Earthq Eng & Eng Vib (2018) 17: 821-834 **DOI**: https://doi.org/10.1007/s11803-018-0478-1

Finite element modeling assumptions impact on seismic response demands of MRF-buildings

Shehata E Abdel Raheem[1, 2†], Ahmed K Abdel Zaher[1, 2‡] and Ahmed MA Taha[1‡]

1. *Civil Engineering Department, Engineering College, Taibah University, Madinah 41411, Saudi Arabia*

2. *Civil Engineering Department, Faculty of Engineering, Assiut University, Assiut 71516, Egypt*

Abstract: Recent seismic events have raised concerns over the safety and vulnerability of reinforced concrete moment resisting frame "RC-MRF" buildings. The seismic response of such buildings is greatly dependent on the computational tools used and the inherent assumptions in the modelling process. Thus, it is essential to investigate the sensitivity of the response demands to the corresponding modelling assumption. Many parameters and assumptions are justified to generate effective structural finite element (FE) models of buildings to simulate lateral behaviour and evaluate seismic design demands. As such, the present study focuses on the development of reliable FE models with various levels of refinement. The effects of the FE modelling assumptions on the seismic response demands on the design of buildings are investigated. the predictive ability of a FE model is tied to the accuracy of numerical analysis; a numerical analysis is performed for a series of symmetric buildings in active seismic zones. The results of the seismic response demands are presented in a comparative format to confirm drift and strength limits requirements. A proposed model is formulated based on a simplified modeling approach, where the most refined model is used to calibrate the simplified model.

Keywords: RC-MRF buildings; design codes provisions; seismic design; finite element modeling; modeling assumptions; response demands

1 Introduction

Throughout recorded history, many earthquakes have occurred resulting in significant damage to buildings and severe human injury and fatality. Recent awareness of potential activity in seismic regions has led to concerns over the safety and vulnerability of RC buildings. Although broad research studies have developed robust modeling techniques for the seismic response of RC-MRF buildings (ASCE, 2006), there is still an essential need for applications of reasonably simple elastic modeling for the practical design of tall buildings (Wallace, 2007), principally in active seismic regions. Practical elastic models could lessen computational complexity and design labor (Shin *et al.*, 2010). Finite element (FE) modeling assumptions and boundary conditions have substantial effects on the analytical assessment of the ductility demand and force response demand measures for building structures. Numerical simulation and robust modeling are of particular importance when viewed in the light of the large capital investment and complications with the satisfaction of dynamic similitude encountered in physical testing (Elnashap and McClure, 1996). The evaluation of a building's seismic response is subjected to a significant degree of approximation and simplification of its physical behavior. The actual seismic lateral response depends on the parameters and assumptions adopted when creating the structural models of an RC building, which will significantly affect the seismic drift and force response demands. Vona and Mastroberti (2018) estimated the behavior factor of existing RC-MRF buildings. Three-Dimensional FE structural modeling is the most appropriate method for structural analysis and seismic design of buildings. Hur *et al.* (2017) investigated the effect of structural modeling assumptions on the dynamic analysis of 3D and simplified 2D stick models of auxiliary buildings to quantify the impact of the uncertainties associated with modeling and analysis of simplified numerical models of structural components subjected to seismic excitation on the predicted seismic failure probabilities. Hwang and Lignos (2017) investigated the effect of modeling assumptions on the earthquake-induced losses and collapse risk of steel frame buildings with special concentrically braced frames. Jianbo *et al.* (2017) studied the dynamic effects of various parameter uncertainties on

Correspondence to: Shehata E Abdel Raheem, Civil Engineering Department, Engineering College, Taibah University, P.O. 344, Madinah 41411, Saudi Arabia
Tel: +966-569080208
E-mail: shehataraheem@yahoo.com
†Professor; ‡Assistant Professor
Supported by: Scientific Research Deanship, Taibah University Grant No. 6363/436
Received May 1, 2017; **Accepted** September 4, 2017

the in-structure floor response spectra of nuclear power plant. Fayun *et al.* (2017) investigated the accuracy of three-dimensional seismic ground response analysis in time domain using nonlinear numerical simulations.

Numerical analysis of building structures relies, to a large extent, on the designer's understanding of structural behavior, the selection of appropriate software, the FE modeling approach and the analysis method chosen. Simple structural analysis is more cost effective and requires less effort if it proves that the building structure is in a satisfactory condition. However, if the structure cannot be proven satisfactory, more advanced structural analysis should be used in order to avoid erroneous or defective conclusions leading to either over-strengthen the structure causing large economical losses or to insufficiently intervene on it and hence generate inadmissible risks (Roca *et al.*, 2010). For analysis of a building structure, analytical models are often developed using line elements based on centerline dimensions of beams and columns. Commercial software programs such as ETABS (CSI, 2015) commonly adopt the rigid diaphragm assumption in the analysis procedure for simplicity. As a result, the flexural stiffness of the floor slabs is typically overlooked. Moreover, even though beams are positioned under floor slabs in the buildings, the analytical model is established with the assumption that beams and floor slabs have conjoint axes. Therefore, the T-beam effect and the flexural stiffness of floor slabs are ignored; hence, significant analytical errors could occur (Lee *et al.*, 2003, Zeris *et al.*, 2007). In spite of that, Krawinkler (2000) has shown that a linear elastic model using centerline dimensions is acceptable for the design of special moment frames. Although this model gives satisfactory results for design, it will not always give a good assessment of the distribution of shears, moments and axial forces throughout the building under lateral seismic loads. An alternative approach that magnifies beam inertia was introduced to simulate realistic T-beam behavior (Mehanny *et al.*, 2010, 2012; Soliman *et al.*, 2012). The inertia of the beams is magnified to simulate the realistic seismic behavior of the projected beams below the floor slab. The dropped beam was modeled as it symmetrically and collinearly centerline to centerline connected to the slab. The magnification of beam inertia due to the T-beam effect in RC frames enhances the overall lateral stiffness of buildings, and could efficiently simulate realistic seismic behavior of RC-MRF buildings. Moreover, buildings with higher beam inertia display a shorter fundamental period of vibration and, consequently, display higher base shear force demands and could satisfy the code requirement for drift limits. However, magnifying beam stiffness relative to the column stiffness could violate the desirable weak beam-strong column design concept for the desired structural failure mechanism. Strong column weak beam design concept gives local failure while strong beam and weak column gives global failure which does not give sign of failure and structure collapse suddenly. Rivera and Petrini (2011) have studied the seismic response of RC MRF buildings designed according to the Eurocode 8 (CEN, 2005). Their results indicated that the design of flexural members in medium-to-long period structures is not significantly influenced by the choice of effective member stiffness; however, calculated inter-story drift demands are significantly affected.

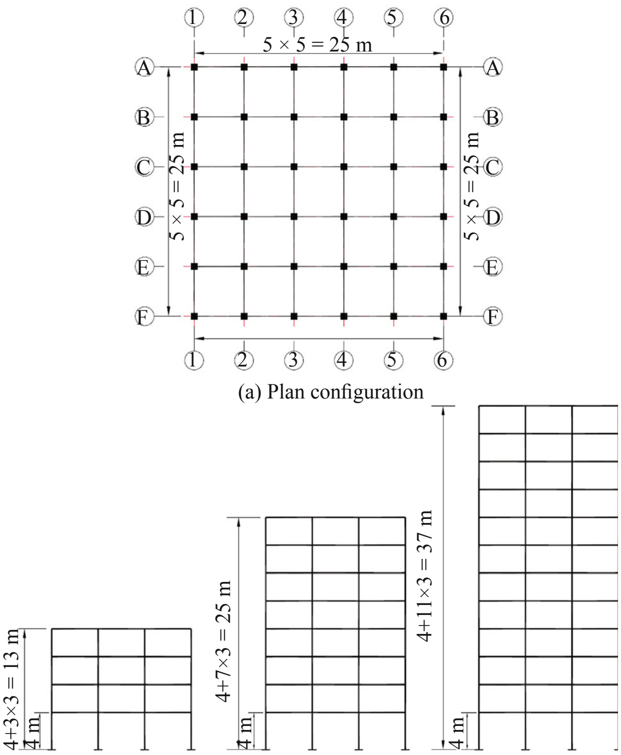
In a more refined modeling approach, a finite dimension of a beam-column joint is modeled by inserting a rigid eccentricity at the ends of the beam and column elements to take into consideration the effect of the joint geometry; a rigid joint is usually assumed (Shin *et al.*, 2010). The rigid offset approach as an alternative to the centerline dimension approach could lead to significant modifications in global stiffness as well as relative story shear force demands. Therefore, there is a substantial modification in the inter-story drift demands along the building's height. However, rigid connections may only accurately represent the building's strength and stiffness in terms of inter-story drift and the global lateral displacement. Results from such models could overrate ductile capacity of the buildings. Tests reveal that beam-column joints can undergo substantial shear deformations even before yielding of the longitudinal reinforcement within the joint (Walker *et al.*, 2002). The shear deformations effects could be estimated by extending the beam or column flexibility into the joint. Some engineering analysis software applications permit the modeling of a panel zone shear deformation explicitly, where the panel zone deformation is typically based on simple mechanical analogy of an assemblage of rigid links and rotational springs. However, other applications account for the contribution of the panel zone implicitly through the implementation of an end zone offset factor that adjusts the length extension of beams and columns in the panel zone region.

The design for seismic hazard has been a difficult aspect of the design process for projects throughout the Kingdom of Saudi Arabia (KSA) mainly due to uncertainty associated with earthquakes, different design methods set out in the various standards, codes, and design provisions, and the various alternative requirements (FEMA, 1997; ICBO, 1997; ICC, 2000; ECP, 2007; SBC, 2007). Structural models are used to define the force and deformation responses demands that are required for the design of new building structures and performance evaluation of existing ones (ASCE, 2005, 2006; Wallace, 2007). The accuracy of section rigidity and element stiffness modeling significantly affect the calculation of structural global stiffness and hence the seismic forces imposed. The effects of T-beam and beam-column joint rigid offset in the modeling of structural elements on the seismic design demands of RC-MRF buildings are investigated to precisely predict the behavior of buildings under seismic lateral loads. This study aims to carry out a thorough evaluation of different modeling techniques ranging from simple to more refined modeling techniques to produce a robust

FE model that could give results similar to the real structural behavior of RC-MRF buildings. A quantitative measure of the importance of modeling assumptions and FE modeling level on the predicted response is formulated through a comparison between simplified and refined models. A reference-refined model based on a shell modeling approach is formulated to quantify the accuracy of the simplified models and to determine a modification factor for the calibration of the simplified model to improve the predictive accuracy. Based on the results, a calibrated FE model that identically matches the response demands of the most refined model is formulated and introduced for structural engineers.

2 Studied buildings and seismic structural design

Three buildings with different numbers of stories, a typical floor height of 3 m, and a ground floor height of 4 m have been considered. In this study, 4-story, 8-story and 12-story buildings were selected, where the layout of the buildings is a bi-symmetric square in plan with 5 equal bays of 5 m width in both directions, as shown in Fig. 1. The building models are analyzed and designed using ETABS following the seismic design provisions (ASCE, 2010; ACI, 2011). In addition, SAFE software is used to design and check the long-term deflection and the punching shear of the floor slab. A moment resisting frame (MRF) structural system is adopted for resisting the vertical and horizontal loads, and a slab with dropped beams is adopted for the floor structural system. A solid slab is used at all floors with a designed thickness of 0.2 m. The dimensions and reinforcement details of the structural members of the MRF building models are given in Table 1. The model used for structural design of the MRF building is based on centerline dimensions without accounting for the finite panel zone dimensions. The bases of the columns are assumed to be fixed to the foundation and have constant cross section along the building's height. The beam-to-column connections were assumed to be fully rigid. A semi-rigid diaphragm constraint is imposed to simulate the effect of the slab. For gravity load, dead loads include the self-weight, a floor cover of 1.5 kN/m^2 and an equivalent load of 1.0 kN/m^2 for plastering and partition walls. A live load of 2.0 kN/m^2 is considered. The concrete has a compressive strength of $f_c' = 30$ MPa and the steel rebar has a yield stress of $f_y = 460$ MPa.



(b) Elevation configuration

Fig. 1 Model configuration of the studied buildings

The ASCE 7-10 code provisions (2010) are adopted for calculating the lateral seismic design loads on the buildings with assumption: soil type B, response modification factor $R = 5$, system over-strength factor $W = 3$, and deflection amplification factor $C_d = 4.5$. A total seismic mass including self-weight and floor cover plus 25% of live load is considered (ASCE, 2010). The calculation of seismic loads is based on ASCE 7-10, Section 12.8. The seismic base shear V, shall be calculated as follows:

$$V = C_s W \tag{1}$$

where C_s is the seismic response coefficient and W is the effective seismic weight. The seismic response coefficient is determined as follows:

$$C_s = \frac{S_{DS}}{R / I_e} \tag{2}$$

where S_{DS} is the design spectral response acceleration at short periods for 5% damping, R is the response modification factor, and I_e is the importance factor. The computed seismic response coefficient shall not exceed the following:

$$C_s = \frac{S_{D1}}{T(R / I_e)} \text{ for } T \le T_L \text{ and } C_s = \frac{S_{D1} T_L}{T^2 (R / I_e)} \text{ for } T > T_L \tag{3}$$

where S_{D1} is the design spectral response acceleration parameter at a period of 1.0 s, T is the fundamental period of the structure, and T_L is the long-period transition period. The design earthquake spectral response acceleration parameters at a short period and at 1 s period are determined from the mapped risk-targeted maximum considered earthquake spectral response acceleration parameters (ASCE, 2010).

Table 1 Design for sizes and reinforcement of structural members of MRF building models*

Building	Beams			Columns	
	Cross section $b \times h$ (cm × cm)	Steel bars		Cross section $a \times a$ (cm × cm)	Steel bars
		Top layer	Bottom layer		
4-Story Building	20 × 60	4ϕ16	4ϕ16	40×40	12ϕ16
8-Story Building	20 × 60	4ϕ16	4ϕ16	45×45	12ϕ20
12-Story Building	20 × 60	4ϕ16	4ϕ16	55×55	16ϕ20

*Reinforcement shown in table for all columns with a square cross-section represents the total number of rebars to be distributed equally along the 4 sides. Reinforcement given for beams represents the number of rebars used per side (top and bottom) of the beam's cross-section. Beams have symmetric reinforcement to accommodate expected reversible bending moments during seismic events.

3 Finite element modeling assumptions

Various three-dimensional (3D) modelling procedures have been used to idealize building structure geometries that range from detailed 3D solid modelling of all structural components to the grillage approach for one-dimensional elements (Chan and Chan, 1999; Lee *et al.*, 2003; Sousa *et al.*, 2012; Kwon and Ghannoum, 2016; Zendaoui *et al.*, 2016). Jayasinghe *et al.* (2017) introduced a conversion solution between solid and beam element solutions of finite element method based on meta-modeling theory. To obtain an accurate seismic response of a building using a mathematical model, an FE model is required that incorporates all the structural elements as well as simulates their true behaviour. Currently available approaches are either too simplified or neglect appropriate inter-component interaction. In order to reflect real structural behaviour, advanced simulations are needed in most cases. These simulations usually require more effort to develop. The outcome for this kind of analysis has generally been more favourable than that for simplified models. Analytical methods and models of varying complexity for RC-MRF buildings are developed to evaluate the different models' ability to predict global and local performance of multi-story buildings and the effects of analysis assumptions on the demand predictions. Three modelling options are investigated: centreline dimensions of elements, rigid offsets, and shell elements. A simplified procedure for assessment of global and local seismic demands is formulated to facilitate decision making in seismic structural design practice. The global response in terms of base shear, lateral displacement and inter-story drift are investigated**.** Analytical models of such frames are often developed using line elements based on centreline dimensions of beams and columns. However, it is usually required to account for the finite dimensions of the beam-column joints and the eccentric T-section beams by considering rigid offsets. Since beams and floor slabs are not located in conjoint axes, rigid offsets are introduced to simulate the T-beam effects as the first step of model refinement approach. The second step in model refinement is accounting for a finite dimension of a beam-column joint by including rigid eccentricities at the ends of the beam and column element as to take into consideration the effect of the joint geometry. Joints are usually assumed to be rigid; however, the use of rigid connections may not properly represent the strength and stiffness of the structural frame, as a result, the model based on rigid connections could not capture the inter-story drift and the overall deflection of the structure. Results from such models may overestimate the ductile capacity of the buildings considered (Le-Trung *et al.*, 2010).

4 Finite element modeling and seismic analysis implementation

A three-dimensional numerical model of the physical structure is used to represent the mass and stiffness distribution of the structure to a degree that is sufficient to determine the substantial features of the building's dynamic behaviour. The FE model and the nonlinear analysis are formulated for geometric nonlinearity due to large deformations and linear elastic material under serviceability limit state. For the seismic analysis, the response spectrum method is used to determine the lateral demands. The response spectrum method satisfies the standard dynamics requirement (ASCE, 2010). The modal response spectrum method provides a more accurate estimation of the lateral forces. The modal base shear force should be greater than 85% of the base shear force from the equivalent static force method (NBCC, 2005; CEN, 2005; ECP, 2008; ASCE, 2010). For response spectrum method, the square root of the summation of the squares (SSRS) is used for the directional combination, while complete quadratic combination (CQC) is adopted for the modal combination.

There is a hierarchy of different levels of modelling suitable for the structural analysis of RC-MRF buildings. A more refined modelling approach provides a more precise simulation of the actual performance of a building under earthquake lateral loads; however, it necessitates greater work in terms of data preparation and computational needs. The structural models considered in this paper represent the progressive steps in modelling complexity that might be adopted in a design office environment. The MRF building analytical model is developed in the FE structural analysis software program, ETABS. Several levels of FE modelling refinement for the slab-beam floor structural system are studied: T-beam effect on dropped beams in the floor structural system, beam-column joint modelling effects, and the use of shell elements. Different 3D FE modelling techniques have been used for modelling buildings. Simple modelling methods widely used as well more detailed models are investigated and compared. Five analytical models are used to evaluate the effect of different modelling refinement levels on local element deformation, story shear force demands, inter-story drift, and story drift demands. The characteristics of these different analytical models are described below.

4.1 Centerline based modeling, Model 1

A number of simplifying assumptions for seismic structural analysis are used while modelling the buildings. The floor slabs are assumed as semi-rigid diaphragms. The axes of beams and floor slabs are assumed to be located in a mutual plane, thereby ignoring the offsets in centreline between beams and floor slab. All columns are assumed co-linear along their centrelines. Beams and columns are modelled as frame elements with the centrelines joined at nodes and extended from centreline to centreline. Frame elements account for axial and biaxial shear deformations as well as biaxial bending and torsion (CSI, 2015). The strength, stiffness, dimensions and shear distortions of panel zones are ignored as shown in Fig. 2.

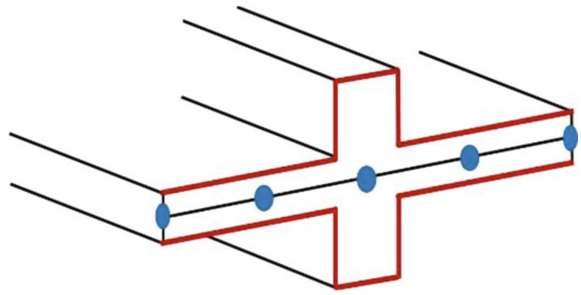


Fig. 2 Model 1: Centric beam element and floor slab shell element, centreline model

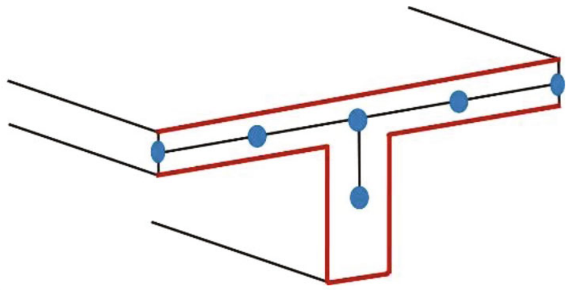


Fig. 3 Model 2: Eccentric beam element and floor slab element using a rigid offset for the T-beam effect

4.2 Beam rigid offset for T-beam effect, Model 2

Considering a beam-slab structural system, the conventional placement of the FE discretization nodes is at the slab mid-thickness and the beam longitudinal axis. However, beams and floor slabs are not positioned in a mutual plane. Thus, an analytical model is developed to assemble the global stiffness to a common location in order to consider the flexural stiffness of the floor beam. Rigid bodies are introduced to consider the T-beam effect in the structural modelling of RC-MRF buildings. The contribution of the T-beam effect on the stiffness of the beams could be important for the seismic assessment of the MRF-building because it will affect the relative stiffness between the beams and columns. The added rigid links stiffen the structure, which could satisfy the drift design criteria and give better estimates of the members' shear force, axial force, and bending moment demands. Model 2 can take into consideration the flexural stiffness of the floor slab and the T-beam effect as shown in Fig. 3.

4.3 Beam-column joint rigid offset, Model 3

The seismic response of RC buildings can be influenced by the behaviour of the beam-column joints involved in the failure mechanism, especially in typical existing buildings. Conventional modelling approaches consider only beam and column flexibility, although joints can provide a significant contribution also to the overall frame deformability. Thus, for structural modelling of RC-MRF buildings, it is required to account for the finite dimensions of the beam-column joints through rigid offsets between the interconnected beam and column elements. Columns and beams have clear span lengths and join through rigid offsets with dimensions equal to the member depth into which the element is being framed. It is reasonably precise to model the joint using effective rigid end offsets (Elwood *et al.*, 2007). The story drift responses are mostly produced by flexural and shear deformations of the beams and the columns as well as shear deformations in the beam-column joint panel zones. The contribution of panel zone deformation to the story drift is significant and should be considered. Some engineering analysis software programs explicitly model the panel zone shear deformation; however, most programs implicitly account for the contribution of panel zone through the implementation of an end zone offset factor to adjust the length of beams and columns in the panel zone region. FEMA 356 overestimates the stiffness of RC moment frames by assuming a rigid zone for the beam-column joints (FEMA, 2000).

Model 4-1 is formulated for both T-beam and beam-column rigid offset effects. Since this model considers the flexural stiffness of dropped beam and beam-column joint dimensions and the stiffness of the panel zone, it estimates the distribution of shear forces, flexural moments and axial forces more precisely than Models 1-3 do. Nevertheless, the beam-column joint model as a

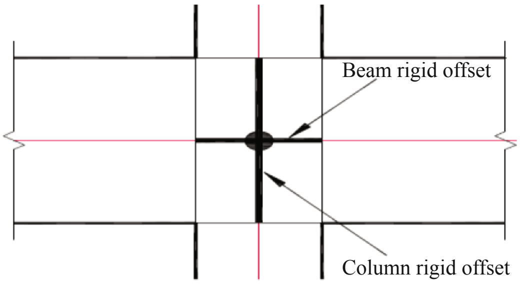


Fig. 4 Model 3: Beam-column joint with rigid offsets at both beam and column ends

rigid zone could overestimate the frame lateral stiffness. The shear deformations effects can be simulated in the analytical model by extending the beam and column flexibility in the joint as shown in Fig. 4. A correction factor is introduced to take into consideration the panel zone contribution to seismic performance and the factor is calibrated by the most refined model.

4.4 Refined model based on shell element modeling: Model 5

A detailed FE model using on shell elements for the dropped beam instead of frame element in the previous models is used for the simulation of the MRF building, as shown in Fig. 5. Beam behavior is ruled principally by flexure, which is best modeled using shell elements. In this model, both the beam and floor slab are modeled by quadrilateral shell elements. The analysis accounts for the three-dimensional interaction of all members. The beam shell modeling does not include intermediate T-beam and beam-column joint rigid offsets, but still retains the material variation and sectional properties of the slab and dropped beams. Based on the results, a proposed model, Model 4-2 is formulated based on the simplified model; Model 4-1 that considers both T-beam and beam-column rigid offset effects, in addition joint shear deformation is considered through a correction factor calculated through calibration to Model 5. The proposed model, Model 4-2, can capture the buildings' seismic response without being computationally expensive. Model 4-2 has vibration periods, seismic design demands, and response time histories that closely match to those attained from the Model 5.

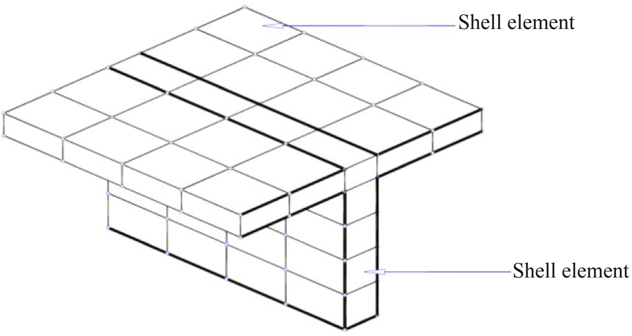


Fig. 5 Model 5: Beam and floor slab directly modeled as shell elements

5 Numerical results and discussion

Three-dimensional FE models of the studied buildings are established, each with different levels of modeling complexity, with centerline, rigid offset and shell elements considered. In the models, a semi-rigid diaphragm is assigned at each floor level. The numerical modeling and seismic analysis in this study are done using ETABS building analysis and design software (CSI, 2015). Models were built of typical existing 4-story, 8-story and 12-story RC-MRF buildings which were designed for moderate seismicity using the ASCE 7 seismic provisions (ASCE, 2010). A range of practical and more detailed FE idealizations are established. Following the seismic analysis, key performance indices at the global and local levels, such as the lateral displacement, the inter-story drift and the story shear force, are calculated and compared to quantify the effects of the modeling assumptions. The FE modeling technique which is simple and accurate enough for daily practice will be chosen and recommended for use in the construction industry. The current prominent practice in the construction industry is centerline modeling. Full stiffness for all structural elements has been assumed in analyses at service limit states.

5.1 Fundamental period and natural vibration

Fundamental period is a crucial parameter for seismic design of a building using the equivalent lateral force procedure. As the building period cannot be analytically calculated before design, empirical building period formulas are required to initiate the design process (BSSC, 2003; ASCE, 2005; Abdel Raheem, 2013; Abdel Raheem *et al.*, 2015). Three-dimensional nonlinear elastic FE models of the case-study buildings are formulated and analyzed. The natural periods, mode shapes, and modal mass participation factors for the first vibration modes are determined as listed in Table 2. The centerline-based model (Model 1) underestimates the story stiffness; hence, it overestimates the natural vibration period by 28, 31 and 32% for the 4-story, 8-story and 12-story buildings, respectively, compared to those of refined model (Model 5). Introducing the T-beam effect to Model 1 and Model 2 improved the estimation of the natural vibration period, this time overestimating the natural vibration period by 20, 17 and 13% for the 4-story, 8-story and 12-story buildings, respectively, compared to those of Model 5. Introducing beam-column rigid joint offsets in Model 3 further improved the estimation of natural vibration period, only overestimating the natural vibration period by 3, 8 and 10% for the 4-story, 8-story and 12-story buildings, respectively, compared to Model 5. Model 4-1 which combines T-beam effects and beam-column rigid joint

Table 2 Period for fundamental of vibration for studied building Models

Building	Vibration Modes	Period of vibration mode, T (s)					
		Model1	Model2	Model3	Model4-1	Model4-2	Model5
4-Story building	1st Lateral Mode	0.76	0.71	0.61	0.57	0.59	**0.59**
	2nd Torsional Mode	0.66	0.62	0.54	0.50	0.51	**0.51**
	3rd Lateral Mode	0.24	0.22	0.19	0.17	0.18	**0.19**
8-Story building	1st Lateral Mode	1.21	1.08	0.99	0.88	0.92	**0.92**
	2nd Torsional Mode	1.06	0.95	0.87	0.77	0.81	**0.81**
	3rd Lateral Mode	0.39	0.35	0.32	0.29	0.30	**0.30**
12-Story building	1st Lateral Mode	1.52	1.30	1.26	1.08	1.15	**1.15**
	2nd Torsional Mode	1.34	1.14	1.10	0.95	1.01	**1.01**
	3rd Lateral Mode	0.49	0.42	0.41	0.35	0.38	**0.38**

offsets slightly underestimates the natural vibration period. So, an end zone factor is explicitly introduced and is calibrated using the refined model, Model 5. The end zone factor values are calculated for 4-story, 8-story and 12-story buildings and are equal to 0.85, 0.80 and 0.65, respectively. These results show that the structural dynamics of the building is meaningfully influenced by the level of modeling refinement. It is concluded that higher vibration modes are less sensitive to the level of modeling refinement than the lower vibration modes. Additionally, the natural period is decreased as T-beam effects and beam-column offsets are included.

5.2 Seismic design demands

The results of the seismic analyses are assessed to identify the modeling parameters and assumptions that have the most significant impact on variability in simulated response. Based on the model's seismic response characteristics, design lateral forces are distributed to the building's structural elements using analysis techniques, and the resulting member forces and structural lateral displacements are calculated. ASCE 41 (2006) offers an acceptance criterion for deformations and forces on individual structural components. Other global seismic design demand parameters, especially inter-story drifts and floor accelerations, are essential indicators of damage to non-structural components and overall building performance (Abdel Raheem *et al*., 2018a&b; PEER, 2010; Willford *et al*., 2008; PEER/ATC, 2010; ATC, 2009). The following seismic design demand parameters are used to evaluate performance levels quantitatively: shear forces and deformations in structural elements, inter-story drifts, and story lateral displacement.

5.3 Displacement response profile

Evaluation of story drifts during the design stage is essential for predicting stability and damage limits on non-structural elements as well as for appropriately assessing the required gap between adjacent buildings. Excessive lateral drift can disturb vertical stability, particularly for massive flexible buildings, and could potentially lead to a collapse due to *P-Δ* effects. Thus, the possibility of reducing the lateral drift of a building would reduce the need for the rehabilitation its functionality and make it easier after a seismic shaking. Moreover, large lateral displacements amplify the internal force and moment demands, thus reducing effective lateral stiffness. With higher levels of internal forces, a smaller percentage of the structure's capacity remains available to withstand lateral loads.

To evaluate the accuracy of the response with the different levels of modeling refinement, the global response of the structure under seismic action is evaluated. The lateral displacement profiles for the studied models are depicted in Fig. 6. Displacement demands are significantly affected when the global stiffness of the structure changes between different models, as shown in Fig. 7. The use of centerline dimensions gives a distorted image of the relative significance of beam versus column stiffness in drift control. If centerline dimensions are used for columns rather than clear span dimensions, the contribution of the column flexural deformations to the inter-story drift can be easily overestimated. This overestimation arises because the column contribution to story drift is proportional to the cube of the column length. The seismic lateral displacement response of the analyzed building models is more affected by the use of rigid offsets compared to the use of centerline element dimensions. Model 1 consistently overestimates the lateral displacements, while Model 4-1 provides reasonable estimates and could be calibrated by Model 5 using end zone factor, as in Model 4-2. Contributions to drift vary with consideration of T-beam and beam-column joint effects. The beam-column joint effect is a significant contributor to the lateral displacement response demands for low rise-buildings; this contribution decreases gradually for high buildings. In contrast, the T-beam effect has a slight contribution to the lateral displacement response for low-rise building,

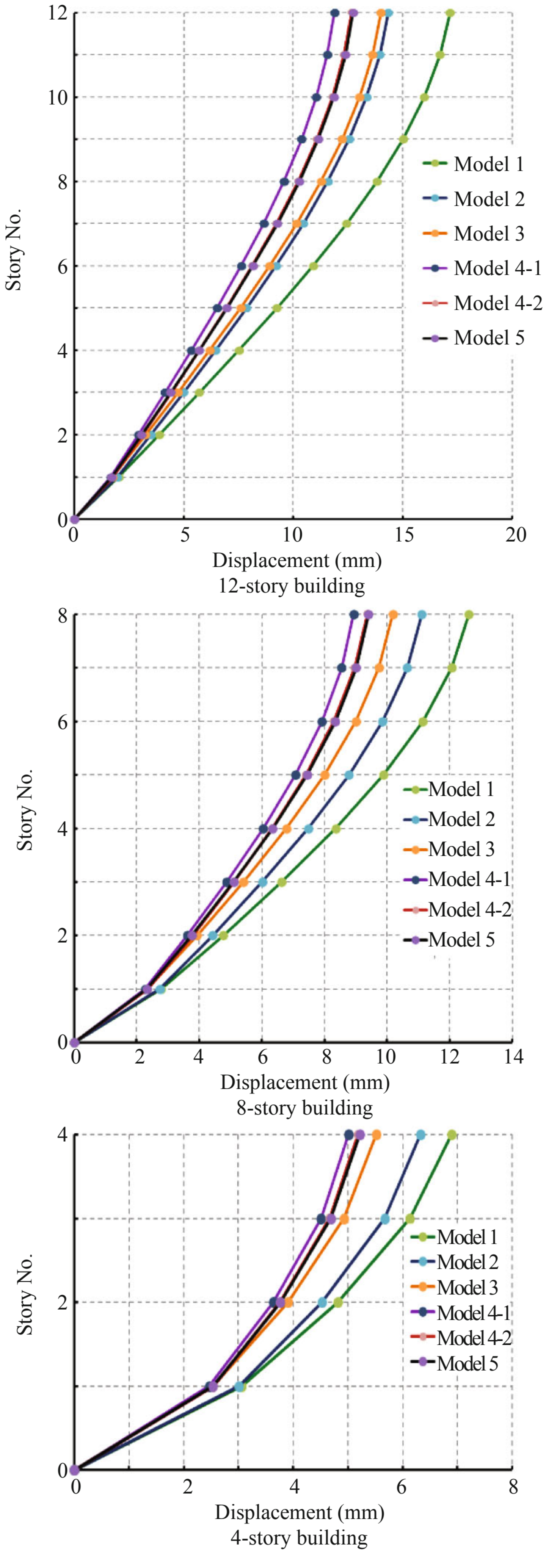


Fig. 6 Displacement profile for different models

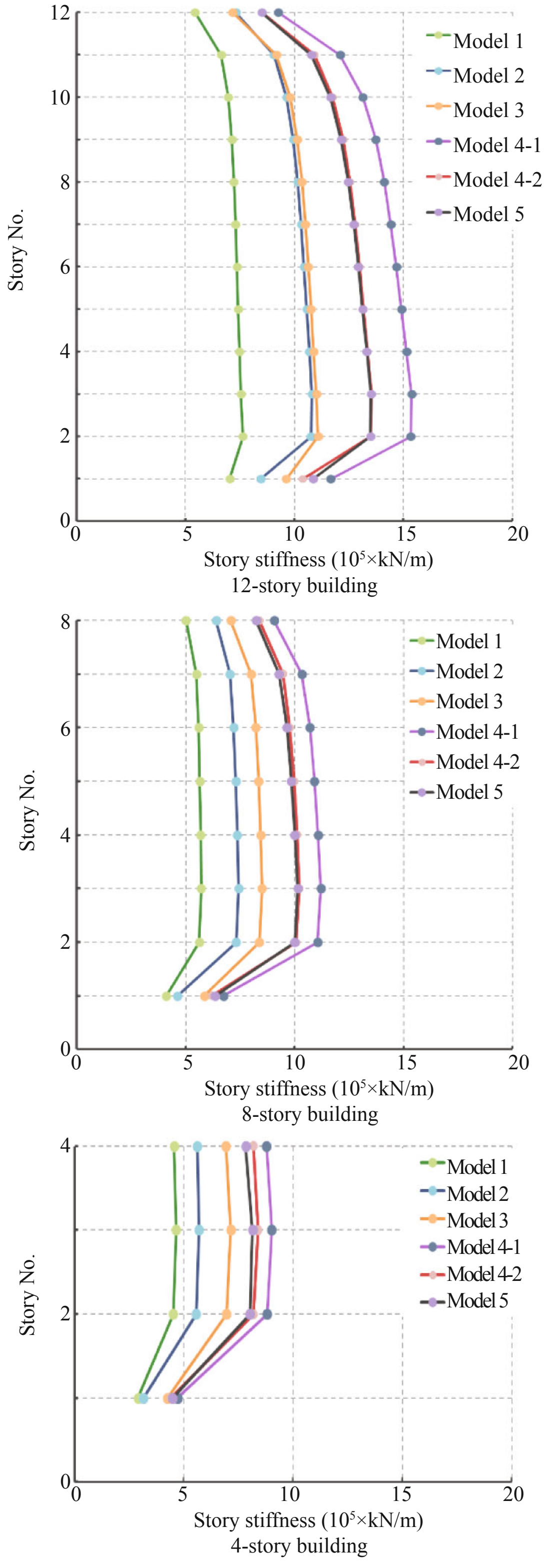


Fig. 7 Story stiffness distributions along building's height for different models

while it has a greater effect for high buildings. The contribution of panel zone deformation to the story drifts is usually substantial and should be considered using suitable mechanical models, especially for low-rise buildings. Lateral displacements are reduced when T-beams, beam-column joint dimensions, or both, are included in the model.

5.4 Inter-story drift ratio response demand

Inter-story drift is the most vital parameter to be analyzed as it is connected to the damage suffered by both structural and non-structural elements. Inter-story drift could be used as an index for the deformation capacity of a building and its performance. Recommended inter-story drifts for serviceability checks range from 0.2 to 0.5% the story height, depending on the partition type. The Egyptian code, ECP-201 (ECP, 2008), stipulates a value of 0.7 for the ratio between the maximum displacement and the calculated elastic design displacement using the equivalent static load analysis method. UBC 1997 section 1630.10 gives guidelines for calculating maximum inelastic drift, , and deflection, , is determined using an elastic analysis under UBC97 shear force limits.

The story drift demands and their patterns for different building models are investigated. The plot in Fig. 8 indicates that modeling assumptions significantly affect the inter-story drift ratio "IDR" demands. Model 1 consistently overestimates IDR demands, while Model 4-1 provides a reasonable estimate and could be calibrated by Model 5 using an end zone factor, as in Model 4-2. Using rigid offsets as an alternative to the centerline dimensions' approach, lead to significant changes in the global structural stiffness and the relative story shear force demands. The centerline model, Model 1, shows higher displacement demands along with a significant change in the distribution of inter-story drift demands over the building's height. Contributions to the IDR vary with consideration of T-beam and beam-column joint effects, as seen in the Model 3 results. The beam-column joint effect is a significant contributor to the IDR demand for low rise-buildings and less so for taller buildings. The IDR varies linearly along the shorter building's height, while it varies nonlinearly with height for high-rise building due to the significant contribution of higher modes of vibration. The IDR plots in Fig. 8 also indicate a decrease in the IDR demands as the total number of stories increase. This phenomenon can be explained by the redistribution of forces and deformations in the structural system that becomes more prominent with an increase in structural members as the number of stories increases. Higher mode responses are important at upper stories and become more important for taller buildings. The location of the maximum inter-story drift demands shows significant higher mode contributions for 12-story building; consequently, dynamic the maximum inter-story drift is relocated from lower level to relative higher level.

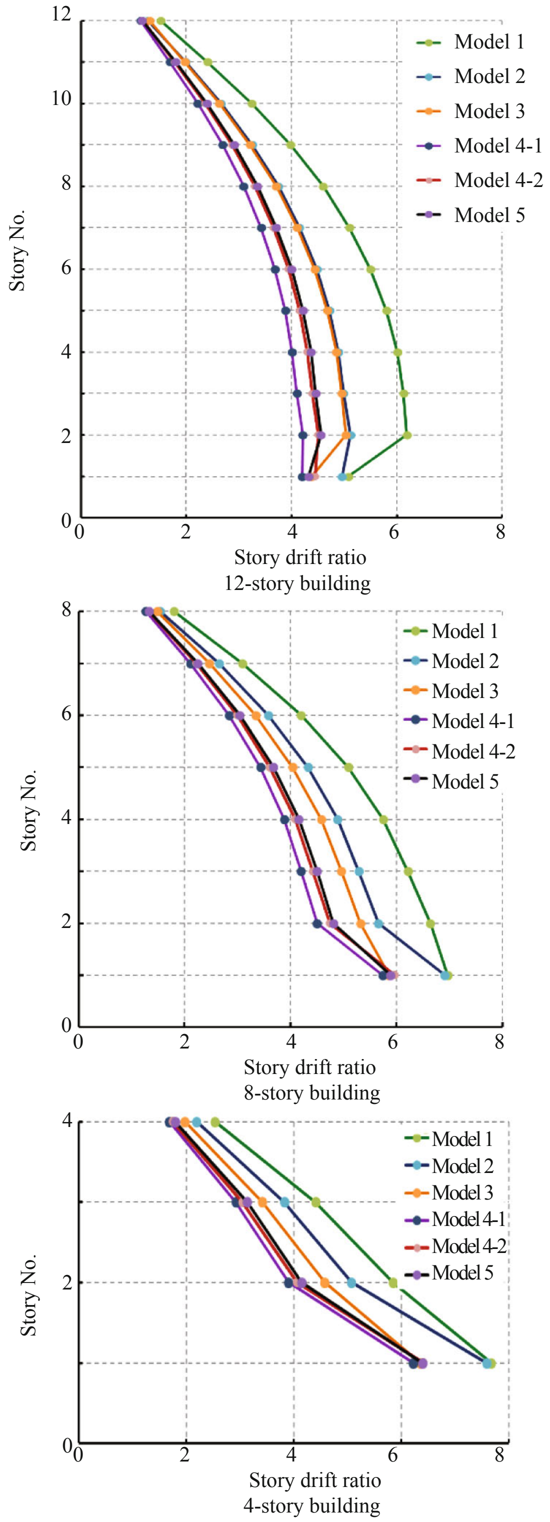


Fig. 8 Inter-Story drift ratios for different models

5.5 Story shear response demand

Structural stiffness and the imposed seismic forces are significantly affected by the accuracy of the assessment of member rigidity. Figure 9 shows story shear force demands for different models. The centerline modeling approach, Model 1, underestimates the story shear force demands compared the most refined model, Model 5, which could lead to an un-conservative design. Consideration of T-beam effects, as in Model 2, or beam-column joint effects, as in Model 3, significantly improve the prediction of the seismic demands. However, the use of combined T-beam and rigid beam-column joint effects, as in Model 4-1, better represents the stiffness of the MRF building as well as the story shear of the multi-story buildings. This model provides a closely matching prediction of the design demands compared to that of Model 5. The proposed enhanced simplified model, Model 4-2, is developed through the introduction of end zone factors calibrated by Model 5. The values of

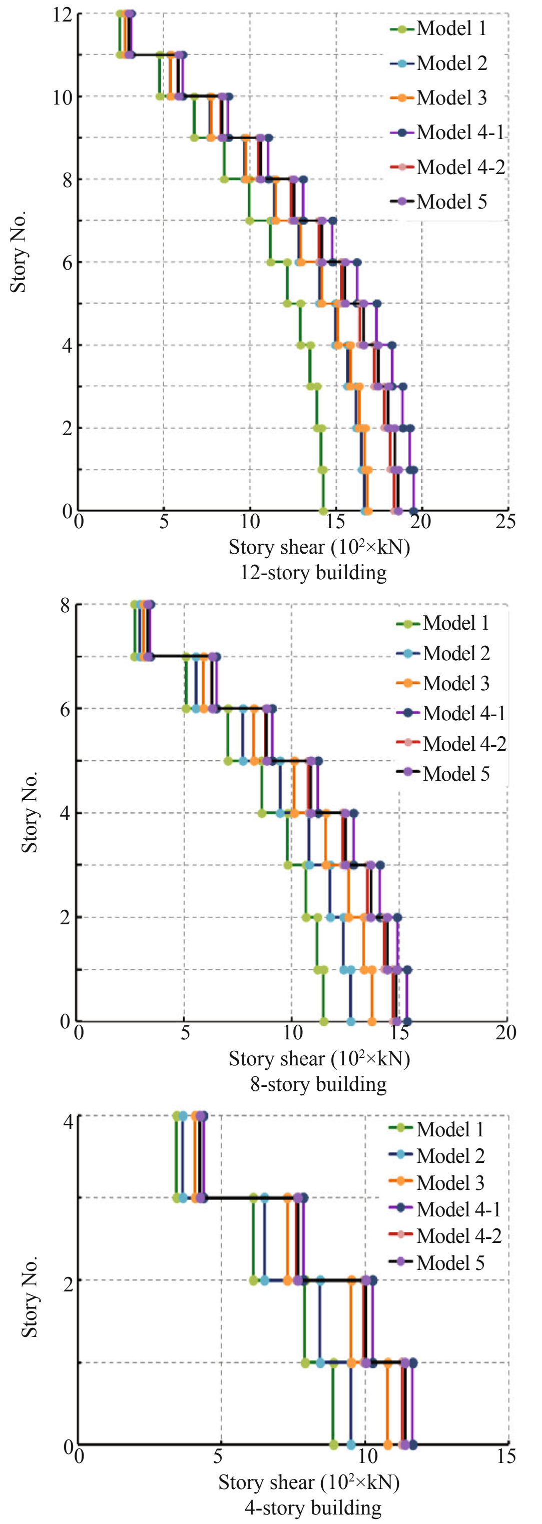


Fig. 9 Story Shear force demand for different models

end zone factor are calculated for the 4-story, 8-story and 12-story buildings and are equal to 0.85, 0.80 and 0.65, respectively.

5.6 Seismic performance comparisons

It is always cost effective for the engineer to simplify the modeling approach employed to estimate the responses of the components within a structure. However, these simplifications compromise the accuracy of one or more aspects of the real building's behavior. Structural analysis and modeling are an integral part of the design process and their accuracy is essential to achieve safe seismic designs. The sophistication of the structural analysis and FE modeling affects both analysis results and the amount of design work needed. Simplified models based on the centerline modeling approach afford a reasonable representation of the seismic behavior and enable rapid evaluation of the building performance for initial design stages. Models that are directly model rigid offsets for either T-beam or beam-column joint dimension effects or use shell elements yield more response information, but take more time to develop and have a computational cost. The building importance, the designer experience, and the accuracy level affect the model refinement level. To evaluate capabilities of different modeling techniques to predict MRF-building responses, five different numerical models with different levels of refinement have been created and compared using ETABS FE packages. The comparison of the results is based on the accuracy for engineering design and the modeling efficiencies. From the analyses performed here, it is found that Model 5 provides excellent accuracy in the results, and it is considered as the reference model. Table 3 compares the maximum roof displacement, inter-story drift ratio and base shear force predicted by the different modeling approaches.

Results reveal considering the effect of T-beams or/and beam-column joint dimensions in modelling MRF-building could improve the global lateral stiffness of buildings, which efficiently simulates the real behavior of RC-MRF buildings under lateral seismic loads. Therefore, detailed slab-beam-column models would be recommended to evaluate and predict seismic performance of MRF buildings. For clarity, the seismic design demand ratios are calculated for different modelling approaches in comparison to that of the shell based refined model, Model5, as a reference Model. The centreline modelling approach, used in Model 1, always gave larger lateral displacements (30%-35%) and inter-story drift ratios (18%-35%) compared to those from the refined model, hence overestimating the drift and ductility demands, while underestimating the story shear demands (22%) along the building height. The use of T-beam and beam-column joint offsets has a significant effect on the seismic design demands, as shown in Fig. 10. The increase in flexural stiffness when considering T-beams substantially affects the system's response, especially in taller buildings. If the flexural stiffness of the slab-beam system is entirely disregarded, lateral displacements are overestimated and seismic base shear is underestimated. Model 2 gives slightly larger lateral displacements and inter-story drift ratios of 10% for 12 story building and 20% for 4-story building compared to the refined model, while underestimating the story shear demands (10%-15%) for buildings of all heights. A model that

Table 3 Peak values of the seismic design demands for studied building Models

Building	Seismic design demands	Peak values					
		Model1	Model2	Model3	Model4-1	Model4-2	Model5
4-Story building	Lateral displacement, mm	6.9	6.3	5.5	5.0	5.2	5.2
	Inter-story drift × 10^{-3}	0.77	0.76	0.64	0.62	0.64	0.64
	Base shear, kN	890	951	1078	1166	1128	1139
8-Story building	Lateral displacement, mm	12.6	11.1	10.2	8.9	9.4	9.4
	Inter-story drift × 10^{-3}	0.70	0.69	0.59	0.57	0.60	0.59
	Base shear, kN	1147	1274	1372	1535	1471	1487
12-Story building	Lateral displacement, mm	17.2	14.3	14.0	11.9	12.7	12.7
	Inter-story drift × 10^{-3}	0.62	0.51	0.50	0.42	0.45	0.46
	Base shear, kN	1426	1665	1684	1949	1836	1860

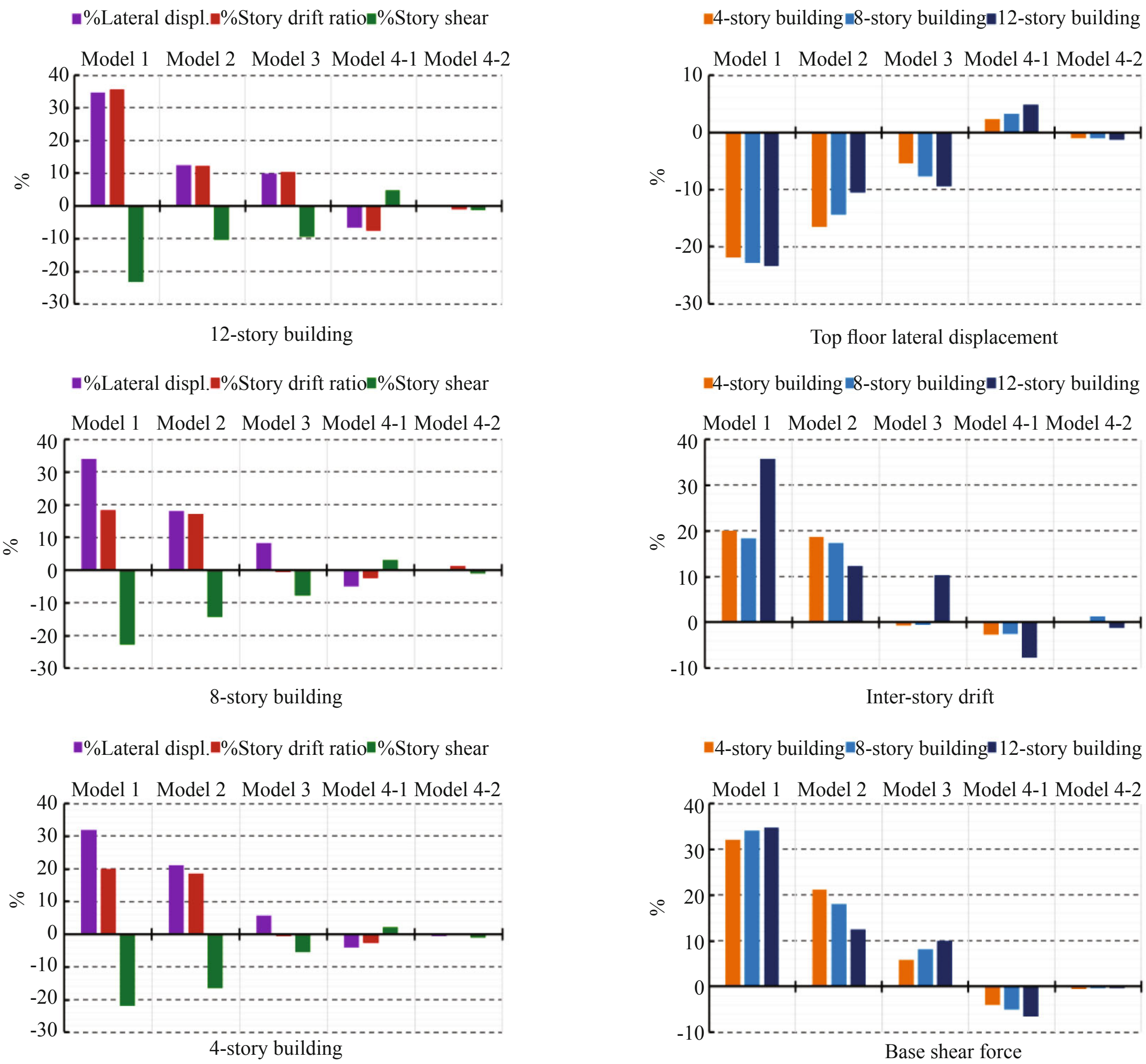


Fig. 10 Variation of seismic design demands for different models

disregards the flexural stiffness of the floor slabs and the T-beam effect would yield incorrect demands.

The effect of the beam-column joint dimensions is significant, particularly for shorter buildings. Model 3 gives slightly larger lateral displacement and inter-story drift ratio responses of 10% for 12 story building and 5% for 4-story building compared to the refined model, while underestimating the story shear demands (5-

10%) for building of all heights. A model that includes T-beams and accurate beam-column joint dimensions closely matches the seismic behaviour of the refined model. Model 4 is conservative for design purposes and could be calibrated to include shear zone effects to match results from the most refined model. Results from Model 4-1 closely match those from Model 5 in inter-story drift, lateral deflection and story shear force demands. To compensate for the slight difference, an end zone factor is explicitly introduced in Model 4-2, which was calibrated by with refined model, Model 5. The end zone factor is calculated to equal 0.85, 0.80 and 0.65 for 4-story, 8-story and 12-story buildings, respectively.

6 Conclusions

Structural modeling and analysis are essential parts of the design process and their accuracy is essential in achieving safe seismic designs. In particular, structural stiffness plays a vital role in defining a structure's natural periods, from which seismic demands ensue. Therefore, there is still a dire need to formulate robust modeling techniques for the practical seismic design of MRF-buildings. Thus, the objective of the study presented herein was to perform a thorough evaluation of different modeling techniques ranging from simple to more refined to produce a robust FE model that could give results like the real structural behavior of an RC-MRF buildings. A quantitative measure of the effect of the modeling assumptions and the FE modeling level on the predicted response is formulated through a comparison among simplified and refined models. Different FE models of the structure are established, taking into account a range of practical and more detailed FE idealizations. Key performance indices that include global and local responses are estimated to quantify the uncertainty introduced by the modeling assumptions made.

The FE method can provide a convenient and effective tool for the numerical analysis of RC-MRF buildings under seismic loads. The choice of model type and level of the refinement have great impacts on the seismic design demands. Five different numerical models have been created and compared using ETABS FE packages. The FE models are based on different modeling approaches: centerline element dimensions, T-beam effects, beam-column joint dimensions, and beam-shell modeling. Comparison of the results of the different models is based on the accuracy for engineering design and the modeling efficiencies. The consideration of rigid offsets for the T-beam effect or/and the beam-column rigid joint as a substitute to the centerline modeling approach could lead to essential modifications in the global structural stiffness and the relative story shear demands. The centerline model yields higher displacement demands and there is a substantial variation in the distribution of the inter-story drift demands. It was found that the model including offset beam elements to consider the T-beam and beam-column joint effects is the best for engineering practice. This choice is made because those models' behavior closely matches that of the refined model that used shell elements for the floor slab-beam. To compensate for the slight difference from the refined model, an end zone factor is explicitly introduced in Model 4-2 and calibrated by Model 5. The end zone factor is calculated to equal 0.85, 0.80 and 0.65 for 4-story, 8-story and 12-story buildings, respectively.

The simplified centerline modeling approach often leads to un-conservative assessments of the story drift, inter-story drift ratio and story shear demands in MRF buildings. Calculated seismic design demands are significantly affected by the modeling assumptions that are made. Even though there are advantages of developing a refined structural model using shell elements, it is costly and time consuming. This issue prompts the development of simpler structural models while still maintaining the vital features of the structure's seismic response. The results of this study demonstrate that manner of modeling the slab and beam floor system considerably changes the global building's response. A model that incorporates T-beam and beam-column joint dimension effects could be a practical solution that also maintains good accuracy. Displacement demands are also shown to be significantly affected when the global stiffness of the building changes based on the modeling assumptions made. Thus, using an FE model that has not been refined enough could lead to violation of drift limits set in design codes. Based on this study's results, a proposed model (Model 4-2) is suggested based on simplified modeling technique and includes a correction factor that was calibrated using a more refined model. The proposed model (Model 4-2) could capture the seismic response of the buildings in less computational time than the shell element model, while still maintaining the same level of accuracy. This study provides better understandings of the changes in dynamic behavior and seismic performance of buildings due to the model's level of complexity. The results help to quantify the accuracy of a simplified numerical modeling of structural components subjected to seismic excitation to predict the structural response and the effects of FE modeling refinement level on the seismic design demands.

Acknowledgement

The financial support by Scientific Research Deanship, Taibah University Grant no. 6363/436 is gratefully acknowledged.

References

American Concrete Institute Committee (2011), *Building Code Requirements for Structural Concrete* (*ACI 318-11*) *and Commentary*, ACI 318R- 11, Farmington Hills, MI.

American Society of Civil Engineers (2005), *Minimum Design Loads for Buildings and Other Structures*, ASCE 7–05, Reston, Virginia.

American Society of Civil Engineers (2006), *Seismic Rehabilitation of Existing Buildings*, ASCE/SEI 41–06, Reston, VA.

American Society of Civil Engineers (2010), *Minimum Design Loads for Buildings and Other Structures*, ASCE/SEI Standard 7–10, Reston, Virginia.

Applied Technology Council (2009), *Guidelines for Seismic Performance Assessment of Buildings*, ATC 58, 50 % Draft Report, Redwood City, CA.

Building Seismic Safety Council (2003), *NEHRP Recommended Provisions for the Development of Seismic Regulations for New Buildings*, FEMA 450, Washington, DC.

Comité Européen de Normalisation (2005), *Eurocode 8 - CEN. Design of Structures for Earthquake Resistance, Part 1: General Rules, Seismic Actions and Rules for Buildings*, EN 1998-1, Brussels, Belgium.

Computers and Structures Inc. (2015), *ETABS: Integrated Software for Structural Analysis and Design*, Computers and Structures Inc., Berkeley, CA.

Housing and Building Research Center (2007), *Egyptian Code of Practice for Design of Reinforced Concrete Structures*, Ministry of housing, utilities and urban communities of the ARE, ECP 203, Egypt.

Housing and Building Research Center (2008), *Egyptian Code of Practice for Loads on Buildings and Bridge*, Ministry of Housing, Utilities and Urban Communities of the ARE, ECP 201, Egypt.

Federal Emergency Management Agency (1997), *NEHRP Guidelines for the Seismic Rehabilitation of Buildings*, FEMA-273, Washington, DC.

Federal Emergency Management Agency (2000), *Pre-standard and Commentary for the Seismic Rehabilitation of Buildings*, FEMA 356 Report, Washington, D.C.

International Code Council (2000), *International Building Code*, Falls Church, VA.

International Congress of Building Officials (1997), *Uniform Building Code*, Whittier, California.

National Research Council of Canada (2005), *National Building Code of Canada*, 12th Ed, Canadian Commission on Building and Fire Codes, Ottawa, Ont.

Pacific Earthquake Engineering Research Center, Applied Technology Council (2010), *Modelling and Acceptance Criteria for Seismic Design and Analysis of Tall Buildings*, PEER/ATC 72-1 Report, Redwood, CA.

Pacific Earthquake Engineering Research Center (2010), *Seismic Design Guidelines for Tall Buildings*, University of California at Berkeley, Berkeley, CA.

Saudi Building Code National Committee (2007), *Saudi Building Code for Load and Forces Requirements*, SBC 301, Riyadh, Saudi Arabia.

Abdel Raheem SE (2013), "Evaluation of Egyptian Code Provisions for Seismic Design of Moment Resisting Frames Multi-Story Buildings," *International Journal of Advanced Structural Engineering*, **5**(20): 1–18.

Abdel Raheem SE, Ahmed MM and Alazrak TMA (2015), "Evaluation of Soil-Foundation-Structure Interaction Effects on Seismic Response Demands of Multi-Story MRF Buildings on Raft Foundations," *International Journal of Advanced Structural Engineering*, **7**(1): 11–30.

Abdel Raheem SE, Ahmed MMM, Ahmed MM and Abdel Shafy AGA (2018a), "Evaluation of Plan Configuration Irregularity Effects on Seismic Response Demands of L-Shaped MRF Buildings," *Bulletin of Earthquake Engineering.* DOI: 10.1007/s10518-018-0319-7.

Abdel Raheem SE, Fooly MYM, AbdelShafy AGA, Abbas YA, Omar M, AbdelLatif MMS and Mahmoud S (2018b), "Seismic Pounding Effects on Adjacent Buildings in Series with Different Alignment Configurations," *Steel & Composite Structures, An International, Techno-Press publishers*.

Chan THT and Chan JHF (1999), "The Use of Eccentric Beam Elements in the Analysis of Slab-on-Girder Bridges," *Structural Engineering and Mechanics*, **8**(1): 85–102.

Elnashap AS and McClure DC (1996), "Effect of Modelling Assumptions and Input Motion Characteristics on Seismic Design Parameters of RC Bridge Piers," *Earthquake Engineering and Structural Dynamics*, **25**: 435–453.

Elwood KJ, Matamoros AB, Wallace JW, Lehman DE, Heintz JA, Mitchell AD, Moore MA, Valley MT, Lowes LN, Comartin CD and Moehle JP (2007), "Update to ASCE/SEI 41 Concrete Provisions," *Earthquake Spectra*, **23**(3): 493–523.

Fayun L, Haibing C and Maosong H (2017), "Accuracy of Three-Dimensional Seismic Ground Response Analysis in Time Domain Using Nonlinear Numerical Simulations," *Earthquake Engineering and Engineering Vibration*, **16**(3): 487–498. DOI :10.1007/s11803-017-0401-1.

Hur J, Althoff E, Sezen H, Denning R and Aldemir T (2017), "Seismic Assessment and Performance of Non-structural Components Affected by Structural Modeling," *Nuclear Engineering and Technology*, **49**: 387–394.

Hwang SH and Lignos DG (2017), "Effect of Modeling Assumptions on the Earthquake-Induced Losses and Collapse Risk of Steel-Frame Buildings with Special Concentrically Braced Frames," *ASCE Journal of structural Engineering*, **143**(9): 04017116-1. DOI: 10.1061/ (ASCE) ST.1943-541X.0001851.

Jayasinghe JASC, Hori M, Riaz MR, Wijerathne MLL and Ichimura T (2017), "Conversion Between Solid and Beam Element Solutions of Finite Element Method

Based on Meta-Modeling Theory: Development and Application to a Ramp Tunnel Structure," *Earthquake Engineering and Engineering Vibration*, **16**(2): 297–309. https://doi.org/10.1007/s11803-017-0383-z

Krawinkler H (2000), "The State-of-the-Art Report on System Performance of Moment Resisting Steel Frames Subjected to Earthquake Ground Shaking," *Federal Emergency Management Agency*, FEMA 355c, Washington, DC.

Kwon J and Ghannoum WM (2016), "Assessment of International Standard Provisions on Stiffness of Reinforced Concrete Moment Frame and Shear Wall Buildings," *Engineering Structures*, **128**: 149–160.

Lee DG, Ahn SK and Kim DK (2003), "An Efficient Model for Seismic Analysis of Building Structures with The Effect of Floor Slabs," *7th Pacific Conference on Earthquake Engineering-7PCEE*, University of Canterbury, Christchurch, New Zealand, 13-15 February 2003, Paper No. 045.

Le-Trung K, Lee K, Lee J and Lee DH (2010), "Seismic Demand Evaluation of Steel MRF Buildings with Simple and Detailed Connection Models," *International Journal of Steel Structures*, **10**(1): 15–34.

Li Jianbo, Lin Gao, Lin Jun and Li Zhiyuan (2017), "Research on the Attribution Evaluating Methods of Dynamic Effects of Various Parameter Uncertainties on the In-Structure Floor Response Spectra of Nuclear Power Plant," *Earthquake Engineering and Engineering Vibration*, **16**(1): 47–54. https://doi.org/10.1007/s11803-017-0367-z.

Mehanny SSF and El Howary HA (2010), "Assessment of RC Moment Frame Buildings in Moderate Seismic Zones: Evaluation of Egyptian Seismic Code Implications and System Configuration Effects," *Engineering Structures*, **32**: 2394–2406.

Mehanny SSF, Soliman AM and Bakhoum MM (2012), "Strength & Drift Seismic Code Requirements for Mid-Rise RC Frame Buildings," *Global Thinking In Structural Engineering: Recent Achievements IABSE Conference*, **98**, Sharm El Sheikh, Egypt, 7 – 9 May, Paper No. 97.

Rivera JA and Petrini L (2011), "On the Design and Seismic Response of RC Frame Buildings Designed with Eurocode 8," *Bulletin of Earthquake Engineering*, **9**: 1593–1616.

Roca P, Cervera M, Gariup G and Pela L (2010), "Structural Analysis of Masonry Historical Constructions. Classical and Advanced Approaches," *Arch Computational Methods Engineering*, **17**: 299–325. DOI 10.1007/s11831-010-9046-1

Shin M, Kang TH-K and Grossman JS (2010), "Practical Modelling of High-Rise Dual Systems with Reinforced Concrete Slab-Column Frames," *The Structural Design of Tall and Special Buildings*, **19**(7): 728–749.

Soliman AM, Mehanny SSF and Bakhoum MM (2012), "Effect of FEM Modelling Assumptions and Code Provisions on Seismic Analysis of RC Buildings," *Global Thinking In Structural Engineering: Recent Achievements IABSE Conference*, **98**, Sharm El Sheikh, Egypt, 7 – 9 May 2012, Paper No. 99.

Sousa R, Eroğlu T, Kazantzidou D, Kohrangi M, Sousa L, Nascimbene R and Pinho R (2012), "Effect of Different Modelling Assumptions on the Seismic Response of RC Structures," *15th World Conference on Earthquake Engineering*, Lisbon, Portugal, 24-28 September 2012, Paper ID 4333.

Vona M and Mastroberti M (2018), "Estimation of the Behavior Factor of Existing RC-MRF Buildings," *Earthquake Engineering and Engineering Vibration*, **17**(1): 191–204. https://doi.org/10.1007/s11803-018-0434-0

Walker S, Yeargin C, Lehman D and Stanton J (2002), "Influence of Joint Shear Stress Demand and Displacement History on the Seismic Performance of Beam-Column Joints," *The Third US-Japan Workshop on Performance-Based Earthquake Engineering Methodology for Reinforced Concrete Building Structures*, Seattle, USA, 16-18 August 2001, Report No. PEER-2002/02: 349–362.

Wallace JW (2007), "Modelling Issues for Tall Reinforced Concrete Core Wall Buildings," *The Structural Design of Tall and Special Buildings*, **16**(5): 615–632.

Willford M, Whittaker A and Klemencic R (2008), "Recommendations for the Seismic Design of High-Rise Buildings," *Council on Tall Buildings and Urban Habitat*, Illinois Institute of Technology, Chicago, IL.

Zendaoui A, Kadid A and Yahiaoui D (2016), "Comparison of Different Numerical Models of RC Elements for Predicting the Seismic Performance of Structures," *International Journal of Concrete Structures and Materials*, **10**(4): 461–478.

Zeris C, Vamvatsikos D, Giannitsas P and Alexandropoulos K (2007), "Impact of FE Modelling in the Seismic Performance Prediction of Existing RC Buildings," *ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering - COMPDYN 2007*, Rethimno, Greece, 13-16 June 2007.