Development, verification, and validation of a buckling-fatigue steel material model

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ABSTRACT

Currently, there are limited constitutive models available in finite element analysis packages that can capture the coupled effects of bar buckling and fatigue. However, such a model is needed for reliably estimating the seismic performance of reinforced concrete (RC) structures and their residual capacity/life following seismic events. This paper describes the development of a steel material model that can capture the coupled effects of bar buckling and fatigue on cyclic stress-strain relationship of reinforcing bars. This buckling-fatigue steel model improves upon the model originally developed and calibrated by Tripathi (2020). The developed model has been implemented in OpenSees, and this paper presents the various tests conducted to check and improve the numerical stability of the model. The developed model is then validated against pseudo-static cyclic tests conducted on bare reinforcing bars. Finally, performance of the implemented buckling-fatigue model is evaluated by simulating cyclic response of RC columns from the PEER column test database. The results provide evidence of significant improvement in performance assessment of simulated RC columns by the newly implemented steel material model in comparison to the traditional steel material models that do not simulate the effects of buckling and fatigue.

1 INTRODUCTION

RC structures located in high earthquake-risk zones, when subjected to seismic excitations, are expected to undergo large inelastic cyclic strain reversals in the critical regions which can lead to bar buckling and bar fracture due to low-cycle fatigue damage. It is well known that the inelastic behaviour of flexural RC members is mainly governed by the inelastic behaviour of reinforcing steel. Hence, a reliable steel material model is needed for numerically assessing fatigue damage and the remaining fatigue life of RC structures following an earthquake.

Tripathi (2020) developed a path-dependent cyclic stress-strain model for reinforcing bars that incorporates the combined effects of bar buckling and low-cycle fatigue. Although the material model developed by Tripathi (2020) has been validated with a considerable number of bare bar test results, the model is yet to be implemented into any structural analysis program to simulate the seismic response of RC columns and structures.

Therefore, this study aims at investigating the computational efficiency of the Tripathi (2020) bar buckling-fatigue model and refining the model to improve its reliability and efficiency. It also aims to quantify the improvement in seismic performance prediction capability of RC structures when this model is used instead of traditional bar models. For this purpose, this study implements Tripathi (2020) bar buckling-fatigue model into OpenSees. Thereafter, the model is validated at both the material and structural levels. The results from the numerical analyses are compared and improvements in seismic performance capability using the implemented material model are discussed.

1.1 Tripathi (2020) buckling-fatigue model

Tripathi (2020) buckling-fatigue model is developed based on the buckling model proposed by Dhakal and Maekawa (2002) and the results from uniaxial cyclic tests on bare bars with different slenderness ratios. This model utilizes Menegotto and Pinto cyclic loop with different tension and compression envelopes to simulate the buckling behaviour of reinforcing bars under cyclic loading. It also captures premature bar buckling, post-buckling stress deterioration, reduction of compressive stress due to residual tensile strains, reduction of unloading and reloading stiffness due to buckling, and stress degradation due to low-cycle fatigue damage in reinforcing bars. A detailed discussion on Tripathi (2020) buckling-fatigue model is reported elsewhere and not repeated here for brevity.

Utilising the results from the fatigue tests conducted on reinforcing bars with different slenderness ratios, Tripathi et al. (2018) developed a total strain-amplitude-based fatigue life model based on the formulations of Koh and Stephens (1991). This model incorporates the detrimental effect of inelastic buckling on the fatigue life of reinforcing bars by calibrating the fatigue life coefficients as a function of the buckling parameter (Dhakal and Maekawa 2002). In this model, the accumulated fatigue damage and strength reduction due to the low-cycle fatigue damage is calculated as:

$$\varepsilon_a = \beta(2N_f)^{\alpha} \tag{1}$$

$$\Delta D_i = \frac{1}{\left(\frac{\varepsilon_{a1}}{\beta}\right)^{\frac{1}{\alpha}}} \tag{2}$$

$$D = \Delta D_i + \Delta D_{i-1} \tag{3}$$

$$\gamma = Z_d D \tag{4}$$

Where α, β =fatigue life constants which are calculated using the buckling parameter λ; $2N_f$ = the number of half-cycle to failure; ε_a = total strain amplitude experienced by the bar; ΔD_i = incremental fatigue damage in the reinforcing bars due to each half-cycle of total strain amplitude ε_{a1}; D = accumulated fatigue damage in reinforcing bars; γ = the strength reduction factor; and Z_d = a linear constant relating the fatigue damage to the cumulative strength reduction factor.

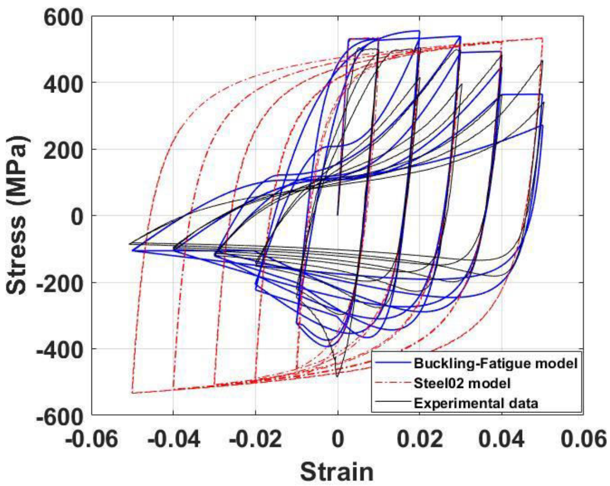
1.2 Implementation and improvement of the proposed model

Tripathi (2020) buckling-fatigue model has now been rewritten in C++ and compiled in OpenSees source code. As the original model was verified against specific strain histories applied in experimental testing of reinforcing bar coupons, after implementing in OpenSees, it was found to be unstable under random strain histories. Hence, new loading/unloading/reloading rules had to be implemented to minimize the unexpected errors and to improve the stability of this material model. These new additions include new partial reversal rule and new target points setting method, which are not described in detail here for brevity (interested readers can contact the Authors or refer to the first Author's PhD thesis from 2024 onwards). A recorder that can track the strength reduction due to low-cycle fatigue damage is also built into the model for future use.

2 VALIDATION OF THE BUCKLING-FATIGUE STEEL MATERIAL MODEL

2.1 Validation of the buckling-fatigue model at the material level

After the implementation and improvement of the buckling-fatigue model in OpenSees, its accuracy is tested against the results of the axial cyclic tests conducted on bare reinforcing bars (Tripathi, 2020). For this purpose, grade 300E and 500E rebar with slenderness ratios of 6, 9 and 15 are selected, and the experimental stress-strain responses are compared against the model prediction. Figures 1-4 show the comparison between the experimental and numerical stress-strain responses of the grade 300E and 500E rebar with a slenderness ratio of 6, 9 and 15 predicted by using the traditional Steel02 bar model and the novel buckling-fatigue bar model.



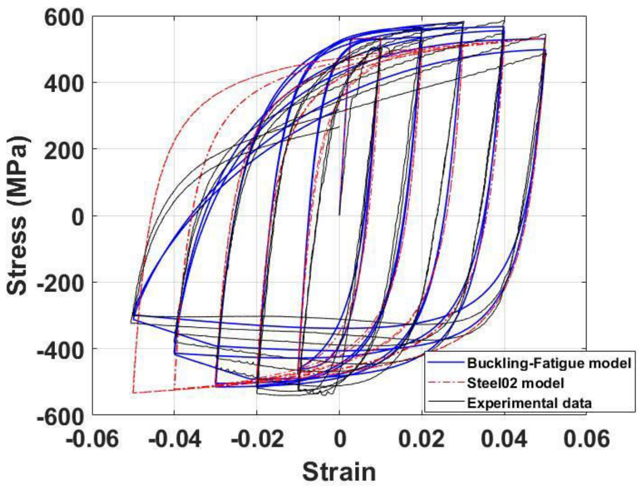


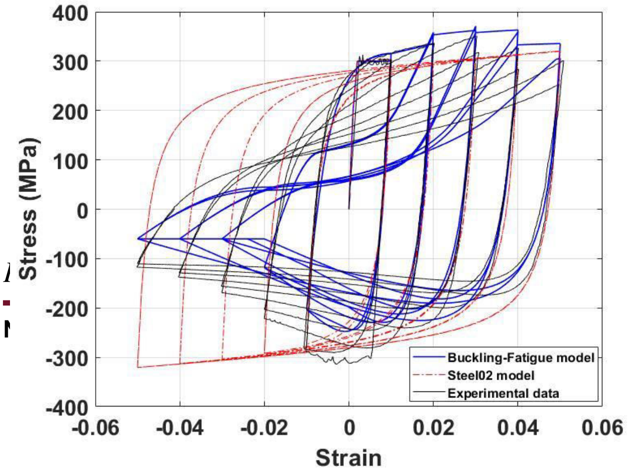
Figure 1. 15D-500E rebar stress-strain response

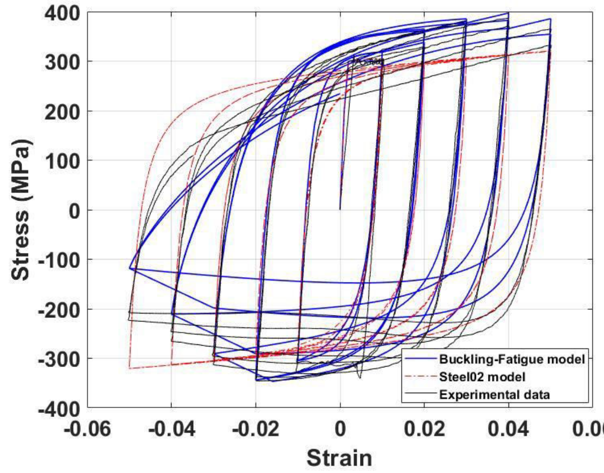
Figure 2. 6D-500E rebar stress-strain response

Figure 3. 9D-300E rebar stress-strain response

Figure 4. 6D-300E rebar stress-strain response

Note that Steel02 model in OpenSees assumes a bilinear stress-strain response with strain hardening and uses Menegotto-Pinto (Menegotto et al. 1973) curves to simulate the unloading and reloading response of steel bars. Further, it does not account for strength and stiffness degradation due to buckling and low-cycle fatigue. As can be seen from these figures, the implemented buckling-fatigue model reasonably captures the strength and stiffness deterioration due to buckling and low-cycle fatigue, and pinching effect due to bar buckling. The implemented buckling-fatigue model also gives a closer prediction of stress-strain response of steel, and the significant improvement in comparison to the Steel02 model is obvious.





2.2 Validation of the buckling-fatigue model at the structural level

2.2.1 Fibre element model development

In order to evaluate the performance of the implemented buckling-fatigue model to simulate the seismic response of RC members, six previously tested RC columns with a wide range of properties (height, axial load ratio, slenderness ratio and transverse reinforcement detailing) are selected from the PEER column database (Pacific Earthquake Engineering Research Center, 2003). The properties of the tested specimens are summarised in Table 1. These selected RC columns have been tested under cyclic loading with an increasing drift ratio until failure. Note that bar fracture was one of the commonly observed failure modes in these specimens.

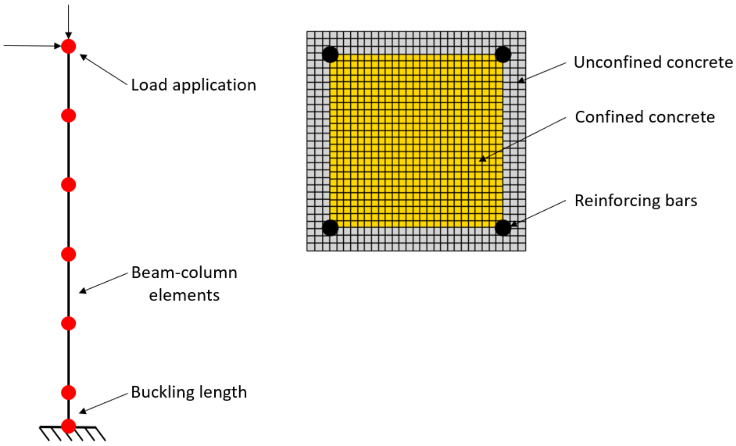
These six columns are modelled in OpenSees using the fibre element modelling technique. Each RC column model is discretised into six displacement-based fibre elements connected end-to-end. The length of the bottom element is calibrated to account for the strain-localisation effect (Dhakal, 2000). The remaining five elements are then evenly distributed over the height of the column. Each element is further discretised into five fibre sections with each section discretised using a large number of confined concrete, unconfined concrete and steel fibres (as shown in Figure 5).

Table 1: Summary of test columns properties.

Specimen	Size	H (mm)	ALR	ρ	D_b (mm)	s (mm)	N	$L_b = s \times N$ (mm)	L_b/D_b
1. Kowalsky and Moyer, 2001, 1	C457	2438.4	0.041	0.0198	19	76.2	3	228.6	12.03
2. NIST, Model N4	C250	750	0.10	0.0196	7	9	5	45	6.32
3. Calderone et al. 2000, 328	C609	1400	0.09	0.0273	19	25.4	5	127	6.68
4. Mo and Wang 2000, C1-2	R400x400	1400	0.16	0.0214	19	50	5	250	13.16
5. Soesianawati et al. 1986, No. 2	R400x400	1600	0.30	0.0151	16	78	2	156	9.75
6. Soesianawati et al. 1986, No. 1	R400x400	1600	0.10	0.0151	16	85	2	170	10.63

Note: C457 represents a circular column with a diameter of 457 mm; R400x400 represents a rectangular column with a width and depth of 400 mm; H = column height; ALR = axial load ratio; ρ = reinforcement ratio; s = transverse tie spacing; N = buckling mode; L_b = buckling length of rebar; D_b = diameter of rebar

The cyclic behaviour of concrete is simulated using the Concrete01 material model in OpenSees. The stress-strain characteristics of confined concrete were calculated using the confined concrete model proposed by



Saatcioglu and Razvi (1992). The cyclic behaviour of steel reinforcing bars is simulated by using the newly-implemented buckling-fatigue model or the pre-existing Steel02 material model.

Figure 5: Fibre element model layout

2.2.2 Cyclic pushover analysis

Cyclic pushover analysis is then carried out for the selected columns based on the applied loading history. The force-displacement response of the selected columns under cyclic loads using both buckling-fatigue model and Steel02 model is compared with the experimental data and is shown in Figure 6.

3 RESULTS AND DISCUSSIONS

As can be seen in figure 6, the force-displacement response using steel02 model cannot capture the strength deterioration observed in the columns' experimental responses. Since the Steel02 model is unable to capture the effects of bar buckling and low-cycle fatigue, which are inevitable in nonlinear response phase of ductile RC structures, numerical simulation of such structures should not be conducted using the Steel02 model. On the other hand, the implemented buckling-fatigue model is capable of simulating the cyclic force-displacement response of RC columns with reasonable accuracy. The buckling-fatigue model reliably simulates the effects of bar buckling and low-cycle fatigue that cause strength and stiffness deterioration in the inelastic cyclic response of the columns, including the pinching in the force-displacement loops and the sudden drop in strength after bar fracture. Hence, this model can be used in nonlinear time history analysis to reliably assess seismic damage in RC structures and estimate their residual fatigue life after seismic events.

In order to quantify the effect of the implemented model on cyclic strength deterioration due to low-cycle fatigue damage, the top drift at which the first critical reinforcing bar fractured in the numerical model is compared with that from the experimental record. Figure 7 shows the normalised top drift; i.e. ratio of the top drift corresponding to the first bar fracture obtained from the numerical analysis (using the buckling-fatigue model) to that from the experimental result. The figure uses experimental results as a benchmark, which means that a value below 1 indicates that the buckling-fatigue model predicts an earlier bar fracture due to fatigue (i.e. overestimates the fatigue damage), and vice versa. As can be seen in the figure, the model closely predicts the bar fracture drift for three specimens (#1, #5, and #6), whereas for the other three specimens the prediction is slightly conservative (i.e. predicted to fracture earlier than observed in the tests). Note that two of these three columns (#2 and #3) are of circular section for which the longitudinal bars were reinforced with spiral/circular hoops. The buckling mode prediction model used herein has not been reliably verified for such cases. The other column (#4) is a poorly confined rectangular column predicted to buckle in the 5th mode (occupying 5 tie-spacing) and a step lesser buckling mode would result in noticeably enhanced buckling-fatigue performance.

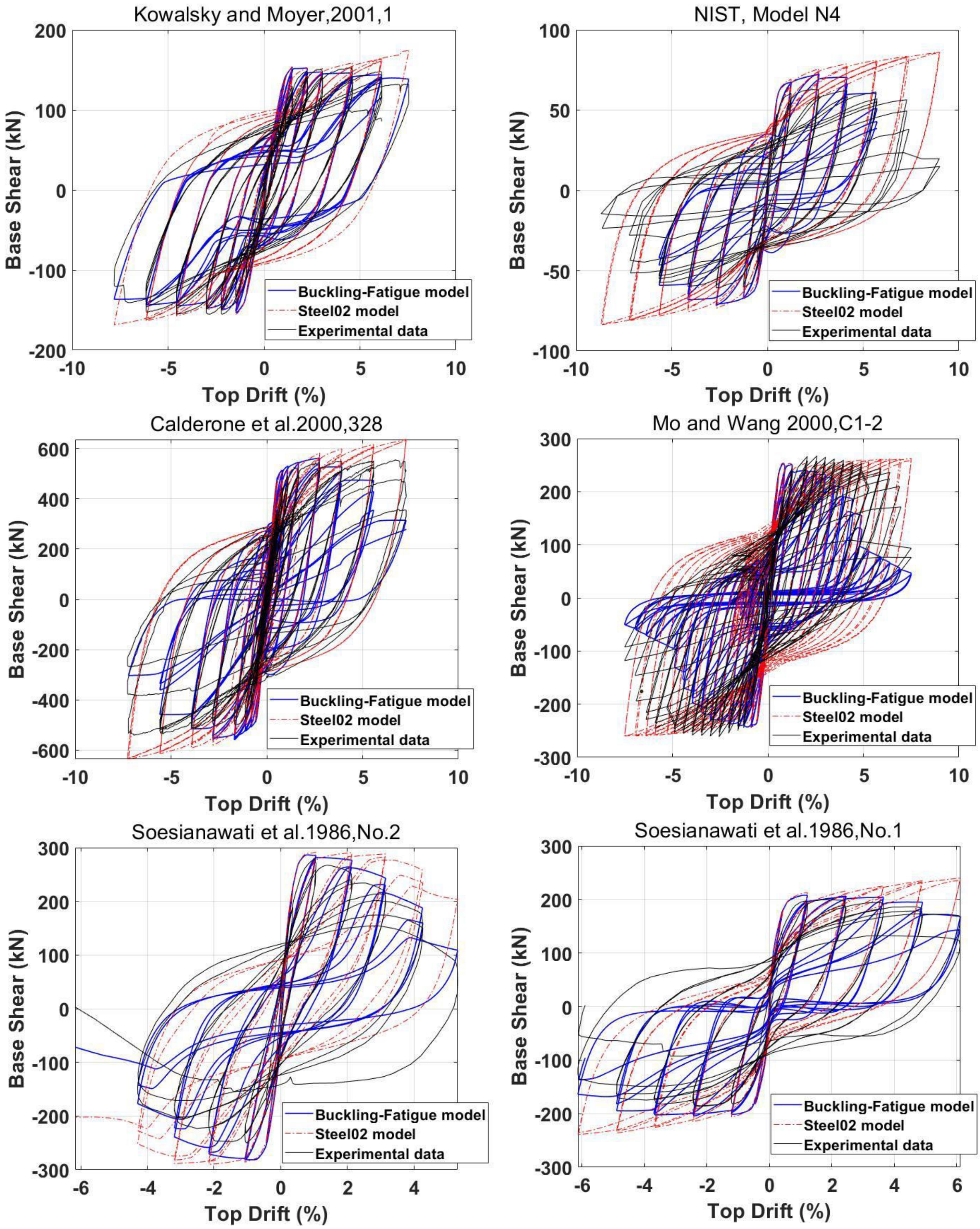


Figure 6: Force-displacement response of RC Columns

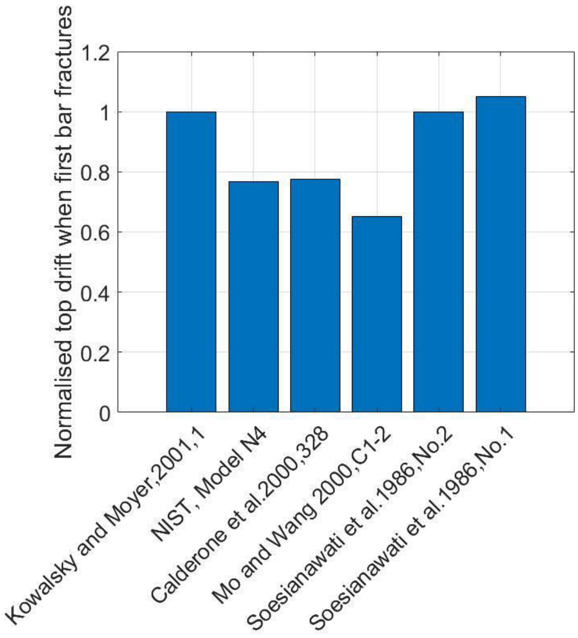


Figure 7: Normalised top drift when first bar fractures

4 CONCLUSIONS

In this paper, Tripathi (2020) buckling-fatigue steel model was implemented into OpenSees with modifications to improve its numerical stability. The buckling-fatigue model was validated at the material level by comparing the stress-strain response of the rebar against the pseudo-static cyclic tests conducted on bare reinforcing bars. The model was then validated at the RC member level by comparing the numerical force-displacement response of the identified columns under cyclic loads with experimental results. Finally, the enhanced capability of the implemented model was quantified by comparing the RC columns' top drift at which the first critical reinforcing bar fractures against that of the experimental records. The key conclusions drawn from this study are:

- The proposed model is capable of simulating the behaviour of the rebars in RC columns. It captures, with reasonable accuracy, the inelastic cyclic response of RC members including the strength and stiffness deterioration caused by buckling and low-cycle fatigue damage of reinforcing bars.
- The model can be further used as a valuable tool to numerically assess and evaluate the progression of low-cycle fatigue damage and residual life of RC structures after being subjected to a sequence of seismic ground motions.

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