where mean values together with standard deviations are plotted. Let us focus on a concrete cover of 45 mm; applying the condition (1) where t_D is the target design life 50 years, we obtain β = 2.85 (P_f = 2×10^{-3}) and β = 0.7 (P_f = 2×10^{-1}) for depassivation due to carbonation and chloride ingress, respectively. The well known fact that the rate of chloride ingress is greater compared to the carbonation rate with respect to time to depassivation is also evident from this example.

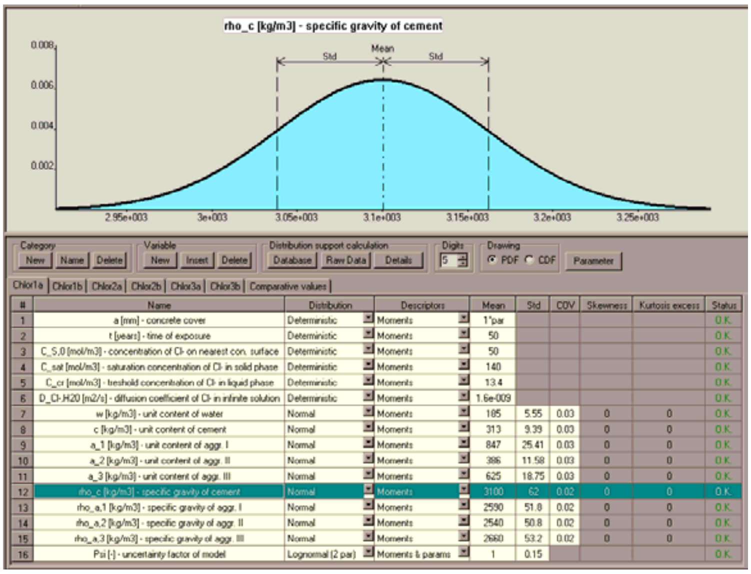

Figure 1 Input window of FReET-D.

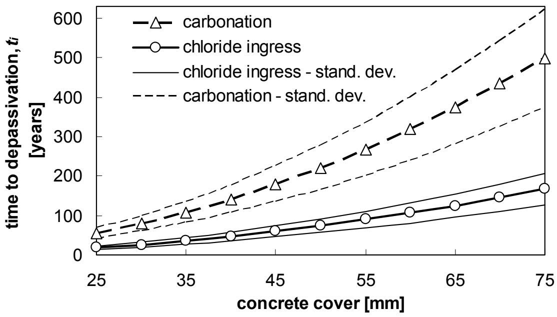

Figure 2 Time to depassivation (± standard deviation) due to carbonation and chloride ingress vs. concrete cover.

Example 2: Time to crack initiation due to reinforcement corrosion (Corr4)

Let us assume a time to corrosion initiation t_i due to chloride ingress calculated in Example 1, and a concrete cover of 40 mm. The best fit for the resulting t_i gained by FReET-D is the two parametric lognormal distribution: t_i = LN (47.4, 11.5) years. This result of the Chlor1a model can now be utilized for combination with the Corr4 model (a “chaining” model) to obtain the time to crack initiation due to reinforcement corrosion, t_{PS}. Among the most important input variables of the Corr4 model are the initial bar diameter: deterministic d_i = 30 mm and current density: i_{corr} = N(1; 0.2) μA/cm^2. A decisive input quantity is also the concrete tensile stress $f_{c,t}$ which is considered in this study as the “parameter” in the range from 3 to 10 MPa. The resulting time of crack initiation $t_{PS} = t_i + t_p$ (t_p is a time of corrosion propagation) dependent on the tensile strength of concrete is plotted in Fig. 3 (left). If we again apply the condition (1) for t_D = 50 years, we obtain the reliability indices plotted in Fig. 3 (right). It follows from this figure that concrete with approximately $f_{c,t}$ > 7.5 MPa would satisfy the reliability recommendations.

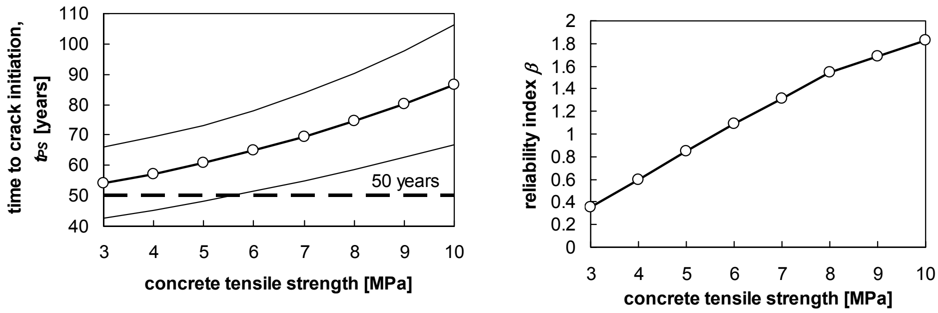

Figure 3 Time to crack initiation (± standard deviation) vs. tensile strength of concrete (left) and reliability indices for t_D = 50 years vs. tensile strength of concrete (right).

Example 3: Loss of reinforcement due to corrosion (Corr1)

Let us assume an initial reinforcement diameter is lognormally distributed (2 par): d_i = LN(30; 0.75) mm and the critical loss of the reinforcement area is 10% (such a loss may e.g. lead to the exceeding of the reliability level for the ULS or SLS – depending on the structure configuration and loading). This limit corresponds to the critical net rebar diameter of 28.46 mm. The main input parameters are current density: i_{corr} = N(1; 0.2) μA/cm^2 and time to corrosion initiation: t_i = LN (47.4, 11.5) years gained by Chlor1a. The decrease in rebar diameter over time is plotted in Fig. 4. The mean value of t_i and t_{PS} (the time of a critical drop in rebar diameter) are marked in this figure. For t_D = 50 years the reliability index of β = 0.38 was gained (a non-acceptable level of reliability).

CONCLUSIONS

The probabilistic approach for the durability assessment of concrete structures has been presented together with the software tool encompassing several models for material deterioration processes. The potentiality of the statistical, sensitivity and reliability analyses makes durability design, optimization and the comparison of variant solutions feasible. FReeT-D can be effectively utilized in combination with FReeT and ATENA software.

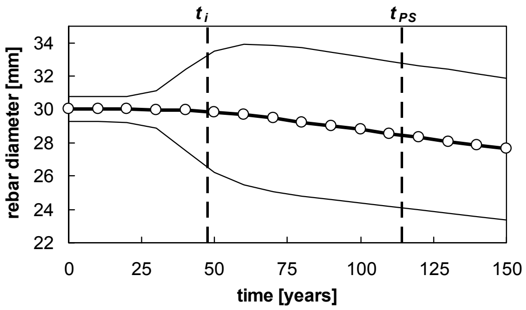

Figure 4 A drop in rebar diameter (± standard deviation) vs. time.

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