Eleventh U.S. National Conference on Earthquake Engineering
Integrating Science, Engineering & Policy
June 25-29, 2018
Los Angeles, California

COLLAPSE ANALYSIS OF RC WALL ARCHETYPES AND SENSITIVITY TO CONSTITUTIVE MODEL PARAMETER UNCERTAINTY

N. Marafi[1], K. Ahmed[2], D. Lehman[3], and L. Lowes[3]

ABSTRACT

Reinforced concrete structural walls are used commonly to resist seismic induced forces in earthquake prone regions. Current design codes intend that these structures have a low probability of collapse under strong shaking through ductile detailing requirements that mitigate damage and enhance deformation capacity. The performance of these systems is typically assessed using nonlinear dynamic collapse analyses. However, the results from these analyses often depend on modelling parameters that have been calibrated to experimental tests. These calibrated parameters vary between tests or in some instances are extrapolations from test results. To determine the collapse sensitivity to variations in constitutive modelling parameters, a series of 4-12 story archetypes located in Los Angeles were designed and modelled in OpenSees. An incremental dynamic analysis found that the collapse probability of a structure was mostly affected by the (1) confined concrete's peak stress and strain and (2) the residual strength at the onset of crushing.

[1]PhD Candidate, Dept. of Civil and Environmental Engineering, University of Washington, Seattle, WA 98115 (email: marafi@uw.edu)
[2]PhD Candidate, Dept. of Civil and Environmental Engineering, University of Washington, Seattle, WA 98115
[3]Professor, Dept. of Civil and Environmental Engineering, University of Washington, Seattle, WA 98115

N. Marafi, K. Ahmed, D. Lehman, and L. Lowes. Collapse Analysis of RC Wall Archetypes and Sensitivity to Constitutive Model Parameter Uncertainty. *Proceedings of the 11th National Conference in Earthquake Engineering*, Earthquake Engineering Research Institute, Los Angeles, CA. 2018.

Eleventh U.S. National Conference on Earthquake Engineering
Integrating Science, Engineering & Policy
June 25-29, 2018
Los Angeles, California

Collapse Analysis of RC Wall and Sensitivity to Model Parameter Uncertainties

N. Marafi[1], K. Ahmed[2], D. Lehman[3], and L. Lowes[3]

ABSTRACT

Reinforced concrete structural walls are used commonly to resist seismic induced forces in earthquake prone regions. Current design codes intend that these structures have a low probability of collapse under strong shaking through ductile detailing requirements that mitigate damage and enhance deformation capacity. The performance of these systems is typically assessed using nonlinear dynamic collapse analyses. However, the results from these analyses often depend on modelling parameters that have been calibrated to experimental tests. These calibrated parameters vary between tests or in some instances are extrapolations from test results. To determine the collapse sensitivity to variations in constitutive modelling parameters, a series of 4-12 story archetypes located in Los Angeles were designed and modelled in OpenSees. An incremental dynamic analysis found that the collapse probability of a structure was mostly affected by the (1) confined concrete's peak stress and strain and (2) the residual strength at the onset of crushing.

Introduction

Reinforced concrete (RC) structural walls are commonly used as part of the lateral-force resisting system for buildings in earthquake prone regions. Current design codes intend that these structures have a low probability of collapse under strong shaking through ductile detailing requirements that mitigate damage and enhance deformation capacity. Researchers typically assess the performance of these systems using experimental tests and nonlinear dynamic collapse analyses. The outcomes of dynamic analyses often depend on modelling parameters that have been calibrated to tests. These calibrated parameters often vary between tests or in some instances are extrapolations from test results. The objective of this paper is to identify modelling parameters that are critical in quantifying the collapse performance of RC walls.

The research presented here investigates the sensitivity of collapse in RC structural walls by (1) identifying critical modelling parameters, (2) determining possible ranges for these parameters, and (3) quantifying the collapse sensitivity to these parameters for a series of archetypical wall structures. The overall study looks at a range of assumptions in the constitutive

[1]Graduate Research Assistant, Dept. of Civil and Environmental Engineering, University of Washington, Seattle, WA 98115 (email: marafi@uw.edu)
[2]PhD Candidate, Dept. of Civil and Environmental Engineering, University of Washington, Seattle, WA 98115
[3]Professor, Dept. of Civil and Environmental Engineering, University of Washington, Seattle, WA 98115

N. Marafi, K. Ahmed, D. Lehman, and L. Lowes. Collapse Analysis of RC Wall Archetypes and Sensitivity to Constitutive Model Parameter Uncertainty. *Proceedings of the 11th National Conference in Earthquake Engineering*, Earthquake Engineering Research Institute, Los Angeles, CA. 2018.

modelling of the concrete and reinforcing steel and varies them within reason to study their impact on collapse. This paper summarizes the sensitivity of collapse probability to the concrete confinement model and concrete residual strength assumed in the analysis.

Modelling

The walls are modelled based on a methodology that was developed by Pugh et al. [1] and vetted with various cyclic-static experimental wall tests. This methodology uses the OpenSees [2] framework to simulate the non-linear response of the RC wall under earthquake loading. The response of the archetype is idealized using a single wall model in 2-dimenstions. Figure 1 shows a schematic of the OpenSees numerical model where each story is segmented into 6 displacement-based beam-column elements with 5 integration points. Each integration point, models the axial and flexural response of the RC wall section using a series of 1-dimensional constitutive models of the concrete and reinforcing steel.

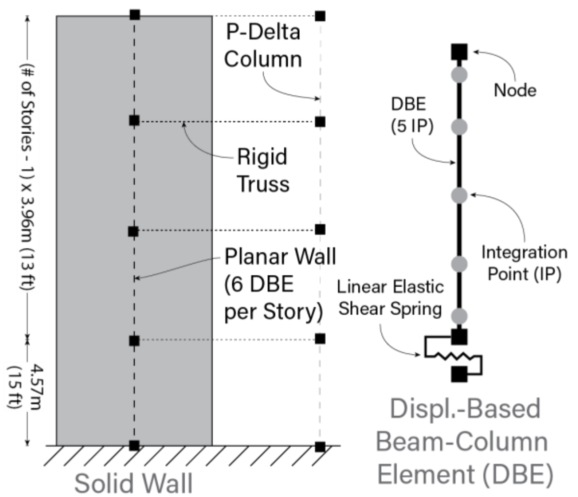

Figure 1. Diagram of the OpenSees analytical model for the RC wall archetype

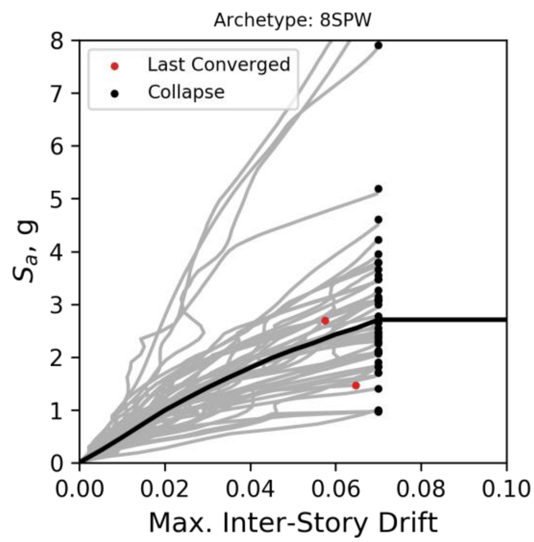

Figure 1. Incremental dynamic analysis results for the 8-story wall archetype

Collapse Analysis

One means of evaluating the performance of the structure is to compute the probability of collapse when subjected to ground-motions corresponding to the maximum considered earthquake. An incremental dynamic analysis is performed for all 3 archetypes using the 22 ground-motion pairs part of the FEMA P695 [3] report. Each ground-motion record was scaled until the structure is considered to have collapsed. Figure 2 shows the maximum inter-story drift for each S_{a} increment from the incremental dynamic analysis for the 8-story solid wall (8SW) and the spectral acceleration corresponding to collapse (denoted as a solid dot).

Collapse Sensitivity to Constitutive Modelling Parameters

Many researchers have shown that concrete with transverse reinforcement enables the concrete to reach larger compressive stresses and at larger strains. There are many empirical stress-strain models for confined concrete that depend on the concrete cylinder strength and the amount of transverse reinforcement (hoops and crossties). Here the sensitivity of collapse to three confinement models are studied: (1) Richart et al. [4], (2) Mander et al. [5], and (3) Saatciolgu and Razvi [6]. Figure 3 shows the normalized base shear versus roof drift under pushover loads. The maximum strength was almost the same between the three confined concrete models whereas the drift at strength loss was found to differ. The drift capacity which is defined as the drift at strength loss (>20%) was found to be at 3.3% for Saatcioglu and Razvi and 3.0% for Mander et al. whereas Richart et al. predicted strength loss at 2.3% drift. This decrease in drift is mainly attributable to a lower strain at peak strength assumed in the Richart concrete model. Similar trends were observed when computing the collapse probability of the three archetypes while varying the confined concrete properties based on the three models. The Richart model resulted in an 95% increase on average in terms of the collapse probability whereas the Mander et al. and Saatcioglu and Razi model were found to be similar.

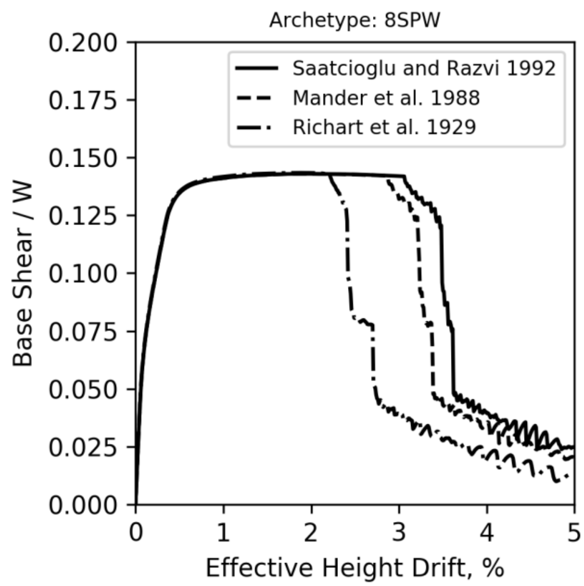

Figure 3. Pushover of 8SW using the (a) Saatcioglu and Razvi model and the (b) Mander et al. model to predict the confined concrete stress and strain.

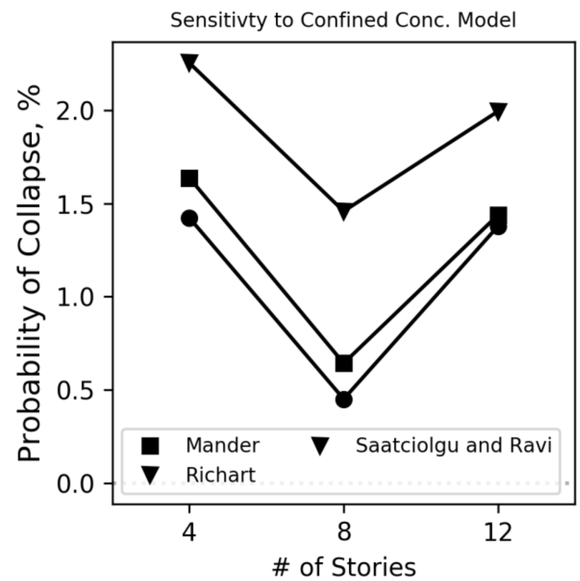

Figure 4. Probability of Collapse for the three archetypes with varying confined concrete models.

The response of RC walls after significant strength loss in experimental tests is unknown as most experiments stop due to safety and equipment damage concerns. The loss of strength at large drifts is mainly attributed to the spalling of concrete especially in compression-buckling controlled failure mechanisms. The compressive capacity of the wall after significant concrete spalling is a function of the residual concrete strength ($\beta f'_{ce}$) assumed in the concrete model.

Park et al. [7], Saatcioglu and Razvi [5], and others have proposed concrete models that can indefinitely sustain a stress equal to 20% of the peak compressive stress. More recent studies by Chang and Mander (1994) proposed a concrete model that goes down to zero stress at large compressive strains. This paper looks at the effects of residual strength on collapse by varying the residual strength ($\beta f'_{ce}$) so that it is equal to 5%, 10%, and 20% of f'_{ce}.

A decrease in residual strength causes a more rapid reduction in strength once the extreme fiber concrete surpasses it's crushing strain. This effect is illustrated in Figure 5 which shows the pushover response of the 8-story archetypes using various concrete residual strengths. Archetype 8SW with a β=5% reaches zero base shear much sooner (3.1% roof drift) than if the β value was greater than 10% (>3.9% roof drift). Similar observations can be seen in the coupled wall archetype 8CW. These variations in residual strength is also shown to increase the collapse probability (shown in Figure 6) by 100% on average when β=5% and by 67% on average when β=10%.

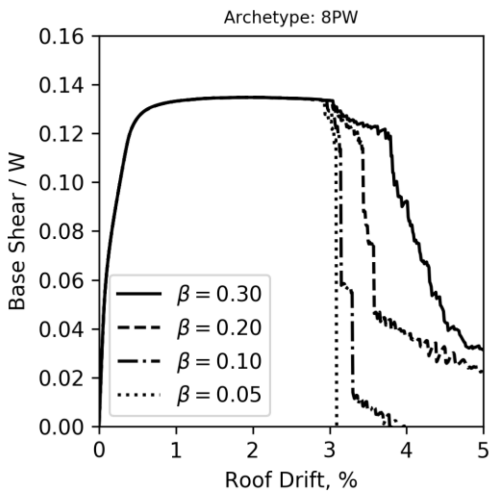

Figure 5. Pushover response for the 8-story wall archetype with varying concrete residual strengths.

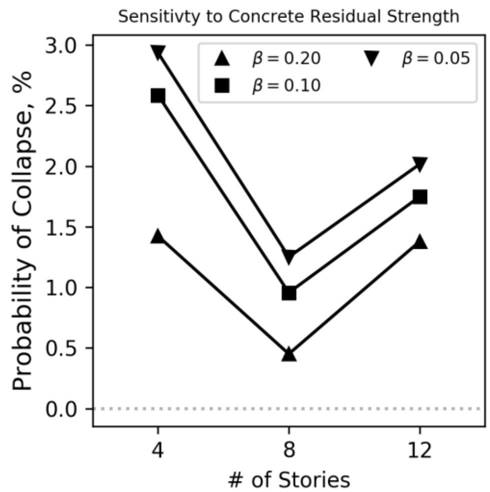

Figure 6. Probability of Collapse at MCE for the three archetypes with varying residual strengths.

Conclusion

The calculated collapse probability for the three RC wall archetypes considered were found to be sensitive to the concrete's calculated confined strength and highly sensitive to the concrete's residual strength. Future studies will quantify the collapse sensitivity to (1) various constitutive modelling parameters such as the concrete crushing energy, and reinforcing bar ultimate strain, and buckling stress-strain response and (2) variations in other design parameters such as the wall axial load ratio and the drift capacity of the gravity system.

Acknowledgments

This research was funded by the National Science Foundation under Grant No. EAR-1331412 and the funds provided by the Applied Technology Council for the ATC-123 report. The authors also acknowledge the University of Texas at Austin and NSF Grant No. 1520817 (NHERI Cyberinfrastructure) for contributing to the research results reported within this paper.

References

1. Pugh, J. S., Lowes, L. N., & Lehman, D. E. (2015). Nonlinear line-element modeling of flexural reinforced concrete walls. Engineering Structures, 104, 174–192. https://doi.org/10.1016/j.engstruct.2015.08.037
2. McKenna, F. (2016). OpenSees. Pacific Earthquake Engineering Research Center. Retrieved from http://opensees.berkeley.edu/
3. Richart, F. E., Brandtzaeg, A., and Brown, R. L. (1929). "The Failure of Plain and Spirally Reinforced Concrete in Compression." *University of Illinois Engineering Experiment Station Bulletin*, 26(190), 1–74.
4. Mander, J. B., Priestley, M. J. N., and Park, R. (1988). "Theoretical Stress-Strain Model for Confined Concrete." *Journal of Structural Engineering*, 114(8), 1804–1826.
5. Saatcioglu, M., and Razvi, S. R. (1992). "Strength and ductility o f confined concrete." *Journal of Structural Engineering*, 118(6), 1590–1607.
6. FEMA. (2009). Quantification of Building Seismic Performance Factors. Redwood, CA.
7. Park, R., Paulay, T., and Bull, D. K. (1997). Seismic Design of Reinforced Concrete Structures.