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Modeling Reinforced Concrete structural walls with micro-scale and macro-scale methods

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Abstract— **The reinforced concrete shear wall is one of the efficient structural elements in the lateral force-resisting system. Simulating the realistic behaviour of this structural member considering various aspects of its functioning is one of the challenging issues in structural engineering. Generally, all the modelling methods of simulating the RC walls can be categorized into two main groups: macro-scale and micro-scale models. In this study, three numerical models, including layered section model, multi-vertical line element (MVLE) model, and fibre section model is defined utilizing OpenSees and SAP2000 as research-oriented and commercial structural analysis software respectively. In the first step, a parametric study is conducted to evaluate the mesh and element size on the global and local responses of each model. Then, they are compared with the results of the experimental test of a typical RC wall from previous studies. Results show that all models, independent of the mesh size, provide a relatively accurate response for global load-displacement results while different results for local strain results.**

Index Terms— **Reinforced concrete shear wall, nonlinear static analysis, OpenSees, SAP2000.**

I. Introduction

There are various strategies to make the structure to resist lateral forces caused by earthquake and wind. One of the strategies is to damp the induced energy to the structure by utilizing damping systems. There are various dampers that can dissipate the dynamic loads and keep the structures safe; for example, recently Barzegar et. al introduced the novel passive variable friction damper (PVFD mitigating wind- and seismic-induced vibrations,[1]. The other strategy is to utilize some structural members such as Reinforced Concrete (RC) walls to actively resist against lateral loads. However, RC walls have highly complex behavior, and various factors influence their behavior significantly. The wall aspect ratio (the ratio of height to width of the wall), steel reinforcement ratio, confinement of the concrete in boundary elements of the wall, presence of opening on the wall are some of those factors,[2]. Generally, the behavior of RC walls is dependent on the combination of three main deformations: flexural, shear, and axial. Typically, RC walls with aspect ratios of 3.0 or more are considered slender walls which their behavior is controlled with flexure. The failure characteristic of this type of wall is horizontal cracks at the edge of the wall. However, at the other end of the range, there are squat walls with an

aspect ratio of 1.5 or less, which their behavior is controlled by shear. The failure characteristic of this type of wall is diagonal cracks. Paulay and Priestley address more detailed failure mechanism of structural walls,[3]. The walls with the aspect ratio between these ranges are controlled by both flexural and shear behavior,[4]. This complexity made researchers in the last decades to conduct various experimental studies on shear walls under monotonic, cyclic, or dynamic loading conditions with different loading seniors

such as progressive collapse and various cross-sections, caused significant development in robust Numerical models to detect accurate inelastic wall response,[5]. In this period, remarkable progress in the computational efficiency of computers helped researchers to expand more advanced Numerical models, which can consider various aspects of RC walls that were used to be ignored in initial models.

Generally, all the modeling methods of simulating the RC walls can be categorized into two main groups: macro-scale and micro-scale models. One of the earliest attempts in utilizing numerical models to simulate nonlinear behavior of generally all RC members utilized by Clough et al. in 1965, [6]. They considered a particular bilinear moment-rotation property assigned independently to beams and columns of a 20-story moment frame under the El Centro earthquake condition and compared the results with elastic analysis of the same frame. They concluded that the maximum story displacement in nonlinear models is significantly higher than the elastic model. Specifically, about RC walls, one of the earliest methods in simulating is using beam-column element at the wall centroid axis with rigid links on beam girders. In this method, nonlinear rotational springs are utilized at the interface of connections to consider the fixed-end rotation of the wall. Takayanagi and Schnobrich in 1976 and Keshavarzian and Schnobrichused in 1984 used this model to simulate the behavior of coupled shear wall system under static and dynamic loading,[4-5]. Since the beam-column model assumes rotation around a fixed point on the centroid axis of the wall, it is not able to consider dominant features in-wall nonlinear behavior such as variation of neutral axis or wall racking. To solve this problem, in 1984 Kabeyasawa et al. tested a full-scale seven-story RC building as part of the U.S.- Japan Cooperative Research and proposed a three-vertical-line-element model (TVLEM),[9]. This model was capable of considering the variation of the neutral axis and wall interaction with other frame elements along with predicting global responses such as lateral displacement, base shear, and rotation at beams ends, which had appropriate conformity with experimental results. TVLEM idealizes the wall element with three vertical spring with rigid beams top and bottom floor level; one horizontal and one rotational spring is also considered at the base of the wall. Utilizing this model needs an accurate definition of the spring's property, which represents the wall panel. In 1984 Oesterle at al. utilized an Numerical model based on truss analogy to evaluate the experimental results,[10]. They assumed that the wall behavior as a statically determinate truss system with diagonal concrete compression struts and horizontal tension ties and also including two boundary elements to simulate the moment acting.

In 1984 Smith and Girgis, for the first time, utilized truss to simulate the behavior of the RC walls,[11]. They introduce two Numerical methods to represent the wall system; one method called braced wide column analogy, includes an x-shape bracing connected to rigid beams at each story level and one column in the middle of the wall section with the area and moment of inertia of the wall. The other method, called braced frame analogy, has the same x-shaped bracing inside a frame, including again two rigid beams at story levels but two columns connected to rigid beams at two ends and excluding the middle column. They utilized these models to study the behavior of the 15-story core wall of the elevator, and the results showed that models are suitable for the analysis of both planar and non-planar walls, and the braced frame model is more efficient than the braced wide-column method.

In 1986 Vulcano and Bertero proposed a modified model of TVLEM,[12]. In their model, two-axial-element-in-series at the wall base were connected by a horizontal rigid member to a one-component model to simulate the axial stiffness of the column segments in the top portion of the wall. The comparison between the model results and experimental tests revealed that global responses were captured very well while there were some discrepancies for shear behavior.

Later, in 1988 Vulcano, Bertero, and Colotti suggested the multiple-vertical-line element model (MVLEM),[13]. In this model, there are uniaxial elements in the vertical direction that simulates the flexural response, and a horizontal spring, which represents the shear response of the wall located at the height c×h (h, is the height of the wall) in-wall plastic hinge region. Factor c is selected based on the curvature distribution in wall height between two-story levels and ranges between 0 and 1.

In 1997 Kabeyasawa introduced a modified model of a three-vertical-line-element model (TVLEM),[14]. In the modified model, the two vertical springs in the original model were kept while middle vertical, horizontal, and rotational springs were substituted with a two-dimensional nonlinear panel member.

In 2000 Chen et al. used a 2-D nonlinear panel element to simulate the nonlinear behavior of the structural wall,[15]. They adopted two different panel elements one an isoparametric element and the other an incompatible element. This model is utilized by Chen et al at 2007 to analyze a full-scale six-story RC frame-wall structure,[16]. The type and stiffness of the lateral resistant system in structures play a significant role in their seismic behaviors as well. According to Wallace (2007), one of the common problems among various macro-model (or fiber-based models in general) in the simulation of the RC wall is underestimating the peak compressive strains originating from uncoupled shear and flexural responses,[17]. To solve this problem, utilizing the MVLEM method, Kolzovari et al., in 2015, proposed an Numerical model that can capture shear–flexural interaction. In this method which is named SFI-MVLEM, the horizontal shear element is removed and vertical axial elements in original MVLEM are replaced with RC panel element subjected to membrane actions which result in achieving coupling of axial and shear responses at the microfiber level,[18]. They showed that SFI-MVLEM is an efficient method to simulate moderately slender RC walls in which shear-flexure interaction behavior is significant. However, the model is not able to address the failure mechanisms observed in experimental specimens caused by rebar buckling, lateral instability of the boundary zone, and sliding shear near the wall base,[18].

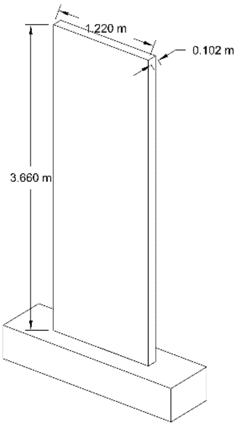
The finite element method is a powerful and robust tool to simulate various kinds of structures by considering detailed features and complicated loading conditions [19]. For the first time, Ngo and Scordelis in1967 utilized this method to analyze reinforced concrete beams on the supported condition,[20]. Nowadays, there are many finite element software which enables researchers and designers to reach accurate response for either member's global behavior (e.g., member forces and displacements) or to its local behavior (e.g., crack pattern, material stresses, and strains). For example, Kolozvari et al. in 2019 investigated the behavior of RC walls using five finite element software including VecTor2, FSAFE, DIANA, QLMEDD and LS-DYNA,[21].

Generally, in the finite element method, the members are discretized into the finite number of small elements sharing the finite number of nodes. However, there is another method of finite element method, which is called fiber (layer) method. In this method, the members are divided longitudinally into several parallel layers. Dependent on the position of the layer, each one can represent different materials. In 2007, Belmouden and Lestuzzi utilized this method to simulate the nonlinear behavior of RC shear walls under reversed cyclic loading,[22]. In 2016, a new formulation for the nonlinear analysis of reinforced concrete (RC) walls using a layered membrane element with drilling degrees of freedom is introduced,[23]. In this method, the drilling DOF refers to the incorporation of the in-plane rotation as a DOF at each element node. The results showed that this formulation can predict both global and local responses with remarkable accuracy and can consider the coupling effect of axial, flexural, and shear behavior in the different configurations of RC wall structures.

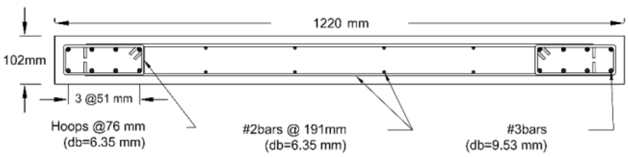
II. Numerical Models

In this study, to compare the local and global responses of different RC wall modeling methods, three Numerical models are selected. Models include the MVLE model, which is one of the macro-scale methods and two micro-scale methods, including fiber section and layered section models. An experimental test of a single rectangular wall which reported by Thomsen and Wallace is selected to compare the performance of each Numerical model,[24]. Figure 1 provides geometrical properties and cross-sectional details of the RW2 wall. Simulating the realistic behavior of the RC wall needs the material nonlinearity consideration in the material definition of models. Figure 2 shows stress-strain curves used in all three Numerical models for confined and unconfined concrete and also for longitudinal steel rebar used the RC wall.

In this study, the effect of elements' size on global and local responses of the Numerical models is investigated. At first attempt, the cross-section and height of the wall are divided into four sections, which are labeled as Mesh1×1 in all three models. In the next stage, the size of the elements is divided into half, and the height and cross-section of the wall are divided into eight sections calling Mesh 2×2 models. Finally, in Mesh 3×3 models, the size of the elements is reduced further, and the wall's height and cross-section are divided into sixteen sections. Figure 3 illustrates the scheme of three Numerical models and their element division. In the following section simulating the RC wall using each previously mentioned model is discussed in detail.

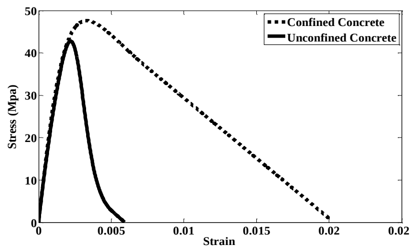


(a)

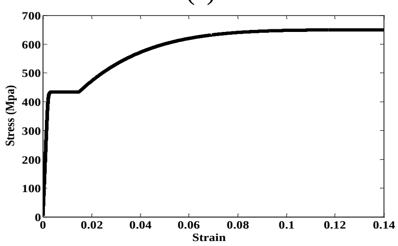


(b)

Figure 1 RW2 Specimen Geometrical Dimension (b) cross section details [25]



(a)



(b)

Figure 2 Nonlinear stress-strain curve of materials: (a) confined and unconfined concrete (b) steel rebar

III. Layered Section Model

For layered section model SAP2000 software is utilized,[26]. This software is one of the commonly used software in the structural engineering aspect. The material property of concrete and steel rebar is defined by introducing the strain and stress values according to diagrams provided in figure 2. For steel material, a multi-linear kinematic hysteresis model and for concrete materials, concrete hysteresis type with no energy degradation factor is selected. The layered shell section is selected to simulate the behavior of the RC wall, which enables the user to utilize the nonlinear material property. This element is a type of area object that could be used to the model membrane, plate, and shell behavior of structural members in the both planar and three-dimensional environment either with linear or nonlinear material property,[27]. This element uses a four-point numerical integration formulation for the shell stiffness. Stresses and internal forces and moments, in the element local coordinate system, are evaluated at the 2-by-2 Gauss integration points and extrapolated to the joints of the element, [27]. The layered shell element could be utilized by one (such as steel shear wall) or any number of layers with an independent location, thickness, behavior, and material,[28].

In this model, the height of the wall is divided into four equal parts, and cross-section of the wall is divided into boundary elements with 0.191 (m) width and two equally width web elements with 0.514 (m) width for each. In model Mesh1×1, the automatic mesh area is assigned to the elements which keep the original discretization of the model. In model Mesh2×2, each element is assigned rectangular mesh with two objects along each edge. Similarly, the Mesh3×3 model includes meshing with three objects on each side. Figure 3-a, b, c illustrate the three models defined by the layered section method and the mesh size.

The reversed cyclic analysis starts with applying approximately 0.10Agf'caxial force, which Ag is the gross area of the wall section, and f'c is the ultimate compressive stress of the concrete. The lateral cyclic load was then applied under displacement-controlled analysis to the top point of the wall. The drift level in experimental test starts approximately from 0.1% and continues up to 2.5% level for specimens RW2, [24]. Figure 4 compares the cyclic behavior of each model using the layered section method. In Figure 5, tensile strain in furthest longitudinal reinforcement and compressive strain in a furthest compressive tendon in concrete at the base of the wall is compared. The numbers are extracted in 0.5%, 1.0% and 2.0% drift ratio.

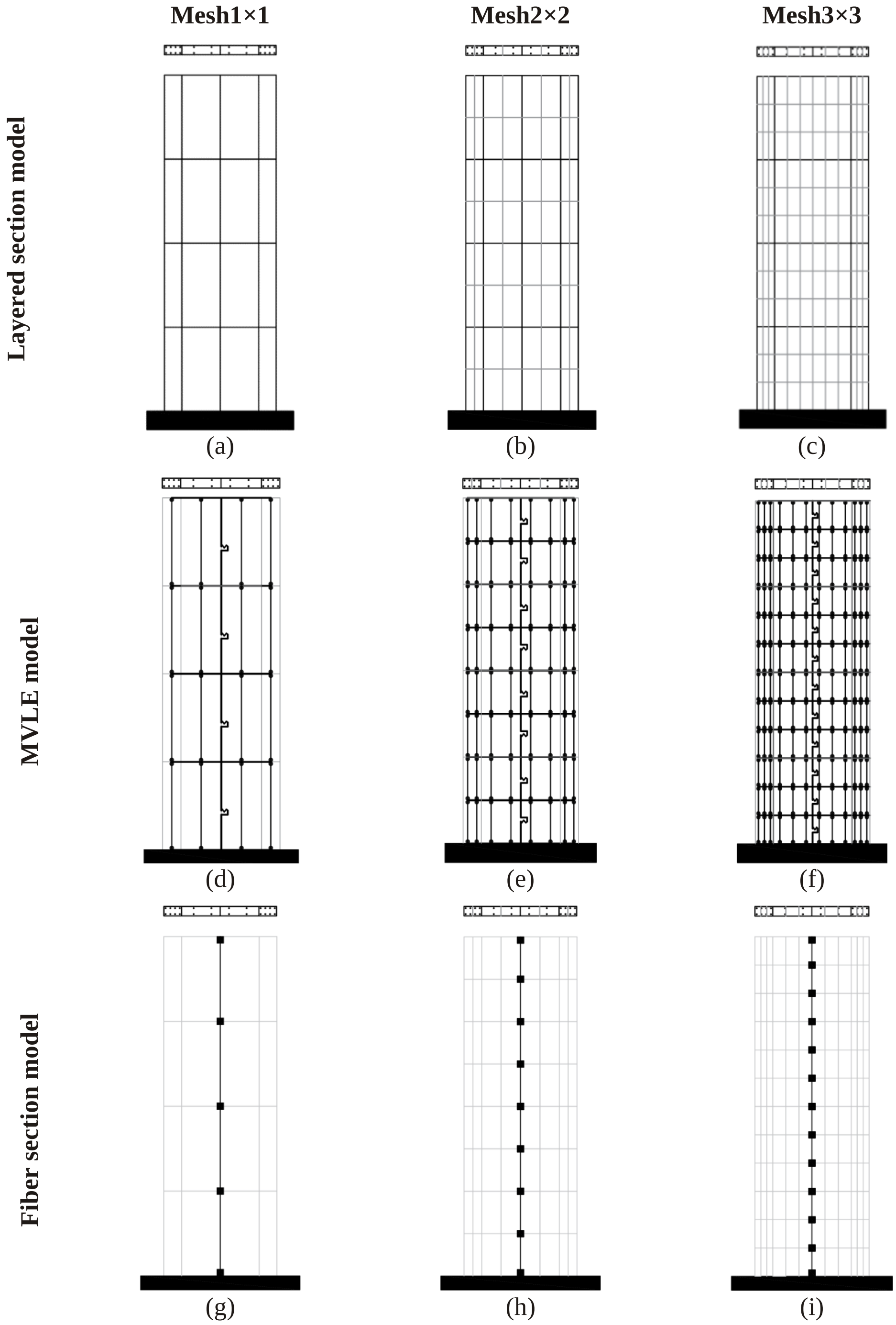


Figure 3 Numerical models and corresponding element size

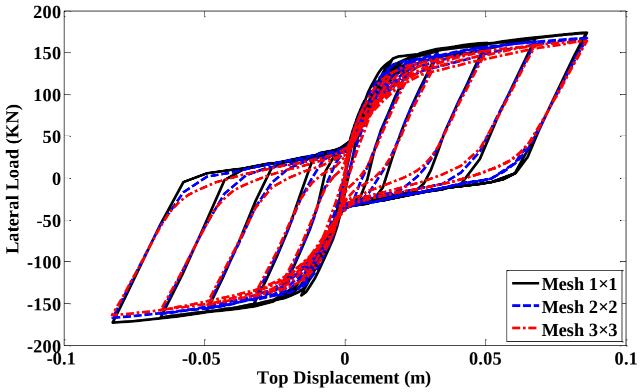


Figure 4 Lateral load-displacement of layered section method with different mesh sizes

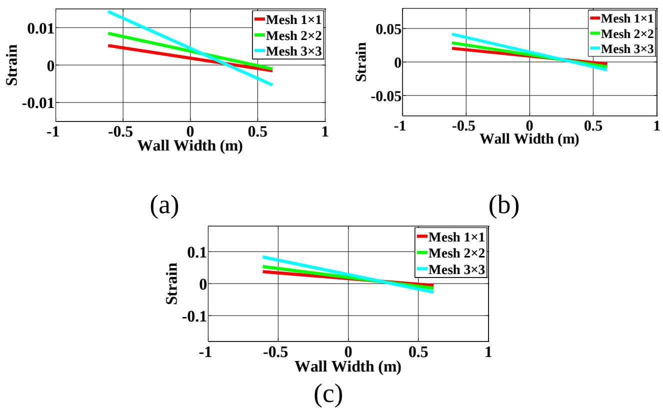


Figure 5 Tensile and compressive strain along at the base of the wall in (a) 0.5% (b) 1.0% (c) 2.0% drift ratio

IV. MVLE Model

To develop an MVLE model OpenSees software is utilized,[29]. In this analytical model, concrete07 and Reinforcing Steel command are selected to define concrete and reinforcing steel property respectively. The vertical line elements are defined by the truss element and the rigid vertical members at the middle of the wall, and rigid horizontal members are defined by elastic beam-column elements. Since the aspect ratio of the wall is 3, the flexural deformation is the dominant behavior of the wall, and the shear springs considered to behave rigidly. Similar to the layered section model, in order to evaluate the size and number of the element on the response of this model, as illustrated in figure 3-d,e,f, the number of the elements is increased while their size is decreased in model Mesh1×1 through Mesh 3×3. Figure 6 shows the three different configurations of the MVLE model of the wall with various numbers and sizes of the elements. Figure 7 compares the lateral load-displacement response of the three models. Figure 7 shows maximum tensile and compression strain in the wall cross-section for each model in 0.5%, 1.0%, and 2.0% drift ratio.

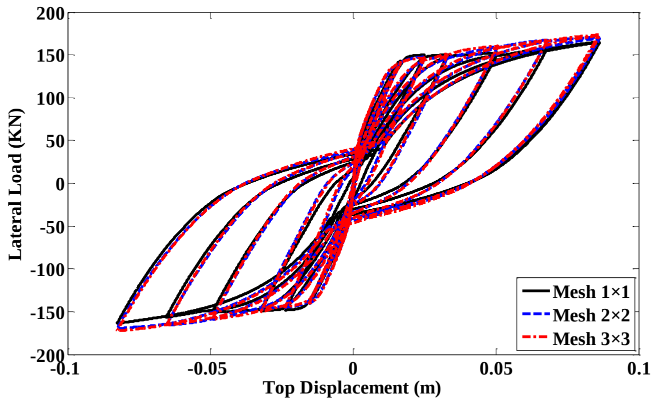
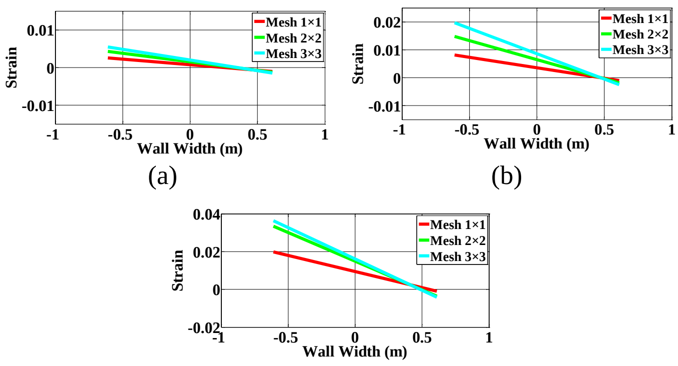


Figure 6 Lateral load-displacement of layered section method with different element sizes



(a) (b) (c)

Figure 7 Tensile and compressive strain along at the base of the wall in (a) 0.5% (b) 1.0% (c) 2.0% drift ratio

V. Fiber Section Method

This model is also developed in OpenSees software. The overall behavior of the wall is modeled with the individual nonlinearBeamColumn element in the OpenSees library. This element can consider the disturbed plasticity along the element. The same material commands are used for this model similar to the MVLE model. The wall cross-section is defined by the fiber section command available in OpenSees. Figure 3- g,h, i shows the number and size of the elements considered for this model. Figure 8 provides a comparison of the lateral load-displacement response of models, and figure 9 compares the tensile and compression strain in-wall cross-section for each model in 0.5%, 1.0%, and 2.0% drift ratio.

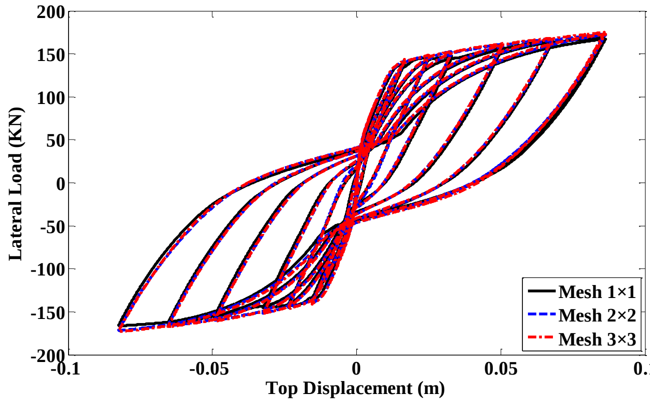
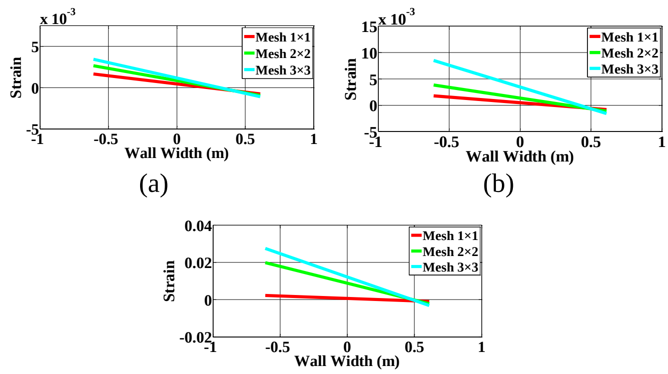


Figure 8 Lateral load-displacement of fiber section method with different element sizes



(a) (b) (c)

Figure 9 Tensile and compressive strain along at the base of the wall in (a) 0.5% (b) 1.0% (c) 2.0% drift ratio

VI. Comparison of Numerical and Experimental Results

A comparison of the experimentally measured and Numerically predicted hysteretic lateral load versus total top displacement responses for the three Numerical models with three element sizes obtained is presented in figure 10.

All models match well with the hysteretic response of representative wall specimen RW2 behavior and capture the strength and stiffness with reasonable accuracy. Comparing three models, pinching characteristics of the layered section models are slightly overestimated, and these overestimating increases by assigning smaller mesh sizes. In these models, the lateral load estimation at each drift level is slightly decreasing while the size of the mesh is decreasing. For MVLE and fiber section models pinching characteristics relatively matches well with the experimental result; however, the lateral load estimation at each drift level is slightly increased while the size of the elements is decreasing.

Fig. 11 depicts the comparison of Numerically predicted and experimentally obtained vertical (longitudinal) maximum compressive and tensile strain at furthest tendons of the cross-section of the wall corresponding to drift levels of 0.5%,1.0%, and 2.0%. In all drift levels, none of the models can capture the accurate value. Figure 12 also shows that relatively in all drift levels and corresponding mesh size, the layered section model gives the highest strain values both for compression and tension comparing the MVLE and fiber section models. It also illustrates that the sensitivity of the layered section to the mesh size is higher than the two other models.

VII. Summary and Conclusion

This paper presents the results of the comparative evaluation of three Numerical models to simulate the nonlinear behavior of reinforced concrete structural walls. Selected software for this purpose is OpenSees and SAP2000, which could be considered as research-oriented or commercial structural analysis software, respectively. Selected modeling approaches include the MVLE model as a representative for macroscale models and also fiber section and layered section models from the microscale Numerical models' group.

A parametric investigation is conducted on each model to evaluate the mesh and element size effect on the global and local responses of each model. Then, Numerical model results were compared with experimental data obtained for a planar RC wall specimen with rectangular cross-sections subjected to cyclic uni-directional loading, characterized by an aspect ratio of 3 (slender wall).

Comparison between experimental results and Numerical predictions was conducted at both global and local response levels, including lateral load versus top displacement and

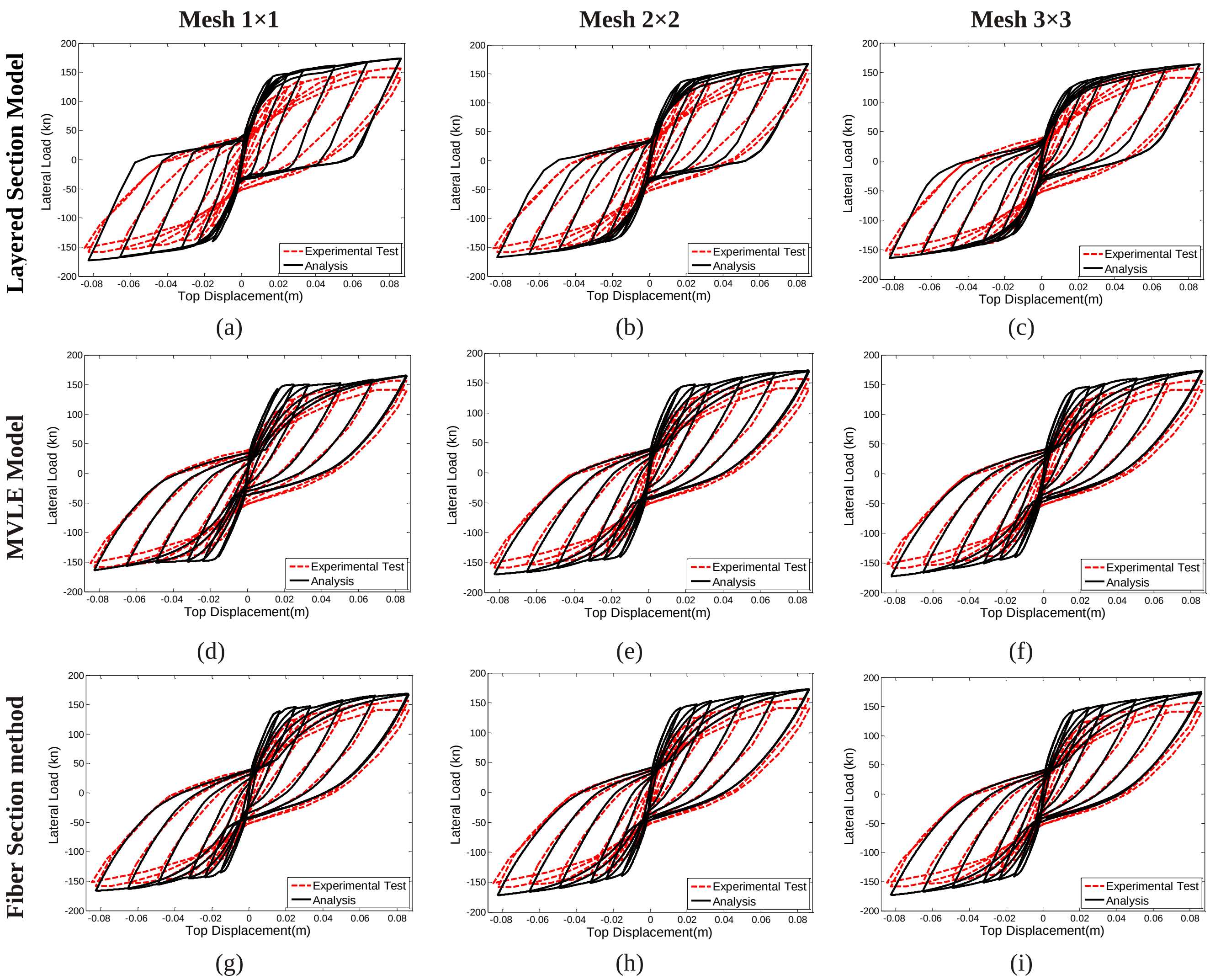


Figure 10 Lateral load versus top displacement responses for RW2 wall specimen and models considered

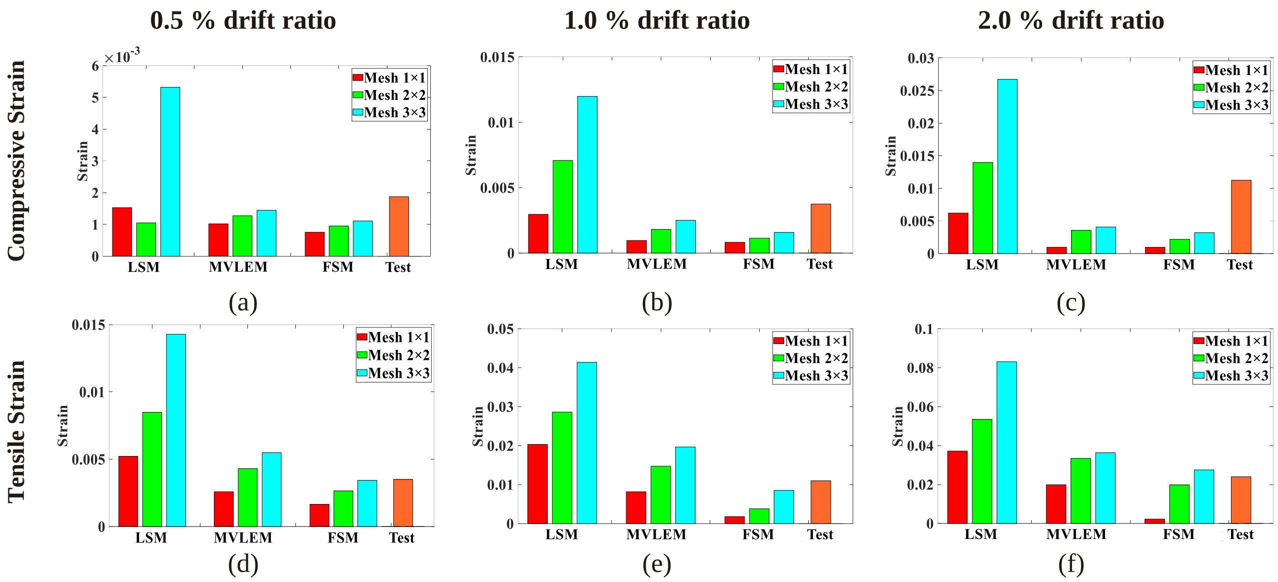


Figure 11 Strain responses for RW2 wall specimens and models considered

maximum tensile and compressive vertical strain at the base of the wall. Based on the comprehensive comparisons between the Numerical and experimental results presented, the following conclusions can be reached:

- All Numerical models predict the hysteretic response well, and loading and unloading paths are matching relatively reasonable with experimental results.

- Variation in mesh size and element size has a negligible effect on the global response of all models.

- None of the models can capture relatively accurate values for a local response (strain), and all models are significantly sensitive to the mesh and element size in predicting strain values.

- The MVLE model provides small values for compression strain and larger values for tensile strain. Fiber section model underestimates the compression strains while can predict close values for tensile strain in small element size.

- It can be observed from the figure that all models considered predicting the linear distribution of strains along the wall base, compatible to typical macroscopic models where the plane-sections assumption enforces a linear strain distribution.

- The results provided by the layered section model shows that this model is capable of predicting relatively accurate results for global responses for nonlinear analysis.

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