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Experimental investigation of the relationships between residual cross-section shapes and the ductility of corroded bars

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HIGHLIGHTS

- Tension test are performed on corroded and non-corroded steel bars.
- Corrosion results of natural process and then corresponds to in-situ conditions.
- Corrosion strongly modify the ultimate elongation of steel bars.
- Residual cross-section shape had considerable influence on the ductility of the bars.

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ABSTRACT

Mechanical experiments were conducted on corroded bars that were retrieved from RC beams exposed to a chloride environment for 26 and 28 years. Three types of corrosion simulation with different residual cross-section shapes, including both uniform and non-uniform cross-section loss, were applied to non-corroded bars to investigate the influence of residual cross-section shape on the ultimate strain of the steel bars. The results showed that the residual cross-section shape and the amount of cross-section loss had considerable influence on the ductility of the bars. For the same simulated degree of corrosion, the steel bar with a symmetrically distributed residual cross-section showed the best ductility.

1. Introduction

Durability is one of the most important properties of reinforced concrete (RC) structures. This property not only has economic impacts, the repair and rehabilitation of highway structures cost more than $20 billion in the US a year [1] and more than £600 million annually for the repair of road bridges in the UK [2], but is also a safety issue problems affecting the reliability of structures. A reduction of ductility will result in brittle performance of the RC constructions, which should be avoided [3]. Steel bars make the major contribution to ductility and any reduction of the service life of corroded RC constructions mainly depends on the degree of corrosion of their steel bars [4].

The mechanical performance of corroded steel bars has been attracting increasing research interest because of their importance in RC constructions. Cairns et al. [5] found that pitting corrosion of steel bars might result in a slight loss of strength but a significant loss of ductility, and a numerical model was proposed to assess the influence of this steel characteristic. Apostolopoulos and Papadakis [6] drew almost the same conclusion by conducting experimental tests on aged bars from corroded concrete structures and bare steel bars. Almusallam [7] investigated the mechanical properties of corroded bars and discovered that 12% or more of corrosion could indicate a brittle failure. Apostolopoulos et al. [8,9] conducted some research on corroded S400 and S500 reinforcing steel bars in order to investigate their mechanical response to low cycle fatigue, and concluded that the corrosion level had significant influence on the mechanical performance of the bars.

However, few conclusions have yet been drawn as to the ductility of corroded bars. Eurocode 2 [10] stipulates a minimum ductility for steel bars to provide an acceptable margin of safety. Du et al. [11] found that 10% corrosion was sufficient to reduce the ductility of bars embedded in concrete to below the minimum requirement specified in the CEM Model Code 90 for class S reinforcement but more attention needs to be paid to the effect of corrosion on the change of ductility. A long-term program on the corrosion of RC beams in a chloride environment under service load [12] has been

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in progress since 1984 at the Laboratoire Matériaux et Durabilité des Constructions (L.M.D.C.) in Toulouse, southwest France. In the previous literature on this program [13,14], the ductility of corroded bars was found to be related to the shape of the residual cross-section and the corrosion distribution in the cross-section was considered to be an important factor in the ductility of the corroded bars.

This paper provides some additional research intended to improve understanding of the relationship between the residual cross-section shape and the mechanical properties, especially ductility, of corroded bars. Eight corroded bars extracted from a beam with a corroded age of 28 years were tested and the results were compared with those of previous studies [13]. Various simulations of loss of cross-section were carried out on non-corroded bars with different diameters to better understand the geometrical parameters that influence ductility in tension. One difficulty with real corroded steel bars lies in determining the effective residual cross-section at the failure location during a tension test, which is needed to calculate both true yield and ultimate stress. The shapes of real corrosion pits do not correspond to simple geometry and measurements of the effective residual cross-section show large scatter. Accurate characterization would thus require sophisticated tools, such as X-ray tomography. The comparison made in this paper with a simulated cross-section provides access to the true stresses and allows a reference to be defined for the scatter on the cross-section measurement of real corroded steel bars.

2. Experimental program

The program was set up in 1984 in Toulouse, France, with the aim of studying the influence of chloride corrosion on the mechanical properties of RC beams. Beams labeled B2Cl2 and B2Cl3 were cast as part of the program and the corroded bars were extracted from them in 2010 [15] and 2012 [16] respectively. In other words, the corroded bars from B2Cl2 were aged 26 years and those from B2Cl3 were aged 28 years. Detailed information about the two corroded beams and the corrosion conditions can be found in the relevant articles and only the mechanical properties of the corroded bars will be discussed here.

2.1. Description of the corroded bars

The corroded tensile bars were retrieved from corroded beams B2Cl2 and B2Cl3. Clarke's solution [17] was applied to clear away the corrosion products from the residual steel bars. Fig. 1 compares corroded bars and a non-corroded bar. As shown in the figure, the steel bars were highly corroded throughout their lengths, both generalized and pitting corrosion being visible. It should be noted that "generalized corrosion" corresponded to corrosion distributed uniformly around the perimeter of the steel cross-section and is therefore called "uniform corrosion" in this paper. Pitting corrosion was localized corrosion. Nevertheless, the distribution of generalized corrosion and pitting corrosion was rather irregular both along the length and around the perimeter, which agreed well with other researchers' conclusions about chloride corrosion [18].

(a) Corrosion distribution on the tensile bars

(b) Non-corroded bar

Fig. 1. Comparison of the corroded and non-corroded tensile bars.

2.2. Tension test specimens

Seven corroded specimens from B2Cl2 and eight corroded specimens from B2Cl3 were cut from different locations of the tensile bars. Detailed information, including the length and mass of the specimens, is shown in Table 1.

The corrosion degree of the corroded bars was measured by gravimetric cross-section loss. The average residual gravimetric cross-section of the specimens could be deduced from the residual mass and the length of each specimen. The minimum residual gravimetric cross-section could also be calculated in the same way by cutting the specimens into small pieces after the tension tests on the corroded bars. The length of the pieces was adjusted to the corrosion pattern of the bars. In Fig. 2(a), the length of each pieces is shown by a dot at each of its extremities, along the bar. The minimum length was only 5 mm as shown in Fig. 2(b) [19,20]. The results of both the average cross-sections and the minimum residual cross-sections are presented in Table 1. The minimum value was much smaller than the average value, which showed that the corrosion distribution tented to be stochastic and non-uniform. It should be pointed out that some differences would be expected between the residual cross-section before and after the tension tests. However, the results showed that brittle failure occurred without any visible necking in the case of the corroded bars. So it was assumed that necking did not influence the ultimate stress calculation.

3. Tensile tests and experimental results

3.1. Tensile tests on the corroded specimens

The tension experiments were carried out on the corroded specimens by a machine of 250 kN capacity. Two linear variable differential transformers (LVDTs) were used to measure the elongation of the bar over the effective length (Ler) as shown in Fig. 3. The load and the elongation were recorded by a computerized data acquisition system. The corroded bars were loaded at a predetermined loading interval of 0.5 kN/s until failure.

3.2. Results of the corroded bars

As discussed in previous literature [12], compared to the results measured directly with a vernier caliper, the gravimetric cross-section at the failure points was considered to be an accurate method to calculate the actual true stress of each specimen. The stress–strain diagrams of the corroded specimens could be deduced from the experimental results. Fig. 4 shows the typical stress–strain curve of one corroded bar TBS-V from B2Cl3.

According to Eurocode 2, elongation at maximum force ε_u is defined as the strain at maximum strength (ultimate strain). The yield strength corresponded to 0.2% of strain. The yield strength, ultimate strength and ultimate strain of all the corroded bars were retrieved from the experimental results of the tension tests as shown in Fig. 4. Table 2 summarizes the mechanical properties of all the corroded bars. Corrosion degree was measured by the gravimetric cross-section loss, as a percentage. The results showed that the failure points corresponded to the maximum corrosion degree of each specimen. According to the table, the maximum corrosion degree ranged from 31.15% to 53.08%. Consequently, the mechanical properties varied. The relationships between corrosion degree and mechanical properties, including yield strength and ultimate strength, of the corroded bars are presented in Figs. 4 and 6.

It should be pointed out that specimen TFS-V was close to the failure point of the bending test in B2Cl3. The yield strength and ultimate strain were considered to have been significantly influenced by the mechanical tests on the beam. So in the table, the values are ignored but the ultimate strength is assumed to be normal. For the other specimens, the locations were far away from the failure points in the mechanical experiments on the corroded