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Finite element investigation of the influence of corrosion pattern on inelastic buckling and cyclic response of corroded reinforcing bars

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ABSTRACT

An optical surface measurement technique was used to characterise three-dimensional corrosion pattern of reinforcing bars subjected to accelerated corrosion. After the optical measurement process was performed, the corroded bar specimens were tested under monotonic and cyclic axial loading. The optical measurement data were used to develop a 3D micro-fibre finite element model developed for simulation of the physical testing and parametric study of the influence of corrosion pattern on stress–strain response of corroded bars. It was observed that the irregular cross sectional shape of pitted sections has a significant influence on the inelastic buckling and nonlinear cyclic response.

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1. Introduction

Corrosion of reinforcing bars in aging reinforced concrete (RC) structures and bridges is a critical issue in developed countries [1–3]. Billions of dollars are spent annually by government and other agencies monitoring, repairing, and replacing RC structures with corrosion damage [1–3]. There have been incidences in which corrosion damage resulted in the complete collapse of in-service structures [3]. Because of this, a substantial body of research in the past decades has focussed on corrosion in RC structures. This research has addressed a number of topics including the corrosion process, the behaviour of corroded reinforcement, performance assessment and repair of corroded structures, and maintenance optimisation for transportation structures [4,5]. A relatively small portion of this research has addressed the impact of corrosion on the seismic performance of RC structures, despite the fact that there are many RC structures located in regions of high seismicity and exposed to corrosive environments.

For RC bridges subjected to earthquake loading, the desired inelastic response mechanism is typically flexural yielding of the columns or piers, and drift capacity (i.e. the drift at which significant lateral strength loss occurs) is typically determined by buckling followed by fracture of longitudinal reinforcing bars [6]. Recent experimental testing of corroded RC elements subject to cyclic loading showed that corrosion significantly reduces plastic rotation capacity, and thus drift capacity; this is due to premature buckling and/or fracture of the longitudinal reinforcing bars as well as premature fracture of horizontal hoop reinforcement that confines core concrete and restrains longitudinal bar buckling [7,8].

In the recent years researchers have investigated the influence of corrosion on the stress–strain behaviour of corroded bars in tension [9–14]. The outcome of theses researches showed that corrosion has significant influence on the ductility and plastic deformation capacity of reinforcing bars owing to the level of non-uniform pitting. To improve understanding of the impact of corrosion on inelastic buckling and cyclic response, Kashani et al. [15,16] conducted a comprehensive experimental investigation of the influence of corrosion on inelastic buckling and nonlinear cyclic behaviour of corroded reinforcing bars. The experimental results show that the non-uniform distribution of pitting along the length of corroded bars changes the buckling mechanism and results in more rapid strength loss under cyclic loading. Kashani et al. report that when the mass loss ratio of corroded bars is more than approximately 25%, pitting corrosion becomes more localised. Since the smallest cross section of the bar determines the yield strength; localisation of pitting corrosion results in premature yielding of the reinforcement at a relatively low tension demand. Additionally, Kashani et al. [17] show that pitting corrosion results in variation in the cross sectional shape of the reinforcement along

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the length of the corroded bar. This results in a change in the moment of inertia of the reinforcing bar and potentially affects the buckling response of the bar under cyclic loading.

This paper explores the influence of the pattern of corrosion along the length of a reinforcing bar on inelastic buckling and cyclic response. Data from a previously presented experimental study [15,16] are reviewed with the objectives of establishing the response of corroded bars under monotonic and cyclic loading and characterising the pattern of corrosion along the length of the reinforcing bar. A computational model, employing nonlinear beam–column elements with fibre-type cross-section models and nonlinear material models, is proposed for simulating the response of a corroded reinforcing bar. The variation in the geometrical properties of corroded bars is modelled using the optical measurement data provided in [17]. Moreover, for the first time, the variation in load eccentricity due to pitting corrosion along the buckling length of bars is also included in the finite element model. The model is validated through comparison with experimental data. The model and experimental data are used to investigate the impact of the corrosion pattern on the buckling strength, tensile yield strength and cyclic response of a reinforcing bar. Finally, experimental data are used to evaluate existing one-dimensional constitutive models for reinforcing steel, which simulate compressive strength loss due to buckling and the impact of buckling and low-cycle fatigue on cyclic response.

2. Corrosion induced mechanical–geometrical degradation of reinforcing bars

Kashani et al. [15] tested a series of corroded reinforcing bars under monotonic and cyclic loading. Experimental data characterise the average stress–strain response of the bars under monotonic and cyclic loading; such data can be used to develop and validate the 1D constitutive models for reinforcing steel used typically in fibre-type models of reinforced concrete flexural elements. Experimental data characterise also the pattern of corrosion along the length of the bars, from which variation in the bar area and first and second moments of area are computed.

2.1. Summary of experimental programme

To develop the corroded reinforcement specimens for testing, a total of eight reinforced concrete prisms were cast. Each specimen was dimensioned $250 \times 250 \times 700$ mm and incorporated 8 No. 12 mm diameter reinforcing bars. An accelerated corrosion simulation technique (known as anodic corrosion) was employed to accelerate the corrosion time in the laboratory environment. Different prisms were subjected to different corrosion times to achieve different levels of reinforcement mass loss due to corrosion. After corrosion simulation, the concrete specimens were broken open and the corroded bars were carefully removed from the concrete and cleaned in accordance with ASTM G1-03 [18]. A total of 120 corroded bars were prepared. Twenty-three (23) randomly selected corroded bars with different mass loss ratios were selected for optical measurement and statistical analysis of the corrosion patterns. Fifty-seven (57) bars were used for monotonic buckling tests and 40 were used for cyclic tests. A detailed discussion of specimen preparation, optical measurement and testing is provided in [15–17].

Mechanical testing was conducted for a series of different slenderness ratios. The slenderness ratios were chosen based on the range of horizontal tie spacings commonly used in RC column construction. The slenderness ratio (L/D) is defined as the unsupported length of the bar (L) divided by the diameter of the reinforcing bar (D). The L/D ratios tested were 5, 8, 10, 15, and 20 for the monotonic buckling tests and 5, 10 and 15 for the cyclic tests. For each slenderness ratio, three control (uncorroded) specimens were also tested.

2.2. 3D optical measurement of corrosion pattern

Twenty-three (23) randomly selected corroded reinforcing bars were taken out of the total of 120 samples for more refined geometrical surface analysis of corrosion patterns. The reinforcing bars varied in length ($L/D = 5$ to $L/D = 20$) and had a range of mass loss ratios. The surface pitting pattern of the corroded bars was measured using a white light scanner followed by a stochastic analysis of the results in MATLAB [19]. Fig. 1 shows an example contour plot of scanned bar. The surface area of the bar is represented by the length along the bar (0–200 mm) and the angle of rotation ($-\pi$ to π) from an arbitrary plane; the impact of corrosion is represented by the radius from the original centroid of the bar to the surface of the corroded bar (2.0–6.0 mm). Fig. 2 also shows an example of cross sections through the solid model of a corroded bar with 54.23% mass loss. A detailed discussion of the optical measurement process and analysis of optical data is provided in [17]. Once the corrosion pattern analysis completed the 23 scanned bars have been tested under monotonic and cyclic loading.

2.3. Observed response under monotonic loading

The experimental results show that the non-uniform pitting corrosion changes the buckling mechanism of corroded bars. The pitted sections have irregular shapes that vary over the entire length of the bar [15]. This irregularity creates strong and weak axes, for which the second moments of area is reduced from the uncorroded state, and creates load eccentricity that results in a significant reduction in buckling capacity for corroded bars. Fig. 3 shows examples of mean stress versus strain data for corroded bars tested in the laboratory under monotonic compression loading. The mean stress presented in Fig. 3 was computed as the applied load divided by the average reduced area of the bar assuming uniform mass loss over the unsupported length (L) of the bar.

The observed responses in Fig. 3 show that considering only the average reduction in bar cross sectional area is not sufficient for characterising the impact of corrosion on stress–strain response. Other parameters such as the minimum area, centroid of the section, and minimum second moment of area must be considered in constitutive modelling of corroded bars.

2.4. Observed response under cyclic loading

The experimental data of the cyclic tests support the following observations of interest to the current work:

- It was found that the cyclic degradation of the reinforcing bars is very sensitive to the strain history. The buckling strength is also significantly affected by the strain history and the tension strain amplitude.
- Corroded bars subjected to cyclic loading exhibit reduced buckling strength in comparison with uncorroded bars but also in comparison with corroded bars subjected to monotonic compressive loading. Strength reduction under cyclic loading is

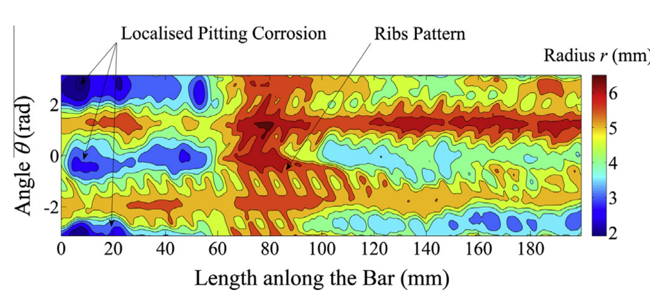

Fig. 1. Contour plot of corrosion pattern in a corroded bar with 36.40% mass loss.

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