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Influence of inelastic buckling on low-cycle fatigue degradation of reinforcing bars

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HIGHLIGHTS

- Influence of buckling low-cycle fatigue life.
- Influence of bar diameter and surface condition on fatigue life.
- Low-cycle fatigue life model accounting for the inelastic buckling.
- New material model accounting for the combined effect of inelastic buckling and low-cycle fatigue degradation.

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ABSTRACT

The effect of inelastic buckling on low-cycle high amplitude fatigue life of reinforcing bars is investigated experimentally. Ninety low-cycle fatigue tests on reinforcing bars varied in amplitudes and buckling lengths are conducted. Using scanning electron microscope the fractography of fractured surfaces are studied. The results show that the inelastic buckling, bar diameter and surface condition are the main parameters affecting the low-cycle fatigue life of reinforcing bars. Through nonlinear regression analyses of the experimental data a new set of empirical equations for fatigue life prediction of reinforcing bars as a function of the buckling length and yield strength are developed. Finally, these empirical models have been implemented into a new phenomenological hysteretic material model for reinforcing bars. The new material model is able to simulate the nonlinear stress–strain behaviour of reinforcing bars with the effect of inelastic buckling and low-cycle fatigue degradation. The results of simulation using the analytical model show a good agreement with the observed experimental results.

1. Introduction

The current performance-based seismic design philosophy of reinforced concrete (RC) structures relies on the proper detailing of plastic hinge regions where most of the inelastic deformations are expected to occur. The inelastic cyclic deformation in plastic hinge regions results in a significant tension and compression strain reversals. Among RC concrete components, RC bridges piers are the most vulnerable components. This is because the structural system of bridges is very simple (a single degree of freedom system). Unlike buildings where plastic hinges are designed to occur in beams, due to the nature of the structural system of bridges the plastic hinges are forced to occur in piers. As a result, they should be able to accommodate a significant inelastic deformation due to earthquake loading. Therefore, several researchers have studied the nonlinear behaviour of RC components under cyclic loading [1,2]. In these studies fracture of vertical reinforcing bars in RC columns under cyclic loading has been observed [1,2] which is due to the low-cycle high amplitude fatigue degradation of vertical reinforcing bars.

Moreover, there is a large number of existing bridges around the world that were designed prior to the modern seismic design codes and therefore they are not properly detailed for seismic loading. One of the most common type of failure mode of RC bridge piers that has been observed in real earthquakes and experimental testing is the buckling of vertical reinforcement which is then followed by fracture of reinforcement in tension due to low-cycle high amplitude fatigue degradation [1–3]. Therefore, several researchers have investigated the nonlinear cyclic behaviour of reinforcing bars with the effect of inelastic buckling [4–12]. The experimental results showed that the inelastic buckling has a great influence on low-cycle fatigue life of reinforcing bars. More recently Kashani [13] investigated the nonlinear behaviour of RC

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Table 1
Mechanical properties of tests specimens.

		16 mm ribbed	12 mm ribbed	12 mm smooth
Yield strain	ε_y	0.0027	0.0028	0.0023
Yield stress (MPa)	σ_y	535.67	544.33	474.5
Elastic modulus (MPa)	E_s	200,000	191666.67	204,500
Hardening strain	ε_{sh}	0.0183	0.0287	0.0046
Strain at maximum stress	ε_u	0.104	0.143	0.061
Maximum stress (MPa)	σ_u	633.75	640.67	510.564
Fracture strain	ε_r	0.195	0.222	0.54185

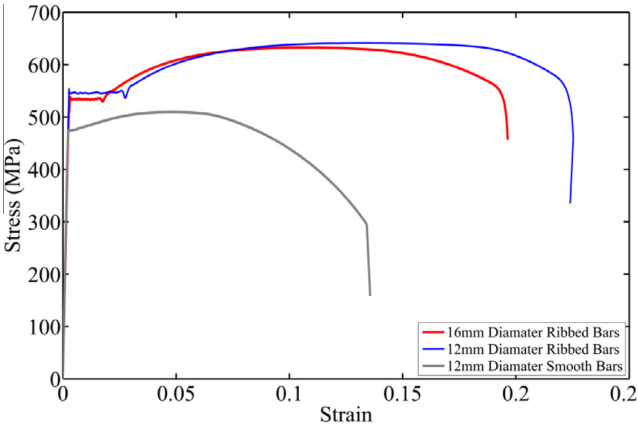

Fig. 1. Stress–strain behaviour of test specimens in tension.

bridge piers numerically and compared with the experimental data reported in [1,2]. They have reported that the buckling length of longitudinal reinforcing bars in RC columns has a significant impact of the fracture of these bars in tension. However, despite the previous research in this area, there has not been any experimental study to explore and quantify the significance of inelastic buckling on low-cycle fatigue life of reinforcing bars.

This paper is addressing this issue and explores the impact of inelastic buckling on low-cycle fatigue life of reinforcing bars. Therefore, a comprehensive experimental testing conducted on ninety reinforcing bars under low-cycle fatigue strain history varied in buckling lengths (slenderness ratio), diameters, yield strengths and surface roughness (ribbed and smooth bars). Using the scanning electron microscope (SEM) a fractography analysis of the fractured surfaces are conducted. Finally, using the experimental results a set of empirical models are developed to predict the low-cycle fatigue life of reinforcing bars as a function of buckling length and yield strength.

Moreover, earlier research by Kashani [13] resulted in development of a new phenomenological hysteretic material model for reinforcing bars which is implemented in the OpenSees [14] an open source finite element code for nonlinear seismic analysis of structures. This model is capable of simulating the nonlinear cyclic behaviour of reinforcing bars with the effect of inelastic buckling and low-cycle fatigue degradation. However, due to the paucity of experimental data in the literature, the fatigue material parameters have not been calibrated to account for the influence of buckling on low-cycle fatigue degradation of reinforcing bars. The experimental data and empirical models in this paper helped to improve this feature of Kashani's model. The results of the improved analytical model are in a good agreement with the observed experimental results. Moreover, this model is readily available in the OpenSees to be used by the earthquake engineering community for nonlinear seismic analysis of RC bridges/structures.

2. Experimental programme

A total of ninety test specimens are prepared for low-cycle high amplitude fatigue tests. The reinforcement used in this experiment are B500B ribbed and B460 smooth British manufactured reinforcing bars [15]. The specimens are including thirty 12 mm diameter ribbed reinforcing bars, thirty 16 mm diameter ribbed reinforcing bars and thirty 12 mm diameter smooth reinforcing bars. For each group of test specimens three tension tests are conducted to evaluate the material properties. Table 1 summarises the material properties of test specimens and Fig. 1 shows the typical stress–strain curve for each group of test specimens.

2.1. Low-cycle high amplitude fatigue test

A total of ninety low-cycle fatigue tests are conducted on reinforcing bars with different buckling lengths and strain amplitudes. It is well known that the buckling length of the vertical reinforcing bars inside RC columns is a function of the stiffness of horizontal tie reinforcement [13]. Therefore, slenderness ratios for the experiment are chosen based on the common observed buckling modes of vertical reinforcement in RC columns as report in [13]. The slenderness ratio is defined by the L/D ratio where L is the length and D is the bar diameter. The L/D ratios tested in this experiment are 5, 8, 10, 12 and 15.

A 250 kN universal testing machine with hydraulic grips was used for the low-cycle fatigue testing of the reinforcing bars. The machine used an integral Linear Variable Displacement Transducer (LVDT) to measure the displacement of the grips. A displacement control loading protocol with zero mean strain using a sine wave loading pattern with constant amplitude is used in the low-cycle fatigue tests. The strain rate is set to 0.005 strain/s throughout the experiment. The total strain amplitudes used in the low-cycle fatigue tests are 1%, 1.5% 2%, 3%, 4% and 5% for 12 mm diameter bars and 1%, 1.5% 2%, 2.5% 3% and 4% for 16 mm diameter bars. A picture of the three groups of bars used in the low-cycle fatigue tests is shown in Fig. 2. It should be noted that the failure of the specimen is taken to be the point at which the bar is completely fractured.

3. Experimental results and discussion

3.1. Influence of inelastic buckling and slenderness ratio

Fig. 3 shows an example hysteretic response of 12 mm ribbed bars under low-cycle fatigue test at 5% strain amplitude. Fig. 3(a) shows that hysteretic response of the bars with $L/D = 5$ are almost symmetrical in tension and

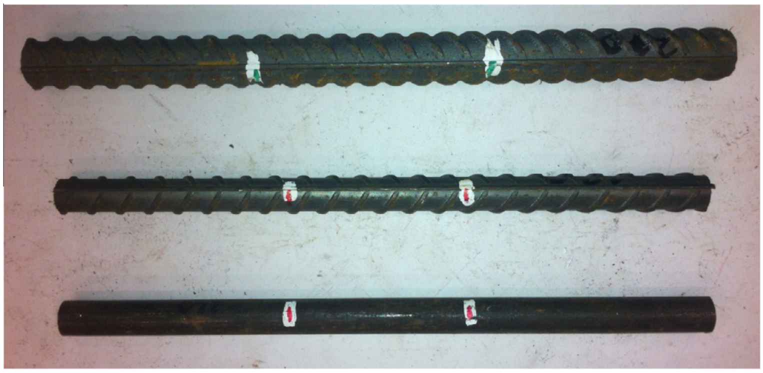

Fig. 2. Low-cycle fatigue test specimens.