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Propagation of corrosion and corrosion patterns of bars embedded in RC beams stored in chloride environment for various periods

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HIGHLIGHTS

- Corrosion propagations of reinforcements with the corroded ages of 14, 23, 26 and 28 years were investigated.
- Spatial distributions of the corrosion were analyzed along the reinforcement.
- The pitting corrosion and general corrosion developed along an improved exponential curve.
- The pitting factor and the general corrosion showed a logarithmic relationship.
- An empirical model on the pitting factors were achieved by the results.

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ABSTRACT

In this paper, the propagation of chloride-induced corrosion of bars embedded in reinforced concrete (RC) beams exposed to a chloride environment was examined. These bars were exposed to chloride environment for various periods. Then, the cracking of the RC beams was observed and the corroded reinforcements were extracted from the beams in order to investigate the corrosion distribution and propagation. The cross-sectional loss and spatial distribution in the longitudinal direction were studied by cutting the residual reinforcement into several small specimens. By analysing the cross-sectional loss results, it was found that the corrosion developed in a stochastic way. However, the corrosion zone developed gradually from the mid-span of the beam to the two ends, and there was a linear relationship between the extent of the corrosion zone and the corrosion period. Similarly, the degree of pitting corrosion and general corrosion also increased. The relationship between pitting corrosion and general corrosion developed along an improved exponential curve, while the pitting factor and the general corrosion showed a logarithmic relationship. The results of this investigation could be treated as an envelope curve, which can be helpful to assess the corrosion state of reinforcements situated in aggressive environment and predict the residual life-cycle of corroded constructions.

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1. Introduction

Chloride-ion-induced corrosion of embedded reinforcements is one of the major causes of deterioration in reinforced concrete (RC) structures [1], especially those structures that are in close proximity to marine environment [2] and structures that come into direct contact with de-icing salt during winter [3]. This corrosion results in numerous problems for RC constructions, including loss of serviceability and load-bearing capacity. For example, pitting corrosion can cause significant cross-sectional loss of the reinforcement embedded in the RC element, which is detrimental to structural serviceability and safety [4–6].

Considerable research on the problem of reinforcement corrosion has been conducted all over the world during the last three decades [7,8]. Otieno et al. [9] investigated the factors that impact the corrosion of RC beams exposed to tidal zones. They found that pitting corrosion was significant in the zone with corrosion cracks, although these zones were generally underestimated in the results of previous lab experiments. Carbonell-Márquez et al. [10] proposed an assessment method to evaluate residual structural capacity by taking into account the layout of the corroded reinforcement. Solgaard et al. [11] investigated the influence of

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uniform reinforcement corrosion on concrete cover cracking behaviour.

The impact of corrosion on the mechanical properties of steel reinforcement has also been widely researched. Fernandez et al. [12] concluded that the fatigue life of steel bars with pitting corrosion was reduced exponentially as the corrosion degree increased. The effect of a notch on the ductility of the reinforcement has also been investigated by experimental tests [13,14]. Apostolopoulos [15] studied the impact of pitting corrosion on the mechanical properties of reinforcements. Zhu et al. [16,17] found that pitting corrosion affected the ductility of the reinforcement more than it affected the capacity. Zhang et al. [18] have also drawn similar conclusions. However, knowledge about the effect of chloride corrosion on the propagation of cross-sectional loss of the reinforcement is still relatively limited. Because most of the research on the corrosion process is conducted in laboratories, experiments are usually based on an accelerated corrosion method, such as applying impressed current and/or introducing a $CaCl_2$ admixture into the concrete [19]. However, this method of experimentation may differ from the cross-sectional loss that occurs in natural corrosion, causing results that do not directly reflect the situation in the field [20,21]. This difference can manifest in the corrosion pattern and corrosion morphology, which can lead to difficulty in applying the conclusions of lab research.

Moreover, because external environment are complicated, not to mention the non-homogeneous properties of the concrete cover and the passive film and the metallurgical and compositional non-uniformity of steel, corrosion is often observed to be non-uniform in spatial distribution along the length of the reinforcement in real-world situations [22,23]. Because of these discrepancies, no scholarly consensus has yet been reached about corrosion distribution in RC elements.

Because of these discrepancies, it is crucial to run studies for long periods of time in the field. It is also important to investigate the propagation of corrosion and its spatial distribution in reinforcements embedded in RC elements for different amounts of time. In this paper, corrosion propagation and its spatial distribution along the length of reinforcements is investigated through a long-term experimental test that has been running since 1984.

2. Experimental context

A program of long-term corrosion experiments has been in progress since 1984 at the Laboratoire Matériaux et Durabilité des Constructions (L.M.D.C.) in Toulouse, which is located in south-western France. The objective is to investigate the process of corrosion in the reinforcement bars of reinforced concrete and the influence of this corrosion on the mechanical performance of the RC. Thirty-six beams with the dimensions of 3000 mm × 280 mm × 150 mm – a typical size in the construction industry in 1984 – were cast. The beams were divided into two groups, named Group A and Group B, according to the depth of the concrete cover and the diameter of the reinforcement. This paper concerns the beams belonging to Group B (see Table 1). A test was conducted in which two load levels were applied to the beams by a three-point loading system, with bending moments at the mid-span of 13.5 kN·m and 21.2 kN·m, noted as level 1 and level 2 respectively.

Table 1
Detailed information on the beams.

Label	Mser (kN·m)	Type	Age (years)
B1Cl1	13.5	Corroded beam	14
B2Cl1	21.2	Corroded beam	23
B2Cl2	21.2	Corroded beam	26
B2Cl3	21.2	Corroded beam	28

*Mser: bending moment applied at the mid-span of the beams.

Table 1 gives detailed information about the four beams studied in this paper. It should be pointed out that in the naming of the beams, the first letter, B, refers to beams belonging to Group B, the next figure stands for the load level, "Cl" means that the beam was exposed to a chloride environment, and the last figure is the serial number for beams in the same group that have the same load level. For example, B2Cl2 indicates a beam in Group B that has been stored in a corrosive environment under the second load level of 21.2 kN·m.

Previous publications have yielded a number of important conclusions about the beams in Group B [9,13,14]. However, most of the available literature considers the residual mechanical performance and the corrosion distribution of the beam separately. This paper will mainly focus on the corrosion process and spatial distribution of the cross-sectional loss in the reinforcement according to the results of experimentation on the beams after various periods of exposure to a corrosive environment. The following sections will investigate the relationships between corrosion degree and corrosion pattern, including pitting corrosion and general corrosion. All of the results and discussions can be treated as a global, improved work on this long-term program.

2.1. Material composition and properties

Table 2 gives the concrete composition and the chemical composition of the cement for all the beams in this program. The concrete mixtures were fabricated with a water/cement ratio of 0.5, which was adjusted to obtain a constant workability of 70 mm in the slump test. The mechanical properties of the concrete were also tested after 28 days by experiments on cylindrical specimens of diameter 110 mm and height 220 mm. The average compressive strength was 45 MPa, and the elastic modulus was 32 GPa. All the reinforcements, including the stirrups, were made of high yield steel with nominal yield strength of 500 MPa.

2.2. Reinforced concrete specimens

The layout of the beams in Group B is shown in Fig. 1. It should be noted that the concrete cover was 10 mm thick, which is in agreement with French regulations [24] at the time the beams were cast (in 1984). Under those regulations, this was the minimum depth of a concrete cover for a non-aggressive environment. It should be noted that 10 mm of cover corresponds to a distance of 16 mm from the concrete surface for longitudinal bars. However, according to current regulations, this distance should be no less than 20 mm. The diameter of the longitudinal bars in the bottom section was 12 mm. For all other bars, the diameter was 6 mm.

2.3. Aging regime

A three-point loading system was applied to the beams by coupling a beam of Group A and a beam of Group B, as shown in Fig. 2. Two load levels were used for the beams. For level 1 (B1Cl1), the moment at the mid-span was 13.5 kN·m, which corresponded to about 50% of the failure load, and the maximum stress in the tensile steel σ_s was 240 MPa, which is approximately the Ultimate Limit State (ULS) in a non-aggressive environment according to French standards. For level 2 (B2Cl1/B2Cl2/B2Cl3), the moment at the mid-span was 21.2 kN·m, which is approximately 80% of the predicted failure load, and the maximum stress in the tensile steel σ_s was 380 MPa, about twice the Serviceability Limit State (SLS) in a chloride environment according to French standards.

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