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SIMULATING BAR-BUCKLING IN REINFORCED CONCRETE COLUMNS UNDER SEISMIC LOADS

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ABSTRACT

Bar buckling is an important damage stage in reinforced concrete (RC) columns subjected to seismic loads. The objective of this research is to develop a simple and efficient constitutive model for reinforcing steel bars which includes the effects of bar buckling. A series of nonlinear finite element simulations are carried out to identify the main parameters controlling the buckling behavior of reinforcing bars. In the first set of simulations, individual bars with varying length to cross-sectional diameter (L/D) ratios are subjected to cyclic loads while in the second phase an equivalent bar-with-spring model is developed to simulate longitudinal bar buckling behavior in RC columns. In both cases, the specimens are subjected to axial compressive loading to observe buckling response of the longitudinal bars. Numerical simulations are compared to experimental results and findings from the study provide a basis for developing a new material model for reinforcing steel bars in RC columns.

Introduction

In reinforced concrete columns subjected to seismic loads, failure is often initiated by buckling of the longitudinal bars. For reliable simulation of the nonlinear response of RC structures, a proper material model for reinforcing bars that includes the effects of buckling is essential. Previous studies, both analytically and experimentally, have focused on different aspects of bar buckling and its impact on structural response. Mau S.T. et al. (1989, 1990) developed a beam-column element for finite element inelastic buckling analysis to determine the column load-carrying capacity. Pantazopoulou S.J. (1998) compiled data from the literature of over 300 column tests and developed requirements for reinforcement stability that recognizes the interaction between displacement ductility demand and section parameters such as tie effectiveness, limiting concrete strain, bar size and tie spacing. Dhakal R.P. et al. (2002) used fiber element analyses to present an average compressive stress-strain relation for reinforcing bars as a function of slenderness ratio and yield strength. Bae S. et al. (2005) conducted an experimental study on bar buckling and examined the effects of three important bar parameters: L/D ratio (length over bar diameter), e/D (initial imperfection over bar diameter) ratio and the ratio of

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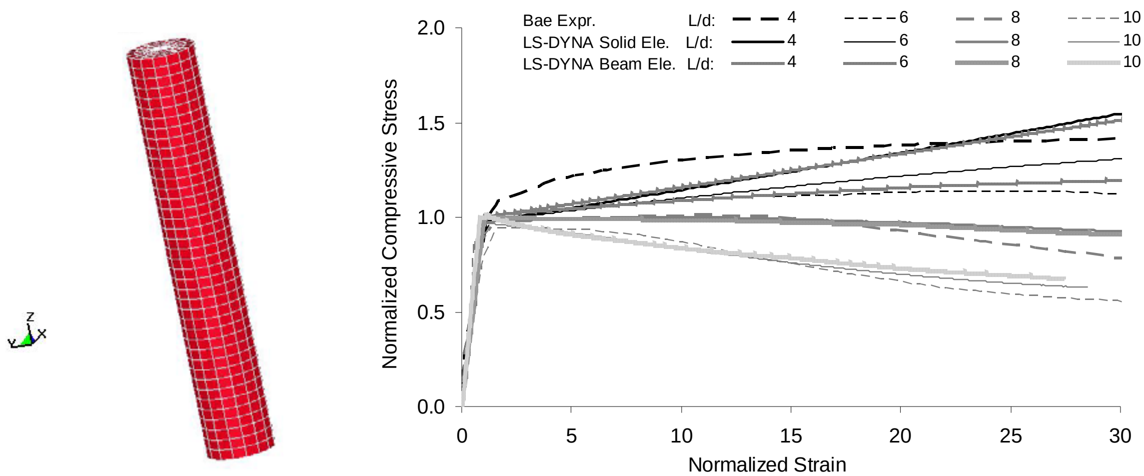
ultimate strength to yield strength. Dhakal R.P. et al. (2002) derived a method to predict the buckling length of longitudinal reinforcing bars using energy methods.

From the literature review, it is clear that many issues related to the prediction of buckling behavior of bars in reinforced concrete columns remain unresolved due to lack of sufficient data and reliable models. Additional research is necessary on the parameters influencing buckling response of bars in reinforced concrete columns, such as effective buckling length, interactions between longitudinal bars, transverse bars and concrete, as well as the development of average bar constitutive relations. This study aims to provide additional insight into bar buckling behavior and proposes a basis for developing a constitutive model for reinforcing steel which incorporates the effect of buckling.

Simulation of single bars

In the first phase of the study, the buckling behavior of single bars is simulated. The objective of this phase is to validate the accuracy and efficiency of element and material models and to identify important parameters controlling bar buckling behavior. Two types of models are developed to simulate single bar buckling: a fully three-dimensional finite element model and a fiber beam element model. Results obtained from both models are compared to gain a better understanding of the advantages and limitations of each model.

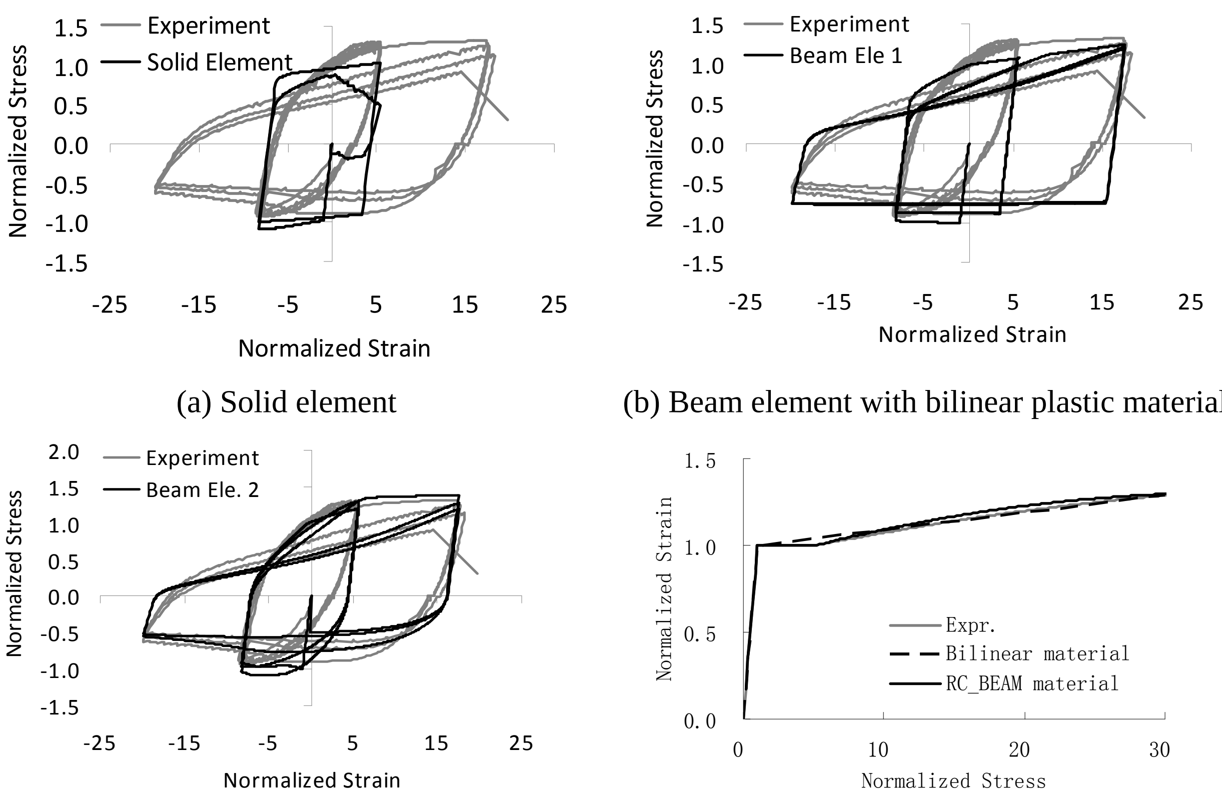


(a) Solid Element (b) Average stress strain curves

Figure 1. Single bar model in LS-DYNA

Both three dimensional finite element single bar models and fiber beam element single bar models are developed using the commercial software LS-DYNA. In the solid element model shown in Figure 1 (a), 6 node pentahedrons and 8 node hexahedrons brick elements are adopted to represent a typical reinforcing steel bar. While in the fiber beam element model, the bar consists of flexural beam elements. The steel material model used for the simulations is a simple bilinear model with kinematic hardening and the properties are based on the experimental results reported by Bae S. et al. (2005). The same boundary conditions are imposed in both models. All the nodes at the two ends of the bar are fixed in all three rotational degrees of freedom and two translational degrees of freedom except for the axial direction Axial displacement control along the axial direction is imposed to obtain the buckling response of the bar.

Axial forces and displacement are recorded and processed to obtain average stress-strain relations in both simulations. The average constitutive relations for various L/D ratio from 4 to 10 are plotted and compared with experimental results reported by Bae S. et al. (2005) in Figure 1 (b). It is observed that reasonably good agreement of simulations with experiments is obtained with a post-yield modulus of 1.5% of the initial elastic modulus in both solid element models and beam element models. It is noted that the average stress-strain response for L/D=4 obtained from the LS-DYNA simulation models is significantly different from the experimentally obtained behavior. That is because when L/D is very small, buckling does not occur in the numerical model and the response simply represents the input stress-strain material property (which in this case is bilinear kinematic hardening). It is also noted that curves from solid element models and beam element models are very close, which indicates that simplified models with beam elements can predict bar buckling behavior quite reasonably and provide comparable results as micro-models with solid elements.



(a) Solid element

(b) Beam element with bilinear plastic material

(c) Beam element with RC_BEAM material

(d) Material models for beam element

Figure 2. Average stress strain curves compared with experimental results under cyclic loading

After validating the reliability and efficiency of beam element models, the single bar specimen tested by Kunnath S. et al. (2009) is simulated to compare average stress strain response under cyclic loading. Figure 2 (a)-(c) compares average stress strain curves using different elements type and material models with experiments. Figure 2 (d) compares two material models for beam element in (b) and (c).

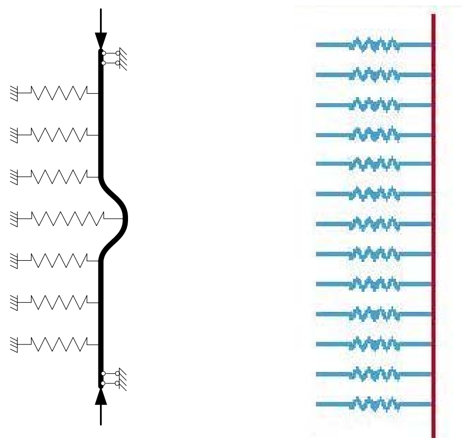
In solid element models, the bar undergoes extremely large deformations and elements in high stress concentration zone become so distorted that the volume of these elements are calculated as negative, which cause failure and deletion of these elements, and sometimes termination of simulation due to accumulated errors. That is why in Figure 2 (a), the darker curve stops much earlier before the end of displacement history and the deformed shape after error termination is shown in Figure 3.

Usually, this problem can be partly resolved by refining element mesh at stress concentration zones, adjusting the hourglass coefficient or changing solid element types. However, all these approaches increase computational time and increases complexity of the problem. Compared with the solid element model, the beam element model is more efficient and stable with comparable results.

Figure 3. Negative volume cause deletion of elements

Simulation of reinforcing bars

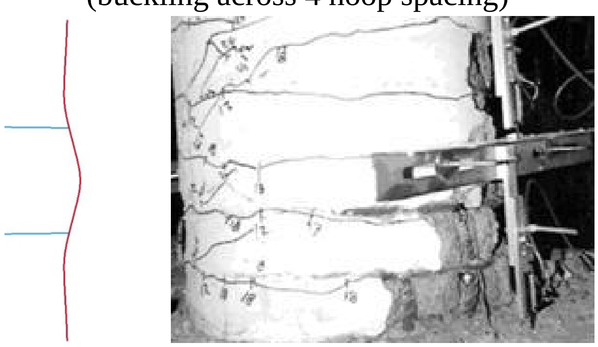
Reinforcing bars in concrete columns under axial compression behave quite differently than single bars due to the interaction between longitudinal reinforcing bar, transverse reinforcing bar and surrounding concrete. A simple bar-with-spring model is developed to simulate bar buckling behavior in concrete columns. Based on a number of experimental observations on damage sequence of concrete column under seismic loading, it is assumed that before buckling of the longitudinal bar, cover concrete has spalled. The bar-with-spring model ignores the effects of cover concrete. The model consists of two parts as shown in Figure 4: a longitudinal bar and a series of springs. The longitudinal bar is simulated by flexural fiber beam elements. Springs are placed at each transverse steel position to represent the combined effect of the confining action which is effected by parameters such as column size and transverse steel properties. Separate simulations were carried out on single hoops to derive spring properties both in numerically and analytically based on mechanics and geometry of the column section (Zong 2010).



(a)Schematic diagram (b) LS-DYNA model

Figure 4. Bar-with-spring models

(a) Column 407 by Moehle (2004)
(buckling across 4 hoop spacing)



(b) Column by Moyer (2003)
(buckling across 1 hoop spacing)

Table 1. Column details

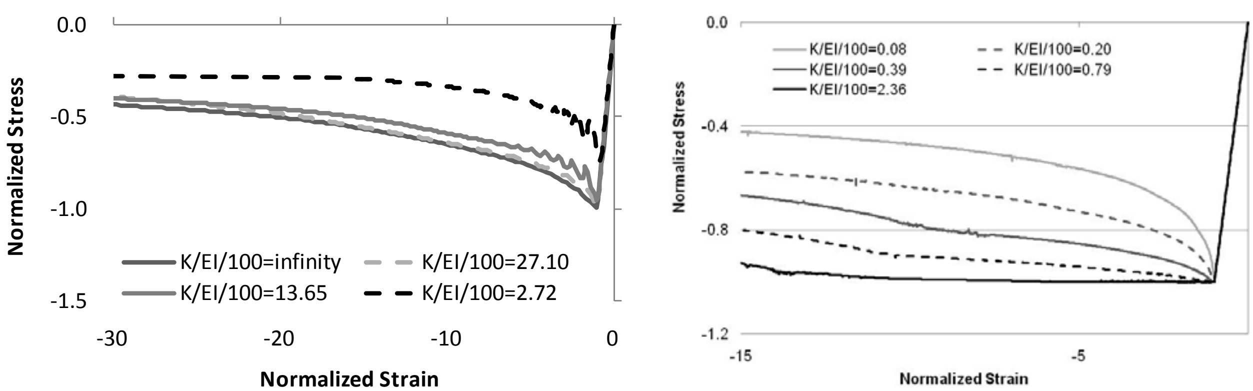
Column test by	Freytag (2006)	Moyer (2004)
Concrete Strength (Mpa)	32.7	32.7
Transverse Steel Yield Strength (Mpa)	634	434
Longitudinal Yield Strength (Mpa)	441	565
Diameter (m)	0.508	0.457
Longitudinal reinforcement		
Diameter (m)	0.01588	0.019
Number	10	12
Reinforcement Ratio	0.98%	1.98%
Transverse reinforcement		
Diameter (m)	0.00635	0.0095
Spacing (m)	0.03175	0.076

Figure 5. Comparisons of simulated buckling shape with experiments

Comparing the buckling shapes predicted by the bar-with-spring models and experimental observations in several damaged columns indicates that the bar-with-spring models can simulate longitudinal bar buckling behavior efficiently and predict buckling length reasonably. Two column samples are plotted in Figure 5with the column details listed in Table. In the first example, both numerical experimental results show that buckling occurs across about four hoop spacing. While in the second example, buckling is observed across two adjacent hoops.

In bar-with-spring models, the main parameters are: longitudinal bar diameter D_b, hoop spacing S and spring stiffness K. It is a formidable task to establish the influence of these parameters on the average cyclic stress-strain relations in reinforcing bars in RC columns undergoing buckling. Hoop spacing S and spring stiffness K control how far and how stiff the hoop constraints are imposed on the reinforcing bars respectively. However, both of them have to be relevant to the size of reinforcing bars to estimate their equivalent effect. Two non-dimensional parameters S/D_b and $K/(EI_b/L^3)$ are selected to express the average stress-strain function. S/D_b represents the density of confinement due to the transverse reinforcement. $K/(EI_b/L^3)$, equal to $K/(EI_b)$ in value with L equal to unit length, is related to the relative strength of the hoop confinement compared to the rebar bending stiffness.

Figure 6 shows sample simulations of average stress-strain curves varying with different spring stiffness parameters $K/(EI_b/L^3)$ (equals to K/EI_b with L equal to unit length and in the figure this parameter is divided by 100 for convenience in plotting). For a certain strain after yielding, the corresponding stress is higher with higher stiffness K/EI_b.

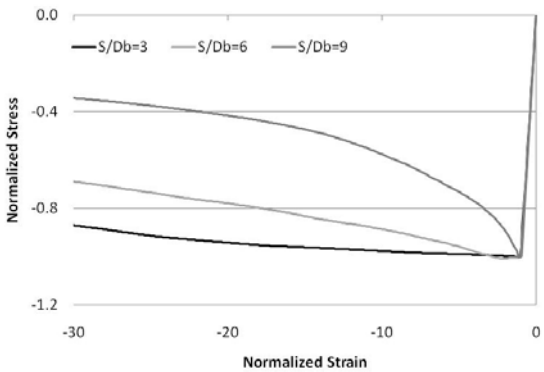


(a)D_b=0.03 S/D_b=8 (b)D_b=0.06 m S/D_b=5

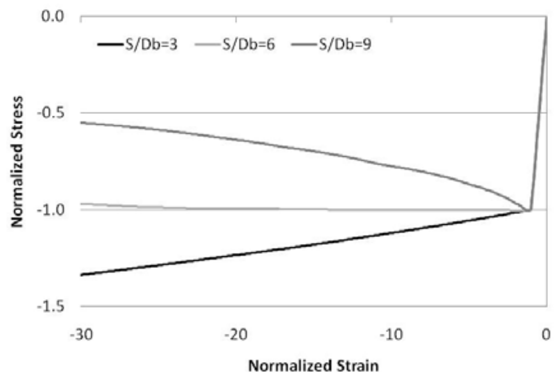
Figure 6. Spring stiffness effects on average stress strain curves

Figure 7 shows an example of the variation of average stress-strain curves for different hoop spacing and bar diameter ratios. As expected, for a certain strain after yielding, the corresponding stress is higher with shorter S/D_b.

A more comprehensive parametric study is being performed to investigate the effects of each combined parameter in more than 150 bar-with-spring models. Average stress-strain relations for longitudinal bars with the effect of buckling are being determined as a function of key column parameters. Theoretical formulations are also being derived to predict buckling length for given concrete columns. A new and convenient method to consider buckling in RC elements during nonlinear analysis of RC structures will be presented in the near future.



(a)D_b=0.02m K/EI_b/100=19.10



(b)D_b=0.05m K/EI_b/100=1.63

Figure 7. Hoop spacing and bar diameter ratio effects on average stress strain curves

Conclusions

Finite element models were developed in LS-DYNA to study bar bucking mechanism in both single bars and bars embedded in reinforced concrete columns with transverse confinement. In the first phase, simplified beam element models were proved effective and accurate by comparing results with experiments and micro finite element models. Its stability and efficiency help to investigate bar buckling behavior under cyclic loads. In the second phase, a simple bar-with-springs model was developed, which can simulate bar buckling behavior for longitudinal bars in concrete columns. It predicts bar buckling length reasonably and provides average constitutive relationship directly with fantastic computational efficiency, which facilitates to generalize average constitutive relation for any given columns. The approach presented by this paper provides a new methodology for generating the compressive stress-strain behavior of reinforcing bars including buckling.

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