# How Reliable is the Durability of RC Structures?

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*The goal of this paper is to show some trends and time profiles of the reliability index relevant to the Serviceability Limit State considering the design service life of RC structures. The interactive web page "RC_LifeTime" – originated by the authors – is used (see http://www.stm.fce.vutbr.cz/). The depassivation of reinforcing steel due to carbonation is considered conservatively as a limiting condition. It is based on model concrete carbonation with 12 random input variables the Latin Hypercube Sampling simulation method is used. RC_LifeTime offers the following options: Service Life Assessment – a statistical evaluation of service life, where optionally the target value of reliability index $\beta$ may be an additional input value and then the corresponding service life is the output value Concrete Cover Assessment – a statistical evaluation of concrete cover value for the target service life, where optionally the required concrete cover value may be input in this case and the relevant reliability index $\beta$ describes the reliability of reinforcement depassivation.*

*Keywords: carbonation depth, concrete cover, durability, RC structures, reliability index.*

## 1 Introduction

Concrete is the premier construction material, and design for durability is a decisive issue in concrete building. Several levels of this design exist, and the most sophisticated level – a probabilistic approach at the micro-level being in the focus of research activities – contrasts with the prescriptive approach given in current codes. In addition to the assessment or design of service life and its statistical features, the probabilistic approach offers the possibility to estimate the reliability grade in the context of durability. The disadvantages of such an approach are the necessity to utilize mathematical models of deteriorating processes, to deal with random variables or random fields, and to use special statistical methods and simulation techniques. The lack of sufficient and reliable statistical data is an important and rather problematic factor in these situations. For these reasons a probabilistic approach is not commonly used in everyday application.

## 2 Designing tool

The authors have recently introduced [1] a simple auxiliary tool for the designing process of concrete structures under the consideration of durability – thus attempting to make a "bridge" between the two approaches mentioned above – the micro-level and the prescriptive level. The interactive web page *RC_LifeTime* is freely accessible on http://www.stm.fce.vutbr.cz/. The depassivation of reinforcing steel due to carbonation is considered conservatively as a limiting condition, i.e. the initiation period governs. This is based on a relatively complex model for carbonation of concrete [2] whose input variables are treated as random variables [3]. The theoretical background and some useful recommendations for the input data are provided.

RC_LifeTime offers the following options:

(i) Service Life Assessment provides an evaluation of service life based on the equality

$$\textit{Carbonation depth} = \textit{Concrete cover} \tag{1}$$

The input data are the concrete cover value (as a deterministic value at present, but another version with a random value option is being prepared) together with 12 model variables (optionally deterministic or random). The output data are the statistical characteristics of the relevant service life – mean value and standard deviation/coefficient of variation (COV). This estimated service life may be used for a structural service life assessment or as the "reference service life" value when using the Factor Method (according to ISO 15686-1 (1998) Buildings – Service life planning – Part 1: General principles).

Optionally, the target value of reliability index $\beta$ may be an additional input value, and then the corresponding service life is the output value.

(ii) The Concrete Cover Assessment option provides an evaluation of the concrete cover appropriate to equality (1). The input data are the target service life value (as a deterministic value) together with 12 model variables (optionally deterministic or random). The output data are the statistical characteristics of the relevant concrete cover (mean value and standard deviation/COV. Note: When designing a structure, this value has to be amended at the end of the process according to the technological or constructional requirements.

Optionally, required concrete cover value may be input and the relevant reliability index $\beta$ is then an output value (describing the reliability of reinforcement depassivation).

## 3 Reliability consideration and limit states

The goal of this paper is to show some trends and time-profiles of the reliability index relevant to the Serviceability Limit State (SLS), taking into consideration the design service life and utilizing the *RC_LifeTime* web application.

First, some comments on the limit state issue are given: According to EN 1990 the Ultimate Limit State (ULS) is defined as "associated with collapse or with other similar forms of structural failure", whereas SLS is defined as a state "corresponding to conditions beyond which specified service life requirements for a structure are no longer met". The failure criteria of ULS are linked to structural resistance, while

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the failure criteria of SLS are, e.g., a limiting deflection or crack width, and might also be characterized by a design service life (a number of years)!

The last type of SLS criteria are however only described in a qualitative manner and are not suited as a direct basis for probabilistic calculations. Moreover, different levels of reliability should be adopted for structural resistance and serviceability. The choice of levels of reliability for a particular structure must take account of the relevant factors, including: the possible cause and/or mode of attaining a limit state; possible consequences of failure in terms of risk to life, injury, potential economic losses; public aversion to failure, and also the expense and procedures necessary to reduce the risk of failure. A problem for SLS is the lack of specific quantified failure criteria for different structural components and materials, and the corresponding required levels of reliability.

Concentrating on reinforced concrete structures and corrosion of the reinforcement, it is evident that the following limit states should be considered: (i) depassivation of the reinforcement; (ii) cracking (visible cracks); (iii) spalling of the concrete cover; (iv) decreases in the effective reinforcement area (leading to excessive deformation or possibly to collapse). Types (i) – (iii) belong to the SLS category of limit states, whereas (iv) belongs to the ULS category.

SLS should be described as specific limit states including a number of years (service life), the limit state itself (for instance a certain percentage of the surface reinforcement depassivated by a decrease in hydroxide ions in the ambient cement paste due to carbonation), and the level of reliability needed to reach these limits, for instance given by a reliability index. Requirements of this kind are not yet included in codes; the authors believe that the utilization of *RC_LifeTime* in general, and some results in the following text specifically, might provide a closer insight into:

(1) The progress of carbonation and its dependence on various parameters/conditions;

(2) The reliability issue in durability design of RC structures.

*Note*: a similar problem (using different models and a different approach) was also treated in [4, 5], and provides some guidance in this field of investigation; they do not allow for practical and versatile use.

*Example 1:*

a) The process of concrete carbonation is driven by the ambient carbon dioxide, the concentration of which varies in different locations. This example shows the influence of $CO_2$ concentration on the progress of the carbonation front in a concrete of medium strength class. According to continuous measurements recently performed in Brno (and compared to existing data from other parts of the world – see [6]) the usual mean value in urban areas is about 800 mg/m$^3$; in heavy industrial areas it can be more than 1500 mg/m$^3$. Fig. 1 depicts the function of carbonation depth versus $CO_2$ concentration and its possible scatter for a service life of 50 years, showing the mean value and this value plus or minus one standard deviation (note: about 66 % of possible realizations are between the upper and lower curve in the case of a normal probability distribution). For the purposes of this study all the input data were considered as deterministic, apart from the coefficient of model uncertainty (lognormal probability distribution, mean value 1.0, standard deviation equal to 0.15 – according to the JCSS recommendation). Fig. 1 shows how the progress of carbonation is influenced by $CO_2$ concentration; certainly, the statistical scatter of carbonation depth would be greater in reality, as all other technological and environmental parameters involved in the carbonation process are more or less random.

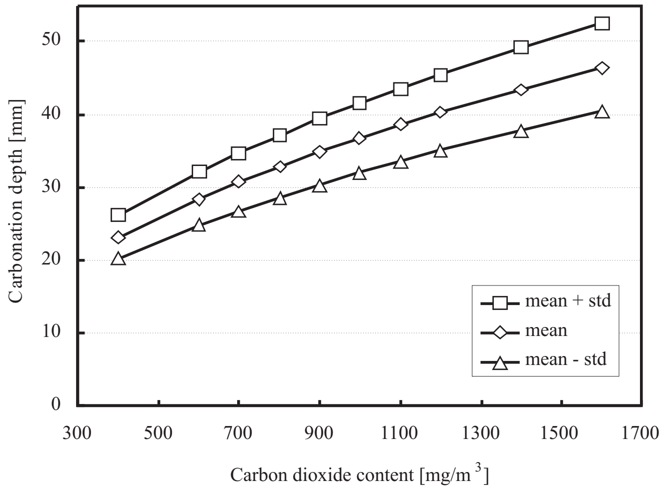


Fig. 1: Carbonation depth vs. $CO_2$ concentration for a service life of 50 years: mean value +/– standard deviation

b) To illustrate this feature, the same example has been solved leaving out this time the coefficient of model uncertainty and consecutively changing the variability of the individual input parameters only. Table 1 lists some of these results showing, e.g., the rapid increase in the coefficient of variation of the carbonation depth due to changes in the input variability of the relative humidity. In other cases, the increase is practically linear.

Table 1: Input vs. output variability [%]

| Input variable | $COV_{inp}$ | $COV_{outp}$ |
|---|---|---|
| Ambient $CO_2$ content | 5 | 2 |
| | 10 | 5 |
| | 20 | 10 |
| Relative humidity | 5 | 1 |
| | 10 | 3 |
| | 20 | 52 |
| Unit cement content | 5 | 9 |
| | 10 | 18 |
| | 20 | 38 |

*Example 2:*

In order to show the trend of the reliability index associated to the carbonation front reaching the concrete cover thickness (i.e. the danger that reinforcement depassivation and possible corrosion will be initiated), again the concrete and environment data from example 1a) were taken and reli-

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ability index $\beta$ computed. Three different concrete cover values are presented – see Fig. 2.

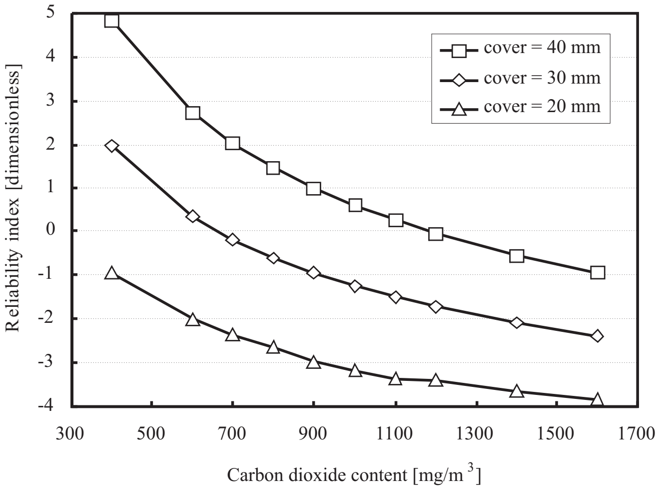


Fig. 2: Reliability index $\beta$ vs. ambient carbon dioxide concentration for a service life of 50 years: three levels of concrete cover

As described above the specific values of b are not standardized and depend on several conditions. The recommended value for irreversible SLS is $\beta = 1.5$ (ISO 2394); lower values are also mentioned in the literature – see [4] and [5]. Considering, e.g., $\beta = 1.0$ and following Fig. 1, 30 mm of cover would be reliable in a very clean environment, while 40 mm of cover can be safely used only up to the $CO_2$ concentration of 900 mg/m$^3$.

## 4 Conclusions

The web-site tool *RC_LifeTime* may serve as an easy-to--use tool for carbonation progress, service life and reliability prediction for reinforced concrete structures. It may be utilized for verification or for justification of special durability requirements.

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