Simulation of Nonlinear Seismic Response of Reinforced Concrete Structural Walls

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SUMMARY:
In this study the performance of three macro-models in predicting the nonlinear response of different walls is investigated. The macro-models used are: Equivalent Beam Model, Multiple Vertical Line Element Model and a shear panel model developed by Massone et al. (2006). The walls are classified as slender, intermediate, and squat walls according to their shear-span ratio. First, three single wall specimens tested by other researchers are modeled. The numerical simulations are compared with available test data to evaluate the performance of the different modeling approaches. Secondly, the height of one wall specimen is varied to obtain different aspect ratios. The simulation results for the three macro-models are compared to examine their ability to incorporate shear behavior, and the loss of accuracy with decreasing aspect ratio. Findings from this study will be useful in advancing nonlinear simulation models for analysis of shear wall structures, especially for intermediate and squat walls.

Keywords: Shear walls, reinforced concrete, macro-models, nonlinear response, shear modeling

1. INTRODUCTION

The use of reinforced concrete shear-wall buildings is quite common in earthquake-prone regions since their seismic behavior has been demonstrated to be adequate during past severe earthquakes, both from serviceability as well as a safety standpoint. An example of this is the response of Chilean multistory reinforced concrete shear-wall buildings after the severe earthquakes of March 1985 and February 2010, which has been shown to be controlled, in most cases, by flexure/compression with mild development of shear cracking.

While shear walls are widely used in building construction, models for simulating the nonlinear response of shear walls has seen limited advances. The need to accurately model shear wall behavior is becoming more important as increased confidence in the seismic behavior of RC walls has led to more relaxed requirements for reinforcement and confinement of typical wall configurations. Consequently, the type of damage expected in Chile after the 1985 earthquake differs greatly from the damage observed in the 2010 earthquake.

Shear wall modeling has evolved through three fundamental methods: approaches derived from beam-column type models (in which flexure is the dominant mode of response), multi-spring macro-models and finite element models. While shear effects can be incorporated by aggregating an inelastic shear spring in series with the flexural beam-column element, true shear-flexure interaction is not accurately modeled. Additionally, inelastic behavior in beam–column elements can be represented through lumped plasticity or by distributing inelastic behavior along a finite length. The calibration of model parameters, in this type of model, is a critical step to obtain reasonable results from the simulations. On the other hand, multi-spring macro-models consists of a set of springs distributed in a configuration that allows a better representation of the strain distribution across the section of the wall as well as the migration of the neutral axis under lateral cyclic loading. Again, in this type of model, calibration of model parameters is crucial in achieving reasonable simulations results. Recently, improvements by Massone et al. (2006) to the multi-spring macro-model incorporated RC shear panel behavior, facilitating shear–flexure interaction.

This study focuses on the ability of simple and advanced macro-models to simulate the nonlinear response of RC structural walls and to assess the advantages and disadvantages of different models. To achieve this objective, a comparative study of isolated walls utilizing three existing modeling approaches is performed: (i) the Equivalent Beam Model (EBM), (ii) the Multiple Vertical Line Element model (MVLEM), and (iii) a shear panel element developed by Massone et al. (2006). The comparison is based on the ability of the models to reproduce experimentally recorded response of available wall tests in the literature. The simulation study is then extended to walls with different aspect ratios to compare the performance of the models and to highlight the differences in the modeling approaches. Finally, it is worth mentioning that the shear walls are modeled only in the 2D plane, therefore out-of-plane 3D effects are not considered.

2. ANALYTICAL MODELS

Three different macroscopic models are used to represent the nonlinear behavior of three shear walls: the Equivalent Beam Model (EBM), the Panel model developed by Massone et al. (2006), and the Multiple Vertical Line Element Model (MVLEM). Only models for isolated walls are considered and a 2D analysis is performed.

The EBM represents the shear wall by a line element at the centroidal axis of the wall (Figure 2.1(a)). This model consists of a flexural elastic member attached to nonlinear rotational springs at each end of the wall to account for the inelastic behavior of the critical regions. Modifications to this model were introduced by Takayanagi et al. (1979) by adding plastic hinges at the ends of each beam elements and the incorporation of inelastic shear deformations effects. In accordance with the modeling approach, one or more elements along the height of the wall can be used. The major disadvantage of this model relates to the fact that all the deformations occur at the centroidal axis. This assumption disregards the migration of the neutral axis of the wall cross-section during loading and unloading; causing effects such as rocking of the wall, and interaction with the frame surrounding the wall to be improperly considered. The three walls presented in this paper use eight elements stacked along the wall height. The plastic hinge length is computed according to the recommendations given by Paulay and Priestley (1992).

The MVLEM (Figure 2.1 (b)) was originally proposed by Kabeyasawa et al. (1983) and improved by Vulcano et al. (1988), followed by Colotti (1993) and Orakcal et al. (2004). The main characteristics of this model are the ability to capture important features such as shifting of the neutral axis; it also offers the flexibility to incorporate various material hysteretic models, confinement, nonlinear shear behavior, and the effect of a fluctuating axial force on strength and stiffness. The inelastic axial and flexural response of the wall are represented by a number of vertical-parallel uniaxial elements with infinitely rigid beams at the top and bottom of the wall element. Additionally, the inelastic shear response is simulated by a single horizontal spring. A rigid element of length ch characterizes the deformation of the wall member under different distributions of curvatures. It is important to note that the investigation conducted by Orakcal et al. (2004) on the model parameters demonstrated that the number of elements stacked on the top of each other along the height of the wall (m), and the number of vertical elements within each wall element (n) have a small effect in the global response. Similarly, the influence of the center of rotation parameter c can be diminished by stacking more elements along the wall height (Fischinger et al. (1992)). Currently, the MVLEM is not capable of simulating the interaction between shear and flexural behaviors. Hence, the model can suitably simulate compression and flexural failure only when the shear component is not important. One of the major problems of this model is the difficulty to estimate the shear properties when experimental results are not available. The three walls considered in the present study are modeled with eight elements along the wall height, with a c value of 0.4 as recommended by Vulcano et al. (1988). The number of vertical springs along the length of the wall varies between 8 and 10 for the different walls.

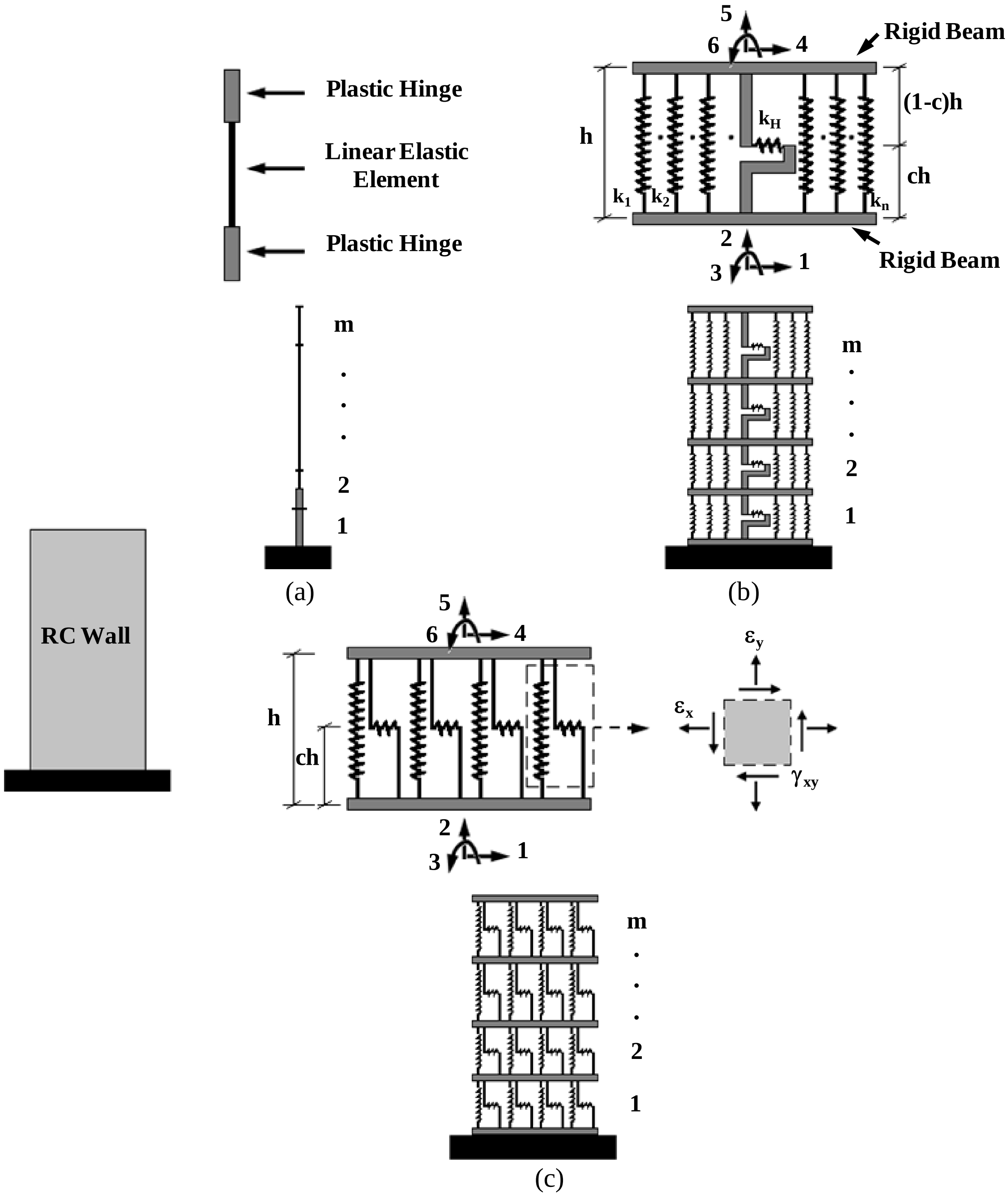

Figure 2.1. Macroscopic models and typical shear wall model. ((b) Modified from Orakcal et al. (2004), (c) Modified from Massone et al. (2006))

Finally, the model developed by Massone et al. (2006), henceforth referred to as the Panel Model (see Figure 2.1 (c)), is an analytical model that couples wall flexural and shear responses, retaining most of the features of the MVLEM. The model replaces the vertical uniaxial element of the MVLEM by a combination of a shear spring with a uniaxial vertical spring. In this way, a reinforced concrete panel behavior is incorporated into a two-dimensional macro-model. Each combination of springs (fibers) act as an RC panel element subjected to in-plane uniform normal and shear stresses, working as a membrane element. Therefore, the fiber is no longer a uniaxial element. In this model each fiber is treated as a biaxial element, incorporating flexure-shear interaction at the fiber level. The constitutive panel behavior can be represented by membrane models, such as the modified compression field theory (MCFT), developed by Vecchio and Collins (1986), or the rotating-angle softened truss model

(RA-STM), developed by Pang and Hsu (1995). The reinforcing steel of the panel is still represented by a uniaxial constitutive stress-strain model applied in the directions of the reinforcing bars. On the other hand, the concrete panel is simulated by a uniaxial constitutive stress-strain model along its principal directions. It is assumed that the principal stress and strain have the same direction. The three walls modeled in the present study are represented by eight elements along the wall height, and the number of vertical fibers along the length of the wall varies between 8 and 10 for the different walls.

2.1. Macro-model simulations using OpenSees

The three shear walls selected for the comparison study in this paper are modeled using the OpenSees platform and following the descriptions of the macro-models illustrated in the previous section. In all the simulations, concrete is modeled using a uniaxial constitutive model with tensile strength, nonlinear tension stiffening, and compressive behavior based on the Thorenfeldt curve (Concrete06model in OpenSees). Reinforcing steel bars are modeled using a modified Menegotto–Pinto model (Steel02 model in OpenSees).

When the EBM is used for the simulations, the wall elements are represented using the Beam with Hinges Element with fiber sections based on patch and layer components (patch for concrete sections, layers for reinforcing steel), and considering a plastic hinge length according to the recommendations suggested by Paulay and Priestley (1992). The shear behavior is imposed by adding a shear spring in series with the flexural behavior through the Section Aggregator command with a uniaxial material model (PINCHING4), which incorporates degradation and pinching behavior through a multi-linear force-deformation curve. The envelope of the force–deformation curve for the uniaxial shear material is derived based on the envelope of the experimental data when the wall is subjected to a cyclic load.
For the MVLEM, the vertical elements are modeled using truss elements with fiber sections based on patch and layer components similar to the case of the EBM element. The horizontal shear springs are represented by zero-length elements. Rigid elements are modeled through multi-point constraints (rigidLink option in OpenSees). As in the case of EBM, the horizontal shear spring is modeled using a uniaxial material model through a multi-linear force-deformation curve. The envelope of the force–deformation curve for the shear spring is derived following the same procedure described before.

The panel model for all the walls is constructed by using the Flexure-Shear Interaction Displacement-Based Beam-Column Element implemented by Massone in the OpenSees platform. This element considers distributed-plasticity, and includes interaction between flexural and shear components. As with the MVLEM, the section of the wall is defined as a fiber section, but based on fiber components instead of patch and layer components. This change was introduced to ensure a proper use of the panel elements, considering smeared properties of the concrete and steel.

3. EXPERIMENTAL DATA

The analytical models described in Section 2 are used to simulate the response of three model walls tested by different researchers. Specimen details for each of these tests are summarized in Table 3.1. All the tests described are single wall 2D tests with specimens subjected to a cyclic load. The tests were selected from the literature to include an example of a slender, an intermediate, and a squat wall. The classification of these three types of wall is made according to their shear-span ratio (*M/(Vl)*), as described in Table 3.1. Slender walls have a shear-span ratio greater than 2, squat walls have a shear-span ratio lower than 1, and intermediate walls have a shear-span ratio between 1 and 2.

The specimen selected to represent the slender walls is the RW2 wall tested by Thomsen and Wallace (1995). The specimen was a rectangular cantilever wall with an axial load of approximately $0.07A_g f_c'$. The wall dimensions were 3.66 m in height, and 0.102 m thick, with a web length of 1.22 m. The concrete compressive strength (f_c') was 27.5MPa, and the longitudinal and web reinforcement used were Grade 60 (f_y = 414 MPa) bars. Cyclic lateral displacements were applied at the top of the wall using a hydraulic actuator. Displacements, loads, and strains at critical locations of the wall specimen were measured during the test. The specimen had shear-span ratio of 3.0.

Table 3.1. Properties of the wall tests

Test	h (m)	l (m)	t (m)	ρ_v (%)	ρ_h (%)	*M/Vl*	Restrictions	Force	Case
RW2	3.66	1.22	0.10	0.327	0.327	3.0	Cantilever	Top	Slender
SW4	1.20	0.60	0.06	0.310	0.390	2.0	Cantilever	Top	Intermediate
N11	1.40	1.40	0.10	0.255	0.127	0.5	Fixed-Fixed	Mid-height	Squat

The intermediate wall selected was the specimen SW5, tested by Pilakoutas and Elnashai (1995). As shown in Table 3.1, the shear-span ratio for this specimen is 2.0. The specimen was a rectangular cantilever wall with a height of 1.2 m, wall thickness of 0.06 m, and a web length of 0.6 m. The concrete compressive strength (f_c') was 36.9 MPa. The reinforcement bars of the boundary elements had a yield stress f_y = 500 MPa, and the longitudinal and web reinforcement bars used had f_y = 550 MPa. Cyclic lateral displacements were applied at the top of the wall. The specimen was free with respect to an in-plane horizontal movement, but was restrained to move vertically and out of plane. The wall was fixed only at the bottom.

To investigate squat walls, the specimen N11 tested by Hidalgo et al. (2002) is used. General specimen information for this wall is illustrated in Table 3.1. The shear-span ratio for this wall was 0.50. The specimen was tested by fixing its base and avoiding rotations at the top. A lateral load was applied at specimen mid-height, generating a linear bending moment distribution with opposite signs and equal magnitude at the wall ends. The specimen was a rectangular wall without any axial load applied. The dimensions were 1.4 m in height, 0.1 m thick, with a web length of 1.4 m. The concrete compressive strength (f_c') was 16.3 MPa, and the longitudinal and web reinforcement bars used had a yield stress f_y = 362.2 MPa.

4. COMPARISON OF MODEL RESULTS WITH EXPERIMENTS

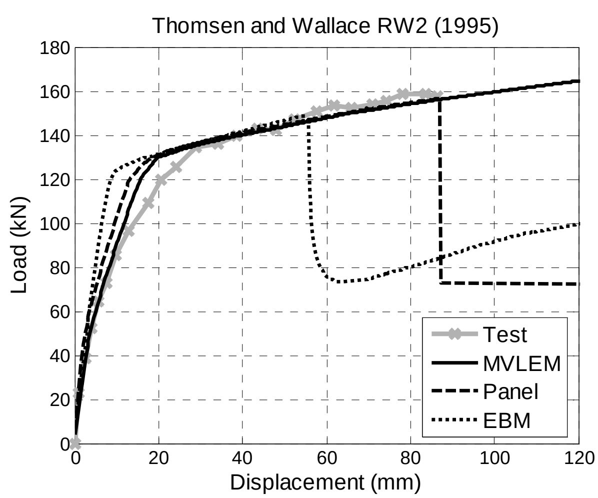

Figure 4.1. RW2: Load-displacement response

4.1. Slender wall response

The RW2 specimen is modeled using the three macro-models described in Section 2. It is important to note that based on its shear-span ratio, this wall is controlled primarily by a flexural response. Therefore, a linear elastic force-deformation behavior is imposed on the horizontal shear spring in the MVLEM and the EBM cases. The analysis is performed by applying an increasing monotonic load at the top of the wall model, and recording the displacement at the top along with the predicted base shear. Figure 4.1 compares the measured and predicted lateral load versus top displacement responses for this specimen, according to the three macro-model representations. The three macro-models capture reasonably well the strength of the wall and the global measured response. An overestimation of the stiffness for displacements between 10 and 30 mm (post-crack range) can be observed in all three models. The MVLEM shows better agreement than the Panel model or the EBM with the measured response. Nonetheless, the MVLEM response is sensitive to the force-deformation behavior adopted for the horizontal shear spring.

4.2. Intermediate wall response

According to its shear-span ratio, this wall response should comprise a combination of its flexural and shear components. Therefore, a multi-linear force-deformation behavior is imposed to the horizontal shear spring in the MVLEM and the EBM cases. This multi-linear curve is derived using the data obtained from the test of the specimen, separating the shear and flexural components using relative stiffnesses. Figure 4.2 compares the measured and predicted lateral load versus top displacement responses for this specimen. As illustrated, only the MVLEM is capable of predicting the strength of the wall, and the global measured response. However, in this case, the MVLEM response might vary greatly if the force-deformation behavior specified for the horizontal shear spring is not accurate. Additionally, it can be observed that the EBM is capable of predicting the shear strength; however the maximum load value is reached at lower displacement values when compared to the test results. On the other hand, the Panel model underestimates the strength of the specimen and does not follow the test plateau. The sensitivity of the MVLEM to the horizontal shear spring behavior indicates that it is possible to model this type of wall with the MVLEM only if the shear behavior can be predicted reasonably when experimental data is not available.

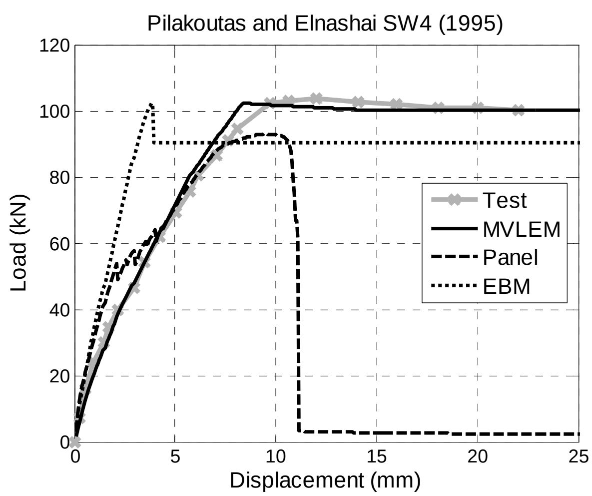

Figure 4.2. SW4: Load-displacement response

4.3. Squat wall response

Since the N11 specimen is a squat wall (shear-span ratio less than 1), its response is controlled mainly by its shear component. Therefore, a multi-linear force-deformation behavior is imposed, following the data obtained from the wall test, to the horizontal shear spring for the MVLEM and the EBM. The analysis is performed by applying an increasing monotonic load at the mid-height of the wall model aided by two rigid elements, which transmit the load in the form of a load plus a moment at the top of the wall. The displacement at the top along with the predicted base shear is recorded. Figure 4.3 compares the measured and predicted lateral load versus top displacement responses for this specimen. In this case, only the MVLEM is capable of predicting reasonably well the strength of the wall and the global measured response. Although the three models are capable of estimating the shear strength, the Panel model and the EBM predict that the shear strength is reached at lower displacement values and the response decays rapidly compared to the observed results. This indicates the limited capacity of these two models when predicting the response of squat walls. Nonetheless, as it was noticed before, the MVLEM response might vary greatly if the force-deformation behavior adopted for the horizontal shear spring is not accurate. This indicates that great effort must be devoted to the estimation of the shear behavior component when experimental data is not available. This is a major issue if the model is to be applied to a full building model.

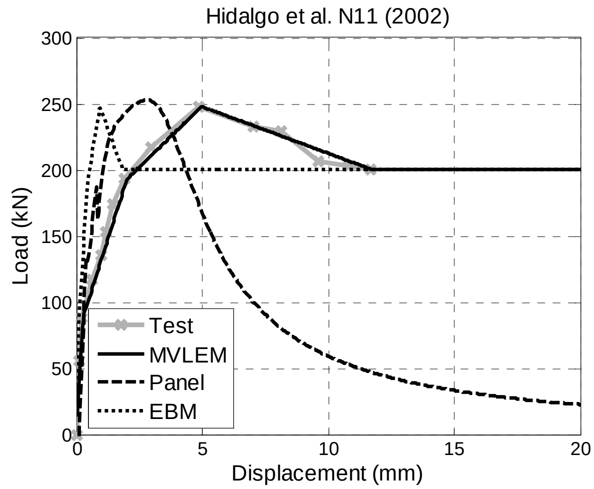

Figure 4.3. N11: Load-displacement response

5. ASPECT RATIO STUDY

In order to investigate the ability of each macro-model to predict the response of walls with different aspect ratios, the height of the specimen RW2 by Thomsen and Wallace (1995) was varied, but its cross section and transverse reinforcement was preserved, as shown in Figure 5.1. The heights chosen are: 4.88 m, 1.83 m, and 6.10 m, which produce aspect ratios of 4.0, 1.5, and 0.5, respectively. Since these walls are cantilever walls, their shear-span ratios are the same as their aspect ratios. This gives one wall for each classification, namely, one slender, one intermediate, and one squat wall.

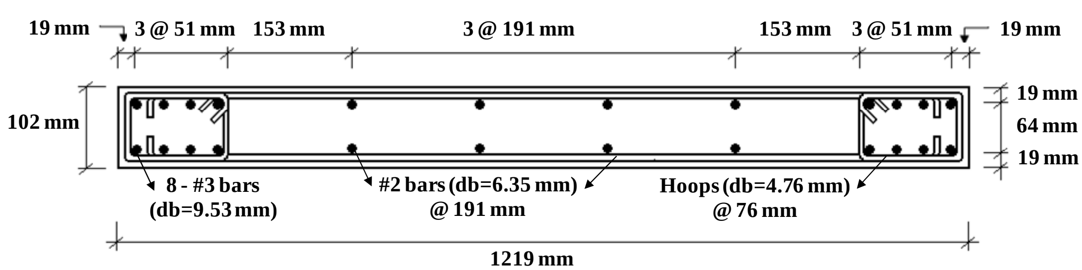

Figure 5.1. Wall cross-section (Modified from Orakcal and Wallace (2004))

The walls described are modeled using OpenSees platform, following the same procedure described in Section 2 for the EBM, the MVLEM and the Panel model. The only feature that differs from the previous modeling is the process for specifying the force-deformation behavior of the horizontal shear spring, for the MVLEM and the EBM cases. In the Panel model there is no need to input directly any special shear properties. Only the detailing of the transverse reinforcement ratio was adjusted in order to preserve the same ratio for the three walls.

Since no experimental data is available for the aspect ratio study, the force-deformation behavior is computed using the Softened Membrane Model (SMM) developed by Hsu and Zhu (2002). The SMM allows the development of a multi-linear shear stress versus shear strain curve of a RC panel, which is extended to a force-deformation curve for the three walls described. It is important to note that instead of the SMM, the Panel model in OpenSees includes the Rotating Angle Softened Truss Model (Pang and Hsu (1995)), with some modifications in the concrete stress-strain model (Massone et al. (2006)).

Figure 5.2 shows the response of the three walls with different aspect ratios. While the predicted response of all models for the slender wall is similar, there is considerable variation in the prediction of the response of the intermediate and squat walls. Figure 5.2(a) illustrates the response using EBM for the different aspect ratios. The estimates of strength are consistent with expected behavior but the post-yield response of the squat wall shows considerable strain hardening which is unlikely for a shear dominant response. Figure 5.2 (b) displays the responses of the different walls using MVLEM. The predicted behavior of the slender and intermediate wall is consistent with expected behavior. The ductility of the squat wall is obviously controlled by the shear spring which is not adequately captured by the response; however this may be attributed to the limitation of the SMM used to predict the shear response of the wall. Finally, the responses obtained with the Panel model is shown in Figure 5.2(c). The response of the slender wall is similar to those predicted by EBM and MVLEM suggesting that all three models are capable of predicting the response of flexural walls. The estimates of strength for both the intermediate and squat walls are lower than those of the other models. Further, the significant decay in the response after reaching the peak strength appears to be overly conservative based on the performance of the model for the walls described in Section 4.

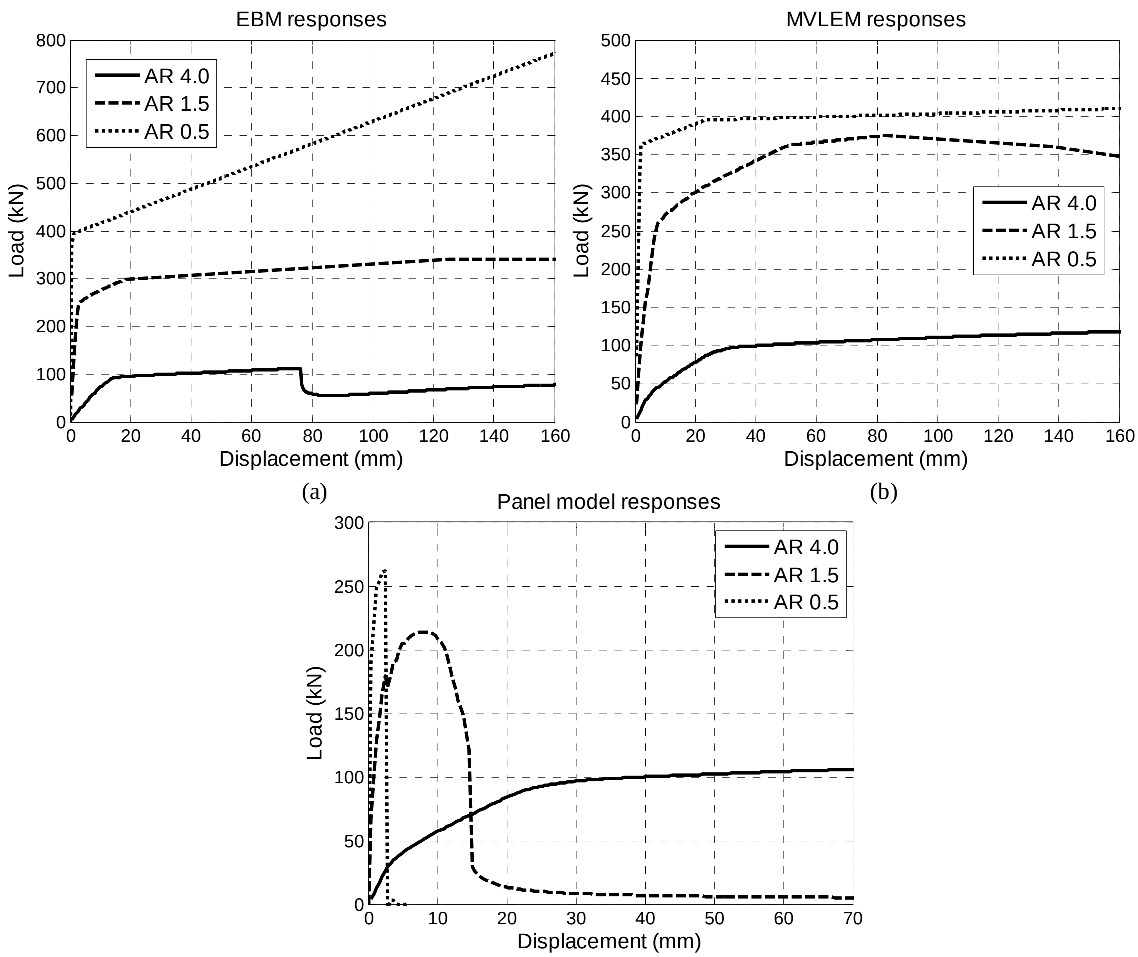

Figure 5.2. Load-displacement response for different aspect ratios

It should be noted that the shear behavior of the shear springs in EBM and MVLEM are based on the results obtained with the Softened Membrane Model. Hence any discrepancy in the post-peak response of these two models should be attributed to the inadequacy of SMM to predict the post-yield behavior of intermediate and squat shear walls.

6. SUMMARY OF FINDINGS AND CONCLUDING REMARKS

In order to assess the advantages and shortcomings in simulating the experimentally observed response of different shear walls, a comparison between three macro-models is undertaken. To obtain suitable simulations, available test data of three shear-walls of varying cross-section tested under cyclic loading is used.

As expected, the three macro-models are capable of predicting reasonably well the strength and the global response of slender walls. However, when the wall enters the inelastic range, some disagreement between the simulated response using the three macro-models and the experimental data is evident. This discrepancy, especially for the Panel model and the MVLEM, is diminished when the aspect ratio of the wall increases.

In the case of intermediate and squat walls, only the MVLEM is capable of predicting the full response of the wall, reaching the expected strength and following the plateau observed in the experimental tests. However, this predictive ability is dependent on the input of the shear spring properties. In the present study, this was determined from available experimental data, but for general simulations when experimental information is not available it is necessary to develop recommendations for estimating the shear behavior of the wall sections. The EBM and the Panel model are generally incapable of predicting the complete response of walls with a significant shear component. Whereas the Panel model tends to underestimate the wall strength and is not capable of reproducing post-yield behavior, the EBM tends to predict the strength at lower displacement demands than the other two models.

With respect to the aspect ratio study, the results obtained with the MVLEM tends to provide the most reasonable and consistent estimates of strength and initial stiffness. While the post-peak response of squat walls is difficult to ascertain without an accurate estimate of the shear behavior, it may be stated that the EBM estimates of post-yield response for the squat walls may be unreliable. Given the observations in Section 4, it may be concluded that the Panel model predictions of post-yield response of intermediate and squat walls is unreasonable.

The specified force-deformation behavior of the shear spring has a major influence in the predicted response of both the MVLEM and EBM. Therefore, further development and calibration of the shear component of these macro-models are needed to obtain more reliable and consistent results. The Softened Membrane Model used in this study to derive the shear properties offers a good starting point but additional work is need to ensure the reliability of the approach.

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