Technical Note

Performance-based design of concrete structures: durability aspects

Břetislav Teplý, Dita Vořechovská* and Zbyněk Keršner

Brno University of Technology, Faculty of Civil Engineering, CIDEAS Research Centre, Veveří 95, 602 00 Brno, Czech Republic

(Received April 22, 2009, Accepted February 5, 2010)

1. Introduction

In the context of performance-based design (PBD), sustainability considerations and whole life costing, time is the critical variable and durability issues are pronounced. These facts have gained considerable attention during recent years, which is reflected also in standardization activities, e.g.: ISO 13823 (2008) and the newly prepared *fib*-Model Code (see *fib* Bulletin 2006). Both these documents are based on probabilistic approaches and enhance the design/assessment of structures for durability.

In a practical sense, for concrete structures considered from the standpoint of durability, PBD means identifying and calculating as design parameters e.g. the service life, concrete cover, quality of concrete and the relevant reliability index value in the context of the appropriate Limit State (LS). This should be done in conjunction with balancing or optimizing the long-term economic consequences, technological feasibility, planning of inspections, maintenance and other factors. Such complex decision making needs special methodology, software tools, an experienced designer and his/her close cooperation with the client.

2. Durability performance-based design for concrete structures

Within the PBD context, Durability Limit States (DLS) are recognized as a relatively new category of Serviceability Limit State (SLS) – see the new ISO and *fib* documents mentioned above. Basically, the reliability level is described by the probability of failure P_f, which may be converted into the reliability index β. For the DLS, the values of $0.8 \le \beta \le 1.8$ are currently being considered.

Generally, the LS condition may be written as

$$P_f = P(B - A \le 0) \le P_d \quad \text{or} \quad P_f(t_D) = P\{t_{PS}(X_i, t) \le t_D\} \le P_d \qquad \text{(1a, b)}$$

where P_f is the probability of failure, A is the action effect, B is the barrier effect (generally being

*Corresponding author, Assistant Professor, E-mail: vorechovska.d@fce.vutbr.cz

time dependant) and P_d is the design (acceptable, target) probability value; t_{PS} is a predicted time value modelled as a function of basic variables $\boldsymbol{X}_i$ (i = 1, 2,..., n) in time t, n is the number of input parameters involved in the model in question and t_D is the design service life.

When assessing the degradation of reinforced concrete structures, *corrosion of reinforcement* is the dominant effect. This is usually preceded by reinforcement depassivation. Generally, the principal factors causing depassivation of reinforcement in concrete are *carbonation* and/or *chloride ingress*. Examples of the variables representing A and B in Eq. (1a) are:

(i) *concrete carbonation*: B is concrete cover and A is the depth of carbonation at time t_D; (ii) *chloride ingress*: B is the critical concentration of Cl^- leading to steel depassivation and A is the concentration of Cl^- at the reinforcement at time t_D; (iii) *reinforcement corrosion*: B is the critical tensile stress that initiates a crack in concrete (in the vicinity of a reinforcing bar), A is the tensile stress in concrete at time t_D; or B is the critical crack width on the concrete surface and A is the crack width on the concrete surface generated by reinforcement corrosion at time t_D; or B is the reinforcement cross-sectional area at time t_D and A is the minimum acceptable reinforcement cross-sectional area with regard to either the SLS or the Ultimate Limit State.

For more details about the DLS see e.g. (*fib* Bulletin 2006, Teplý *et al.* 2007, 2008). It is believed that the full probabilistic approach will be employed in the design of concrete structures more frequently in the near future using proper tools and models. Conveniently, a *parametric approach* may also be utilized to facilitate the making of decisions about the variants of the design and the client's general service life strategy. Such a methodology is advocated by the authors of this technical note.

As mentioned in (Bickley *et al.* 2006), there is still a lack of reliable test procedures for evaluating concrete durability performance, which is a major barrier to the adoption of performance specifications. The authors of the present paper suggest that it may be possible to overcome this partially by the utilization of mathematical models; this notion is also compatible with Annex J of EN 206-1 (2000), where the utilization of models for performance based specifications of concrete is listed among other possibilities. The parametric approach may be organized in an easy 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 the automation of such a process.

In the following paragraphs the features of two software tools are described, both being equipped with computational options for parametric studies (developed by the authors and co-workers):

1) Th*e RC-LifeTime* programme uses three models for the carbonation process – two models for concretes made from Portland cement (Papadakis *et al.* 1992), one model for concretes made from blended cements (Papadakis and Tsimas 2002) – and allows the handling of the input data as random variables; outputs are statistical characteristics. *RC-LifeTime* is freely accessible on http://rc-lifetime.stm.fce.vutbr.cz and offers the following options:

(i) "Service Life Assessment", providing the evaluation of service life and its statistical characteristics based on the depassivation of reinforcing bars. The statistical characteristics of the relevant service life – mean and standard deviation – are output data automatically generated for a series of cover values or for a specific concrete cover. Optionally, the reliability index may be an additional input value associated with the given cover value, with the corresponding service life then becoming an output value.

(ii) "Concrete Cover Assessment", providing the statistical evaluation of concrete cover. Optionally, apart from model variables, the target service life may also serve as input. The statistical characteristics of the carbonation depth vs. time are output data automatically calculated for a series of time values. Optionally, the value of the required concrete cover may be an input value and the relevant reliability index β then becomes an output value, again along the time axis.

(iii) Simple cost and embodied emissions may be assessed (considering binder types while designing a concrete mix with blended cements).

2) *FReET-D* is a feasible and user friendly utilization of stochastic approaches (a combination of analytical models and simulation techniques) to form specialized software for assessing the potential degradation of newly designed as well as existing concrete structures (Teplý *et al.* 2007). It is a module of *FReET* software (Novák *et al.* 2003). Implemented models for carbonation, chloride ingress, corrosion of reinforcement and frost attack may serve directly in the durability assessment of concrete structures in the form of a DLS, i.e., the assessment of service life and the level of the relevant reliability measure. Several features are offered including parametric studies and Bayes updating. Altogether, 32 models are implemented as pre-defined *dynamic-link library* functions.

3. Example: design of concrete cover

As an example of *RC-LifeTime* utilization a parametric study supporting an effective decision on concrete cover in the context of service life and reliability is shown. The model published by Papadakis *et al.* (1992) is utilized (denoted as model B in the software) and the option "Concrete

Table 1 Input data

Variable	Unit	Mean	COV [%]	PDF
Ambient CO_2 content	mg/m^3	800	10	Normal
Relative humidity of environment	%	75	–	Deterministic
Unit content of cement	kg/m^3	313	2.9	Normal
Unit content of water	kg/m^3	185	2.2	Normal
Uncertainty factor of model	–	1	–	Deterministic
Concrete cover	mm	25, 30, 35 or 40	17	Lognormal (2par)

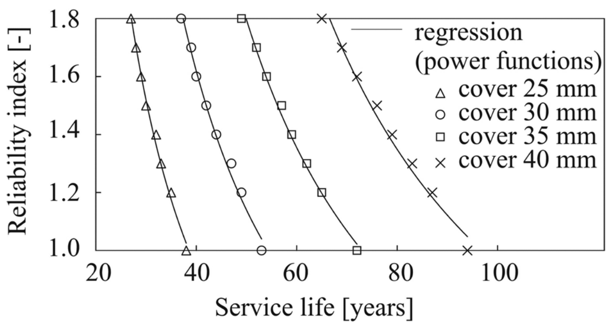

Fig. 1 Reliability index vs. service life for different concrete covers

Cover Assessment" was chosen for this example. Input data are listed in Table 1 – mean values, coefficients of variation (COV), and probability distribution functions (PDF). After several runs (each for a different cover value), complex information on the mutual dependencies of service life, concrete cover thickness a and the reliability index β value becomes available – see Fig. 1. It may be easily stated that e.g., for a design service life of 50 years and a mean cover equal to 30 mm the condition $\beta \geq 1.2$ would not be fulfilled. In a similar way any other combination of t_D, a and β may be assessed. Clearly, such an approach may serve a designer effectively.

Acknowledgements

This outcome has been achieved with the financial support of the Czech Ministry of Education, project No. 1M0579, within the activities of the CIDEAS research centre.

References

Bickley, J., Hooton, R.D. and Hover, K.C. (2006), *Preparation of a Performance-based Specification for Cast-in-Place Concrete*: *Phase I*, P2P Initiative, RMC Research & Educ., Foundation, Silver Spring, USA.

EN 206-1 (2000), *Concrete – Part 1: Specification, Performance, Production and Conformity*, EU Standard.

fib Bulletin (2006), No. 34, *Service Life Design* (part of the *fib* Model Code 2010).

ISO 13823 (2008), *General Principles on the Design of Structures for Durability.*

Novák, D., Vořechovský, M. and Rusina, R. (2003), "Small-sample probabilistic assessment - FREET software", *Proceedings of International Conference on Applications of Statistics and Probability in Civil Engineering (ICASP 9)*, San Francisco, USA.

Papadakis, V.G., Fardis, M.N. and Vayenas, C.G. (1992), "Effect of composition, environmental factors and cement-lime mortar coating on concrete carbonation", *Mater. Struct.*, **25**(149), 293-304.

Papadakis, V.G. and Tsimas, S. (2002), "Supplementary cementing materials in concrete, Part I: efficiency and design", *Cement Concrete Res.,* **32**(10), 1525-1532.

Teplý, B., Matesová, D., Chromá, M. and Rovnaník, P. (2007), "Stochastic degradation models for durability limit state evaluation", *Proceedings of 3rd International Conference on Structural Health Monitoring of Intelligent Infrastructure*, Vancouver, Canada.

Teplý, B., Chromá, M. and Rovnaník, P. (2008), "Durability assessment of concrete structures: Reinforcement depassivation due to carbonation", *Struct. Infrastruct. E.,* (published on-line in February 2008).