Construction and Building Materials 41 (2013) 388–400

Contents lists available at SciVerse ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Nonlinear cyclic response of corrosion-damaged reinforcing bars with the effect of buckling

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HIGHLIGHTS

- ▶ Influence of corrosion on buckling collapse mechanism of corroded bars.
- ▶ Influence of corrosion on fracture mechanism of corroded bars in tension.
- ▶ Analytical modelling of low-cycle high amplitude fatigue degradation.
- ▶ Corrosion influence on slenderness ratio and energy dissipation capacity.
- ▶ Modelling the combined effect of buckling and low-cycle fatigue degradation.

ARTICLE INFO

Article history:
Received 14 September 2012
Received in revised form 3 December 2012
Accepted 6 December 2012
Available online 17 January 2013

Keywords:
Reinforcing steel bars
Corrosion
Inelastic buckling
Stress–strain relations
Nonlinear analysis
Cyclic behaviour
Low-cycle high amplitude fatigue

ABSTRACT

Corrosion of reinforcing bars is the most common reason for the premature deterioration of reinforced concrete structures and bridges in a chloride laden environment. There are large numbers of existing reinforced concrete bridges in earthquake prone regions that are suffering from corrosion. Therefore, in this paper, the effect of corrosion on cyclic response of reinforcing bars is investigated experimentally. A total of 39 corroded reinforcing bars with varying mass loss and slenderness ratios have been tested. The effect of corrosion on the buckling behaviour of bars in compression, their fracture in tension and their hysteresis response is investigated. Furthermore, an analytical model is proposed to describe the low-cycle high amplitude fatigue degradation of corroded bars. The results of the experimental investigation show that corrosion has a significant influence on the buckling behaviour of corroded bars in compression and also changes their hysteresis response. For a few bars the localised corrosion also caused fracture of corroded bars in tension after a significant buckling episode in the previous compression cycle. The proposed corrosion extended low-cycle fatigue and inelastic buckling models have been incorporated into the existing material models and simulated computationally for the whole cyclic loops. A good qualitative fit is observed between the computational simulation and the experimental response when the corrosion is relatively uniform along the bar. However, some disagreements were found between the computational and experimental responses in cases where the corroded bars had severe and localised pitting corrosion. It was observed that the most important parameter governing the nonlinear cyclic response is the distribution of localised pitting corrosion along the length of the corroded bars.

1. Introduction

Reinforced Concrete (RC) bridges are a major part of any transport infrastructure. A large number of bridges in Europe and the US are located in aggressive environments [1,2]. Many of these bridges are currently suffering from material aging and deterioration. Among the different deterioration mechanisms corrosion of reinforcing steel is the most common reason for the premature deterioration of RC structures in chloride laden environments. Many of these bridges are also located in high seismicity regions and will be subjected to cyclic dynamic loading during an earthquake. Therefore consideration needs to be given to the effect of material deterioration on the nonlinear response of these structures under seismic loading. In recent decades the nonlinear analysis of RC framed structures subject to seismic loading has received a lot of attention. This has been focused on the development of the fibre element technique [3–6]. In this approach the member cross section is decomposed into a number of steel and concrete fibres at selected integration points. The material nonlinearity is represented through a uniaxial constitutive material model of steel (tension and compression) and concrete (confined core concrete and uncon-

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http://dx.doi.org/10.1016/j.conbuildmat.2012.12.011

fined cover concrete). More recently, Choe et al., Berto et al., Ghosh and Padgett, and Alipour et al. [7–10] have investigated the effect of reinforcement corrosion on the behaviour and response of RC bridges subject to seismic loading through nonlinear fibre-based finite element analysis. Ou et al., Akiyama et al., and Ma et al. [11–13] have investigated the effect of corrosion on the nonlinear response of RC beams and columns subject to cyclic loading experimentally. The results from these experimental studies showed that non-uniform pitting corrosion affects the global response of corroded RC elements subject to cyclic loading. This is mainly due to the influence of corrosion on cyclic behaviour and premature buckling of corroded bars.

Previous experimental studies on corroded bars have confirmed that corrosion will result in a reduction to the cross sectional area of reinforcement and in changes to the stress–strain behaviour of the reinforcement in tension [14–20]. However corrosion has an even more significant effect on the nonlinear response of bridge piers subject to seismic loading and high axial loads, where the buckling of vertical bars in plastic hinge regions is the governing parameter. Therefore, there is a need for research to understand the effect of corrosion damage on the nonlinear behaviour of reinforcing bars under both monotonic compressive and cyclic loading. As an initial study Kashani et al. [20] performed a comprehensive set of experimental tests to investigate the effect of corrosion on the inelastic buckling behaviour of corroded bars under monotonic loading.

There are currently a number of analytical models available in the literature for monotonic and cyclic stress–strain response of uncorroded reinforcing steel in tension and compression, with and without buckling [21–32]. The effect of corrosion on the behaviour of reinforcing bars subject to low-cycle fatigue loading has also been studied [19,33,34]. However, the effect of corrosion damage on the nonlinear stress–strain response of corroded bars subject to cyclic loading with high strain demand in compression including the effect of buckling has not been explicitly studied to date. This paper explores this issue and reports the results of an extensive experimental study on the cyclic stress–strain behaviour of corroded bars with different mass loss and slenderness ratios with large compression strain demand. The influence of corrosion on fracture mechanisms in tension and buckling mechanisms in compression is investigated. The influence of corrosion on the slenderness ratio and the qualitative shape of hysteresis cycles is investigated. The influence of corrosion on total energy dissipation and the accumulated energy dissipation capacity of corroded bars has also been investigated quantitatively. Moreover, an analytical methodology has been developed to describe the low-cycle high amplitude fatigue degradation of corroded bars. It is based on the Kunnath et al. [32] model which has been extended to include the effect of corrosion based on the results of low-cycle fatigue tests conducted by Apostolopoulos [19]. The corrosion parameters have been incorporated into the existing material models in OpenSees [6] and validated with the experimental results. The result of the OpenSees simulation showed a good qualitative fit with the experimental results. This model accounts for the strain history effect and allows for the influence of inelastic buckling and low-cycle high amplitude fatigue degradation and can directly be used in nonlinear analysis of corroded RC structures subject to seismic loading.

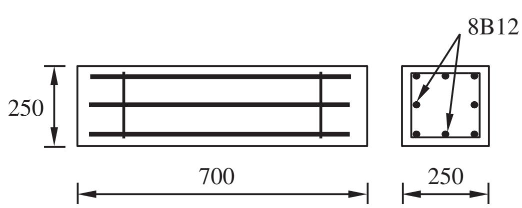

Fig. 1. RC specimens prepared for the accelerated corrosion of reinforcement bars.

2. Experimental programme

In order to realistically simulate the corrosion of steel reinforcement embedded in concrete a total of four reinforced concrete specimens were cast. Each specimen dimensioned 250 × 250 × 700 mm incorporated 8 number 12 mm diameter B500 British standard reinforcing bars [35] as 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 a nominal cover of 25 mm.

2.1. Accelerated corrosion procedure

An accelerated corrosion procedure was used to simulate long term corrosion. The concept of using external currents is 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 as shown in Fig. 2. A summary of the experimental specimens and corrosion duration is provided in Table 1.

The time required to get the desired corrosion level was estimated using Faraday's 2nd Law of Electrolysis [20]. After corrosion simulation, the concrete specimens (shown in Fig. 1) were broken open and the corroded bars 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 [36]. The corroded bars were then washed

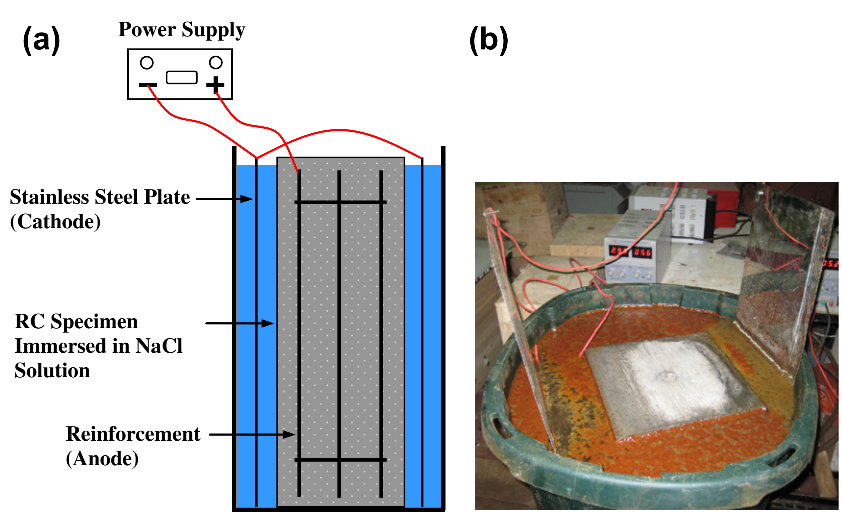

Fig. 2. Corrosion procedure: (a) schematic illustration of accelerated corrosion procedure and (b) accelerated corrosion test setup in the laboratory.