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Engineering failure analysis of corroded R.C. beams in flexure and shear

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ABSTRACT

In the present paper, a simple model to reproduce the load-deflection response of corroded beams failing in flexure and shear is presented and discussed. Effects of diffused and pitting corrosion on steel bars, compressive concrete strength degradation and concrete bond strength degradation due to rust formation are included in the model. Engineering approach based on limit state theory was here adopted to predict the peak and the residual flexural and shear strength of corroded beams with corresponding deflections and ductility estimation. Calculation of deflection at cracking taking into account of rust formation and deflection at yielding and the ultimate state taking into account also of slippage of steel bars due to rust formation were made. The model was also widely verified against tests available in the literature referred to crack opening, pit depth, attach corrosion penetration, load-deflection curves.

1. Introduction

Corrosion of reinforcing steel is one of the main causes of deterioration of reinforced concrete structures. Its effects include cracking and spalling of the concrete cover, reduction, loss of bond between concrete and corroded reinforcement, and reduction of the cross-sectional area of the reinforcing steel.

Numerous experimental studies have investigated the effects of corrosion of material such as on steel bars [1–4] and steel-concrete bond [5–8], There have also been studies at a structural level, relative for example to the flexural behavior of beams [9–11] and columns [10].

Two types of corrosion of reinforcement can affect an RC structure: general and pitting. General corrosion affects a substantial area of longitudinal and transverse reinforcements with more or less uniform metal loss over the perimeter of reinforcing bars. It also causes cracking and possibly spalling and delamination of the concrete cover and produces rust staining on the concrete surface. Pitting is a localized corrosion type, which concentrates on small areas of reinforcement, causing spalling of the concrete cover.

Despite a large body of literature on the corrosion of reinforcing steel induced by chlorides and correspondence influence of reinforcing steel corrosion on the flexural capacity of RC beams, there are few works that dealt with the reduction in shear capacity of RC beams due to corrosion of stirrups in RC beam [7].

To describe the structural behavior of corroded beams, most studies are based on numerical analyses carried out with the finite element method [3] able to predict the whole response of corroded beams. These are complex and require detailed information on the constitutive laws of the damaged materials. Analytical analysis using simple equations to calculate the effects of corrosion on mechanical parameters are carried out by [12]. In this paper a simple mechanical model to predict the load-deflection response of RC

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beam in flexure and shear subjected to corrosion process is proposed. The main phenomena, such as reduction of steel area, concrete strength reduction, bond degradation and reduction in working stress of stirrups, are considered in the analytical expressions proposed for the calculation of the flexural and shear strength of corroded RC beams. The paper deals with the structural behavior of corroded RC elements, and it uses results from "accelerated corrosion". In real structures results come from natural corrosion which are difficulty comparable and characterized the corrosion damage. In this paper average values both for accelerated process and the natural process are utilized.

2. Effect of corrosion on the strength and the ductility of materials

The main phenomena observed experimentally [1–8] and here considered to describe the effects of corrosion on steel and concrete are: - uniform reduction of the steel area in the longitudinal bars and the stirrups and available ductility; - bond strength reduction; - concrete strength reduction in the compressed zone of the beam due to cover cracking induced by the rust formation. According to [13] the yield and ultimate strength and elastic modulus of steel reinforcement are not markedly decreased by uniform corrosion.

For a constant general corrosion rate uniform corrosion with rust formation occurred. The thickness of the corrosion attack penetration X, as suggested in [13] can be expressed as:

$$X = 0.0116 \cdot i_{corr} \cdot t \tag{1}$$

Eq. (1) is a rearranged form of Faraday's law of electrolysis.

Where i_{corr} is the corrosion current density in the reinforcing bar expressed in μA/cm^2 and t the time in years.

Eq. (1) reflects the psychical circumstance that general corrosion produces a reduction of the steel area linearly proportional to time and the corrosion current density in the reinforcing bar [11].

Therefore, the reduced area of the reinforcing bar or stirrups can be determined as:

$$A_s(t) = n_{bars} \cdot \frac{\pi \cdot [D - 2 \cdot X]^2}{4} \tag{2}$$

with D the diameter of the bar (or stirrup) and n_b the number of the bars in tension.

If the attack corrosion is measured through the loss of mass X_p the relationships between X and X_p results:

$$X_p = \frac{4 \cdot X}{D} \cdot \left(1 - \frac{X}{D}\right) \tag{3}$$

It has to be stressed that in the application of Eq. (2) two times of X is subtracted to D; it means that if was assumed that the reinforcement is uniformly corroded. This is a conservative hypothesis because, during the slight and moderate corrosion degree, only the outer surface of the steel is corroded in actual corrosion environment. Some authors suggest adopting 1 or 2 in Eq. (2) to describe attack penetration depending on the position of bars in the cross-section. A value of 2 is here adopted (as suggested in [11]) if the corrosion attack is on each side of the bars and 1 if the carbonation reaches only one side of the bar. In the intermediate condition, a parabolic variation between 1 and 2 is suggested. In the current paper, a constant value 2 was assumed.

Fig. 1, referring to the data in [11], shows the ratio of X deduced theoretically and experimentally with time t for a given current density $i = 100$ in μA/cm^2.

For the calculation of the reduced area of the corroded steel, it should be taken into account that the corrosion of longitudinal

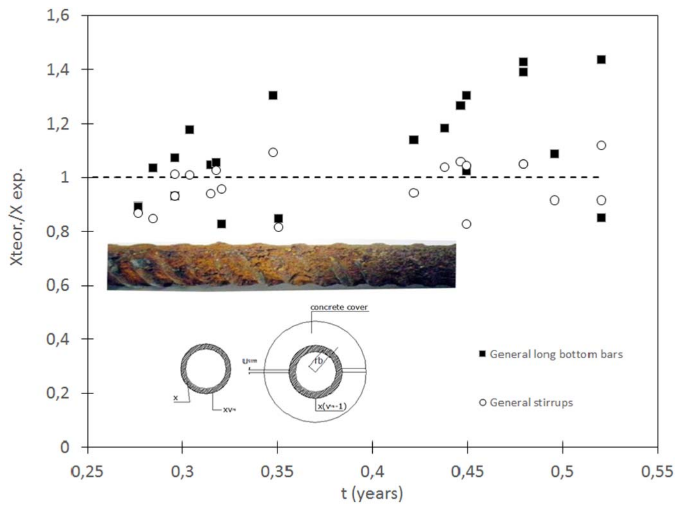

Fig. 1. Theoretical versus experimental general corrosion effects (data given in [11]).

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