Nonlinear Analysis Methods for Reinforced Concrete Buildings with Shear walls

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ABSTRACT:
Proper modeling of the shear walls is very important for both linear and nonlinear analyses of building structures. In linear analyses of structures, Reinforced concrete (RC) shear walls are modeled utilizing different techniques either using shell elements or combination of frame elements. In the nonlinear analyses, the nonlinear material model of mid-pier frame is generally based on plastic hinge concept located on the plastic zones at the end of the structural elements or distributed along the member span length. The nonlinear behavior of the shell elements is generally modeled using multi layer shell element with layered material model. In this approach, the concrete and the reinforcement inside the structural elements are modeled respectively with different layers. In this study, different approaches for linear and nonlinear modeling of the shear walls in structural analyses of buildings are studied and applied to RC building with shear walls. The analyses results of different approaches are compared in terms of overall behavior of the structural systems.

Keywords: RC shear wall, nonlinear analysis, multi layer shell, plastic hinge

1. INTRODUCTION

In the countries with active seismicity, reinforced concrete structural walls are widely used in multi-storey structure systems. Therefore, a proper modeling of the shear walls is very important for both linear and nonlinear analyses of building structures.

In linear analyses of structures, shear walls are modeled utilizing different techniques either using shell elements or combination of frame elements. The most common modeling technique is to use a composition of mid-pier frame to represent the shear wall stiffness and a horizontal frame (rigid arm) to allow proper connections with intersecting beams and slab components. Shell elements formulations generally consist of out-of-plane (plate) and in-plane (membrane) degree of freedoms (Kubin et al, 2008).

In practice, even though, the nonlinear analysis procedures for frame structural systems (columns, beams) are well-developed, the nonlinear models for shear walls need further researches to adopt it to the structural engineering applications. Different analytical models for the material nonlinearity of the shear walls are used depending on either mid-pier frame or a composition of shell elements. The nonlinear model of mid-pier frame is generally based on plastic hinge concept and a bilinear moment-rotation relationship. Taking into account the analysis purpose, the plastic (P-M-M Interaction) hinges can be assumed either on the plastic zones at the end of the structural elements or distributed along the member span length (Otani, 1980). More comprehensive hinge model can be considered using a fiber model to predict the plastic behavior of the hinge. The nonlinear material of the shell elements can be modeled using layered shell element with directional material model (dorninger and Rammerstorfer, 1990). In this model, the concrete and the reinforcement inside the structural elements are modeled respectively with different fibers so that the cyclic behavior of material can be properly simulated. On the other hand, most of the applications do not include nonlinear shear models for such members.

In this study, a nonlinear static Pushover analysis is performed for RC frame building with shear walls. The shear walls are modeled either with Mid-Pier frame elements or with shell elements. The nonlinear material for the Mid-Pier model is assumed to be plastic (P-M-M Interaction) hinge; while a multi layer model considering the concrete and reinforcement as a layered shells. The results of different models are compared in terms of overall behavior of the structural systems.

2. LINEAR MODELS FOR SHEARWALLS

Application of the finite element method for the analysis of building structures with shear walls requires an understanding of the approximations involved in the modeling assumptions to build these elements. The two modeling procedure and assumptions are explained below:

2.1. Frame Elements Based Model

The shear walls are modeled using a set of frame elements. The most common modeling technique is to use a composition of mid-pier frame to represent the shear wall stiffness and a horizontal frame (rigid arm) to allow proper connections with intersecting beams and slab components (Figure 1). The most critical point for this model is the proper selection of rigidity and stiffness property for the horizontal frame. Infinite rigidity of the upper frame can highly overestimate the bending moments especially at the connecting beams. This model is used widely in practice to model planar shear walls in building structures for linear and nonlinear analyses. This model might have no reliable results for very long, interacting or complex shear walls with openings.

2.2. Shell Elements Based Model

The shell element can be used efficiently for the analysis of building structures with shear walls. The shell element considered in most of the design software has six degrees of freedom at each node and an in-plane rotational degree of freedom, which makes it compatible with three-dimensional beam-type finite element models. It is worth to know that a bilinear shape functions are used to define the displacement field of the quadrilateral elements, Wilson (2002). Therefore, shear wall modeling requires a mesh discretization in order to get realistic behavior. The advantage of using shell elements is the ability to model very long, interacting and complex shear walls within the three dimensional model. Although the shell element formulations include the drilling degree of freedom, analytical results show inconsistency and sensitivity of the drilling moment to mesh sizes and loading conditions. This shortcoming has significant effects on the bending moment of the in-plane beams connected to the shear wall. To resolve this problem, in engineering practice, the beam connecting to shear wall are generally modeled to some extend inside the shear wall shell elements (Figure 1).
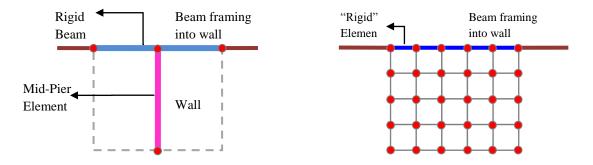

Figure 1. Mid-Pier and shell elements models for shear wall

3. NONLINEAR MATERIAL MODELS SHEAR WALLS

The nonlinear element models of shear walls are ranged from three dimensional nonlinear solid elements, two dimensional nonlinear shell elements to simplified models using frame elements.

3.1 Continuum Finite Element Models

The shear wall is modeled with continuum elements using nonlinear solid elements existed in many advanced finite element analyses' software as ANSYS, ABAQUS, etc. The continuum elements offer superiority in accurately modeling the concrete and reinforcement details (Nicolae and Reynouard, 2000). Reinforcement can be defined in three different directions. The plasticity model for concrete is based on the flow theory of plasticity, Von Mises yield criterion, isotropic hardening and associated flow rule. The continuum elements also capture important behavioral responses such as axial-flexure interaction, inelastic shear deformation, steel confining effect on concrete behavior, concrete compression softening, and concrete tension stiffening (Spacone and El-Tawil, 2004). Even though, the continuum element models require larger amounts of input parameters, they are very effective in analysis of one or more RC element members. In the other hand, the continuum elements model still is not practically applicable for the analysis and design of full-size building structure.

3.2 Multi-Layer Shell Element

The shear wall is modeled using a fine mesh of smeared multi-layer shell elements. The multi-layer shell element is based on the principles of composite material mechanics and it can simulate the coupled in-plane/out-plane bending and the coupled in-plane bending-shear nonlinear behaviors of RC shear walls (Miao et al, 2006). The shell element is made up of many layers with different thickness. And different material properties are assigned to various layers (Figure 2). This means that the reinforcement rebars are smeared into one layer or more. During the finite element calculation, the axial strain and curvature of the middle layer can be obtained in one element. Then according to the assumption that plane remains plane, the strains and the curvatures of the other layers can be calculated. And then the corresponding stress will be calculated through the constitutive relations of the material assigned to the layer. From the above principles, it is seen that the structural performance of the shear wall can be directly connected with the material constitutive law. For performance based design, the recommendation of ACI 40 and FEMA 356 define the performance criteria for the flexural RC members in terms of plastic rotations. Therefore for practical engineering, further development of this model is needed. In the case of the wall or wall segment behavior is governed by shear, shear drift ratio as the deformation measure can be used as defined in ATC-40.
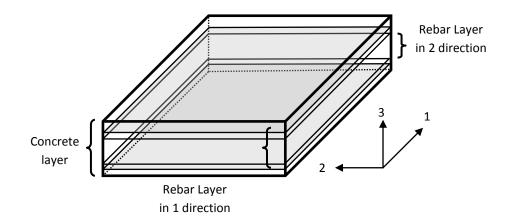

Figure 2. Multi-layer shell elements

3.3 Frame Element Plastic (P-M-M Interaction) Hinge

The shear wall is model with a composition of frame elements. Equivalent frame model can be assume of Mid-Pier and rigid beams. The material nonlinearity of the shear wall can be modeled considering a plastic hinge on Mid-Pier element.The plastic hinge frame structure is analyzed by placing a rigid plastic spring at the location where yielding is expected. The part of a member between the two rigid plastic springs remains perfectly elastic. All inelastic deformation is assumed to occur in these springs (Otani, 1980). This one-component model was generalized by Giberson (1967). The nonlinear model of mid-pier frame is generally based on plastic hinge concept and a bilinear moment-rotation relationship (Figure 3). Taking into account the analysis purpose, the plastic (P-M-M Interaction) hinges can be assumed either on the plastic zones at the end of the structural elements or distributed along the member span length (Otani, 1980). FEMA 356 proposes plastic hinge properties for the shear walls with bilinear moment-rotation relationship that define the acceptance criteria. More comprehensive plastic (P-M-M) hinge model can be computed using a fiber model to predict the plastic behavior of the hinge. In practical engineering, the plastic hinge assigned to Mid-Pier model can be used directly for nonlinear analysis of shear walls.,
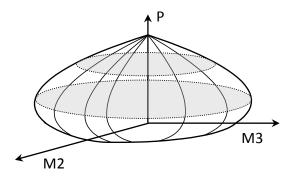

Figure 3. Plastic (P-M-M Interaction) hinge

4. NUMERICAL EXAMPLE

The structure is an existing school building. Column, wall and beam cross-section dimensions and the slab thicknesses are summarized in Table 1. The cross-sections of the vertical structural members are assumed constant over the entire height. The building has five stories with a typical storey height of 3.5 m. Three dimensional physical and analytical models are shown in Figure 4. After a detailed site survey conducted inside the building, existing reinforced concrete grade used for structural members is determined as C14. This corresponds to a modulus of elasticity value of 2.615x107 kN/m2 , according to Turkish Reinforced Concrete Design Code (TS500). Reinforcement grade came out to be grade S420. The storey masses are formed using appropriate distribution of the slabs loads. The slab loads composed of self weight (G) and 30% of the live load (Q), where, G = own weight + 1 kN/m2, Q = 3.5 kN/m2 and 5 kN/m2 for classes and corridors respectively. The centre of mass of the building is calculated based on the mass distribution at each node. Probina Orion (2010), structural design software is utilized for three dimensional modeling and analyses of the example building. The shell element formulations in the software are based on formulations proposed by Wilson (2002). The building is located in the first seismic zone, with local soil profile Z2 and building importance coefficient (I) equal to 1.5. The design spectrum curve is constructed according to Turkish Earthquake Code for Buildings, DBYBHY, (2006). The existing reinforcement in the concrete members are provided in Table 2. The reinforcement distributions in the column and in the shear wall are demonstrated in Figure 5.

Table 1. Member dimensions of the example building

Columns (mm)	250x600
Walls (mm)	3250x250 and 5250x250
Beams (mm)	250x500
Slab Thickness (mm)	120

Table 2. Existing reinforcement in members of the example building

Columns (mm)	Longitudinal Rebars: 8ϕ14 Confinement: ϕ8/20
Walls (mm)	Longitudinal Rebars: ϕ12/20 Transverse Rebars: ϕ12/20
Beams (mm)	Top Reinforcement %8, bottom Reinforcement %4 at both ends

Three analysis models for the example building are considered using different modeling techniques of the shear walls:

1) Shear walls are modeled by multi layer shell elements; 3.0m and 5.0 m wide shear walls are modeled with shell elements with mesh sizes of 75x87 cm and 83x87 cm respectively. For nonlinear multi layer material shell model, Mander stress-strain relation (Mander et al., 1988) is adopted to represent the concrete material model with compressive strain at maximum stress is 0.002 and ultimate strain is 0.005. The Kinematic nonlinear model is selected for rebar steel with stain at onset strain hardening to be 0.01 and ultimate strain capacity 0.09. The reinforcement in both longitudinal and transverse directions is considered as a separate layer. Two layers for each direction are considered to account for upper and lower reinforcement in the cross section.

2) Shear walls are modeled by Mid-Pier Frame with plastic hinges defined according to FEMA 356; Mid-Pier is modeled as a frame element with the shear wall cross sectional parameters. Thickness of the rectangular rigid beam section can be considered the same as the wall itself. The plastic P-M-M hinge is defined according FEMA 356 with the given rebar distribution given in Table 2 . The axial force level is considered from a combination of dead and live loads (G+0.3Q) and the transverse reinforcing is not conforming.

3) Shear walls are modeled by Mid-Pier Frame with plastic hinge computed from fiber model of the cross section. Mid-Pier is modeled as a frame element with the shear wall cross sectional parameters as in model (2). The fiber hinge is constructed using rebar distribution as in Model (1). The concrete and rebar steel nonlinear material model is considered to be Mander and Kinematic as in Model (1).

To investigate the nonlinear behavior of the three proposed shear wall models, Nonlinear Static Analyses (Pushover) are performed. Pushover analysis is a static, nonlinear procedure in which the structural loading compatible with the specified modal shape is incrementally increased. At each increment, the weak hinges and failure modes of the structure are found. Pushover curve define the change of top displacement with relation with the applied base-shear force at all the increments. At each increment, the behavior of each structural element can be studied. To study the performance of the buildings under a specified earthquake force level defined by design spectrum, the performance point concept is introduced. FEMA 356 and ATC40 have different approaches to compute the performance point. Turkish Earthquake Code for Buildings, DBYBHY, (2006) recommends a computation of the performance point satisfying the equal displacement rule.

The nonlinear analyses of the different models are performed using SAP2000 (CSI, 2009). The

nonlinear properties for columns and beams are assumed to be a plastic P-M-M hinge and one component plastic moment hinge, respectively. The plastic hinges are defined according FEMA 356 with the given rebar distribution given in Table 2. The axial force for columns, and shear force for beams is considered from a combination of dead and live loads (G+0.3Q) and the transverse reinforcing is not conforming. The pushover curves for the three models are shown in Figure 6. To compute the performance, the Pushover curves are converted to capacity curve using the modal properties of the system. The performance point is computed as 0.107 cm for all the different models according to DBYBHY, (2006) procedure. The Storey drifts ratios for RC buildings using different shear wall models are shown in Figure 7. Plastic hinge status for beams and columns at performance point for multi layer shell and Mid-Pier Frame models are given in Figure 8.
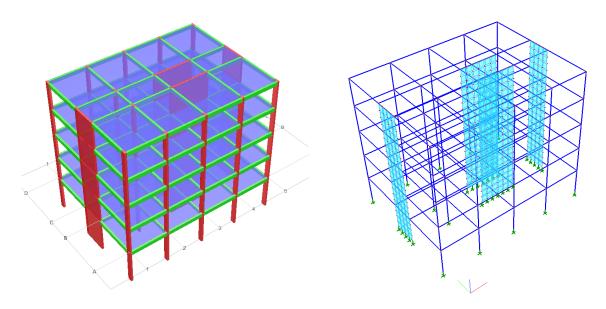

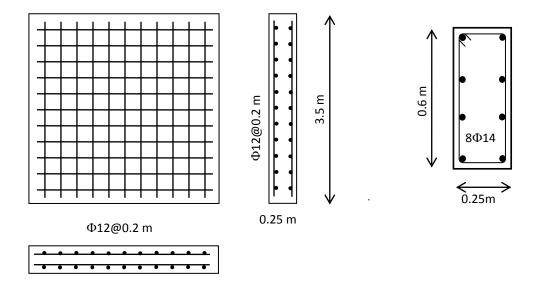**Figure 4.** Three dimensional physical and analytical model of the example building

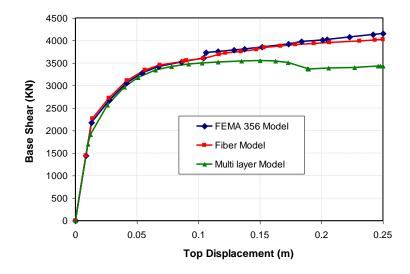**Figure 5.** Example of reinforcement distribution in the shear wall and column members

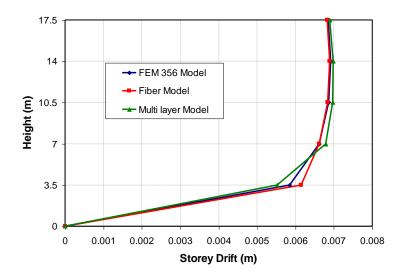**Figure 6.** Pushover curves for RC buildings using different shear wall models

Figure 7. Storey drifts ratios for RC buildings using different shear wall models

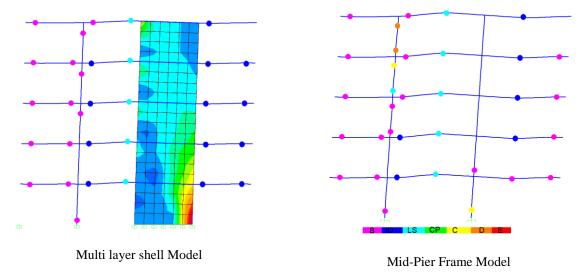

Multi layer shell Model

Mid-Pier Frame Model

Figure 8. Plastic hinge status at performance point for multi layer shell and Mid-Pier Frame models

5. DISCUSSIONS AND CONCLUSIONS

Based on numerical results for different buildings models and shear walls configurations and the different analyses set results of the example building, the following conclusions can be made.

The shear wall with two layers of longitudinal and transverse reinforcement bars could be modeled with different techniques to account for the RC material nonlinearity (multi layer shell and Mid-Pier frame with plastic hinges). The plastic hinges characteristics of the shear wall could be defined using FEM356 recommendation or Fiber based Hinge property. The pushover analysis for FEM356 model and Fiber model produce identical top displacement-Base shear curves for the example building. These curves are approximately the same as curve generated using multi layer shell model for the first 0.1 m of the incremental analysis. FEM356 and Fiber models overestimate the capacity of the structure for incremental displacement greater than 0.1m in comparison with multi layer shell model.

Taking into account that the performance point of the example building is equal to 0.107 m where the pushover curves of the three models are approximately identical, the storey drifts ratios are identical for the three models. The hinge status of the three models at the performance point provided almost the same pattern. To examine the shear walls performance, FEM356 and Fiber hinge models produce plastic rotations that could be checked with ACI 40 and FEMA 356's acceptance criteria recommendations. Although, the nonlinear behavior of multi layer shell can be examined by checking out the stresses in concrete and reinforcement layers, ACI 40 and FEMA 356 plastic rotations performance levels could not be applied. In the case of the wall or wall segment behavior is governed by shear, shear drift ratio as the deformation measure can be used as defined in ATC-40.

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