PUSHOVER ANALYSIS FOR PERFORMANCE BASED-SEISMIC DESIGN OF RC FRAMES WITH SHEAR WALLS

Y.Fahjan
Gebze Institute of Technology, Istanbul, Turkey

B.Doran
Yıldız Technical University, Istanbul, Turkey

B.Akbas
Gebze Institute of Technology, Istanbul, Turkey

J.Kubin
Prota Eng.Comp., Istanbul, Turkey

SUMMARY
Over the past several years, seismic design codes which have consequently been updated for the seismic rehabilitation of buildings have become more stringent for the implementation of Performance Based Design principles, especially for existing structures. Performance-Based Design requires rigorous nonlinear analysis. Nonlinear static analysis (pushover analysis) under constant gravity loads and monotonically increasing lateral forces during an earthquake until a target displacement is reached is generally carried out as an effective tool for performance based design. The major outcome of a pushover analysis is the capacity curve which shows the base shear vs. the roof displacement relationship and represents the overall performance of the building. Therefore, the numerical modeling technique used for reflecting the physical behavior of structural elements such as frame and shear walls, becomes most important issue in design process. For nonlinear analyses, the nonlinear material model of mid-pier frame element is generally based on plastic hinge concept located at plastic zones towards the ends of structural elements or distributed along the member span length. The nonlinear behavior of shells is generally modeled using multi-layer shell element with layered material model. In this approach, the concrete and the reinforcement contained in the structural elements are modeled using different layers respectively. This paper evaluates and comments on the consistency of different approaches for nonlinear shear wall modeling that are used in practice. For this purpose, 3, 5 and 7-story reinforcement concrete (RC) frames with shear walls are analyzed using nonlinear two dimensional nonlinear finite element method under constant gravity loads and incrementally increased lateral loads. The analysis results for these models are compared in terms of overall behavior of the structural systems. Besides, definition of the plastic hinge properties which strongly affects the prediction of the capacity curve of RC wall in the pushover analysis is also discussed.

Keywords: Seismic design, Pushover analysis, RC Shear wall, Plastic hinge

1. INTRODUCTION

For medium- and high-rise reinforced concrete (RC) buildings, the use of coupled and/or uncoupled shear walls (SWs) is almost indispensable, since they resist the lateral loads very efficiently. Several modeling techniques are suggested for the evaluation of the elastic and inelastic behavior of the lateral load resisting structures with SWs. The studies of system behavior have indicated that SW systems possess sufficient stiffness and strength for successful performance especially in regions of high seismicity. SWs were modeled as 2D conjugate frames, where rigid members were introduced at the intersection potions between story beams and walls in order to characterize the large size finite widths of the SWs (Figure 1). In nonlinear push-over analysis which is mainly used in structural design for determining the lateral capacity and evaluating the seismic performance of a building, moment-curvature relationships for the structural elements are strongly needed. Equivalent frame or conjugate frame model can be used for this purpose as it is simple, clear in concept, and is widely used in practice. In reinforced concrete shear wall (RCSW) systems, the conjugate frame analogy may be easily employed replacing SWs by conjugate frames for the purpose of simplicity in defining these curves. S.L. Lee (1958) investigated the extension of the conjugate beam method in order to study the deformation of rigid-frame structures in elastic and plastic domain. A. Abdul-Shafi (1985) introduced the conjugate beam concept to the solution of the combined effect of shear and flexure in frames and nonprismatic elements, provided an efficient tool for frame analysis, especially when evaluation of displacements is required at several locations in the structure. Xenidis et al. (2000) evaluated and commented on the reliability of several simplified models for open two-cell cores that are often used in practice. Doran, B. (2003), studied the structural behavior of coupled shear walls using equivalent beam algorithm to obtain the actual stiffness of tie beams in elasto-plastic space. Rana, R. et al. (2004), performed pushover analysis on a nineteen story, slender concrete tower building located in San Francisco. Lateral system of the building consisted of concrete shear walls which were modeled as equivalent frame elements and performance level was computed according to 1997 Uniform Building Code. Li Qin and Xiao-gang Jia (2009) discussed RC frame-shear wall structure with specially shaped columns. They also carried out time-history analysis to study the seismic responses of two different layouts of RC frame-shear walls with specially shaped columns. Belmouden, Y., Lestuzzi, P. (2009), presented a novel equivalent planar-frame model with openings and seismic analysis using the Pushover method for masonry and reinforced concrete buildings having walls. The constitutive laws were modeled as bilinear curves in flexure and in Shear and a biaxial interaction rule for both axial force–bending moment and axial force–shear force were considered. Doran, B. (2009) conducted a study on coupling ratio which is considered to be a key parameter in the nonlinear analysis and design of coupled shear walls using magnified beam theory. Guner, S., and Vecchio, FJ. (2010) studied nonlinear analyzing procedure on the previously tested structures consisting of beams, frames, and shear walls. In proposed frame procedure, computed parameters such as crack widths, reinforcement strains, and member deformations were represented successfully and the procedure was exhibited excellent convergence and numerical stability, requiring little computational time. Fahjan et al. (2011), studied different approaches for linear and nonlinear shear wall modeling and applied to a RC building case with shear walls.

This paper focuses on nonlinear modeling of RC shear walls for low and mid-rise buildings. In current practice, plastic hinges develop along the critical height of the shear walls. In this study, the shear walls were assumed to be a part of a RC frame so that different nonlinear modeling techniques would fully be investigated, i.e. the frames in this study might be assumed as the frames that were strengthened with RC shear walls. The need for such models is to analyze structures in a very short time and second.

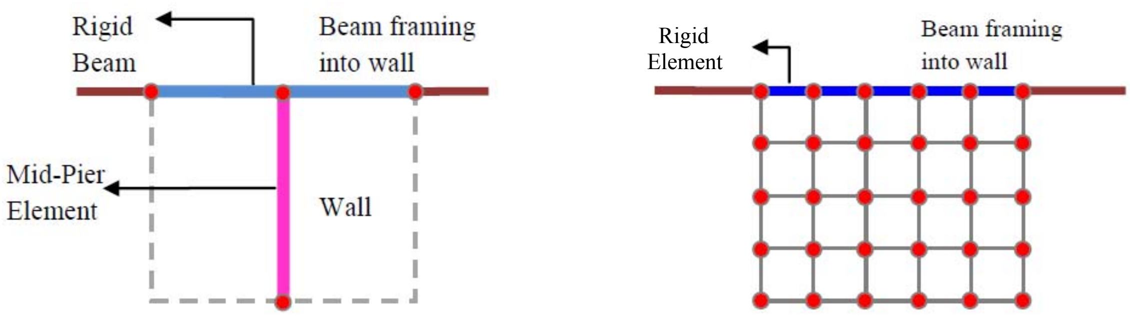


Figure 1. FE model definition of RC shear wall

2. NONLINEAR MODELLING TECHNIQUES FOR RC SHEAR WALLS

Under a strong seismic event, a structure may probably be subjected to forces beyond its elastic limit. Therefore, nonlinear relationship between the lateral shear force and lateral deformation of RC Wall should be considered. With the availability of fast computers, these relations where inelastic structural analysis is combined with seismic hazard assessment can be defined more easily. In this paper, the nonlinear modeling of shear walls are ranged from two dimensional nonlinear shell elements to simplified models using frame elements.

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-of-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 (Hafjan et al., 2010). 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.

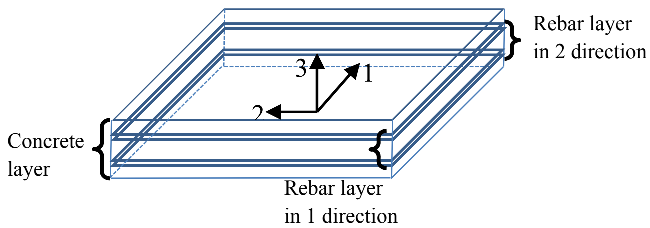


Figure 2. Multi-layer shell elements

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

The shear wall is model with a composition of frame elements. Equivalent frame model can be assumed of mid-pier and rigid beams. The material nonlinearity of the shear wall can be modeled considering a plastic hinge on mid-pier element (Hafjan et al., 2010). 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.

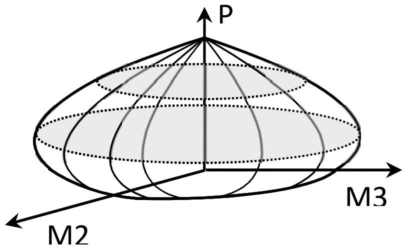


Figure 3. Typical P-M-M interaction curve

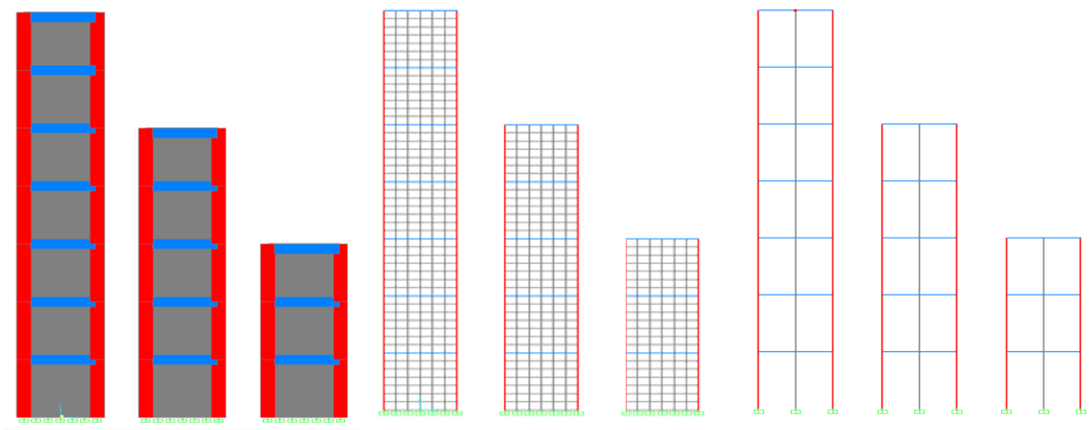
3. NUMERICAL EXAMPLE

For a contribution to the seismic vulnerability assessment of existing buildings through the development of simplified analytical models, 3, 5 and 7-story two dimensional frames with single RC shear walls surrounded by RC beams and columns were considered for the nonlinear static analysis. Physical and analytical models of considered frames with shear wall subjected dead load (G) are shown in Figure 4. On behalf of the short analyzing time and optimal solutions in structural retrofitting, such models are strongly needed. Wall cross-section dimensions and reinforcement details are kept same for 3, 5 and 7-story frame systems and summarized in Table 1 and Figure 5.

Table 1. Wall geometrical properties and reinforcement details

Structural elements	Dimensions (mm)	Reinforcement distributions
Wall	3500/250/3000	Longitudinal Rebars: ϕ12/20 Transverse Rebars: ϕ12/20
Column	250/600	Longitudinal Rebars: 8ϕ14 Confinement: ϕ8/20
Beam	250/500	Top Reinforcement %0.8 Bottom Reinforcement %0.4 at both ends

Concrete and reinforcement grades used for structural members were assumed to be 14 MPa and S420, respectively. This corresponds to a modulus of elasticity value of 2.615x107 kN/m^2 according to Turkish Reinforced Concrete Design Code (TS500).



(a) (b) (c)

Figure 4. Two dimensional 3, 5 and 7-story frames (a) physical model (b) analytical model with multi-layer shell elements (c) analytical model with mid-pier frame elements

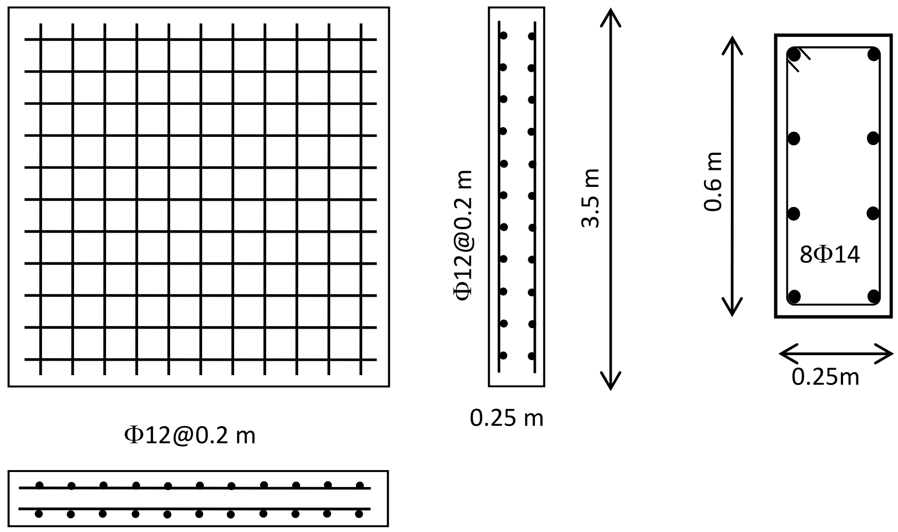


Figure 5. Reinforcement distribution in the shear wall and column

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; 3.5 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 1. The axial force level is considered from dead loads (G).

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).

Nonlinear Static Analyses (Pushover) are performed to explore the nonlinear behavior of proposed shear wall models. Pushover analysis is a nonlinear static procedure in which the magnitude of the structural loading is incrementally increased in accordance with a certain predefined pattern and is an effective tool for performance based design. At each increment, failure modes of the structure, base reactions and maximum roof displacements are found. With the relations between base-shear force at all the increments and the roof displacement; a capacity curve (Pushover curve) can be defined. The nonlinear analyses of 3, 5 and 7-story RC frames with shear wall are performed using SAP2000 (CSI, 2009) using three different modeling techniques for RC wall. Deformed shapes can be seen in Figure 6. In these figures, one can easily see that mid-pier frame models experience exactly the same deformation compared to multi-layer shell element model as expected.

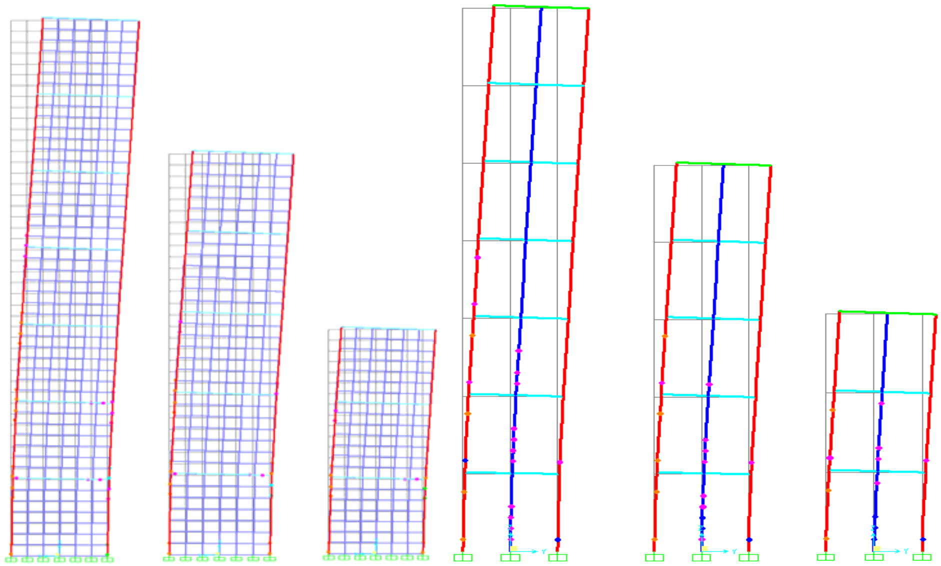


Figure 6. Deformed shapes (a) Multi-layer shell element model (b) Shear walls with mid-pier frame models

In all these models, 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 1. The axial force for columns, and shear force for beams is considered from a dead load (G) and the transverse reinforcement is not conforming. In mid-pier frame concept, plastic hinges defined generally at the top and bottom of the shear wall may not be adequate for representing the inelastic phenomenon. In order to investigate the effect of the number of potential plastic hinges and locations (Figure 7), 3, 5 and 7-story RC frame models with mid-pier frame concept are analyzed separately. The pushover curves for all cases are provided in Figure 8 for comparison. Besides, the inter-story drifts ratios using different shear wall models are shown in Figure 9. At the global inter-story drift ratio of 0.02, roof displacement demands of 3, 5 and 7-story frames are evaluated 21 cm, 35 cm and 49 cm respectively.

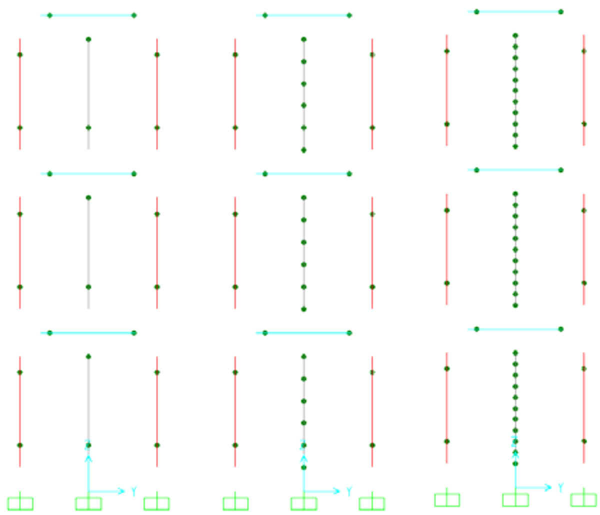
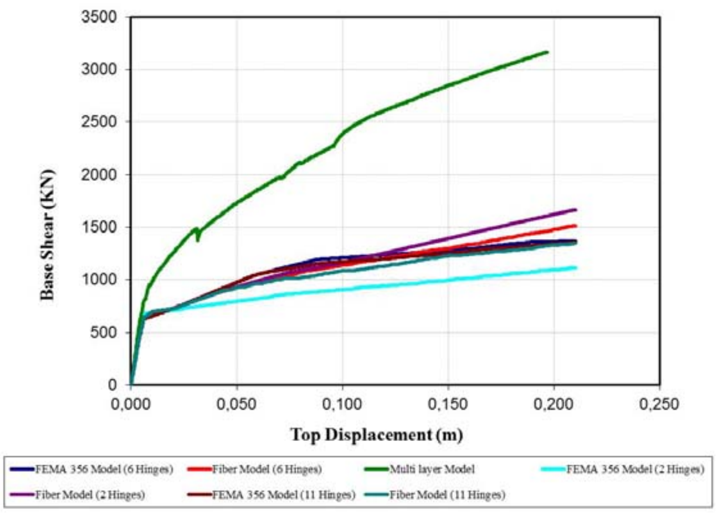
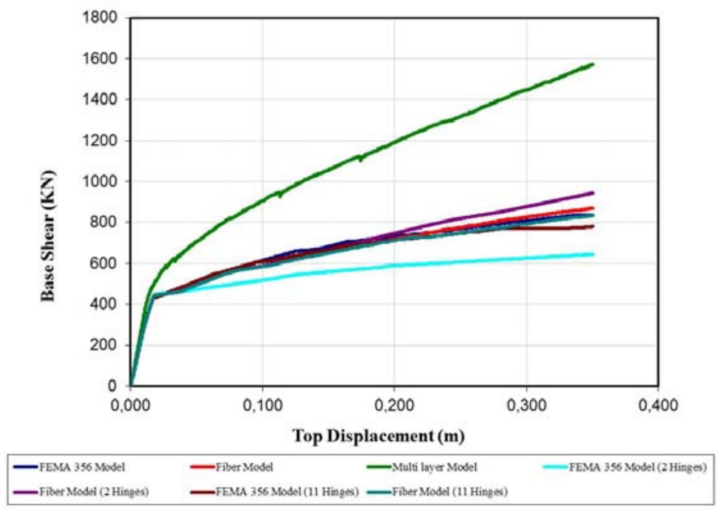


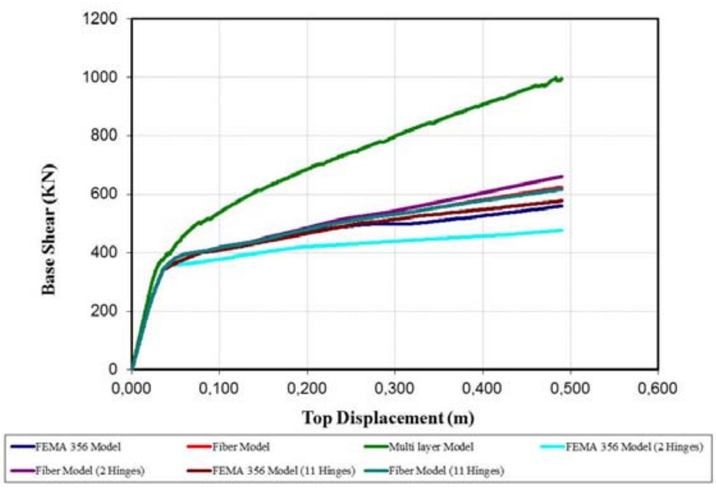
Figure 7. Variation of potential plastic hinge for 3-story frame



(a) 3-Story frame

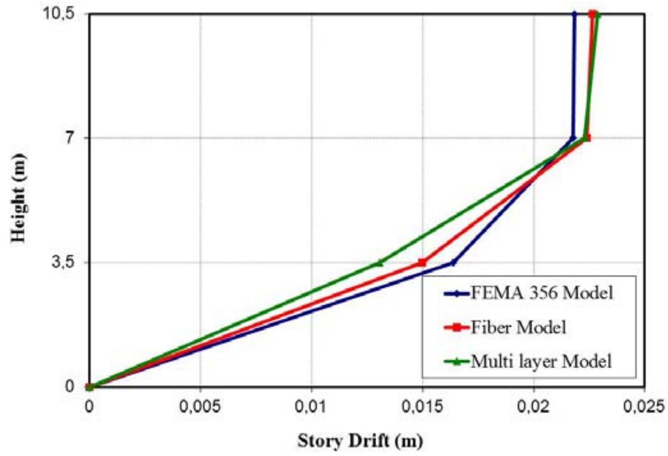


(b) 5-Story frame

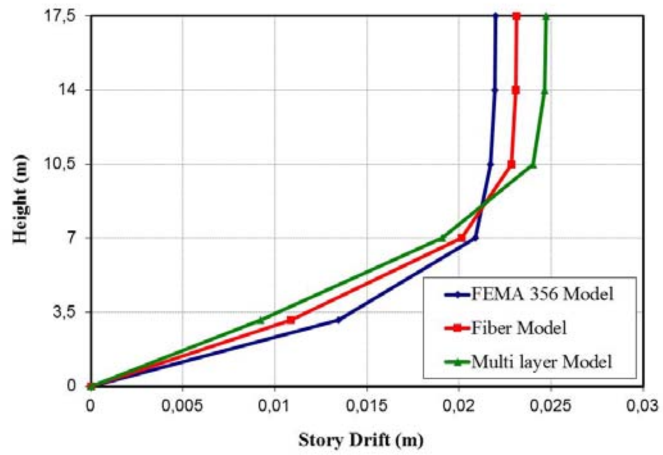


(c) 7-Story frame

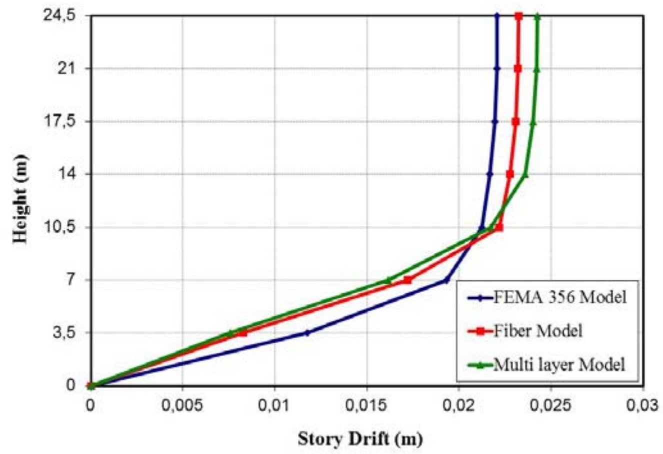
Figure 8. Pushover curves for different shear wall models



(a) 3-Story frame



(b) 5-Story frame



(c) 7-Story frame

Figure 9. Inter-story drift ratios for different shear wall models

4. CONCLUSIONS

As the numerical simulation technique used for reflecting the physical behaviour of frame and shear walls becomes most important issue in design process, this study is primarily concerned with the consistency of different approaches for nonlinear shear wall modelling. For this purpose, 3, 5 and 7-story RC frames with shear walls are analysed in two dimension nonlinear finite element method. Based on numerical results for different frame models with shear wall, the following conclusions can be drawn.

1. The shear wall with two layers of longitudinal and transverse reinforcement bars could be modeled with multi-layer shell and mid-pier frame with plastic hinges to reflect the material nonlinearity. The plastic hinge properties of the shear wall could be defined using FEMA 356 recommendation or fiber-based hinge property. The pushover analysis based on FEMA 356 model and fiber model produced identical top displacement-base shear curves for the sample frames. These curves are approximately similar except multi-layer shell model for all cases.

2. Number of plastic hinge locations is a major key for the accurate representation of the inelastic phenomenon for the RC shear walls. FEMA 356 model with 2 plastic hinges overestimates the capacity of the structure for all cases as depicted in Figure 8.

3. Since the capacity curves for mid-pier frames with plastic hinges defined using FEMA 356 recommendation and fiber-based hinge property are identical with each other, shear walls can be modeled using mid-pier frame with plastic hinges defined using FEMA 356 recommendation for short time modeling.

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