PEER "Research Nuggets"

Title: Evaluation and Calibration of an OpenSees Layered Shell Element Model for Simulating the Earthquake Response of Flexure-Controlled Reinforced Concrete Walls

Authors: Joshua Stokley, Laura N Lowes

Motivation: Reinforced Concrete (RC) walls are used commonly to resist lateral loads; often, RC walls have three-dimensional configurations to maximize stiffness and strength. Seismic design, evaluation, and retrofit often requires nonlinear analysis to predict performance; assessment of earthquake risk for regions and individual structures often requires nonlinear analysis to predict damage, loss of functionality, and repair time and cost. Currently, few options exist for efficient nonlinear dynamic analysis of multi-story buildings with three-dimensional RC walls.

This report presents the results of research funded by PEER and the NSF-funded NHERI DesignSafe facility. Jupyter notebooks [1] were used to create and run OpenSees models of individual walls included in an experimental dataset published in the DesignSafe DataDepot [2]. The NHERI SimCenter quoFEM software was used with the Jupyter notebooks to calibrate model parameters. Computational time was reduced by using computing resources provided by the DesignSafe facility. Results include recommendations for modeling walls to provide accurate simulation of response and a suite of Jupyter notebooks that can support future projects.

Objectives: The primary objects of the project were as follows:

1. Evaluate, calibrate, validate and develop modeling recommendations for use of the layered shell elements, planar concrete constitutive model, and one-dimensional steel constitutive model available in OpenSees 3.3.0 to simulate the response of flexure-controlled RC walls.
2. Investigate use of the SimCenter quoFEM application to support OpenSees model calibration.
3. Develop Jupyter notebooks to support the OpenSees model evaluation, calibration and validation workflow using quoFEM and DesignSafe resources.

Methodology: Research results were developed as follows:

1. Using data from the Wall Database [2] published in the DesignSafe Data Depot, two experimental data sets were assembled. Each comprised a set of RC walls exhibiting flexure-controlled response, with failure due to concrete crushing and simultaneous reinforcing steel buckling (CB failure) or rupture of previously buckled reinforcing steel (BR failure), when subjected to reversed cyclic lateral displacement histories and constant axial load. One data set was used to calibrate and the second was used to validate the OpenSees model.
2. Jupyter notebooks were created to i) generate OpenSees models walls, ii) accomplish OpenSees analyses using DesignSafe HPC resources, and iii) visualize simulation data. Initial analyses were used to establish basic model characteristic including mesh size, approach for modeling reinforcing steel, and shell element formulation.
3. Jupyter notebooks were created also to support use of the quoFEM "Gradient-free Parameter Estimation" algorithm to calibrate the OpenSees model to provide accurate simulation of strength and deformation capacity. Three model parameters were calibrated: cracked concrete

shear retention factor (calibrated for each specimen), steel rupture strain ratio (calibrated for each BR failure specimen), concrete crushing energy (calibrated for each CB specimen).
4. Jupyter notebooks were updated to simulate all walls (calibration and validation datasets) using a single preferred value for the concrete shear retention factor, the steel rupture strain ratio, and the concrete crushing energy; these values were determined using calibration results.

Results: The research resulted in recommendations for modeling walls using OpenSees as well as a suite of Jupyter notebooks that can be used by the community to accomplish future model evaluation and calibration efforts. Specific results of interest include the following:

1. Accurate simulation of the cyclic response of RC walls exhibiting flexure-controlled response using shell elements that can represent 3D wall configurations is best achieved using i) the DKGQ layered shell element and planar concrete constitutive model developed and implemented in OpenSees by Lu [3], ii) the OpenSees Steel01 constitutive model applied to truss elements in boundary element regions and applied to a shell element layer in web regions, and iii) a concrete shear retention factor of $\beta = 0.056$, a confined concrete crushing energy ratio of $\frac{G_{fc,confined}}{G_{fc,unconfined}} = 2.56$, and a steel cyclic rupture strain ratio (srs) of $\frac{\varepsilon_{fracture,cyclic}}{\varepsilon_{fracture,mono}} = 0.29$.
2. Using the modeling approach above for the 17 wall test specimens in the model "validation" dataset resulted in an average ratio of simulated to measured strength of 1.10 (cov = 16%), an average ratio of simulated to measured deformation capacity of 0.92 (cov = 45%), and 65% accuracy in prediction of failure mode (concrete crushing versus steel fracture).
3. Jupyter notebooks [1] and the SimCenter quoFEM application enable an efficient workflow and facilitate use of NHERI DesignSafe HPC resources.

Conclusions: Primary results of the research are (1) a set of rigorously calibrated OpenSees model parameters that can be used to simulate, with known accuracy, the cyclic response and failure of three-dimensional RC wall buildings subjected earthquake loading, and (2) a suite of Jupyter notebooks that facilitate use of the SimCenter quoFEM application and DesignSafe HPC resources to accomplish OpenSees model calibration. Both products are ideally suited for reuse. Research activities and results are summarized in [4].

References:

1. Stokley J, Lowes LN (2022). "Seismic Response of Concrete Walls" https://www.designsafe-ci.org/user-guide/usecases/seismicusecases/#seismic-response-of-concrete-walls.
2. Shegay A et al. (2021) "UoA-UW Reinforced Concrete Wall Database." DesignSafe-CI. https://doi.org/10.17603/ds2-r12q-t415 v1.
3. Lu XZ et al. (2015). "A shear wall element for nonlinear seismic analysis of super-tall buildings using OpenSees," *Finite Elements in Analysis & Design* 98: 14-25.
4. Lowes LN, Stokley J. (2023). "Calibration and Validation of an OpenSees Model for Reinforced Concrete Walls Using NHERI SimCenter and DesignSafe Resources." *Proceedings of the fib Symposium: 5-7 June 2023, Istanbul, Turkey*. 10 p.

Keywords: OpenSees, reinforced concrete, walls, earthquake engineering, finite element analysis, nonlinear analysis.