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Failure mode transitions of corroded deep beams exposed to marine environment for long period

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ABSTRACT

This paper presents an investigation of the residual structural response of corroded, deep, reinforced concrete (RC) beams. A three-point loading test was carried out on two corroded deep beams that had been stored in a natural corrosive environment for 28 years. Two uncorroded beams with the same steel configuration and span were tested to understand the impact of corrosion on the residual mechanical performance of the deep beams. The distribution of corrosion and gravimetric cross-section loss of the tension bars were measured. The corroded tension bars were extracted from the beams to study the residual mechanical properties. The load-bearing capacities of the corroded beams were assessed using the measured mechanical properties and the residual cross-section of the bars according to different failure mechanisms. The results show that, in this case, the corrosion of steel reinforcing bars could change the failure mode of the reinforced concrete beams from shear to flexure.

1. Introduction

The corrosion of reinforcement is considered as one of the dominant causes leading to the premature deterioration of reinforced concrete (RC) constructions [1]. Corrosion reduces the residual cross-section of the steel bars and usually results in the concrete cover cracking and even spalling. Moreover, the corrosion products decrease the bond and anchorage between the steel bars and the concrete [2,3]. As a result, the structural performance of the concrete elements, including the serviceability and ultimate capacity, can be reduced [4].

Considerable research on the influence of reinforcement corrosion on the flexural performance of RC beams has been conducted during the last three decades. Mangat et al. [5] investigated three degrees of reinforcement corrosion in RC beams and found that the corrosion reduced the residual bending performance of RC members significantly. Malumbela et al. [6] examined the mechanical behavior of the corroded beams and reached the conclusion that a maximum mass loss of reinforcement of 1% can reduce the load-bearing capacity of RC beams by 0.7%. Torres-Acosta et al. [7] concluded that pitting corrosion plays an important role in the reduction of the flexural response of corroded beams.

The shear response of corroded RC beams is also currently attracting increased attention all over the world [8]. Cairns [9] studied the shear capacity of RC beams in which different parts of the longitudinal reinforcement were corroded and suggested that the shear capacity of the corroded beams was increased when the reinforcement was exposed in all but the most lightly reinforced sections. Higgins et al. [10] investigated the impact of corrosion of stirrups on the shear capacity of RC beams and indicated that corrosion reduced shear capacity and, therefore, overall deformation of the corroded beams.

However, most of the corrosion studies reported have been accelerated by impressed current or addition of calcium chloride during casting [11]. Yuan et al. [12] found that such accelerated corrosion led to different patterns from those of natural or climatic corrosion. Therefore, experiments dealing with natural corrosion are important to improve our understanding and confirm the applicability of the results from accelerated corrosion tests.

François et al. [13] have been carrying out a long-term programme concerning the corrosion of concrete beams at Laboratoire Matériaux et Durabilité des Constructions (L.M.D.C.) in Toulouse, in south-west France. All the beams have been stored in a chloride environment under service load since 1984, which is considered to be close to the natural conditions affecting real

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Nomenclature

A_{sres}	residual cross-section of the tension bars	f_{sui}	stress of the bar i
A_{swi}	residual cross-section of the stirrup i	f	yield or ultimate strength of the tension bars
A	cross-section of steel bar	P	applied load in the mechanical test
Σ	perimeter of the tension bar	T	tension force in the reinforcement
θ	angle of the inclined compression strut with respect to the tension bars	τ_u	peak bond strength
l_i	lever arm with respect to the forces of the tensile bars and the stirrups T_i from the top node O	σ_{max}	anchorage strength of the tension bars
L_{anch}	anchorage length	α	parameter of τ – slip curve
		γ	coefficient of the reduced perimeter length between the residual concrete and reinforcement

structures. A series of research works have been performed on the corroded beams and published results include the deterioration of the flexural performance of the corroded beams [14], the cracking process [15] and the residual mechanical properties of the corroded bars [16].

Shear behavior of RC beams is complex and can rarely be entirely isolated from flexure. A common way to study shear effect is to use deep beams where the flexural behavior becomes less significant and thus the failure mode is less influenced by flexural cracking. Two corroded deep beams with a shear span to depth ratio (a/d) of 1.84 were tested in 2010 [17]. The results showed a change in failure mode for the corroded beams compared to that of uncorroded beams of the same age and same a/d ratio. It was decided to study both higher and lower a/d ratios in order to confirm and better understand these results.

2. Experimental program

This programme was set up in 1984 in Toulouse, France. The aim was to investigate the process of reinforcement corrosion and its influence on the mechanical performance of the RC beams. The whole programme involved 36 beams with dimensions 3000 mm × 280 mm × 150 mm. Another 36 beams were cast and stored in a non-corrosive environment to be used as control beams. The beams were divided into Group A and Group B according to the diameters of the bars and the depths of concrete cover. In each group, the beams were loaded at two levels by a three point loading system, with bending moments at mid-span of 13.5 kN m and 21.2 kN m respectively.

The beams studied in this paper belonged to Group B, i.e. the moment was 21.2 kN m. The beams were labelled as B2Cl2 and B2Cl3. The original length of the two corroded beams was 3000 mm. In order to study the performance of the short-span corroded beams, each beam was cut to produce beams shorter than 1200 mm. The detailed information about the beams and the corrosion conditions will be presented in the following sections.

2.1. Material composition and properties

The concrete and cement compositions are shown in Table 1. The coarse aggregate was gravel with a maximum diameter of 15 mm. The ratio of water to cement was designed to be 0.5. However, the water content was readjusted in the casting process in order to achieve a constant workability of 70 mm in the slump test.

The concrete used for the RC beams was made with ordinary Portland cement. The compressive strength was 45 MPa, measured in tests on 110 mm × 220 mm cylindrical specimens at 28 days. The porosity was about 15.2%. The nominal yield strength for the steel bars was 500 MPa.

2.2. Loading system and chloride exposure conditioning

All the beams were loaded in a three-point loading system by coupling a beam of Group A and a beam of Group B as shown in Fig. 1. The span of all the beams was 2800 mm in the loading process. The moment at mid-span was 21.2 kN m for B2Cl2 and B2Cl3. Two uncorroded beams, B2T2 and B2T3, were subjected to the same loading condition.

As shown in Fig. 1, once the beams were loaded, they were all transferred into a chloride-spraying environment with a salt fog of 35 g/L, which was similar to the salt concentration of sea water. The beams were always stored in the room. However, the fog-spraying was varied at different periods so as to accelerate the corrosion process of the RC beams. Detailed information about the spraying system and the status of the beams is included in

Table 1
Concrete composition.

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 performance)							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

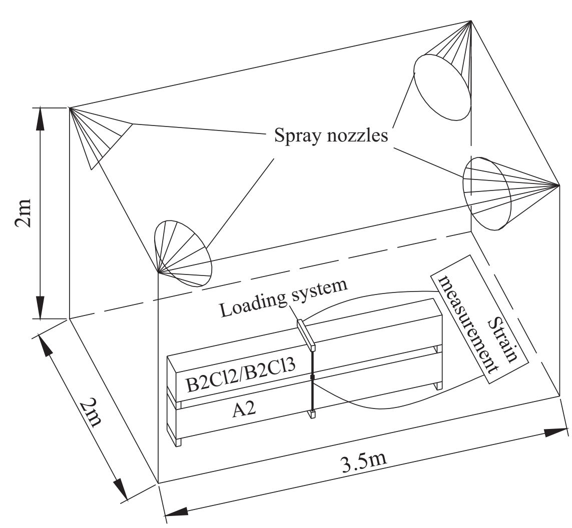

Fig. 1. Loading system and chloride environment.