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Corrosion effects on the mechanical properties of reinforcing steel bars. Fatigue and σ–ε behavior

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HIGHLIGHTS

- Experimental studies on fatigue and monotonic tests with corroded an uncorroded steel bars.
- Variation of the mechanical properties of corroded reinforcement as a function of the corrosion degree.
- Pit characterization in the critical cross-section.
- Influence of the corrosion degree on the fatigue life.

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ABSTRACT

Corrosion of steel reinforcement is one of the most severe problems of durability in reinforced concrete structures. A good understanding of the corrosion effects on the reinforcing steel mechanical properties is necessary to adequately assess impaired structures. A study of the mechanical response of corroded reinforcement subjected to monotonic and cyclic loads by means of an experimental study is presented in this work. More than 180 corroded specimens, 40 monotonic and 140 fatigue tests were performed. Relationships between corrosion penetration and the mechanical properties of reinforcing steel bars were identified. In addition, a study of the influence of the pit geometry on the fatigue life was carried out. A severe non-linear reduction in the mechanical properties studied, related to the corrosion degree was observed. These phenomena can provide relevant information for the assessment of existing structures and for life cycle evaluation.

1. Introduction

Corrosion of the reinforcement steel bars is one of today's most frequent and significant types of damage in existing reinforced concrete structures. Therefore, the study of the structural effects of bars corrosion is crucial for determining the structural performance and residual strength of impaired structures. Volumetric expansion of corrosion products may induce splitting stresses along corroded reinforcement, and damage to the surrounding material. Generally, the splitting stresses are not well tolerated by concrete, resulting in cracking and eventually spalling of the concrete cover. As the reinforcement becomes more exposed, the corrosion rate may increase and facilitate the deterioration process. Either generalized corrosion, which affected uniformly to the whole bar length, or pitting corrosion, which affected in a specific part of the bar, have important effects on the mechanical behavior of the steel reinforcement bars. In this work are presented artificially corroded specimens by means of induced current methods, in which corrosion degree is defined as the loss of mass due to corrosion with respect to the uncorroded bar, that could be described as the corrosion penetration expressed in % of cross-section reduction. It is obtained by means of gravimetric methods following the ASTM code [18]. The specimens were cleaned by means of mechanical methods.

One significant steel corrosion effect is the change in the mechanical properties of reinforcing bars. Even though most of the investigations are not focused on this effect, steel reinforcement corrosion yields into material mechanical properties changes [1–4]. The study of the local impacts of corrosion is critical to define the mechanical properties of corroded steel bars to be used in structural models, in order to adequately assess the structural behavior and safety at local or global levels. The change in steel behavior may give place to an unexpected structural response, producing even undesired brittle failures.

The classical approach to consider corrosion of steel reinforcement in the response of concrete structures has been to consider a reduction of nominal cross-section area proportional to the

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corrosion degree. However, both generalized and pitting corrosion produce other effects than just the loss of steel area, such as stress concentration at the notch tip. In addition, the displacement of the center of gravity of the cross-section due to a non-uniform corrosion or because of the pit itself produces a non-uniform stress distribution along the pitted cross-section. Furthermore, some modern production systems of reinforcing bars, such as TEMPCORE®, produces heterogeneous material properties throughout the steel cross-section, being the apparent σ–ε characterization of the bar, the mean response of the heterogeneous section. Specifically annular distribution of the mechanical properties takes place for this steel manufacture system [5–9]. Obviously the loss of part of the cross-section modifies the balance of the mechanical properties distribution not only because of the reduction of steel cross-section itself but because of the loss of the external crowns of material which provides higher load capacity to the outfit.

Several experimental studies were performed during the last years to evaluate the influence of the corrosion degree of steel bars embedded in concrete on their mechanical properties [1–4,10–15]. A smaller number of studies have been undertaken on the evaluation of the response of corroded steel bars subjected to low-cycle loads [16,2,17]. Even fewer investigations are found in the literature studying the corroded steel behavior under high-cycle loads [15].

In this research work, a study of the mechanical reinforcing steel properties, either corroded or uncorroded, using monotonic tensile tests and cyclic loading fatigue tests, is presented. Two experimental phases were carried out in order to define the main mechanical properties of 10 mm and 12 mm diameter artificially corroded steel bar. Phase 1 consisted on monotonic tests while phase 2 encompassed high-cycle load tests. The variation of the mechanical properties is related to the corrosion degree by comparing the results with those obtained from tests performed on uncorroded bars.

Along the monotonic tests performed in experimental phase 1, the main parameters defining the σ–ε curves of corroded steel were measured. A total of 40 specimens of 310 mm to 320 mm lengths were satisfactorily tested having corrosion degrees ranging from 8% to 22%.

At Phase 2, 140 specimens of 310 to 320 mm length with corrosion degrees ranging from 8% to 28% were tested under several cyclic loads. Three different stress ranges (ΔS = 150 MPa, 200 MPa and 300 MPa) were defined in order to evaluate the influence of the stress range on the fatigue life of corroded bars. These stress ranges were selected to represent the stress levels that take place in reinforcing bars under common service load conditions. By applying those load levels, it is possible to measure the fatigue life reduction at the service load level with respect to the uncorroded steel. The characteristic pit was measured on all the tested specimens in order to evaluate its influence on the reduction of fatigue life.

2. Materials

B500SD (see Table 1 for different EU denominations and standards) reinforcing steel was used in the monotonic and fatigue test for corroded and uncorroded specimens. Uncorroded steel main properties are described in Table 2. Fig. 1 shows the measured σ–ε behavior for the two steel diameters used in this work.

3. Corroded steel bars under cyclic and monotonic loads

3.1. Test setup and execution

The tests presented next are part of a larger experimental campaign, conducted at the Universitat Politècnica de Catalunya – Barcelona Tech (UPC), which encompassed tests of statically indeterminate beams under different corrosion degrees to assess the structural effects due to steel reinforcement corrosion, Fig. 2. This work focuses on direct monotonic and cyclic loading tests of the corroded steel reinforcement extracted from the above mentioned beams having the underlying purpose of extending the existing database of monotonic test of corroded steel bars and contributing to a new significant database of corroded specimens tested under cyclic loads.

Table 1
Denomination and standards for grade 500 MPa ductile steel bars.

Country	Standard	Denomination for f_y = 500 MPa
Belgium	NBN A-24-302	BE-5005
France	NF A35-016-1996	FER 500-3
Germany	DIN 488	BST 500 S-IV
Netherlands	NEN 6008	FEB 500 HWL
Spain	UNE 36-065 EX 200	B500S AND B500SD
Switzerland	SIA 262/1 2003	TEMPCORE 500-A
United Kingdom	BS 449:2005	GRADE B500B

Steel bars were extracted from beams exposed to different corrosion degrees by means of induced corrosion procedure [19–21]. The beams were casted incorporating in the mixture 4% NaCl in cement weight, breaking the steel passive protective layer. The applied current density was designed to assure the desired corrosion degree in each case. This was done through a DC power supply with an ammeter to monitor and fix the current intensity. The current direction was defined fixing the reinforcing steel as anode and the stainless steel bar as the cathode. A schematic representation of the accelerated corrosion test setup is presented in Fig. 3a. Each beam had two different bar diameters (10 mm and 12 mm). Monotonic load tests were carried out in the continuous beams and subsequently bars were carefully extracted from the non-critical section of the beams in order to perform the characterization of the corroded bars under monotonic and cyclic loads.

Using gravimetric methods, the loss in weight of the specimens was determined according the ASTM code [18]. A pressure sand cleaning method was applied in order to remove both rust and bonded cement, Fig. 3b. In total 241 specimens were obtained covering corrosion degrees from 7% to 28% for both the 10 mm and the 12 mm diameter bars, see Fig. 4.

3.2. Monotonic test

The tests were carried out following the standard recommendations [22] and an INSTRON 8803 Universal Testing machine.

The specimens employed for monotonic testing had between 310 mm and 320 mm length. The ends of the tested specimens were affixed by two clamps, which were used to transfer directly the load to the specimen. The tested free length for all the specimens was 170 mm letting 70/75 mm length for each clamp. Monotonic tests were conducted by means of displacement control. The load was applied directly to the bar controlled by the load cell placed on the top of the hydraulic jack. Total displacement, as well as deformation, were registered too. Specimen deformation was measured using a displacement transducer of 50 mm length positioned in the middle of the tested bar (see Fig. 5). The load was applied until specimen failure. Uncorroded specimens were also tested to compare and assess the influence of the corrosion degree on the mechanical properties. In total, 40 specimens were tested satisfactorily. The weakest section, where most likely the bar would fail, was identified for all the specimens by means of the description of the observed critical pit. The critical pit geometrical specs, pit depth and pit length, were measured using a Vernier caliper (Fig. 9). Recent studies tried to relate the pit characteristics