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Mathematical models to predict the mechanical behavior of reinforcements depending on their degree of corrosion and the diameter of the rebars

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HIGHLIGHTS

- Models that relate mechanical properties with corrosion degree have been obtained.
- The variation of yield stress and ultimate strength does not depend on the diameter.
- Bar resistance reduction is lower than the one caused by section loss.
- Deformation energy density undergoes higher decreases than yield stress or strength.

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ABSTRACT

Tensile strength of high ductility reinforcements with different corrosion levels have been tested. Results have led to obtain models that relate yield stress, ultimate strength and energy density of deformation with corrosion degree and diameter. Good relations in the models analyzed have been obtained. Due to the lack of homogeneity in the composition and the lack of uniformity in the material loss in the bar due to corrosion, the strength decrease is smaller that the one predicted by the loss of steel section. Percentage decrease of energy density is higher than the decreases experienced by yield stress and ultimate strength.

1. Introduction

Corrosion of the reinforcement is the main factor of deterioration in Reinforced Concrete Structures (RCS), since once its passive layer is destroyed, the moisture in the environment can easily damage it [1–3]. The consequence of this corrosion process is the important decrease in the service life of RCS leading to values extremely lower than those initially stated in the project [4,5]. Once the corrosion process has started, the rehabilitation of RCS is very expensive [6,7]. However, its prevention in the design and implementation stages is by far, less costly [8].

The reduction of the bearing capacity of an element of reinforced concrete affected by corrosion of the reinforcement is due, mainly, to the following effects resulting directly from the corrosion [9].

- Loss of concrete effective section due to cracking and detachment of the cover.
- Reduction of the section and the ductility of the reinforcement.
- Reduction of the concrete–steel bonding and that of the reinforcement anchor embedded in concrete.

The progress of these factors is in relation to the speed the process develops, which depends, in turn, of the type of aggressiveness and environmental conditions [10–12]. The volumetric expansion implied by the formation of by-products by reinforcement corrosion, leads to radial stresses that make the surrounding

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concrete to be under tensile stresses [13–15]. If the corrosion products do not spread through the pores, small amounts of corroded metal can generate a stress state exceeding the tensile strength of concrete and causing cracking and detachment of the cover. The expansion stress exerted by the corrosion products is estimated to vary from 32 to 500 MPa [16–19]. Small corrosion penetrations, even less than 20 μm can produce cracking for regular concrete cover depths of about 3 cm and rebar diameters of 13 mm [20–23].

Reinforcement corrosion affects the bonding performance because of the variation of the existing interphase between steel and concrete, which results in the formation of concrete-corrosion products [23–25], due to the loss of the rib height of the rebar and the concrete cracking. This implies a drastic reduction of the steel bar anchoring [26–28]. When corrosion occurs in the stressed area of the beam span center, the consequences appear primarily at the level of service limits, with an increase of cracking and deformations of the beam [29]. If corrosion is not stopped, the beam would behave at the limit similarly to a cable stayed arch; and the strength would also be affected. When corrosion occurs in the anchoring area of the reinforcement, the consequences are more serious, and a brittle failure in the structure can occur [30]. In this case, the existence of transversal reinforcement significantly improves the anchoring residual strength of the corroded reinforcement [31,32]. The beneficial effect on the anchoring residual strength of the corroded bars has also been proved with pull-out tests [33,34]. When regarding the whole element, corrosion implies a reduction in rigidity, ductility and bearing capacity of the beam. In many cases, a change in the failure mode of the beam can also be produced, appearing shear fracture in the beams with corroded reinforcement, while those without reinforcement corrosion do not bend [35].

Consequences of reinforcement corrosion are: loss of the reinforcement carrying capacity (mainly due to the section reduction) and ductility loss. Tests performed on corroded rebars show the changes experienced in the steel stress/strain diagram, demonstrating a systematic deformation decrease under maximum load with the degree of corrosion, up to values that, in many cases, are below the minimum required by the standards and regulations in force, due to the notch effect caused by the corrosion [36–38]. It has been proved in previous researches [27] that even the reinforcement can fracture in the beam tensile zone during a loading test when corrosion pit are deep enough.

In previous research conducted by the authors [39–41] in which 96 corroded reinforcement were tested, it was found that, as the level of reinforcement corrosion increases, a systematic increase of the ratio between the steel maximum strength and the yield strength (f_s/f_y) was observed. The corrosion process implies the disappearance of the martensite outer layer, increasing the ferrite proportion at the rebar section. Ferrite has a much higher f_s/f_y value than martensite, and therefore, when corrosion levels increase, the f_s/f_y value of the rebars also increase. The metal thickness removed by corrosion does not depend on the bar diameter, but indeed the martensite section loss does depend on the bar diameter. That is, for a specific corrosion level, the martensite outer thickness loss is the same for diameters 16 and 20, but the f_s/f_y ratio increases more in 16 mm bars than in 20 mm ones when corrosion takes place. In these cases, the use of the deformation energy density concept as a ductility criterion, obtained as the area of the stress/strain curve until reaching the maximum load deformation, can be very beneficial [42].

The research undertaken in this study is motivated by the need to contribute to the knowledge of the mechanical performance of RCS with corroded reinforcement. An experimental work has been carried out to assess the effect of corrosion on the mechanical characteristics of the reinforcement. In order to do so, accelerated corrosion tests have been developed on steel bars of diameter 16 and 20 mm, embedded in concrete elements. Subsequently, reinforcements were tested to tensile strength to determine the following mechanical characteristics: yield strength, maximum (ultimate) strength and deformation energy density.

With the obtained results, models have been obtained to predict the steel mechanical properties depending on the corrosion degree and the rebar diameter.

Research has been previously performed to study the effect of corrosion on the mechanical properties of steel [37,41,43,44]. In some of these works studied, models have been obtained that explain the mechanical behavior of corroded reinforcement. These models have formulated from data obtained by subjecting rebars to different experimental conditions. Regression models or simple nonlinear models have been obtained in which the explanatory variable has been the exposure time. In this study, a multiple regression analysis has been performed considering the influence of two variables (corrosion percentage and diameter) in order to analyze the dependence of mechanical properties with the both of them together.

2. Experimental procedure

2.1. Materials

To determine the evolution of the steel mechanical properties regarding the corrosion process, concrete slabs of dimensions 46 × 60 × 10 cm were performed, in which B 500 SD steel bars, 16 and 20 mm in diameter and length 50 cm were embedded (Fig. 1). This type of steel, defined in the UNE 36065 EX2000 standard [45], has special ductility characteristics, and is therefore intended to use in seismic zones. In addition, it is the one most commonly used in many construction works in Spain. Table 1 shows the minimum mechanical characteristics that must be met, according to the EHE-08 standard [46].

In the manufacture of the concrete slabs, calcium chloride has been added in order to destroy the passive state of steel, in a 2% concentration of ion chloride by cement weight. After placing the concrete and removing the formwork, the slabs were cured in a moisture chamber at 25 °C temperature and 99% humidity for 28 days.

Corrosion attacks preferably the area of the concrete-air interphase, and to avoid it, the part of the reinforcement located in that heterogeneous area was covered with insulating tape, so that the tape would surround the reinforcement at an approximate length of 2 cm inside and outside of the concrete.

2.2. Accelerated corrosion techniques

Steel ribbed bars were externally short-circuited and corrosion was forced by applying a constant anodic current between the reinforcement and a lead plank placed on the surface of the slabs. The uniform distribution of electric current was achieved by inserting a cloth soaked with water between the surface of the slabs and the lead plate. This cloth piece was dampened as it dried (Fig. 2).

During the process, current flowing through each of the bars was periodically recorded using a digital multimeter, performing daily measurements and correcting any voltage drop by varying the power supply electrical potential. The current average density in each of the bars was approximately 10 $\mu A/cm^2$. This corrosion density was obtained in real structures exposed to chloride environments where there was enough humidity [47].

Bars were disconnected from the power supply at different times to obtain varying levels of attacks by corrosion (Fig. 3).

2.3. Tensile tests

Once the bars had been extracted from the concrete slabs, and after removing the oxide formed by chemical pickling, the corrosion degree produced in each one of them was determined by gravimetric loss, and the rebars were tested to tensile. Tensile tests have been performed following Spanish standards [48] in a hydraulic servo controlled press machine MIB-40-MOD-AM with a load capacity of 610 kN. Tests have been carried out with load control on the elastic area and strain control once the yield strength had been surpassed. The strain measurements have been obtained with a JB-MFA-2 strain gauge of 50 mm base. The mechanical properties of the reinforcement yield strength, ultimate stress and energy density were evaluated.

3. Results obtained

Results of tensile strength tests on 16 mm diameter rebars are shown in Table 2, where the data corresponding to the mechanical