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Propagation of corrosion-induced cracks of the RC beam exposed to marine environment under sustained load for a period of 26 years

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ABSTRACT

This paper presents the corrosion-induced cracking process of a corroded reinforced concrete beam exposed to a chloride environment for 26 years. The cracking maps of the beam were drawn during different corrosion periods. The first corrosion-induced cracks in the compression zone occurred at about the 5th year and then developed significantly. The corrosion-induced cracks in the tension zone appeared at about the 7th year, followed by the stirrup zones in the transversal sections. At about the 14th year, the width of the cracks in the tension zone exceeded that in the compression zone. The cracks in the tension zone became connected almost throughout the span. The top-bar effect, bleeding and the “top surface ponding effect” led to the appearance of corrosion-induced cracks first in the compression zones, while the corrosion-induced cracks in the tension zone increased more significantly in both length and width as a result of the sustained load.

1. Introduction

Chloride-induced corrosion of the reinforcement in reinforced concrete (RC) structures is considered as one of the most important pathologies, resulting in the deterioration of concrete constructions [1]. In an aggressive environment, especially in marine conditions, the degradation of RC constructions is particularly serious and the costs of repair and rehabilitation are becoming huge [2]. As a result, the corrosion problem has drawn much attention from researchers and engineers all over the world in the last few decades [3–4].

Generally, the volume of corrosion products is greater than that of the original steel (from about two to six times depending on the chemical compositions of corrosion products in different environmental conditions) [5], and the volumetric expansion of the corrosion products takes place gradually between the reinforcement and the concrete, which induces internal pressure in the surrounding concrete. Corrosion-induced cracks occur in RC elements when the internal pressure exceeds the tensile strength of the concrete [6–7].

Considerable research programs have been conducted on the corrosion-induced cracking of RC constructions. Maaddawy et al. [8] developed a method to predict the time from corrosion initiation to corrosion cracking, based on a thick-walled cylinder model and Faraday's law. Guzman et al. [9] proposed a model of internal cracking around the bar due to the expansive pressures produced by the corrosion products. Solgaard et al. [10] investigated the influence of various parameters, such as the reinforcement diameter, concrete cover thickness and concrete material properties, on the corrosion cracking behavior of concrete constructions according to the literature data available on corrosion rates and Faraday's law.

However, most research programs have been carried out in the lab on RC beams subjected to accelerated corrosion due to an impressed electrical current or with addition of chloride during the casting of concrete [11]. The literature data on the continuous propagation of corrosion-induced cracks of RC elements in a natural corrosion environment are rather limited. Moreover, no agreement has yet been reached on how to limit corrosion-induced cracking. Some suggestions for limiting the effects of corrosion cracking of RC constructions are based on safety considerations and aesthetic aspects. For example, standards such as Eurocode 2 [12] or the American Concrete Institute (ACI) limit crack width to 0.3 mm for visible cracks and such limits have also been extended to corrosion-induced cracks by DuraCrete [13]. Moreover, the DuraCrete report indicates that spalling of the concrete cover can occur when the cracks reach 1.0 mm in width.

In 1984, François et al. [14] undertook a long-term program studying the corrosion of RC beams exposed to a chloride environment under sustained service load. The corrosion in this program was similar to those occurring in a marine environment, including the corrosion distribution, the corrosion products and the corrosion patterns [15]. As

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this project ran continuously over 30 years, a series of articles have gradually been published, dealing with specific aspects ranging from the serviceability limit state [16] to the ultimate load-bearing capacity in a three-point bending experiment [17], and from the corrosion process of the RC beams to the mechanical performance of the residual reinforcement [18].

The present paper mainly investigates the propagation of corrosion-induced cracks in an RC beam named B2Cl2 up to the age of 26 years. Thanks to this continuous long-term program, the cracking maps of this beam were recorded at different ages, including 28 days, 6 years, 14 years, 17 years, 23 years and 26 years.

2. Descriptions of the experiments

A long-term program of chloride-induced corrosion of RC beams has been in progress since 1984 at Laboratoire Matériaux et Durabilité des Constructions (LMDC), INSA-Toulouse, south-western France. The intention was to investigate the corrosion process of the reinforcement in load-induced cracks and the influence of corrosion on the mechanical performance of the RC elements.

In 1984, 36 beams were cast with the dimensions 3000 mm × 280 mm × 150 mm, a typical beam size in the RC construction industry. The beams were cast in two configurations, labeled as Group A and Group B, having different rebar diameters and concrete cover depths. A three-point loading system was applied to the beams. Two load levels were adopted: 13.5 kN·m for level 1 and 21.2 kN·m for level 2. The corroded beam named B2Cl2, investigated in this paper, belonged to Group B and was subjected to the level 2 load. More detailed descriptions of the experimental setup can be found in previous publications [19–20].

2.1. Material composition and properties

The concrete composition and the cement chemical composition adopted in this program are shown in Table 1. It should be pointed out that the ratio of water to cement in the concrete mixture was about 0.5, which was suitable for obtaining a constant workability of 70 mm in the slump test.

2.2. Configuration of beam B2Cl2

The configuration of the beams in Group B (including beam B2Cl2) is shown in Fig. 1. It is worth noting that the depth of concrete cover (over the stirrups) was only 10 mm for these beams, and corresponded to the minimum value in a non-aggressive environment specified by the French regulation at the time of casting of the beams in 1984 [21]. However, the depth of concrete was 16 mm for longitudinal reinforcement.

2.3. Aging regime

A three-point loading system was applied to the beams by coupling one beam from Group A with one beam from Group B as shown in Fig. 2. The moment at the mid-span of B2Cl2 was 21.2 kN·m, corresponding to 80% of the failure load, which was monitored by measuring the strain on the loading device as shown in the figure.

Once the beams were coupled, they were kept in a chloride environment with a salt fog of 35 g/l, which was similar to the salt concentration of sea water. The salt fog was generated by four spray nozzles located in the upper corners of the chamber as shown in Fig. 2. After 6 years, the environmental conditions of the beams were changed to wetting-drying cycles, as shown in Table 2, to accelerate the corrosion process.

Table 1
Concrete and cement compositions.

Mix composition		
Rolled gravel (silica + limestone)	5/15 mm	1220 kg/m^3
Sand	0/5 mm	820 kg/m^3
Portland cement: OPC HP (high perform)		400 kg/m^3
Water		200 kg/m^3

Cement composition	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O
Weight (%)	21.4	6.0	2.3	63.0	1.4	3.0	0.5

3. Experimental program and results

The cracking maps for the four longitudinal surfaces of the corroded beam B2Cl2 were drawn at the corroded ages of 28 days, 6 years, 14 years, 17 years [22], 23 years and 26 years. Both the longitudinal and transversal cracks were depicted carefully, including their morphologies and configurations. The width of the corrosion-induced cracks was also measured by means of a portable microscope with an accuracy of 0.02 mm and magnification ranging from 25 to 175 times.

3.1. Information about the beam B2Cl2 before cracking

The service load of the beams was applied by a three-point loading system as described above. In order to further study the influence of mechanical action on the cracking behavior of the beam, the beam was divided into three zones on the lateral surfaces: zone influenced by the compression bars, zone influenced by the tension bars and the neutral zone.

Based on the experimental results of this investigation, it was supposed that the corrosion-induced cracks developed in the zone within 45° along the lateral surfaces as shown in Fig. 3, which meant that the length of the corrosion-induced cracking zones was about twice the distance from the longitudinal steel reinforcement to the concrete surface: the length of each zone was 44 mm for the compression zone (noted Zone C), 56 mm for the tension zone (noted Zone T) and 180 mm for the neutral zone (Fig. 4). The locations of reinforcements in beam B2Cl2 are also indicated by gray dashed lines in Fig. 4 so that the relationships between the corrosion of reinforcement and the cracking behavior of the concrete cover can be investigated.

3.2. Load-induced cracking maps of B2Cl2 at 28 days

The cracking maps of B2Cl2 at the age of 28 days are shown in Fig. 5. The transversal cracks were induced by the applied load, with a moment of 21.2 kN·m at mid-span, and considered as flexural cracks. Most of the flexural cracks were parallel to the stirrups. The initial load-induced cracks originated from the tension surface and disappeared gradually by extending to the compression zone. The maximum width of the flexural cracks reached 0.25 mm at mid-span, as the tension stress was most significant at this section.

No corrosion-induced cracks were observed at this time. However, it was easy for a pond to be formed on the top of the coarse surface during the spraying process as shown in Fig. 2. The top surface with chloride ponding corresponded to the compressive surface of B2Cl2. Moreover, the existence of bleed water defects at the bottom of the upper compressive reinforcement, and the exposure, also influenced the aging process [16].

3.3. Corrosion-induced cracking maps of B2Cl2 at various times

Fig. 6 shows the cracking maps of B2Cl2 at the corrosion age of 6 years. Some longitudinal cracks were visible at the surfaces. However, the corrosion-induced cracks were found to be located only in the compression zones parallel to the longitudinal reinforcement, labeled Zone C1 to Zone C6. The width of almost all the corrosion-induced