TOOLS FOR MODELING THE LATERAL RESPONSE OF SQUAT REINFORCED CONCRETE SHEAR WALLS

C. M. Adorno-Bonilla¹, A. L. Vidot-Vega² and M. Miranda³

ABSTRACT

Squat reinforced concrete (RC) walls are important structural components in nuclear power plant (NPP) facilities and in many civil structures. These walls have aspect ratios less than or equal to 2. Due to their geometry, squat shear walls tend to have shear-dominated behavior and exhibit strong coupling between flexural and shear responses. An adequate understanding of the lateral load vs. deformation behavior along with analytical modeling tools that can simulate such behavior is essential for the seismic design and performance assessment of NPP structures and other low rise shear wall civil structures. This paper evaluates the applicability of two simplified modeling approaches for further calibration and their feasibility for design and evaluation of squat RC walls. A Fiber-Based Model with flexure-shear interaction and a Macro-Hysteretic Model are studied. Three large scale RC squat walls with rectangular cross section are modeled using both approaches and compared against experimental data. Monotonic and cyclic analyses are performed within the OpenSees analytical platform. Data from existing experimental tests of squat RC walls are used to develop and calibrate the models. The paper discusses the advantages and disadvantages of each method and provides recommendations for future research in this topic. Performed analyses show that both, the fiber-based model with shear-flexure interaction and the macro-hysteretic models can be calibrated to obtain a reasonable prediction of the lateral loading behavior of squat reinforced concrete walls.

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C. M. Adorno-Bonilla\textsuperscript{2}, A. L. Vidot-Vega\textsuperscript{2} and M. Miranda\textsuperscript{3}

ABSTRACT

Squat reinforced concrete (RC) walls are important structural components in nuclear power plant (NPP) facilities and in many civil structures. These walls have aspect ratios less than or equal to 2. Due to their geometry, squat shear walls tend to have shear-dominated behavior and exhibit strong coupling between flexural and shear responses. An adequate understanding of the lateral load vs. deformation behavior along with analytical modeling tools that can simulate such behavior is essential for the seismic design and performance assessment of NPP structures and other low rise shear wall civil structures. This paper evaluates the applicability of two simplified modeling approaches for further calibration and their feasibility for design and evaluation of squat RC walls. A Fiber-Based Model with flexure-shear interaction and a Macro-Hysteretic Model are studied. Three large scale RC squat walls with rectangular cross section are modeled using both approaches and compared against experimental data. Monotonic and cyclic analyses are performed within the OpenSees analytical platform. Data from existing experimental tests of squat RC walls are used to develop and calibrate the models. The paper discusses the advantages and disadvantages of each method and provides recommendations for future research in this topic. Performed analyses show that both, the fiber-based model with shear-flexure interaction and the macro-hysteretic models can be calibrated to obtain a reasonable prediction of the lateral loading behavior of squat reinforced concrete walls.

Introduction

Reinforced concrete (RC) walls with aspect ratios less than or equal to two are designated as squat. Such walls constitute the main lateral load resisting system in nuclear power facilities (NPP) and in many civil structures. Walls with aspect ratios lower than 1.0, which are even more commonly found in NPP structures, tend to exhibit shear-controlled failure modes while walls with aspect ratios between 1.0 and 2.0 are generally governed by mixed flexure-shear modes [1]. The cyclic behavior of shear-dominated concrete members is characterized by very high lateral stiffness and strength, but also by relatively limited ductility and energy dissipation capacity.

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An adequate understanding of their lateral load vs. deformation behavior is necessary to develop and calibrate analytical modeling tools that can simulate the seismic behavior of squat walls for the seismic design and performance assessment of NPP structures and other low rise shear wall civil structures. This paper assess the applicability of two simplified modeling approaches for further calibration and their feasibility for design and evaluation of squat RC walls. A Fiber-Based Model with flexure-shear interaction and a Macro-Hysteretic Model available in the OpenSees analytical platform [2] are studied by comparing the simulated behavior with experimental data from three large scale RC squat walls with rectangular cross section.

Experimental Database

Experimental tests of twelve large-size, low aspect ratio, RC shear walls have been conducted at the University at Buffalo [3, 4] and the digital data has been recently published on the Network for Earthquake Engineering Simulation (NEES) website [5, 6, 7, 8]. The wall specimens had rectangular cross sections with a length of 120 in and thickness of 8 in with conventional reinforcement placed in two curtains. The specimens had varying aspect ratios ranging from 0.33 to 0.94, varying reinforcement ratios ranging from 0.33% to 1.5% and concrete strength varying from 3500 to 7800 psi.

Each specimen was tested without axial load and subjected to quasi-static cyclic lateral loading by means of high capacity actuators and the foundation was fixed to the test floor with post tensioning bars. The loading protocol consisted of increasing drift levels with 3 cycles on the first load step (drift level) and two cycles at every other load step. The drift was increased at each load step and ranged from about 0.01% to measure initial stiffness and up to maximum drifts of around 3%. This paper presents the analytical modeling of the lateral load vs. displacement behavior of three of these specimens, namely SW1, SW3 and SW6. The properties of these walls are presented in Table 1.

Table 1. Properties of the studied specimens.

<table>
<thead>
<tr>
<th>Wall</th>
<th>$h/w$</th>
<th>$\rho_l$ (%)</th>
<th>$\rho_t$ (%)</th>
<th>$f'_c$ (psi)</th>
<th>$f_y$ (ksi)</th>
<th>$f_u$ (ksi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SW1</td>
<td>0.94</td>
<td>0.67</td>
<td>0.67</td>
<td>3600</td>
<td>67</td>
<td>102</td>
</tr>
<tr>
<td>SW3</td>
<td>0.54</td>
<td>0.67</td>
<td>0.67</td>
<td>7800</td>
<td>63</td>
<td>87</td>
</tr>
<tr>
<td>SW6</td>
<td>0.33</td>
<td>0.67</td>
<td>0.67</td>
<td>3800</td>
<td>67</td>
<td>102</td>
</tr>
</tbody>
</table>

Analytical Models

Macro-Hysteretic Model

In this modeling approach the cyclic lateral load vs. displacement behavior of the wall is modeled as a single degree of freedom structure and the experimental displacements were applied at the free end. The hysteretic material model from OpenSees called *Hysteretic Material* [9] was used. This model requires the definition of a backbone curve which was calibrated with the experimental data as shown in Figure 1.
Figure 1. Example backbone curve fitting for the Macro-Hysteretic Model (SW1).

The calculated backbone curve is optimized in by taking the peak strength and maximum drift points equal to the experimental values. The initial stiffness is also set to be equal to the obtained experimentally. The control point associated with the “yielding” is adjusted so that the area under the experimental cyclic envelope equals the area under the calculated backbone. Table 2 shows the calculated backbone parameters.

Table 2. Calculated backbone parameters.

<table>
<thead>
<tr>
<th>Wall</th>
<th>s1p</th>
<th>e1p</th>
<th>s2p</th>
<th>e2p</th>
<th>s3p</th>
<th>e3p</th>
<th>s1n</th>
<th>e1n</th>
<th>s2n</th>
<th>e2n</th>
<th>s3n</th>
<th>e3n</th>
</tr>
</thead>
<tbody>
<tr>
<td>SW1</td>
<td>181</td>
<td>0.00193</td>
<td>256</td>
<td>0.0134</td>
<td>200</td>
<td>0.0212</td>
<td>-179</td>
<td>-0.00093</td>
<td>-250</td>
<td>-0.0128</td>
<td>-242</td>
<td>-0.0173</td>
</tr>
<tr>
<td>SW3</td>
<td>317</td>
<td>0.00121</td>
<td>474</td>
<td>0.0177</td>
<td>340</td>
<td>0.0262</td>
<td>-242</td>
<td>-0.00073</td>
<td>-386</td>
<td>-0.0086</td>
<td>-343</td>
<td>-0.0228</td>
</tr>
<tr>
<td>SW6</td>
<td>440</td>
<td>0.00221</td>
<td>578</td>
<td>0.0096</td>
<td>388</td>
<td>0.0264</td>
<td>-352</td>
<td>-0.00119</td>
<td>-414</td>
<td>-0.0073</td>
<td>-357</td>
<td>-0.0232</td>
</tr>
</tbody>
</table>

*All values of force are in kips and deformation is taken as drift.

The hysteretic model is defined by several parameters that control pinching in force (pinchy) and deformation (pinchx), damage based on ductility (damage1) and energy (damage2), and unloading stiffness degradation (beta) based on ductility. To be consistent, the damage was calibrated based on ductility. Table 3 shows the calibrated parameters and the results are presented in the next section.

Table 3. Calibrated pinching and damage parameters.

<table>
<thead>
<tr>
<th>Wall</th>
<th>pinchx</th>
<th>pinchy</th>
<th>damage1</th>
<th>damage2</th>
<th>Beta</th>
</tr>
</thead>
<tbody>
<tr>
<td>SW1</td>
<td>0.6</td>
<td>0.15</td>
<td>0.010</td>
<td>0</td>
<td>0.3</td>
</tr>
<tr>
<td>SW3</td>
<td>0.6</td>
<td>0.15</td>
<td>0.012</td>
<td>0</td>
<td>0.4</td>
</tr>
<tr>
<td>SW6</td>
<td>0.75</td>
<td>0.15</td>
<td>0.016</td>
<td>0</td>
<td>0.4</td>
</tr>
</tbody>
</table>
Fiber-Based Model

The OpenSees Flexure-Shear Interaction Displacement-Based Beam-Column Element was used [10, 11]. On this approach the wall is modeled using \( m \) stacked elements composed of \( n \) strips each (Figure 2b). Each strip consists of vertical fibers corresponding to the steel and concrete tributary areas and a horizontal fiber representing the total area of horizontal steel within one element. The interaction between flexure and shear is incorporated at the strip level where the constitutive laws for concrete and steel are applied treating each strip as a reinforced concrete panel or membrane element (Figure 2a). It is important to note that this model as implemented in OpenSees is not able to model the cyclic response of a wall.

![Model element](image)

Figure 2. Flexure-Shear Interaction Displacement-Based Beam-Column Element.

The constitutive models for concrete and steel materials used are the Concrete06 [12] and Steel02 [13] which are available in OpenSees (Figure 3). The former uses a Thorenfeld-based curve to describe the compressive stress strain behavior of concrete and the tension stiffening equation proposed by Belarbi and Hsu [14] for the tensile portion of the curve. The later uses a simple bilinear relationship with smooth transition between the initial and post-yield tangents. Further information regarding the constitutive models can be found on the OpenSees documentation.

![Constitutive models](image)

Figure 3. Constitutive models for concrete and steel.

The calibration of concrete parameters was done by using the reported material properties and other typical values. The concrete tensile cracking stress was taken as \( 7.5(f'_c)^{1/2} \) while the
value of the tensile cracking strain (0.00008) was proposed by Belarbi and Hsu [14]. The model
was found to be sensitive to the tension envelope exponent \( b \) and the calibration of this parameter
is discussed on the next section. Parameters \( \alpha_1 \) and \( \alpha_2 \) are related to the cyclic
unloading and reloading of concrete, thus not significant for monotonic analyses. Therefore
default values were used. Table 4 shows the parameters used in the analyses for the concrete
constitutive model.

Table 4. Concrete06 constitutive model calibrated parameters.

<table>
<thead>
<tr>
<th>Wall</th>
<th>fc</th>
<th>e0</th>
<th>N</th>
<th>k</th>
<th>( \alpha_1 )</th>
<th>fcr</th>
<th>Ecr</th>
<th>b</th>
<th>( \alpha_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>SW1</td>
<td>-3600</td>
<td>-0.003</td>
<td>2.0</td>
<td>1.0</td>
<td>0.32</td>
<td>450.0</td>
<td>0.00008</td>
<td>4.0</td>
<td>0.08</td>
</tr>
<tr>
<td>SW3</td>
<td>-7800</td>
<td>-0.003</td>
<td>3.75</td>
<td>1.0</td>
<td>0.32</td>
<td>662.4</td>
<td>0.00008</td>
<td>4.0</td>
<td>0.08</td>
</tr>
<tr>
<td>SW6</td>
<td>-3800</td>
<td>-0.003</td>
<td>2.0</td>
<td>1.0</td>
<td>0.32</td>
<td>462.3</td>
<td>0.00008</td>
<td>4.0</td>
<td>0.08</td>
</tr>
</tbody>
</table>

*Model units: lb, in

Calibration of constitutive model parameters for steel was obtained from the reported
material properties. However some parameters require experimental data from cyclic tests which
is not usually available. Therefore the \( R_0 \), \( cR_1 \) and \( cR_2 \) were taken from recommended
values found on the OpenSees documentation and the values for the hardening parameters \( a_1 \) and
\( a_2 \) calibrated with experimental data by prior researchers were obtained from Elmorsi et al.
(1998) [16]. Default values were used for \( a_3 \) and \( a_4 \) (no hardening in tension was considered).
Table 5 presents the parameters used for the steel constitutive model.

Table 5. Steel02 constitutive model calibrated parameters.

<table>
<thead>
<tr>
<th>Wall</th>
<th>Fy</th>
<th>E</th>
<th>bs</th>
<th>R0</th>
<th>cR1</th>
<th>cR2</th>
<th>a1</th>
<th>a2</th>
<th>a3</th>
<th>a4</th>
</tr>
</thead>
<tbody>
<tr>
<td>SW1</td>
<td>67300</td>
<td>29x10^6</td>
<td>0.018</td>
<td>15</td>
<td>0.925</td>
<td>0.15</td>
<td>18.5</td>
<td>0.0015</td>
<td>0</td>
<td>1.0</td>
</tr>
<tr>
<td>SW3</td>
<td>63000</td>
<td>29x10^6</td>
<td>0.013</td>
<td>15</td>
<td>0.925</td>
<td>0.15</td>
<td>18.5</td>
<td>0.0015</td>
<td>0</td>
<td>1.0</td>
</tr>
<tr>
<td>SW6</td>
<td>67300</td>
<td>29x10^6</td>
<td>0.018</td>
<td>15</td>
<td>0.925</td>
<td>0.15</td>
<td>18.5</td>
<td>0.0015</td>
<td>0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

*Model units: lb, in

Modeling Results and Discussion

The selected specimens studied herein had vertical and horizontal reinforcement ratios of 0.67%
which results in two curtains of #3 reinforcing bars spaced at nearly 7 in. on center. The cross
section was modeled with one strip at the location of every vertical bar along the length of the
wall (Figure 4). Wall models were initially discretized with one element per horizontal bar
location along the height resulting in 14, 10 and 5 elements for the specimens SW1, SW3 and
SW6, respectively. Since Massone et al. [11] suggested that the model was sensitive to the
number of vertical elements, the number of elements was then reduced to 7, 5 and 3 elements for
the specimens SW1, SW3 and SW6, respectively. This resulted in a better representation of the
displacement capacity while maintaining a good approximation of the peak strength.

Figure 4. Cross section discretization model for the studied specimens.
Figure 5. Calibrated model results for wall specimen SW1, SW3, and SW6. (a) Macro-Hysteretic Model, (b) Fiber-Based Model.
The obtained results for the fiber-based model (with the reduced number of elements) and the macro-hysteretic model are illustrated in Figure 5 and compared to the experimental results. All the parameters used were shown in the previous section.

One of the major limitations of the Hysteretic Material model is that the backbone curve has only three linear segments. These types of walls and other shear-controlled RC structural members tend to show a substantial stiffness reduction upon cracking. Then they would experience another large reduction in stiffness at the “yielding” point (which is not necessarily related to the yielding of the reinforcement but may be related to other failure modes) until it reaches the peak strength or “capping point” where the strength degradation becomes more pronounced and the slope of the envelope becomes negative until reaching the residual strength. This behavior would be more accurately modeled with the incorporation of a fourth line segment into the backbone curve such as in the backbone curve suggested on the Supplement No. 1 to ASCE 41-06 [17] for members controlled by shear. In order to compensate for this deficiency, the backbone curve was adjusted based on an equal area concept as explained before (Figure 1). Notwithstanding, the hysteretic model can be calibrated to reasonably simulate the lateral response, capturing the pinching and damage characteristics with good correlation to the experimental data.

As mentioned before, the flexure-shear model was found to be very sensitive to the number of elements in which the wall is discretized and also to the concrete tension stiffening curve exponent (parameter $b$). In order to illustrate the effect of these parameters, the wall specimen SW3 has been modeled using three different values of $b$ and then using three different number of elements. The rest of the parameters were kept constant using the calibrated values. Results of the monotonic analytical responses are plotted against experimental data for comparison purposes (Fig. 6), and only the first quadrant is shown for clarity.

![Figure 6. Sensitivity of the Fiber-Based model to: a) concrete tension stiffening curve exponent and b) vertical wall discretization (wall specimen SW3).](image-url)
From Figure 6a it can be observed that the concrete parameter $b$ has a major effect on the apparent stiffness of the wall model and also has a moderate effect on its peak strength. When the value of $b$ is increased the apparent stiffness, as well as the peak strength, decreases due to the fact that the tension stiffening curve is decreasing more rapidly. The effect of this parameter on the response is more pronounced for values of about 0.8 and less. A value of $b$ equal to 0.4 is suggested by Belarbi and Hsu [14], however by adjusting this parameter to a higher value (e.g. 4.0 as also found by Whyte and Stojadinovic [18]) results with better fit to experimental data were obtained.

On the other hand, Figure 6b shows the sensitivity to the number of vertical elements in which the model is discretized. The number of stacked elements used to represent the wall affects mostly the predicted displacement capacity of the wall but does not have a significant effect on the peak strength. As the wall is modeled using fewer elements, the predicted drift capacity increases substantially. This effect may be attributed to the localization of stresses and damage as the model is further discretized, which causes earlier failure of the element leading to loss of overall stability of the model.

Finally, Table 6 shows the ratio of the predicted to experimentally measured peak shear strength for the fiber-based model. The experimental peak strength is taken as the average of the peaks from first and third quadrants since on specimens with lower aspect ratios these values can be substantially different.

Table 6. Experimental vs. Fiber-Based model peak shear strength.

<table>
<thead>
<tr>
<th>Wall</th>
<th>$V^+_{peak}$</th>
<th>$V^-_{peak}$</th>
<th>$V^\text{avg}_{peak}$</th>
<th>$V_{model}$</th>
<th>$V_{model}/V^\text{avg}_{peak}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SW1</td>
<td>256</td>
<td>250</td>
<td>253</td>
<td>249</td>
<td>0.98</td>
</tr>
<tr>
<td>SW3</td>
<td>474</td>
<td>386</td>
<td>430</td>
<td>361</td>
<td>0.84</td>
</tr>
<tr>
<td>SW6</td>
<td>578</td>
<td>414</td>
<td>496</td>
<td>444</td>
<td>0.90</td>
</tr>
</tbody>
</table>

Conclusions

The obtained results suggest that both models are feasible to be calibrated and used to simulate the lateral load vs. displacement behavior of squat RC walls with rectangular cross sections. Great care should be taken in the selection of the number of elements to model squat RC walls using the flexure-shear interaction element if the prediction of displacement capacity is considered important in the analysis. In a similar manner, judgment is advised on the selection of the concrete tension stiffening curve exponent ($b$ parameter) when the prediction of initial stiffness is of particular interest. However, flexure-shear interaction model was able to reasonably predict the peak strength and drift capacity of the studied experiments.

Among the most significant advantages of macro-hysteretic model over the fiber-based model presented herein are the substantially less computational effort and the ability to simulate the cyclic performance of a wall with reasonable accuracy. Also the use of simplified macro-hysteretic models for structures that include squat walls would be generally preferred for performance based assessment of structures due to their ability to represent the cyclic force...
deformation at the story level with relative simplicity. This model can be easily calibrated to fit a
given experimental dataset since it has fewer pinching and degradation parameters than other
hysteretic models that have been proposed in literature. Despite the few parameters required, it is
shown that the Hysteretic Material can reasonably capture the key characteristics of the
hysteretic behavior of squat walls with rectangular cross sections. Moreover, the simplicity of the
model makes it suitable for empirical calibration with a larger database.

Further Studies

Further calibration is under way to assess the ability of both models to represent the behavior of
squat RC walls with other features such as: axial load, different reinforcement ratios, boundary
elements and different types of cross sections. Experimental data from other experimental
programs are used to perform these calibrations. Analysis using the Hysteretic model with
additional specimens will be focused in the identification of a generalized set of damage and
degradation parameters for walls with different features. Additional sensitivity analysis of the
tension stiffening curve exponent (b parameter) will be performed to put forward
recommendations. Also, after calibrating both models, it may be possible to use them in
conjunction to model a wall’s response without having experimental data available. The flexure-
shear interaction model would be used to obtain the backbone curve, which may then be used as
input on the macro-hysteretic model to simulate the dynamic response. Additionally, work on
evaluating the applicability of the cyclic softened membrane model (CSMM) proposed by Hsu
and Mo [19] for the modeling of squat RC walls is under way.

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centralized data repository for sharing and publishing earthquake engineering research data from
experimental and numerical studies [5].

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