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Pro-active maintenance and efficient repair strategies for corrosion-affected RC structures

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ABSTRACT: The development of maintenance and repair strategies for corrosion-affected reinforced concrete (RC) structures is often untimely and hence not efficient nor effective. In most cases, repairs are implemented based on a reactive approach where detailed assessments and hence interventions are motivated by visual observations. Such an approach can be inadequate in restoring serviceability and structural integrity. For an efficient and effective management (maintenance and repair) of corrosion-affected RC structures, reliable tools for prognosis of corrosion propagation (t_p) are necessary to inform the maintenance and repair decisions made by engineers. Prediction of t_p will aid in the development of pro-active maintenance strategies for new, undamaged and repaired RC structures, and the selection of optimal maintenance and repair strategies; this will help ensuring that the design service life is achieved or extended. This paper provides an overview of maintenance and repair strategies of corrosion-affected RC structures, and advocates for the adoption of pro-active management strategies. An on-going research project aimed at developing a prediction model for chloride-induced corrosion rate in these structures is also presented.

1 INTRODUCTION

Over the years, the prevalence of reinforcement corrosion (both chloride- and carbonation-induced) in RC structures in aggressive service environments has led to two dominant scenarios. Firstly, as the stock of corrosion-affected RC structures continues to increase, engineers are constantly faced with the challenge of selecting and specifying maintenance and repair materials and strategies for these structures, and substantial resources are also being spent on their maintenance and repair. Secondly, owners are increasingly demanding guaranteed durability and maintenance-free service life for their structures. As a result, it is imperative that engineers engage with these challenges in a bid to provide working (i.e. practical, efficient, effective and sustainable) solutions. Some progress has been made towards achieving these goals but research input is still required to objectively streamline certain aspects, e.g. the improvement of maintenance and repair strategies for corrosion-affected RC structures.

It is now acknowledged that in a marine environment, chloride-induced corrosion, as opposed to carbonation-induced corrosion, can cause widespread damage of a RC structure and may ultimately lead to its failure (depending on the pre-defined limit state) within a short period of time relative to its design service life. Consequently, much research has focused on chloride-induced corrosion initiation and a good understanding exists on this topic. However, the advance of chloride-induced corrosion (i.e. corrosion propagation) is still not well understood both in terms of process and prediction, and as a result, maintenance and repair of corrosion-affected RC structures is in most cases carried out at the wrong time and hence may not be efficient or effective.

With the current paradigm shift towards extending the service life definition of corrosion-affected RC structures beyond the corrosion initiation phase, t_i (i.e. incorporating the corrosion propagation phase, t_p), there is an urgent need to comprehend the corrosion propagation process to facilitate its prediction, and hence improve maintenance and repair strategies. While t_i is usually associated with minimal or negligible corrosion-induced damage, the damage associated with t_p may have negative structural implications. It must therefore be acknowledged that the incorporation of t_p in the design service life of RC structures has inherent risks which should be identified and adequately dealt with a priori.

The impetus of the paradigm shift towards including corrosion propagation in the design service life of RC structures can be assigned to a combination of the following aspects:

- The exponential increase in the number of deteriorated RC structures due to corrosion and the resulting urgent need to develop pro-active maintenance and repair strategies for RC structures.
- At the end of the initiation phase, the RC structure may still have adequate residual serviceability and strength with or without remedial measures.
- The propagation phase may in some circumstances be relatively long to merit quantification and hence be part of the structure's service life e.g. in the presence of service load-induced concrete cracking where active corrosion initiation may be almost instantaneous in the presence of corrosion-inducing species i.e. $t_i = 0$ or $t_{service} = t_p$ (Otieno *et al.*, 2010a).
- For existing RC structures, there is a need to predict the propagation state of the structure in order to design appropriate maintenance and repair strategies.
- For new RC structures exposed to corrosion-aggressive environments, t_p may extend several years after the depassivation of steel depending on the ultimate limit state indicator adopted and the effectiveness of the maintenance and repair actions undertaken.

Coupled with this paradigm shift is a strong interest to understand, predict and hence design for the propagation phase. Consequently, a demand exists for both reliable prediction models for the propagation phase (i.e. durability and structural performance forecasting) and non-destructive in-situ corrosion propagation assessment techniques to meet the aforementioned goals. This paper presents an introduction to pro-active maintenance and repair strategies, emphasizing the need to develop corrosion rate prediction models to assist in the process. An overview of an ongoing study to achieve the above goals and predict chloride-induced corrosion rate is presented.

2 PRO-ACTIVE MAINTENANCE AND REPAIR OF CORROSION-AFFECTED RC STRUCTURES

ISO 2394 (ISO-2394, 1998) defines design service life as the assumed period for which a structure or part of it is to be used for its intended purpose with anticipated maintenance, but without major repair(s). In the perspective of corrosion-affected RC structures, this definition may be applicable in the context of a design service life defined with respect to the corrosion initiation phase but not when t_p is considered or when the objective is to extend the service life beyond t_i. In these cases, both maintenance and repair may be inevitable. Furthermore, the predicted performance of the RC structure during its service life may be significantly under- or over-estimated at the design stage. Therefore, the gap between the actual performance level of a structure, before and/or after repair, and the pre-defined limit of performance (LOP) has to be bridged by appropriate maintenance and/or repair actions. Planned and/or unplanned maintenances and repairs are usually carried out during the life of the structure to abate the probability of failure/malfunction of its element(s). These actions are targeted towards assessing and quantifying the risk of failure and taking appropriate measures to avoid or mitigate them. In day to day practice, most of these maintenance and repair actions may be based on inaccurate prognosis of the actual level of damage such that:

- The RC structure continues to deteriorate to a level where intervention is inevitable (Option I, Figure 1) or,
- Repair of the corrosion-damaged RC structure is carried out based on visual corrosion assessment of the structure only, e.g. by identifying presence of rust stains on the concrete surface and corrosion-induced cover cracking and spalling, which would result in re-active repair strategies (Faber and Sorensen, 2002).

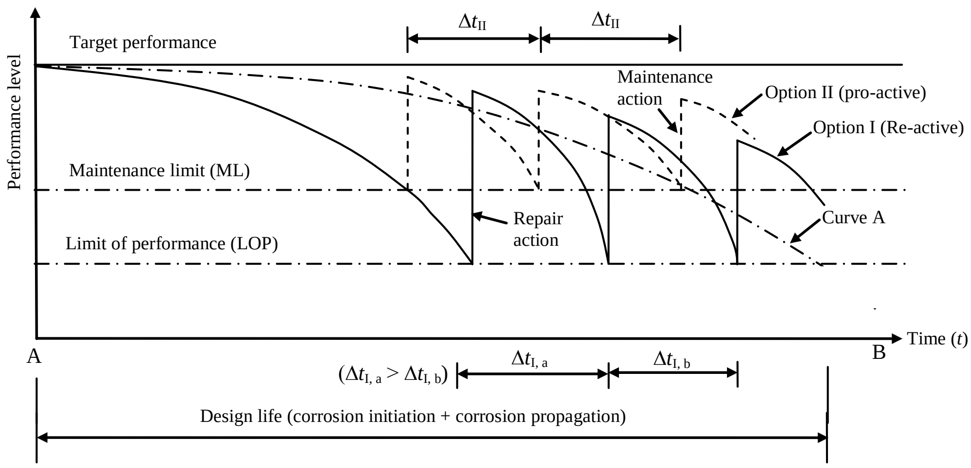

Figure 1: Maintenance and repair strategies for RC structures (modified from (Bijen, 1989))

In Figure 1, Δt_I and Δt_{II} are the time intervals between the repair and maintenance actions respectively, and curve A represents the ideal performance of the structure during its service life. The above outcomes can be avoided by adopting pro-active maintenance systems (Option II, Figure 1). In a pro-active maintenance system:

- Relevant corrosion assessment techniques and prognosis tools (prediction models) are used to plan for the maintenance actions a priori based on a pre-defined LOP.
- Maintenance planning is done at the design phase and later continuously revised/updated based on both actual (corrosion) monitoring data and future expected deterioration trends and levels from prediction models.
- A quantifiable maintenance limit (ML) is pre-defined, with ML > LOP (Figure 1). When a pre-defined ML is attained, maintenance is carried out to restore the structure to an acceptable level of performance. ML differs from LOP in that, while the attainment of the latter may be linked to severe damage and hence costly repair measures, the former is not and cost-effective remedial measures can be implemented.

2.1 Important aspects of a pro-active maintenance and repair strategy

As stated earlier, one of the objectives of a pro-active maintenance and repair strategy is to plan and implement timely and cost-effective repair and maintenance measures. This can be achieved by taking into account the following:

(i) Minimizing the probability of failure (PoF) with respect to a pre-defined LOP. This may involve the use of conventional safety factors or probabilistic methods in design to cover for uncertainties (Sancharoen *et al.*, 2008, Tinga, 2010).

(ii) Identifying the potential failure modes and locations and the inter-dependence (Bijen, 1989, Straub and Faber, 2005).

(iii) Inspection results should be be related to salient aspects which affect the performance of the RC structure e.g. stiffness, cracking (Faber and Sorensen, 2002).

The flow chart in Figure 2 presents an example of a pro-active risk-based maintenance and repair programme for corrosion-affected RC structures.

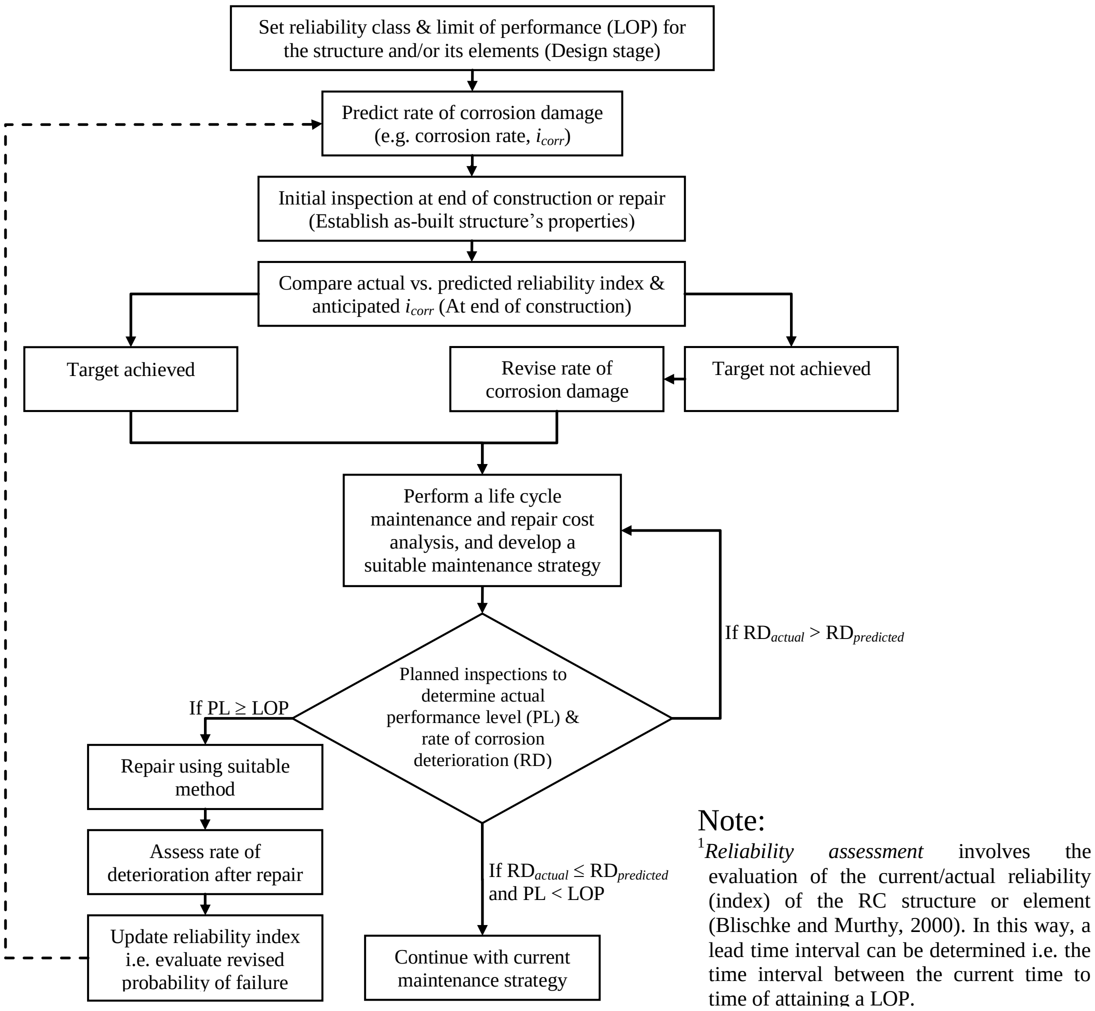

Figure 2: Example of a pro-active risk-based maintenance and repair programme

The reliability class that is set at the design stage by the engineer depends on various factors such as probability of failure and severity of the consequence of failure or malfunction, and is well detailed in BS EN1990 (2002). Based on the design parameters, and using available models, the engineer can predict the expected corrosion rate in the structure at a given time. However, this prediction should be substantiated with actual measurements and inspections of the as-built structure just after completion of construction (Walraven, 2008). In case of reinforcement corrosion, salient aspects such as concrete cover quality, cover depth and cracking should be quantified. This process aids in checking if the design specifications (e.g. concrete cover quality, cover depth and maximum surface crack widths) are achieved or not. In case they are not, both the corrosion damage prediction and the maintenance strategies should be revised to ensure the structure meets its target performance during its service life. It is important to note that the maintenance strategies should incorporate life cycle cost analyses in their development. Furthermore, maintenance and inspections should be planned for at appropriate intervals depending on the expected rate of serviceability deterioration. Depending on the outcome of the inspections either, (*i*) timely and effective repairs can be carried out to maintain a given performance level and the maintenance strategy can be revised to avoid future major repairs or, (*ii*) the current maintenance strategy can be adhered to.

It is apparent from the previous sections and the above example that a good deterioration prediction tool is essential for the development of a successful maintenance strategy. In the case of corrosion affected RC structures, accurate models are necessary for both the prediction of corrosion rate and corrosion-induced damage. In this regard, the next section will present an on-going study aimed an prediction chloride-induced corrosion rate in RC structures.

3 RESEARCH PROPOSAL: PREDICTION OF CHLORIDE-INDUCED CORROSION RATE

3.1 Background

Accurate quantification of t_p , similar to t , is important for its incorporation in the service life of RC structures. The quantification should be carried out based on salient quantifiable corrosion-induced damage indicators that can be directly or indirectly related to the serviceability and structural performance e.g. loss of flexural stiffness. A damage indicator can be adopted as a limit of performance (LOP) i.e. the acceptable damage limit. Corrosion-induced damage prediction models to predict the time-to-occurrence of a pre-defined LOP are currently available (Otieno *et al.*, 2010b). These models have a number of input parameters such as tensile strength of concrete, porosity and corrosion rate (i_{corr}), among others. However, i_{corr}, which is one of the most important input parameters for such models (Li *et al.*, 2006), is seldom well defined with respect to its prediction and measurement. A critical examination of the available i_{corr} prediction models by various researchers (see review by Otieno *et al.*, 2010c) clearly indicates that they are not universally applicable, and more importantly, do not explicitly take into account the effects of factors such cover cracking and concrete quality on i_{corr}, including their inherent variability.

It is therefore important that the influencing parameters are taken into consideration for t_p to be accurately predicted and quantified. An on-going study by the first author focuses on predicting chloride-induced i_{corr} trend and will, in addition to accounting for the effect of cracking and concrete quality, incorporate the relevant variability of the various variables. With knowledge of the i_{corr} trend in a RC structure, an appropriate corrosion-induced damage prediction model can be used to predict the end of the propagation period, defined by a given damage indicator. In general, prediction of the structural and durability performance of a RC structure after corrosion initiation is an important step towards understanding its overall service life performance. The process will also aid in the development of optimal maintenance and repair strategies for corrosion-affected RC structures with respect to structural and durability performance. The next sections present brief outlines of the objectives and framework of the on-going study.

3.2 Objectives, framework and expected outcomes of the study

The main objectives of the study are to:

1. Develop a numerical i_{corr} prediction model for chloride-induced t_p in RC structures. The model will be based on the well-established fundamental (thermodynamic and kinetic) principles of corrosion of steel in concrete.
2. Validate the model using natural corrosion assessment data.

The study focuses on the quantification of the variability (using probabilistic techniques) and effect of crack width, concrete quality (binder type and w/b ratio) and concrete cover on chloride-induced i_{corr}. The study is divided into two main parts viz experimental work and numerical corrosion rate prediction model development. Further, the experimental work is categorized into laboratory (accelerated) and field (natural corrosion in a spray/splash marine zone) corrosion rate assessments. The laboratory and field experiments will be carried out in parallel. The objective of this framework is to:

(a) Validate the numerical corrosion rate model to be developed using natural corrosion rate results. This has been a shortcoming of some previous models mainly due to either not carrying out model validation or using accelerated corrosion rate results for the validation process.

(b) Establish the correlation, if any, between the laboratory (accelerated) and field (natural) corrosion rates. If correlation is found between the two, it will be useful in the future to relate accelerated corrosion rate results to (expected) natural corrosion rates.

The experimental set up of this study with respect to specimen size, crack widths (and crack inducement), cover and binder type is similar to that reported in Otieno *et al*., (2010a). A series of corrosion assessments will be carried out on the specimens: corrosion rate, half-cell potential, concrete resistivity and visual inspections. In addition, other tests such as the durability index and strength tests will also be performed on companion specimens to characterise both the fresh and hardened concretes.

It is envisaged that at the end of the study, with the above objectives met, the following outcomes will be realised:

(i) Determination of corrosion acceleration factors to relate accelerated (laboratory) and in-situ/field corrosion rates i.e. enable the determination of equivalent natural corrosion rates from accelerated corrosion rates.

(ii) Inclusion, in the design framework, of principles for obtaining performance diagnosis and prognosis of RC structures from corrosion assessment techniques and prediction models.

(iii) Provision of recommendations with respect to maintenance and repair strategies that can be undertaken to either attain the initial design service life (incorporating t_p) or extend it.

4 OUTLOOK

This paper presented an overview of the relevance of pro-active maintenance and repair strategies as opposed to reactive systems. The need to incorporate structural reliability and risk management was also underscored. While it must be appreciated that maintenance and repair actions on RC structures may be more economical and effective at or before the end of the corrosion initiation phase t_i , this paper (and the on-going study) focuses on the corrosion propagation phase t_p. This has been prompted by the worldwide realisation that the number of corrosion-affected/damaged RC structures (i.e. those past the initiation phase) is increasing at an alarming rate, which makes accurate corrosion rate prediction an important tool for the design and implementation of effective and efficient maintenance and repair measures. The on-going study presented in this paper is expected to contribute to the prediction of chloride-induced corrosion rate in RC structures.

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