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Modelling corrosion propagation in reinforced concrete structures – A critical review

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ABSTRACT

The adoption of corrosion initiation as a limit state to define service life of RC structures has been challenged by researchers and engineers alike in light of the advancements in the concrete construction industry: improved reliability and safety, reduction in costs, and conservation of both materials and energy, which contribute towards sustainable concrete construction. The corrosion propagation phase is now appreciated as a significant component in the service life of RC structures and a good understanding of the propagation process is paramount. Various models have been developed to simulate and/or predict the propagation phase. This paper presents a critical review of some of the available models for corrosion propagation, and proposes ways forward to overcome some of these problems. Salient issues including the modelling techniques, input parameters and limit states are covered. Emphasis is also placed on the usefulness of the propagation models as tools to aid in the repair and maintenance of corrosion-damaged RC structures.

1. Introduction

Modelling has become a powerful tool used by researchers and engineers alike to understand the response of RC structures to service loads and to predict their performance, especially with respect to deterioration and residual load-carrying capacity under different service conditions. This trend has now been extensively embraced in the study of corrosion-affected RC structures, where focus has shifted to the propagation phase, but without neglect of the initiation phase. Several reasons may be cited for the increased use of modelling in the field of corrosion-affected RC structures but the main reasons are: (i) laboratory and field experiments (even with accelerated tests) are relatively expensive and time consuming and (ii) difficulty in replicating different test scenarios, i.e. isolating different variables in the test environment to replicate different real exposure conditions for RC structures.

However, even though numerical simulation of the corrosion process has been used to develop prediction models for the corrosion propagation phase in RC structures, results so far have shown that it cannot be used independently of laboratory and/or field tests to obtain accurate results. This is because in the majority of cases, the simulations do not replicate the real corrosion process and/or exposure conditions [1]. To overcome this limitation, parallel laboratory and/or field experiments, and modelling may be carried out, with the laboratory/field test results being used to validate the modelling process [2] and hence the model developed. The two approaches can be said to be complementary and should be treated as such. Only a few studies where such a process has been carried out can be cited in the literature [3–5].

Nevertheless, even models that have been validated may not be infinitely applicable with respect to their accuracy over a given period of time. It is therefore recommended that calibration of such models [6] using data from long-term field tests is done. Furthermore, improved understanding of both the corrosion mechanisms (chemical and kinetic processes) and material (concrete, steel and concrete–steel composite) properties warrants the refinement of previous models to account for such improvements.

This paper presents a critical review of the modelling of the corrosion propagation phase in RC structures. First, a brief overview of the different approaches that can be used to model corrosion propagation are presented. These will then be critiqued, and conclusions drawn.

2. Prediction models for corrosion propagation

The service life ($t_{service}$) of RC structures, with respect to reinforcement corrosion, is usually modelled as comprising of distinct phases following pre-defined (serviceability and ultimate) limit states with distinct corrosion-induced damage indicators. This approach was first used by Tuutti [7] who proposed a conceptual model dividing the service life of a RC structure into two distinct

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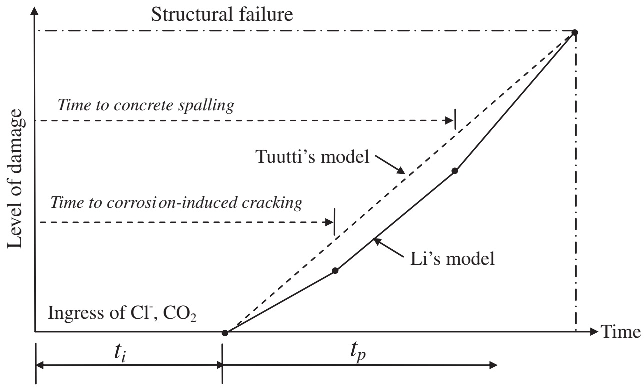

Fig. 1. Phases and sub-phases in the service life of corrosion-affected RC structures [7,8].

phases viz the corrosion initiation phase (t_i) and corrosion propagation phase (t_p), i.e. $t_{service} = t_i + t_p$ (Fig. 1). However, Tuutti's model was generalised with respect to t_p; it does not depict the different sub-phases of corrosion-induced damage in the propagation phase. To account for this (i.e. differentiate structural response to corrosion-induced damage), t_p, which is the focus of this study, can further be sub-divided into sub-phases as shown in Fig. 1, for example [8].

The duration of the propagation period depends principally on the corrosion rate, which is affected by several factors [9–14]. The associated deterioration leads to a variety of negative effects with respect to both structural and durability performance of the RC structure. The prediction of corrosion propagation is therefore a complex process mainly due to the difficulty in incorporating all the relevant factors affecting the process and the associated damage in a prediction model. Usually, one of the negative corrosion-induced damage effects is adopted as a limit state in the prediction model. The pre-defined acceptable level of damage (i.e. the *limit state* or *damage indicator*) can be said to denote the *end of corrosion propagation period*. Corrosion-induced damage in RC structures can range from loss of steel cross-section [15], loss in stiffness [16], loss of steel–concrete interface bond [17], cracking of concrete cover [3,4], to local or global failure of the structure or its members respectively. However, for repair purposes, global failure (collapse of the structure) cannot be adopted as a limit state mainly due to human safety reasons. A detailed coverage of these limit states can be found in the literature; but in summary, some of the basic requirements of a limit state indicator adopted should include the following: (i) it should be easy to assess and quantify, (ii) the level of damage should not compromise structural integrity such as its stability and hence safety of the users/occupants, and (iii) the damage should be relatively easy to repair in terms of restoring both structural integrity and durability performance requirements.

A corrosion propagation prediction model can be developed based on any, or a combination of, the already mentioned corrosion damage indicators. However, it is important to note that, to date, the available prediction models adopt only one damage indicator and are therefore only valid for the given damage indicator. The possibility of using more than one limit state criterion still remains to be explored objectively.

Regardless of the damage indicator adopted, prediction models for corrosion propagation can be grouped as either analytical, numerical or empirical depending on the criterion used in their development [18]. The following section will give a brief overview of prediction models for corrosion propagation, but without specific mention of specific available models, as this will be done in the next section.

2.1. Empirical models

These are models based on assumed direct relationships between corrosion rate and basic concrete parameters, e.g. w/b ratio, binder type and environmental parameters [19]. They are usually developed using data from laboratory factorial experiments that, by design, isolate other corrosion-influencing parameters. Empirical models are sub-divided into three types viz [20]:

(i) *Expert Delphic oracle models*: Corrosion rate is estimated based on past years' experience. However, it has not been used for chloride-induced corrosion due to its complexity.
(ii) *Fuzzy logic models*: In these models, sets of assumed relationships are defined hence allowing the calculation of corrosion rate using fuzzy set logic theory [21,22]. It has been used for the assessment of corrosion-induced deterioration and to estimate the reduction in steel cross-sectional area [19]. Fuzzy set theory has been criticised in the past for its inability to reflect different kinds of fuzzy phenomena in the natural world (e.g. corrosion process) correctly but this has been modified [23].
(iii) *Models based on electrical resistivity and/or oxygen diffusion resistance of concrete*: These assume that concrete electrical and oxygen diffusion resistance are the main controlling factors for the corrosion process. They indirectly takes into account other influencing factors including exposure conditions, w/b ratio and binder type [24,25].

One of the main disadvantages of empirical models is that the selected variables under consideration (for both concrete (*material*) and corrosion (*process*)) are investigated in isolation from other influencing parameters and/or the interaction thereof. Consequently such models may be limited to the set of conditions under which they are developed. However, the end-users are usually either not aware of the limitations associated with the models or choose to neglect them. A common procedure, especially among practising engineers, is to select the most convenient model (based on the available or easily quantifiable input parameters) and use it depending on the available input parameters. This can lead to either under- or over-estimation of the service life of the RC structure, of which the latter may be catastrophic with respect to structural failure and hence occupants' safety.

2.2. Numerical models

A numerical (mathematical/analytical) model is a set of mathematical (analytical) equations which when solved, gives approximate solutions of the subject parameter(s) over time [26]. Numerical simulations can be used to estimate corrosion rates, the effects of changes in electrochemical conditions, and structural response to corrosion-induced damage. Three different approaches can be used to develop numerical models viz [27]: (i) finite element method (FEM), (ii) boundary element method (BEM), and (iii) resistor networks and transmission line method. These are covered in the following sections.

2.2.1. Finite element method approach

The finite element method (FEM) is a process of approximation to continuum problems such that: (i) the continuum is sub-divided into a finite number of individual parts (elements), the behaviour of which is specified by a finite number of parameters whose behaviour can be readily understood and (ii) the solution/understanding of the complete system is an assembly of its individual elements, i.e. the sum of sub-models [28].

With respect to RC structures, the steel, concrete, concrete–steel interface and the bulk phase of the concrete can all be modelled