CORROSION MODELS FOR STRUCTURAL DESIGN

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ABSTRACT

Depending on the aggressiveness of the environment, corrosion of the reinforcement induced by chemical actions is a major problem for concrete structures. This paper shows how the stochastic characteristic of the corrosion process can be taken into account in a simple model, which is applicable for design purposes. The integration of the corrosion effects in the traditional Limit States Design format, together with the mechanical actions is emphasised. This integration is needed to permit an optimum structural design in terms of life cycle cost.

1. INTRODUCTION

Current codes of practice traditionally emphasise requirements related to the load carrying capacity. Durability aspects are often considered as being of secondary importance, and they are usually treated as rules for detailing and execution, choice of materials, etc. Load carrying capacity and durability are therefore treated separately, and in daily practice the latter is often disregarded. On the other hand it is more and more generally accepted that optimum structural design should be carried out in terms of life cycle cost [Sarja97], which is dependent on the required cost for maintenance and repair, and thus on durability.

Durability of a structure depends, among other factors, on the environmental conditions to which it is exposed. These conditions are characterised by chemical actions which constitute risks for the structure. As chemical and mechanical actions act simultaneously, they can not be treated separately and a change in the current design philosophy for durability is needed. Models should be established for the effects of the chemical and physical processes which lead to the deterioration of a structure. Once these models are known, the design for durability can be integrated in the traditional design procedure for structural safety and serviceability. Such models also facilitate the planning of rational inspection, maintenance and repair strategies. Finally, an optimum design in terms of life cycle cost is possible.

This paper presents a possibility for the integration of chemical or environmental actions –in the following refered to as environmental actions– in the design process of reinforced concrete structures. To this end, the case of deterioration due to corrosion is considered.

2. CORROSION OF REINFORCEMENT

2.1 Evolution

Corrosion is assumed to initiate when the passive layer on the surface of the reinforcement is destroyed, for example by carbonation or by chloride ingress. Both causes of corrosion initiation are due to the penetration of an aggressive agent (carbon-dioxide and chloride ions, respectively) from the environment into the concrete.

In order to describe the corrosion process, a two-phase model is normally used [Tuutti82] (figure 1a): the initiation phase, t_0, lasts until the concentration of the aggressive agent exceeds, at time T_d, the threshold value for depassivation at the depth of the reinforcement (concrete cover, d). The deterioration of the reinforcing steel is modelled by a time dependent function, a(t). During the propagation phase, t_p, the depth of the corrosion attack increases from the initial dimension, a_0, to the critical dimension, a_{cr}, for which either a safety or a serviceability criteria is no longer reached. In carbonated concrete usually a homogeneous loss of cross-section can be observed, whereas a localised attack has to be expected in the case of chloride ingress.

For a given concrete structure, as well the penetration rate of an aggressive agent as the propagation rate of corrosion depend on environmental parameters such as temperature, humidity, wind, etc. which are variable in space and time. Therefore, the initiation and the propagation are stochastic processes. Hence it is necessary to clearly distinguish between the penetration or propagation rates at one particular point, and the mean velocity (in time) of penetration or propagation. The slope of the time dependent function for the corrosion depth from figure 1a), a(t), represents a mean velocity of propagation, and da/dt(t) from figure 1b) the corrosion rate.

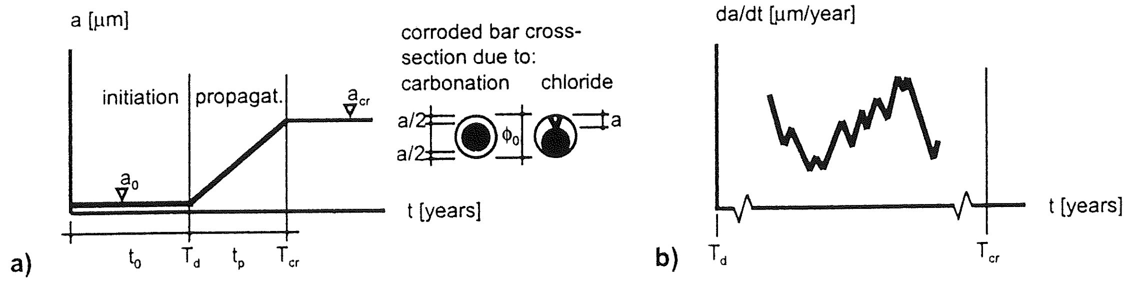

Figure 1. Schematic representation of the corrosion process; a) two-phase model, b) corrosion rate.

The main effects of the corrosion of the reinforcement bars are the decrease of both the bar cross-section and the ductility of the material, the cracking of the concrete cover due to the expansion of the corrosion products, and the loss of the composite interaction between concrete and steel due to bond deterioration (figure 2) [Rodríguez96].

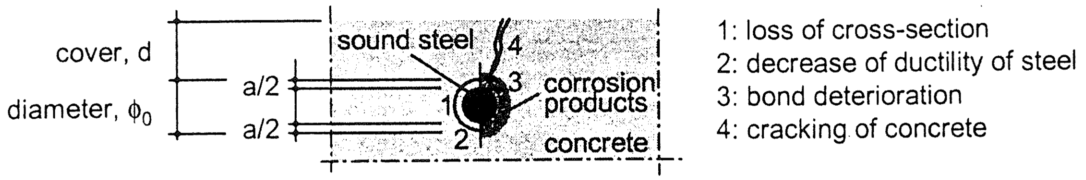

Figure 2. Main effects of corrosion.

2.2 Corrosion tests

At present, it is possible to predict neither the initiation nor the propagation phase based on theoretical models only. To this end, tests must be carried out. The selection of test specimens, test conditions and arrangements should be made in accordance with the characteristics of real structures. In order to determine the mean velocity of penetration and propagation (2.1), respectively, the duration of these tests should be as long as possible. The available time for the execution of tests, however, is usually very short. Accelerated test procedures have therefore been developed [Andrade97], which are to be calibrated against long term test results.

Samples should be representative for different combinations of material properties and exposure conditions, and a sufficient number of specimens should be tested in order to determine the variability of the results with adequate certainty. The results obtained can be represented in diagrams as shown in figure 3, with the penetration of the aggressive agent, p, and the depth of the corrosion attack, a, respectively, on the vertical axis and the time, t, on the horizontal axis. In the case of the initiation a logarithmic scale is usually chosen (figure 3a), in a way that the mean value of the test results can be represented by a straight line (the slope of which corresponds to the mean value of the mean velocity of penetration). The mean value of the propagation test results, on the other hand, can be described by a linear function (figure 3b). The evaluation of test results according to statistical methods permits the establishment of the distribution of the investigated variable. A characteristic value based on a 95% fractile with a confidence level of 75% can be derived for the mean velocity of penetration or propagation. For a sufficient number of test results, the law which represents the characteristic value is parallel to the law for the mean value, at a distance of approximately twice the standard deviation, $2 \cdot s$.

For practice purposes, the obtained characteristic values for the mean penetration and corrosion velocities, respectively $v_{pen,test,k}$ and $v_{corr,test,k}$, should be represented depending on the material properties and the environmental conditions. To this end, it is proposed that the material can most adequately be represented by its apparent electrical resistivity [Andrade98]. The different environmental conditions, on the other hand, can be described by the exposure classes defined in current codes of practice [ENV 1992-1-1 91].

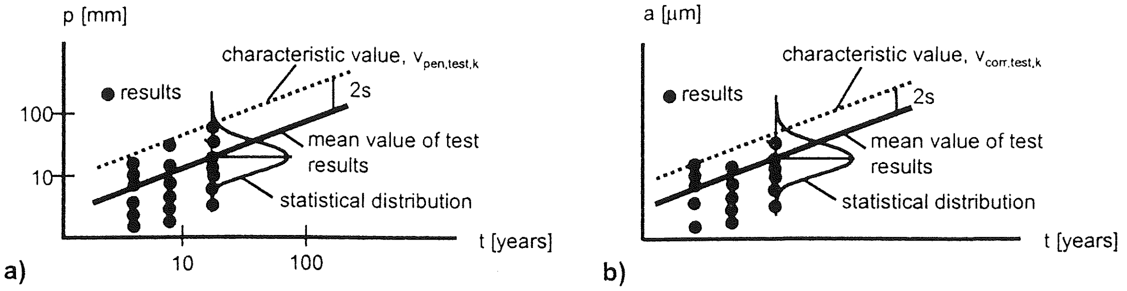

Figure 3. Schematic representation of the corrosion test results; a) initiation, b) propagation.

2.3 Models for the corrosion process

Mathematical models exist for describing the different phases of the corrosion process (2.1), which depend on a large number of parameters, mainly related to the material properties and environmental conditions. Distinction can be made between refined and simplified models. The former explicitly take into account the most important among the mentioned parameters. However, these models are not aimed at the practising engineer for everyday use. To this end, simplified models can be deduced from the test results according to 2.2 [Tanner98]. They implicitly take into account the parameters on which the stochastic corrosion process depends. In order to account for the existing differences between the effects of chemical actions on the test specimens and on the real structure, respectively, a series of duly calibrated coefficients can be introduced [Andrade97]. The most important of these differences are those due to exposure, execution including curing (concrete quality) and geometry.

The time development of the penetration of an aggressive agent may be described by the following simplified model, valid for a given combination of material properties and exposure conditions:

$$p_k = v_{pen,\,test,\,k} \cdot c_{exp} \cdot c_{cur} \cdot c_{geom} \cdot \left(t_{pen}\right)^m \tag{1}$$

p_k	characteristic value of the depth of penetration of an aggressive agent [mm]
$v_{pen,test,k}$	characteristic value of the mean penetration velocity according to test results obtained [mm·year^{-m}]
c_{exp}, c_{cur}, c_{geom}	coefficients for exposure, execution including curing and geometry
t_{pen}	duration of penetration [years]
m	constant according to test results, usually less than 0.5

In the case of the depth of the corrosion attack, the time development may be described by the following simplified model:

$$a_k = v_{corr,\,test,\,k} \cdot c_{corr} \cdot t_{corr} \tag{2}$$

a_k	characteristic value of the depth of the corrosion attack [μm]
$v_{corr,test,k}$	characteristic value of the mean corrosion velocity according to test results obtained [μm·year^{-1}]
c_{corr}	coefficient for taking into account the difference between tests and real structure
t_{corr}	duration of corrosion [years]

3. PERFORMANCE OF CORRODED STRUCTURAL ELEMENTS

Corrosion of reinforcement bars can affect the performance of concrete structures at the ultimate as well as at the serviceability limit states. The main results of an extensive research work that has been undertaken with a view to evaluate the performance of concrete beams and columns with corroded reinforcement bars are reported in [Rodríguez96]. In the following, the most important findings are summarised for corroded beams. Similar rules have been developed for corroded columns.

It has been found that a rough and conservative estimate of the ultimate bending moment of a corroded concrete beam can be obtained if in the traditional resistance models the reduced bar sections are introduced and the contribution of the concrete cover in the compressive zone of the analysed cross-section is disregarded. The ultimate shear resistance can be predicted conservatively by using the traditional resistance models in combination with the reduced bar sections and without taking into account the concrete cover. If the beam behaviour at the serviceability limit states is to be determined, the reduced bar section must be introduced in the calculation models and the bond characteristics are to be considered without taking into account the contribution of the bar ribs.

4. VERIFICATION OF STRUCTURAL SAFETY

4.1 Overview

Environmental actions not only affect the resistance of a structure (2.1). Due to chemical action-induced deformations, expansions, etc., the effects of mechanical actions can also be affected. In order to reach the required structural safety level, any member of a structure, which is simultaneously exposed to mechanical and environmental actions, must fulfil condition (3).

$$S_{env,d} \leq R_{env,d} \tag{3}$$

$S_{env,d}$ design action effects including those due to environmental actions
$R_{env,d}$ design value of the corresponding resistance

As environmental actions also can affect the performance of concrete structures at the serviceability limit states, the simultaneousness of mechanical and environmental actions has to be taken into account in the corresponding verifications. However, considerations concerning serviceability are out of the scope of the present paper.

4.2 Integration of mechanical and environmental actions

A possible integration of mechanical and environmental actions for the verification of structural safety is shown for the case of a structural member affected by corrosion. In a first stage, a previous design of the member has to be carried out according to standard procedures in order to define its main dimensions. It must then be shown that the required structural safety level is reached during the intended service life of the structure, t_{ser}. To this end, the following steps are required:

Initiation of corrosion
The characteristic value of the duration of the initiation phase, $t_{0,k}$, can be calculated from equation (1), by introducing the condition that at the end of this phase the depth of penetration corresponds to the nominal depth of the concrete cover, d_{nom}:

$$t_{0,k} = \left(\frac{d_{nom}}{v_{pen,test,k} \cdot c_{exp} \cdot c_{cur} \cdot c_{geom}} \right)^{\frac{1}{m}} \tag{4}$$

Propagation of corrosion
Knowing the characteristic value of the duration of the initiation phase as well as the intended service life of the structure, the characteristic value of the depth of corrosion, a_k, can be determined from equation (2):

$$a_k = v_{corr,test,k} \cdot c_{corr} \cdot \left(t_{ser} - t_{0,k} \right) \tag{5}$$

Design action effects
The design action effects can be determined in a similar way as the resistance of corroded structures, according to the rules given in section 3, by introducing in the calculation models for example the reduced bar sections and bond characteristics, where relevant. The design action effects including those due to the environmental actions, $S_{env,d}$, are defined by the following expression:

$$S_{env,d} = S\left(\sum_{j} \gamma_{G,env,j} \cdot G_{k,j};\ \gamma_{S,env} \cdot a_k;\ \gamma_{Q,env,1} \cdot Q_{k,1};\ \sum_{i>1} \gamma_{Q,env,i} \cdot \psi_{0,env,i} \cdot Q_{k,i} \right) \qquad (6)$$

$G_{k,j}$, $Q_{k,i}$	characteristic values of permanent and variable mechanical actions, respectively
$\gamma_{G,env,j}$, $\gamma_{Q,env,i}$	partial safety factors for permanent and variable mechanical actions in design situations with environmental actions
$\gamma_{S,env}$	partial safety factor for environmental actions
$\psi_{0,env,i}$	coefficient of simultaneousness for variable mechanical actions in design situations with environmental actions

Design value of the resistance

Empiric models exist for the estimation of the resistance of structural members depending on the depth of corrosion (section 3). The design value of the resistance, $R_{env,d}$, is calculated according to these models, by taking into account the design value of the depth of the corrosion attack, $\gamma_{S,env} \cdot a_k$, and the design values of the material properties depending on the exposure conditions, $X_{env,d}$, and can be represented in the following terms:

$$R_{env,d} = R\left(X_{env,d};\ \gamma_{S,env} \cdot a_k;\ldots\right) \qquad (7)$$

$X_{env,d}$	design value of a material property in design situations with environmental actions

Verification

Structural safety is verified if for the relevant design situations condition (3) is fulfilled.

5. CONCLUSIONS

Optimum structural design should be carried out in terms of life cycle cost, which includes the cost for maintenance and repair. In this context, durability is a main issue. The purpose of minimum life cycle cost only can be reached if chemical actions, on which durability strongly depends, and mechanical actions are simultaneously taken into account in the structural design. To this end, chemical actions need to be modelled in such a way that the integration with mechanical actions is possible. Research needs include the calibration of models for chemical actions, applying reliability methods, and the establishment of simple deterioration models for structures exposed to such actions.

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