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Assessment of Residual Life of concrete structures affected by reinforcement corrosion

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Abstract The corrosion process in reinforced concrete structures, exposed to marine or industrial environments, causes the appearance and growth of cracks. As a consequence, this produces a slow degradation of the material physical properties, steel fragilization and a decrease of the bond strength and steel reinforcements, cross section, affecting its static and dynamic behavior.

In the second half of the twentieth century, the importance of constructions' service life was noticed, so different techniques have been developed to predict the Residual Life of existing structures, in order to increase it. This situation has a significant economic impact on society.

This paper presents a non-destructive technique to predict the Residual Life of reinforced concrete beams having different cracking levels, as results of steel reinforcement corrosion, considering the variation produced in the dynamic behavior, through the variation of the first natural vibration frequency.

The reinforcement corrosion is an electrochemical process that can be quantified by measuring the intensity of the current on the concrete surface. In this paper, to simulate the corrosion process, a current is externally applied to the studied structure reinforcement and then crack widths and vibration natural frequencies are measured. Based on these measurements a mathematical model is proposed to predict structure remaining life.

Introduction

The damage occurring in a concrete structure could be the result of loads exceeding its structural capacity or expiration of its service life. Its physical and mechanical properties can change because of environmental conditions, which is the case for structures exposed to marine environments, such as ports, offshore structures, reefs, bridges, silos or for structures exposed to certain industrial environments.

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Consequently, there are important risks of failure and even of collapse that could have an impact on different aspects, such as humans, social, economic and environmental [1].

Due to corrosion of the embedded reinforcement steel, the mechanical behavior of a damaged reinforced concrete structure is different than that of an undamaged one. The main structural damages are reduction of the reinforcement bar diameter, loss of bond between the steel bars and the concrete, steel embrittlement and concrete cracking [2].

Produced rust exerts radial pressure on the surrounding concrete of the reinforcement subjecting it to biaxial tensions which induce cracking [3,4]. The width of these cracks depends on the quality and the cover thickness of the concrete [5], along with spatial distribution of the reinforcement [6] and stress state to which the reinforcement steel is subjected to [7]. Corrosion may affect residual strength of reinforced concrete elements in several ways, such as, cross section loss of the reinforcement bar, reduction in the strength of corroded reinforcement bar, reduction in the concrete cross-section due to reinforcement corrosion that induced cracking and spalling, and loss of bond strength [8,9].

As a consequence, there is a gradual degradation of the material physical properties that leads into the reduction of the reinforced concrete element cross section, which diminishes the effective Moment of Inertia, influencing the element's dynamic and static behavior.

Research has shown that concrete bar deterioration caused by corrosion, diminishes the service life of the structures [10,11]. Besides, rigidity and load carrying capacity of the beams damaged by corrosion are affected [9,12,13].

Considering that most of the affected structures need to remain in good conditions for a relatively long time, it is important to develop non-destructive tests to evaluate the state of structure deterioration, without removing them to perform the analysis, for instance, tests of traditional static load. In addition, more than twenty years ago the CEB 162 [14] proposed empirical ways to assess the structural damage and to determine damage levels, based on visual inspections of the structural member vertical displacement and the concrete and reinforcement state. Then, according to the damage level, it is decided when the studied structure is repaired (Residual Life), to restore the serviceability level of the affected structure or of the structural component.

Several studies have been related to the service life and the Residual Life considering the penetration of chlorides and/or carbonation, establishing a limit to the service life when reinforcement depassivation. In subsequent research it was established an admissible degree of reinforcement corrosion to set the threshold of life service [15], this is an analysis that usually takes only into account aspects of the material, not the mechanical behavior of the structural member.

Other studies take under consideration the structural behavior of the affected element. In this way, it can be established the ultimate load capacity [10,16], data that from a practical point of view is very important because it allows to establish whether the structural safety coefficient has been exceeded or not. Moreover, it is important to estimate when it is needed to make a repair or to put out of service the damaged structure, for this reason is very important to know the structural Residual Life [17,18].

The experimental–numerical methodology to estimate the end of the functional service life (Residual Life) presented in this paper, is based on laboratory determinations developed [19] in a previous stage, where the corrosion degree of the reinforcement of concrete beams, and its collateral effects, such as longitudinal cracks, is correlated with the changes produced in its dynamic behavior, in this case the natural vibration frequencies. Experimental results obtained by other authors show that reinforcement corrosion produces significant changes in the Load-carrying Capacity (static considerations) and at the same time, modal parameters are affected (natural frequencies and to a lesser extent, the damping ratio) [20].

According to Khan et al. [21], the steel loss in the stirrups had no relationship with the crack width of longitudinal corrosion cracks. The proposed method allows quantifying the degree of structural alterations based on the change in dynamic properties [21–23], with a minimum influence on the serviceability level of the studied beams.

Experimental model

Test specimen characteristics

In this work, beams with different types of concrete were used (Table 1), having a similar composition to concretes found in actual structures, which not always fulfill the prescribed standards (curing treatment and particle sizing of fine aggregates). Concretes with the following characteristics were considered [24]:

Concretes were made with a water/cement ratio of 0.60, a value within the parameters of a great number of constructions in use, which can have durability problems depending on their atmosphere. So, using this water/cement ratio, aggregates with the correct amount and working with an adequate cure/treatment, reinforced concretes with a characteristic compressive strength (cylindrical) of approximately 17 MPa can be obtained. Currently, the standards recommend lower water/cement ratio values to improve structure durability [26].

Two types of test specimens were made for the experimental work:

i. Those of reinforced concrete have the following dimensions [cm]: $8 \times 16 \times 110$ assembled with steel bars of natural hardness (ADN 420, IRAM-IAS U 500-528) having a nominal diameter of 4.2 mm and a smooth steel stirrup with a nominal diameter of 2.1 mm, and a constant concrete cover thickness of 10 mm. These test specimens were the ones used in the accelerated corrosion tests. The filling up of the molds was done in two stages, compacting them with a laboratory vibrator.
ii. The cylindrical ones (15×30 cm), were used in the permeability (IRAM 1554) [27] and mechanical tests: compression strength (IRAM 1546) [28] and at indirect tensile (IRAM 1658) [29]. They were cast in accordance with current legislation in Argentina (IRAM 1534) [30].

After 24 h under laboratory conditions (Temperature: 20 ± 2 °C and Relative Humidity $\approx 50\%$), the test specimens were demolded.

Each series was treated according to the following curing type:

A. in laboratory environment: Temperature: 20 ± 2 °C and Relative Humidity $\approx 50\%$, until an age of 28 days;