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Probabilistic lifetime assessment of RC structures under coupled corrosion–fatigue deterioration processes

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ABSTRACT

Structural deterioration is becoming a major problem when considering long-term performance of infrastructures. The actions of corrosive environment, cyclic loading and concrete cracking lead to structural degradation. The interaction between these conditions can only be taken into account when modeling the coupled phenomena. In this paper is proposed a new model to assess the lifetime of RC structures subject to corrosion–fatigue deterioration processes. Separately, corrosion leads to cross-section reduction while fatigue induces the nucleation and the propagation of cracks in steel bars. When considered together, pitting corrosion nucleates the crack while environmental factors affect the kinematics of crack propagation. The model is applied to the reliability analysis of bridge girders located in various chloride-contaminated environments. Overall results show that the coupled effect of corrosion–fatigue on RC structures strongly affects its performance, leading to large reduction in the expected lifetime.

1. Introduction

Long-term performance of infrastructures is governed by structural deterioration, which is defined as the loss of capacity due to physical, chemical, mechanical or biological actions. Since corrosive environments and cyclic loading are among the main causes of reinforced concrete (RC) deterioration, a significant amount of research has been devoted to these two specific damage mechanisms [1–3]. Corrosion is the most common form of steel deterioration and consists in material disintegration as a result of chemical or electrochemical actions. Most metals corrode on contact with water (or moisture in the air), acids, bases, salts, and other solid and liquid chemicals. Metals will also corrode when exposed to gaseous materials like acid vapors, formaldehyde gas, ammonia gas, and sulfur containing gases [3]. Depending on the case, corrosion can be concentrated locally to form a pit, or it can extend across a wide area to produce general wastage. On the other hand, fatigue is the damage of a material resulting from repeated stress applications (e.g., cyclic loading). Fatigue is conditioned by many factors such as high temperature, i.e., creep–fatigue, and presence of aggressive environments, i.e., corrosion–fatigue [1,2].

The damage to RC structures resulting from the corrosion of reinforcement is exhibited in the form of steel cross-section reduction, loss of bond between concrete and steel, cracking, and spalling of concrete cover [4,5]. The corrosion of steel reinforcement has been usually associated with chloride ingress and carbonation [4]; however, recent studies have shown that other deterioration processes like biodeterioration might contribute significantly to this process [6]. In RC structures, the coupled effect of corrosion and fatigue has not been studied in as much detail as their separated effects. Coupled corrosion–fatigue deterioration results from the combined action of cycling stresses in corrosive environments. Localized corrosion leading to pitting may provide sites for fatigue crack initiation. Several experimental studies have shown that pitting corrosion has been responsible for the nucleation of fatigue cracks in a wide range of steels and aluminum alloys [7–9]. In such studies, pits are usually found at the origin of the fracture surface. Corrosive agents (e.g., seawater) increase the fatigue crack growth rate [10], whereas the morphology of metals/alloys at micro-level governs the pit nucleation sites [11]. Under these conditions, the formation and growth of pits is influenced by both a corrosive environment and cyclic loads and become a coupled damage mechanism.

Examples of structures that experience this type of damage are offshore platforms, bridges, chimneys and towers situated close to the sea or exposed to the application of de-icing salts. The effects of gradually accumulated corrosion on the low cycle fatigue of reinforcing steel have been recorded experimentally by Apostolopoulos et al. [12] showing that corrosion implies an appreciable reduction in the ductility, the strength and the number of cycles to failure.

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Large research efforts have been made to predict the corrosion–fatigue life of structural members constituted by aluminum, titanium and steel alloys. Goswami and Hoeppner [13] proposed a seven-stage conceptual model in which the electrochemical effects in pit formation and the role of pitting in fatigue crack nucleation were considered. Other research studies focused on particular stages of the process. For instance, a transition model from pit to crack based on two criteria: stress intensity factor and competition between pit growth and crack growth, was proposed by Kondo [7], and further discussed by Chen et al. [14]. In order to take into consideration the entire progressive damage process and the uncertainties in each stage, Shi and Mahadevan [15] proposed a mechanics-based probabilistic model for pitting corrosion–fatigue life prediction of aluminum alloys.

The objective of this paper is to combine previous works on corrosion and fatigue to develop a probabilistic lifetime prediction model for RC structures under the coupled effect of corrosion and fatigue. The model assesses the total corrosion–fatigue life as the sum of three critical stages: (1) corrosion initiation and pit nucleation; (2) pit-to-crack transition, and (3) crack growth. The first considers the time from the end of construction until the generation of a pit. The length of this stage is estimated by considering Fick's diffusion law and electrochemical principles. The second stage includes the pit growth until crack nucleation. In this stage the interaction between electrochemical and mechanical processes is taken into account. The latter stage covers the time of crack growth until reaching a critical crack size, which is defined as the crack size at which the RC member reaches a limit state of resistance.

The proposed model is described in Section 2. Section 3 presents a discussion about the probabilistic lifetime assessment and the reliability analysis. Finally, an application to bridge girders is given in Section 4.

2. Coupled corrosion–fatigue model

The corrosion–fatigue damage process in RC structures is conceptually depicted in Fig. 1. The process takes into account the interaction between (1) chloride ingress, (2) RC cracking and (3) cyclic loading. Chloride ingress leads to steel depassivation, and takes part in the kinematics of the corrosion process. Besides, the corrosion resulting from chloride ingress induces high localized corrosion (i.e., pitting corrosion), leading to reinforcing steel crack nucleation [7–9]. Concrete cracking generated by the accumulation of corrosion products in the steel/concrete interface plays an important role in the steel corrosion rate. Its importance depends on both the width of the crack in the concrete and the aggressiveness of the environment. On the other hand, cyclic loading governs the transition from pit to crack as well as the crack growth.

The corrosion–fatigue deterioration process is basically divided into two stages: (1) pit formation and growth and (2) fatigue crack growth. Pit formation and growth involves electrochemical processes depending predominantly on environmental factors. Crack growth is estimated in terms of linear elastic fracture mechanics (LEFM) and depends mostly upon both cyclic loads and material properties. Goswami and Hoeppner [13] proposed to separate conceptually the corrosion–fatigue life into the following stages: (1) electrochemical stage and pit nucleation, (2) pit growth, (3) competitive mechanisms between pit growth and fatigue crack nucleation, (4) chemically, "short" crack growth, (5) transition from "short crack" to "long crack", (6) long crack growth, and (7) corrosion–fatigue crack growth until instability. However, assuming initial immunity of RC structures and the fact that some of these stages proposed by Goswami and Hoeppner are transitional stages, the total corrosion–fatigue life, τ_T, will be divided into the following stages (Fig. 1):

1. corrosion initiation and pit nucleation, τ_{cp};
2. pit-to-crack transition, τ_{pt}; and
3. crack growth, τ_{cg}.

2.1. Corrosion initiation and pit nucleation

This stage is divided into two sub-stages:

1. time to corrosion initiation, τ_{ini}; and
2. time to pit nucleation, τ_{pn}.

The first sub-stage describes the time from the end of construction until the depassivation of the corrosion protective layer of reinforcing steel, and subsequently, corrosion initiation. For RC

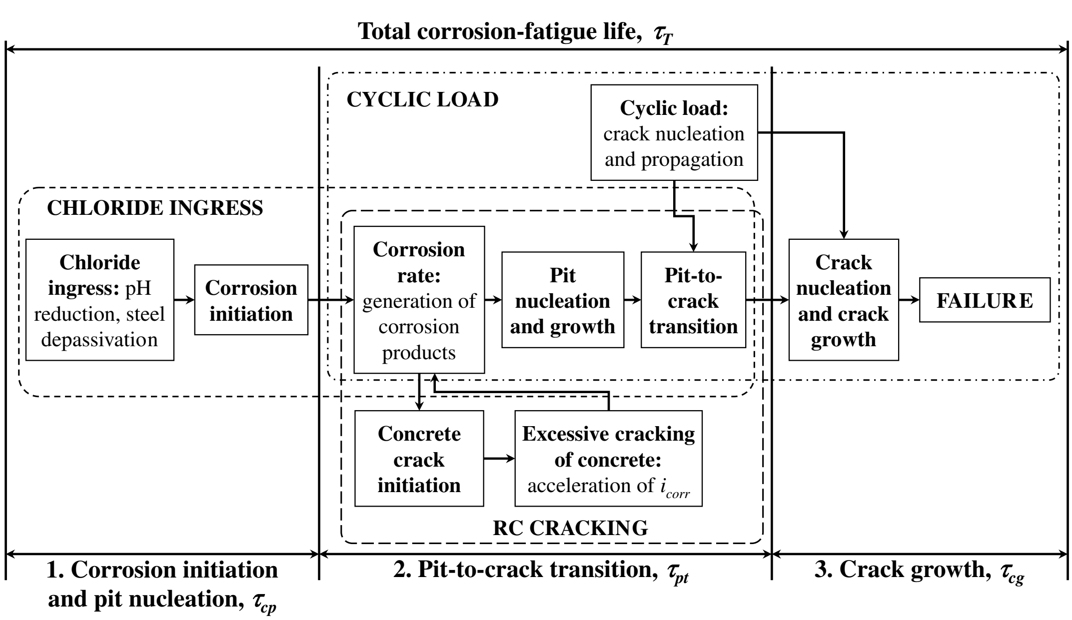

Fig. 1. Scheme of corrosion–fatigue deterioration process in RC structures.