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Coupled reliability model of biodeterioration, chloride ingress and cracking for reinforced concrete structures

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Abstract

Maintaining and operating civil infrastructure systems has been recognized as a critical issue worldwide. Among all possible causes of safety reduction during the structural lifetime, deterioration is particularly important. Structural deterioration is usually a slow time-dependent process controlled by safety and operation threshold specifications. This paper presents a model of RC deterioration by coupling biodeterioration (i.e., chemical, physical and mechanical action of live organisms), steel corrosion, and concrete cracking. The final purpose of the model is to compute the reduction of the concrete section and the area of steel reinforcement in order to assess the change of structural capacity with time. Given the uncertainties in both the parameters and the model, the probabilistic nature of loads, the material properties and the diffusion process are taken into account to evaluate structural reliability. The model is illustrated with an example where the inelastic behavior of a pile subject to random loading is considered. The results of the analysis have shown that the effect of biodeterioration on the structural performance is significant and can cause an important reduction of its lifetime. On the whole, the paper states that modeling the effects of biodeterioration in RC structures should be included as part of infrastructure planning and design, especially, when they are located in aggressive environments.

Keywords: Biodeterioration; Chloride ingress; Corrosion; Crack initiation; Crack propagation; Reliability

1. Introduction

Civil infrastructure systems are critical assets for any country's socioeconomic development. Designing these systems for a particular service lifetime and maintaining them in operation has been recognized as a critical issue worldwide. The life-cycle of a structure can be thought of as the time during which the structure is able to meet specific technical requirements with an acceptable level of safety. In life-cycle analysis, the tech-

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nical problem focuses on defining the interaction among three main processes: (1) the structural deterioration (e.g., aging, obsolescence), (2) the occurrence of unexpected extreme events (e.g., earthquakes, floods); and (3) the maintenance/rehabilitation program [1]. This paper will focus only on the first aspect. Nowadays, many deteriorated structures are evaluated for possible repair and continued service because they are in a situation where their replacement would be economically unfeasible. Thus, developing robust models for prediction and strategies for periodic inspection and maintenance play a significant role in enabling target reliabilities to be met over a period of continued service [6,7].

Deterioration is common in structures located in aggressive environments and subject to, for instance, sulfate attack, chloride penetration and biodeterioration. Numerous studies have addressed the problem of chloride ingress in concrete structures. However, in addition to chloride penetration, biological processes can accelerate the degradation process by modifying severely the structural durability and reliability. This aspect is particularly important in marine structures (e.g., ports and offshore platforms), sewage systems and waste water treatment plants [2–4].

The cause of failure of reinforced concrete (RC) structures subject to deterioration is a loss of capacity resulting from a combination of steel corrosion and concrete cracking. Corrosion leads to a loss of the effective area of the reinforcement and has proven to be a common cause of failure. In a study conducted by CC Technologies Laboratories Inc. in 2001 [5], it was found that the total direct cost of corrosion in USA is close to US$ 137.9 billion/year. The industrial and infrastructure sectors more susceptible to corrosion damage are shown in Table 1. On the other hand, concrete cracking is the result of many factors among which loading, steel corrosion and the action of live organisms are of particular interest.

Structural deterioration is usually a slow time-dependent process controlled by a safety/operation threshold specification. In RC structures, cover reduction is caused by the joint action of live organisms and the accumulation of large amounts of chlorides and carbon dioxide on the structure surface. As concrete cover is the principal mean of protection from corrosion, live organisms facilitate the diffusion process by eroding the concrete surface and destroying the concrete microstructure. This accelerates time to corrosion initiation and increases the corrosion rate. Predicting the deterioration of RC structures due to chloride penetration when accelerated by live organisms depends on many factors. It is first necessary that the chloride and carbon dioxide concentration on the structural surface becomes high enough. Besides, it is required that the environment provides conditions for live organisms to survive and to carry out their vital processes, i.e., appropriate climate conditions, temperature, light intensity, oxygen availability, surface roughness and so forth. Biodeterioration of concrete structures is a subject that requires further analytical and experimental investigation.

This paper presents a work on modeling RC deterioration by coupling biodeterioration (i.e., action of live organisms), steel corrosion, and concrete cracking. The final purpose of the model is to compute the reduction of the concrete section and the area of steel reinforcement in order to assess the change of structural capacity with time. Given the uncertainties in both the parameters and the model, the probabilistic nature of loads, the material properties and the diffusion process are taken into account to evaluate structural reliability. The RC deterioration is discussed in Section 2, reinforcement corrosion induced by chloride ingress is treated in Section 3 and the proposed model is presented in Section 4. Finally, as an illustrative example, the model has been applied to evaluate the inelastic performance of RC piles located in aggressive environments.

Table 1
Cost of corrosion in several industrial and infrastructure sectors

Industrial sector	Cost of corrosion 2001 (US$Billion/year)
Gas and liquid transmission pipelines	7.0
Hazardous materials storage	7.0
Highway bridges	8.3
Waterways and ports	0.3
Drinking water and sewer systems	36.0
Transportation	29.7
Defense and nuclear waste storage	20.1
Production and manufacturing	17.6
Others	11.9
Total	137.9