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Nonlinear stress–strain behaviour of corrosion-damaged reinforcing bars including inelastic buckling

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ABSTRACT

In the seismic design and assessment of reinforced concrete structures in earthquake zones buckling of longitudinal reinforcement in plastic hinge regions is an important limit state that needs to be considered. If the structure is located in an environmentally aggressive area, it is also subject to material deterioration over its service life. Corrosion of reinforcement is the most common type of deterioration of reinforced concrete (RC) structures and bridges. In this paper the nonlinear stress–strain behaviour of corroded reinforcing bars has been investigated by extensive experimental testing. The effect of different corrosion levels on the tension and compression behaviour of bars with different slenderness ratios is presented. The results of this study show that a corrosion level above 15% mass loss significantly affects the ductility and plastic deformation of reinforcement in tension and that corrosion changes the buckling collapse mechanism of the bars in compression. The results of buckling tests show that 10% mass loss produces about a 20% reduction in the buckling capacity of corroded bars. The results also show that the distribution of corrosion pits along the length of corroded bars is the most important parameter affecting the stress–strain response in both tension and compression. Furthermore, a constitutive material model to predict the post-yield buckling behaviour of high-strength steel without a yield plateau is also developed. The proposed analytical model is based on Dhakal–Maekawa buckling model. The analytical model has been validated against experimental tests on uncorroded and corroded bars. The results of this corrosion extended buckling model show a good agreement with the physical testing.

1. Introduction

The deterioration of reinforced concrete (RC) bridges, an important part of our transport infrastructure, is recognised as one of the major challenges facing bridge owners and managers [1,2]. In 2010, it was estimated that deficiencies due to deterioration in America's surface transport systems cost households and businesses nearly $130 billion [2]. The deterioration mechanisms reducing the durability of reinforced concrete bridges can be categorised into three groups: (a) corrosion of reinforcement (carbonation or chloride induced corrosion), (b) deterioration of concrete (freeze–thaw effects, sulphate attack, alkali silica reaction, etc.) and (c) external physical damage (earthquake/seismic event, overloading, fire, etc.) [3]. The corrosion of steel reinforcement leads to concrete fracture through cracking, delamination and spalling of the concrete cover, reduction in member strength (flexural, shear, etc.) and a reduction in member ductility. As a result, the safety and serviceability of concrete structures are reduced, their useful service lives are shortened and the probability of failure under extreme loading (e.g. earthquake) is increased.

Previous work on the corrosion of RC structures has focused mainly on corrosion induced cover cracking, corrosion prevention and repair of corrosion damaged structures. In recent years researchers have studied the effect of corrosion on the residual tension capacity and mechanical properties of reinforcing bars [4–9]. In most previous studies researchers have used accelerated corrosion techniques on bare bars and bars embedded in concrete to simulate the corrosion process in a laboratory environment [4,5]. Some studies have also used reinforcing bar samples from real corroded bridges [10]. A key aspect that almost all these researchers agree on is that the non-uniform cross section loss due to pitting corrosion along the bar has a significant influence on the force–extension response of reinforcement in tension tests.

As mentioned, all of the previous studies have focused on the effect of corrosion on residual capacity and ductility of reinforcement in tension and there have been no studies on the effect of corrosion on the inelastic buckling of bars in compression. Buckling of reinforcement is a very important limit state (performance criteria) in seismic assessment of RC structures in earthquake regions. Based on recent experimental studies on the cyclic behaviour of corroded RC columns and beams, corrosion has a significant effect on the buckling behaviour of reinforcing bars and leads to changes in the global response of corroded RC elements [11–13]. Currently

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there is no experimental data available showing the extent of corrosion damage on the buckling response of reinforcing bars with large compressive strain demand. Therefore this paper examines the effect of corrosion on the stress–strain response of corroded bars in tension and compression taking into account the effects of inelastic buckling. As a result of extensive physical testing a constitutive material model based on the Dhakal–Maekawa buckling model is also developed. The analytical model is capable of predicting the post-yield buckling behaviour of corroded high-strength reinforcing bars without yield plateau.

2. Specimen preparation and corrosion simulation

2.1. Test specimens

In order to simulate the corrosion of steel reinforcement embedded in concrete a total of six reinforced concrete specimens were cast. Two specimens dimensioned $200 \times 150 \times 500$ mm incorporated the 8 mm and 12 mm diameter reinforcing bars which would be used in the tension tests, and four specimens dimensioned $250 \times 250 \times 700$ mm incorporated the 12 mm diameter reinforcing bars which would be used in the buckling tests. The RC specimens are shown in Fig. 1. The concrete mix was designed to have a mean compressive strength of 30 MPa at 28 days with a maximum aggregate size of 12 mm. The specimens were cast with nominal cover of 25 mm.

The reinforcing bars used were typical B500B British standard reinforcing bars. For each bar size a set of three tension tests were used as control specimens to identify the mechanical properties of the original uncorroded reinforcement.

2.2. Accelerated corrosion procedure

Even in a very severe and aggressive environment, where the corrosion rate is quite fast, it takes years to get moderate to heavy corrosion of reinforcing bars. Therefore, it is necessary to use artificial techniques to accelerate the corrosion process in the laboratory when extended time testing is not practical. However, it is important to ensure that these techniques realistically simulate the deterioration process in the natural environment.

Previously, researchers have successfully used external current methods to induce accelerated corrosion in reinforcing bars [4,5]. The concept of using external currents is very simple and consists of forming an electrochemical circuit using an external power supply. The reinforcing bars act as an anode in the cell and an external material acts as the cathode. Fig. 2a–c shows a schematic arrangement of the test setup for inducing accelerated corrosion, a typical test specimen during accelerated corrosion, and some cleaned corroded reinforcement after removal from the concrete. Common materials that can be used as external cathodes are copper, stainless steel, and regular carbon steel. A saline solution is commonly used to function as an electrolyte to carry the ionic current from the interior of the concrete to the external cathode. In this experiment a stainless steel plate was used as the external cathode along with a 3% NaCl (sodium chloride) saline solution. To improve the conductivity 5% of cement weight sodium chloride was added to the concrete mix.

Eq. (1) is Faraday's 2nd Law of Electrolysis which was used to estimate the duration of the corrosion process in relation to mass loss (Δm) due to corrosion [4,5]:

$$\Delta m = \left(\frac{Q}{F}\right)\left(\frac{M}{z}\right) \tag{1}$$

where Q is the total electric charge passed through the substance, M is the molar mass of the substance (55.847 g for steel), z is the ionic charge (electrons transferred per ion = 2), F is the Faraday's constant (96,500 A/s) and Q can be calculated as below (Eq. (2)):

$$Q = \int_0^T I dt = IT \tag{2}$$

where I is the magnitude of the electric current (A) and T is the duration of exposure (s).

Eq. (1) was used to estimate the corrosion duration for desired mass loss. However, the actual mass loss ratio was calculated by measuring the mass loss of the steel bar relative to the mass of the bar before corrosion.

After corrosion simulation, the concrete specimens (shown in Fig. 1) were broken open and the corroded bars (for both tension and compression testing) were carefully removed from the concrete. To ensure that the concrete was completely removed from the corroded bars, a mechanical cleaning process using a bristle brush was used, in accordance with ASTM G1-03 [14]. The corroded bars were then washed with tap water and dried. The brushing and washing process was then repeated a second time. It should be noted that the same brushing process was applied to the uncorroded control specimens and it was found that the effect of brushing on the mass loss of base material is negligible. This method has been successfully used by other researchers [8,9].

The following Eq. (3) was used to determine the actual mean mass loss ratio (γ):

$$\gamma = \frac{m_0 - m}{m_0} \tag{3}$$

where m_0 is the mass per unit length of the original steel bar, m is the mass per unit length of the steel bar after removal of the corrosion products. Eq. (3) gives an average corrosion level (mass loss) along the bar length.

Table 1 summarises the predicted and measured mass loss the six test specimens. The results show that the values of predicted mass loss, based on Faraday's law, are much higher than the measured values. El-Maaddawy and Soudki [15] studied the effectiveness of the external current approach experimentally. They found that for mass losses ranging from 4% to 7.27% at current density levels ranging from 0.1 to 0.5 mA/cm^2, the predicted mass loss based on Faraday's law was in a good agreement with the measured mass loss of the steel reinforcement. However, the current density levels used in this experiment were 2.4 mA/cm^2 and 1.1 mA/cm^2 for the tension and compression specimens respectively. In addition, at higher degrees of corrosion the amount of corrosion products around the steel bars may have prevented the

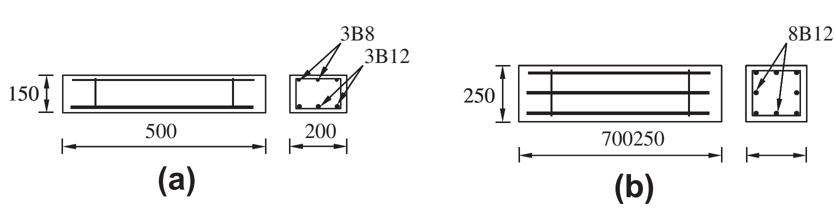

Fig. 1. Corrosion specimens (a) for tension tests (b) for compression tests.