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Prediction of reinforcement corrosion using corrosion induced cracks width in corroded reinforced concrete beams

Inamullah Khan [a], Raoul François [a], Arnaud Castel [b]

[a] Université de Toulouse, UPS, INSA, LMDC (Laboratoire Matériaux et Durabilité des Constructions), 135, Avenue de Rangueil, F-31077 Toulouse, France
[b] Centre for Infrastructure Engineering and Safety, School of Civil and Environmental Engineering, The University of New South Wales, Sydney, NSW, Australia

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ABSTRACT

This paper studies the evolution of reinforcement corrosion in comparison to corrosion crack width in a highly corroded reinforced concrete beam. Cracking and corrosion maps of the beam were drawn and steel reinforcement was recovered from the beam to observe the corrosion pattern and to measure the loss of mass of steel reinforcement. Maximum steel cross-section loss of the main reinforcement and average steel cross-section loss between stirrups were plotted against the crack width. The experimental results were compared with existing models proposed by Rodriguez et al., Vidal et al. and Zhang et al. Time prediction models for a given opening threshold are also compared to experimental results. Steel cross-section loss for stirrups was also measured and was plotted against the crack width. It was observed that steel cross-section loss in the stirrups had no relationship with the crack width of longitudinal corrosion cracks.

1. Introduction

Corrosion is one of the major causes of premature damage of reinforced concrete structures. When reinforcement corrosion develops, the corrosion products that accumulated at the rebar surface first fill the air voids formed at the steel–concrete interface due to bleeding and settling of the concrete at the time of casting. Corrosion products are expansive and their volume depends on the type of oxide and the degree of hydration. These corrosion products then exert a pressure on the surrounding concrete which easily surpasses the very limited tensile strength of the concrete and thus leads to cracking and spalling of the concrete cover. In addition, corrosion of the reinforcing steel bars weakens the bond between steel and concrete and hence can reduce the service life of the structure [1,2].

How to predict the degree of reinforcement corrosion in corroded reinforced structures has been a subject of discussion for several decades. Several non-destructive techniques for predicting the degree of corrosion exist, such as electrochemical techniques [3–5] and radar measurements [6] but these methods are not very precise and they do not provide the means to evaluate the loss of steel cross-section. Visual inspection is the most popular technique for assessing structure degradation and drawing maps of corrosion cracks. Few experimental works have attempted to establish a relationship between crack width and corrosion. Rodriguez et al. [7] and Alonso et al. [8] put forward a relationship between corrosion and crack width on the basis of an attack penetration parameter. They used electrically accelerated methods to produce corrosion. Vidal et al. [9] studied corroded beams that had been subjected to an aggressive saline environment in wetting–drying cycles under sustained loading. They proposed a model to relate the crack width with the loss of cross-section of the steel reinforcement. Zhang et al. [10] also proposed a model to relate the crack width with average mass loss of steel reinforcement. According to Zhang et al., Vidal's model worked well when corrosion was more localized but as the corrosion pattern changed from localized to generalized corrosion, the model predictions were significantly over-conservative. Therefore, Zhang et al. used the average steel cross-section loss between two stirrups instead of taking the maximum steel cross-section. Their model is used for the second stage of crack propagation [10]. Rodriguez et al.'s and Vidal et al.'s models take into account the concrete cover and reinforcement diameter of the specimen while Zhang et al.'s model does not take into account these parameters.

In literature, a number of research work have been carried out on time prediction for corrosion cracks initiation based on the change of volume of corrosion products [11–15] but very few are concerning about the prediction of corrosion crack openings during propagation. Andrade et al. [16] have performed experiments on small artificially corroded RC specimens, both the corrosion induced crack and the evolution of crack width in relation to rebar corrosion were studied but no relationship between corrosion damage and crack width was proposed. Vu et al. [17] proposed a model to predict the time to excessive cracking for RC structures subjected to corrosion for cracks up to 1 mm in width. Recently, an empirical cover cracking propagation model was developed by Mullard and Stewart [18] which considers the effect of concrete strength, cover, reinforcement bar diameter and concrete confinement. This model was based on experimental results obtained from an accelerated corrosion tests on RC slabs. A rate of loading correction factor k_R is developed to allow the cracking time for accelerated corrosion tests to be adjusted for the lower corrosion rates which are generally found in real RC structures. This model is sensitive to cover and reinforcing bar diameter.

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In the present work, the pattern of corrosion evolution was studied in a 26-year-old corroded reinforced concrete beam and cracking and corrosion maps were drawn. The experimental results were compared with existing models relating crack width to loss of mass of steel cross-section. The three models built by Rodriguez, Vidal and Zhang were chosen for comparison with experimental results. Rodriguez et al.'s model was based on the results obtained from accelerated corrosion while Vidal et al.'s and Zhang et al.'s models were obtained for beams naturally corroded in a saline environment and subjected to wetting–drying cycles. The time of crack propagation from the first cracking to a limit crack width was also calculated and was compared with Mullard and Stewart's model.

2. Experimental context

A long-term experimental program was started in 1984 at the Laboratoire Matériaux et Durabilité des Constructions (LMDC) of INSA-Toulouse (France). A set of 36 reinforced concrete beams of similar dimensions (300 × 28 × 15 cm) as supplied by industry, cast with two different section types, A and B, were stored in a chloride environment under sustained loading. At the same time, another set of 36 reinforced concrete beams of the same composition were cast but stored under normal laboratory conditions (non-aggressive environment) to serve as controls. At different stages, experiments were carried out to collect data such as the cracking map, chloride content, and mechanical behavior under service load [19,20]. Some of the beams were tested until failure to evaluate their ultimate capacity and inspect the distribution of rebar corrosion. In this paper, a highly corroded beam was studied in order to observe the corrosion pattern and to compare the results with the existing models.

2.1. Reinforced concrete specimens

The beams were divided into two groups, type A and type B beams, which had different reinforcement layouts but used the same ordinary reinforcing steel (yield strength = 500 MPa). Beams A had the maximum 40-mm concrete cover and beams B had the minimum 10-mm cover (Fig. 1). The composition of the concrete is given in Table 1. Water content was adjusted to obtain a slump of 7 cm. The average compressive strength and elastic modulus obtained on cylindrical specimens (110 × 220 mm) at 28 days were 45 MPa and 32 GPa respectively.

Table 1
Concrete composition (kg/m^3).

Mix component		
Rolled gravel (silica + limestone)	5/15 mm	1220
Sand	0/5 mm	820
Portland cement: OPC HP (high perform.)		400
Water		200

2.2. Conservation of the beams

The beams were kept in an aggressive chloride environment. The aggressive environment was a salt fog (35 g/l of NaCl, corresponding to the salt concentration of seawater) generated by four sprays located at each of the upper corners of a confined room (Fig. 2). After 6 years of storage, the beams were subjected to wetting–drying cycles in order to accelerate the corrosion process:

- 0 to 6 years: continuous spraying under laboratory conditions (T° ≈ 20 °C),
- 6 to 9 years: spraying cycles under laboratory conditions (T° ≈ 20 °C), one week of spraying and one week of drying.
- 9 to 19 years: spraying cycles, one week of spraying and one week of drying. However, the confined room was transferred outside so the beams were exposed to the temperatures reigning in the south-west of France, which ranged from −5 °C to 35 °C.
- 19 to 27 years: cycles were stopped and the beams were unloaded; the beams were subjected to the temperature of the south-west of France and corroded naturally.

The control beams had the same concrete composition and reinforcement layout but were stored in a laboratory room at 50% R.H. and 20 °C.

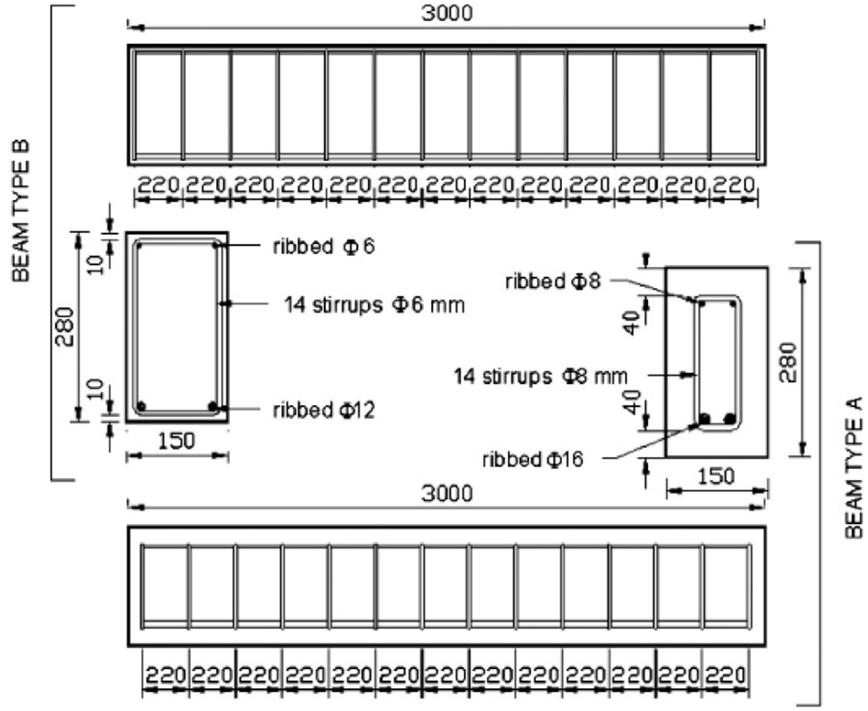

Fig. 1. Layout of reinforced concrete beams types A and B (all dimension are in mm).