Available online at www.CivileJournal.org

Civil Engineering Journal

Vol. 3, No. 10, October, 2017

Linear and Nonlinear Dynamic Analysis of Masonry Infill RC Framed Buildings

Ayman Abd-Elhamed [a, b*], Sayed Mahmoud [c]

[a] *Faculty of Engineering at Mataria, Helwan University, Cairo, Egypt.*

[b] *Faculty of Engineering & Technology, Egyptian Chinese University, Cairo, Egypt.*

[c] *Department of Civil and Construction Engineering, College of Engineering, Imam Abdulrahman Bin Faisal University, Saudi Arabia.*

Received 18 September 2017; Accepted 28 October 2017

Abstract

This paper aimed to investigate the seismic response of reinforced concrete (RC) frame buildings under linear and non-linear dynamic analysis. Different building models as bare frame and fully masonry infill frame have been developed for performing the analysis. In order to investigate the effect of irregular distributions of masonry infill walls in elevation on the seismic response behavior, an infill frame model with soft story has also been developed. The linear response spectrum (RS) dynamic analysis and the nonlinear time-history (TH) analysis methods are employed. Moreover, the induced energies in terms of input, potential and kinetic are also obtained from the TH analysis. Moreover, the interaction between infill walls and frames leads to considerable change in the induced responses comparable with the bare model.

Keywords: Response Spectrum; Time-History; Masonry Infill; Soft Story.

1. Introduction

It is well-established fact that masonry infill walls play an important role in lateral load resistance of RC buildings. Nevertheless, masonry infill walls are widely used as partitions to fill the gap between RC frames, and used either to divide the spaces to any required purposes or to protect inside of the structure from environment. Although the structural contribution of masonry infill walls is often overlooked in the structural analysis and design of such structures, it affects both the structural and non-structural performance of RC structures and alters the load resisting mechanism and failure pattern of the RC frame [1-3]. Treating infill walls as architectural elements is reasonable and justifiable assumption under gravity loads and neglecting their influence on the behavior of the structure under lateral load can lead to uneconomical design as well as unexpected behavior and even catastrophic collapse [4]. Recent researches have clearly shown that the damages done to the buildings with masonry infill walls were considerable less than those without masonry infill and the difference was quite a bit significant. This can be due to the dramatic increase in the global strength, stiffness, damping and the dissipated energy of the structures with masonry infill walls [5-9]. Therefore, in moderate and high seismicity regions, the structural contribution of infill walls cannot simply be neglected.

Although the inclusion of such masonry infill interaction may improve the performance of the structure under seismic actions, it may cause some negative effects such as the induced torsional effect due to in plan-irregularity. In addition,

* Corresponding author: aymanm79@hotmail.com

http://dx.doi.org/10.28991/cej-030922

the discontinuity of infill throughout the building height due to existence of a soft story may induce irregularities in elevation. Moreover, short columns effect due to openings may arise.

Under seismic loads, the existence of masonry walls change the structural mechanism of transferring the induced lateral forces from a frame action mechanism into truss action mechanism (see Figure 1) [10-11]. Such change in load transfer mechanism leads to reduction in the induced straining actions in terms of bending moments and shearing forces but with increase in axial forces. Although the capacity of the structure to the applied lateral loads gets increase, it may result in attracting part of the lateral shear forces due to seismic or wind actions to undesired parts of the building structure causing structural deficiency.

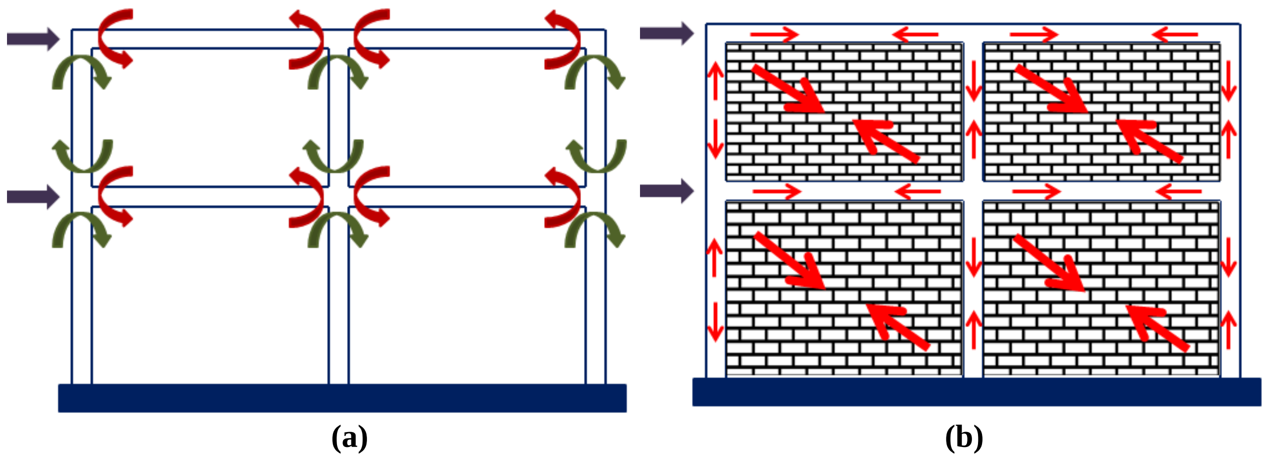


Figure 1. Lateral load transfer mechanisms due to ignorance and inclusion of infill actions: (a) Frame action as in bare frame (b) Truss action as in infilled frame

A large number of buildings had soft stories at the first-floor level due to the absence of masonry infill walls in this story, i.e., columns in the ground story do not have any partition walls between them. This happens because the stiffness of such story is less than 70% of the story above or less than 80% of the combined stiffness of three stories above. In a multistoried building, soft story is adopted to accommodate parking which is an unavoidable feature, especially in the developing countries, and then heavy masonry infill walls start immediately above the soft story. This open ground story is vulnerable to collapse during earthquake. Moreover, absence of masonry infill in a first story result in increased deformation demands significantly, and formation of plastic hinges and finally collapse [12-14].

During the last few decades, many researchers have studied the effects of the infill walls on the response of RC structures either experimentally or analytically. One of the most recent experimental works has been performed in 2017 by Mochamed [15]. In this work, experimental investigations of RC framed buildings with masonry infill under cyclic in-plane loading have been conducted. The structural behaviour in terms of ductility, strength and stiffness have been experimentally investigated employing three typical RC frames with and without masonry infill walls. For the purpose of analyzing infilled frames analytically, researchers developed different modelling techniques. These models can be divided into two groups in terms of micro-models and macro-models. Andre et al., [16] developed a macro-model in order to account for the infill masonry out-of-plane behaviour as a main cause of failure of non-structural elements under seismic excitations. The corresponding interaction between in-plane and out-of-plane has also been considered in the analysis performed by the developed model. On the other hand, a simplified macro-model that simulates the nonlinear behaviour of the infill panels when subjected to in-plane actions and the respective application in the computer program OpenSees has also been developed [17].

The primary objective of this study is to investigate the interaction effect between the masonry infill walls and RC on the dynamic response of framed building structures as bare frame, masonry infill frame and infilled frame models with open first story. First, in the category of bare frame the three-dimensional (3D) finite element model of the building without stiffness and strength contributions of the infill walls are considered. However, infill wall masses on each floor are added to the mass of the corresponding floor. Second, in the category of masonry infill frame, the 3D structure is modeled considering the effects of strength and stiffness of infill masonry walls, as well as their masses. Finally, in the category of infill wall model with absence of infill masonry action only in first story is also considered. The interaction between masonry infill walls and the analyzed RC structures are modelled with the finite element modeling technique using ETABS software. Two types of dynamic analysis namely; RS analysis and the dynamic TH analysis have been used to perform the current study in both X and Y directions.

2. Modeling of Infill Wall

Many of the structural engineering designers consider the infill walls typically as nonstructural elements during analysis and design of reinforced concrete framed structures. However, due to expected interaction between bounding frames and filling walls in between, these infills can significantly change the mechanism describing the resisting behavior of RC structures subjected to seismic loads as well as failure modes. For modelling of such interaction between infill walls and bounding frames, several methods have been proposed. Micro-models, and macro-models are the two main categories grouping these methods. The micro-models category is mainly based on the commonly used analysis tool for complex engineering problems namely; the finite element method which enables the Micro-models to simulate the structural behavior with great detail. In order to represent the infilled frames behavior under dynamic lateral load, three different kinds of elements in which a beam element is used to represent the frame, a plane element represents the infill and an interface element or one-dimensional joint element to simulate the interface behavior. One of the main disadvantages of the previously described micro-models category is the needed extensive computations. In addition, this category of methods is difficult to be applied numerically for structures with large scales. On the contrary, the second category namely macro-models is based on the equivalent diagonal strut method. This modelling strategy are simplicity in performing computations and capability of employing and utilizing the masonry mechanical properties obtained from experimental tests. In addition, this strategy helps in describing the most common modes of failure of the modelled panels with infills.

Thus, the masonry infill walls, which are enclosed by two columns and two beams, are usually modeled as equivalent diagonal compression strut as shown in Figure 2. Following FEMA-306 [18] and early studies of Holmes [19] which recommend to replace the infill by an equivalent pin-jointed diagonal strut, the infill wall is idealized as a diagonal strut and the frame is modelled as a truss element. Several expressions given by different researchers have been proposed to help in finding strut width empirically. Holmes [19] proposed a theoretical relation between the width W_e of the diagonal strut and its length d as:

$$W_e = \frac{1}{3} d \tag{1}$$

Where d can be computed in terms of infill panel length l and panel width h as:

$$d = \sqrt{h^2 + l^2} \tag{2}$$

The above relations clearly states that strength of infills is independent of framed panel stiffness.

Following test results and analytical data, Mainstone [20] proposed an empirical formulation accounts for the stiffness of the masonry panel together with the diagonal strut length as:

$$W_e = 0.175(\lambda h)^{-0.4}\sqrt{h^2 + l^2} \tag{3}$$

Where λ is a dimensionless parameter can be calculated as:

$$\lambda = \sqrt[4]{\frac{E_m t \sin(2\theta)}{4 E_c I_c H_w}} \tag{4}$$

Where *Ec* and *Em* respectively denote the elastic moduli of the column and the masonry wall, θ is the angle defining diagonal strut inclination, *Ic* is the moment of inertia of the column and *Hw* is the clear height of the infill wall. Here t defines the infill thickness.

The area of diagonal compression strut A_e as a function of the width and thickness of strut can be written as:

$$A_e = W_e t \tag{5}$$

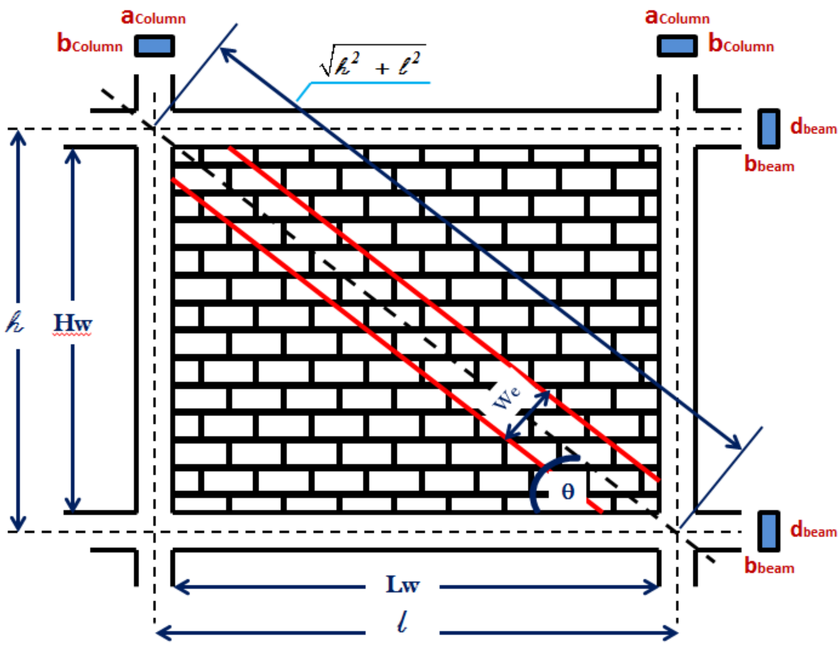


Figure 2. Equivalent strut model for masonry infill walls in frame building structures

3. Building Description

This study investigates the seismic behavior of multi-story RC frame building with 6-story for residential use. The building is with plan dimensions of 20.0 m in longitudinal direction and 12.0 m in the lateral direction as shown in Figure 3. In order to avoid torsional response under the applied lateral load, the building layout is essentially bi-symmetric in plan. Similarly, the issue of columns directions is avoided through designing the supporting columns to be square in shape. The typical bay dimension is 4.0 m in both directions and the typical floor height (column height) is 3m, except for the first-floor height which is considered to be 4m, as a normal height for residential buildings. The structural elements of the considered building elements have been first designed under gravitational dead and live loads assuming an un-cracked section in the analysis. Following the deflection control requirements, the slab thickness has been set to be of 12 cm. The cross section of the columns is reduced every 3 stories towards the last floor of the building. All columns are assumed to be of fixed condition at the foundation level. The dimensions of all frame members are presented in Table 1.

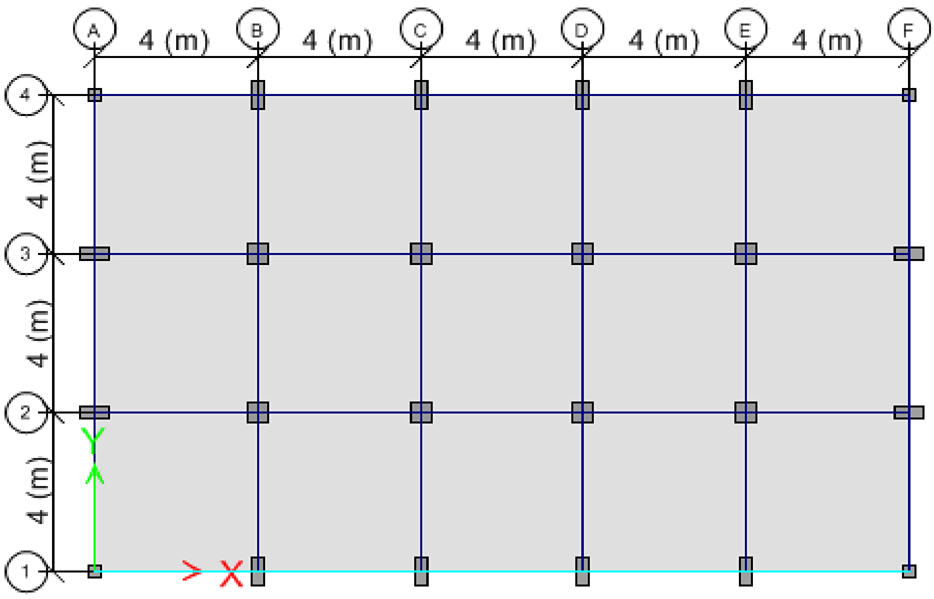


Figure 4. Schematic representation of typical floors Plan of the 6-story residential building

The reinforced concrete has been selected as the material assigned for construction of the building. The properties of the assigned material in terms of modulus of elasticity, Poisson ratio, density of concrete, compressive strength and yield strength have been set to be of $E_c = 22 \times 106\ KN/m^2$, $\mu = 0.2$, $\gamma_c = 25\ KN/m^3$, $f_{cu} = 25\ N/mm^2$, $f_y = 360\ N/mm^2$ respectively. For gravity load design, the dead loads include the weight of flooring cover as $1.5\ KN/m^2$

and the weight of partitioning elements including plastering as 2 KN/m^2. The live load for residential RC building is taken equivalent to 2.5 KN/m^2. For masonry infills; the compressive strength is taken as $5 \times 106\ KN/m^2$ which are modeled as equivalent diagonal strut, with width of 0.484 m and thickness of 0.12 m for interior walls and with width of 0.450 m and thickness of 0.25 mm for exterior walls. The results of the linear and nonlinear dynamic analysis are obtained for all models in a comparative way.

Table 1. Dimensioning of building elements

Structural element		Story number	
		1, 2, 3	4, 5, 6
Beams	Cross section (m^2)	0.25 x 0.50	
Edge Columns		0.30×0.80	0.30×0.70
Inner Columns		0.60×0.60	0.50×0.50
Corner Columns		0.40×0.40	0.30×0.30

4. Developed Models

4.1. Bare Frame Model

The capability of the bare frame building model to predict the dynamic response behavior under lateral seismic loads is investigated. In bare frame building model (see Figure 4), infill walls are modelled as nonstructural elements although the masses of infill walls are included in the model. In such a case, the mechanism to resist the dynamic lateral loads known as frame action mechanism in which bending moments and shear forces are developed in beams and columns by means of rigid joint action.

4.2. Fully Infilled Building Model

The Fully infilled framed building presented in Figure 5. refers to the presence of infill walls distributed throughout the whole stories. The truss action mechanism in which the frame panel with masonry infill behaves in such a way like a diagonal strut. In this mechanism, the induced bending moments in beams and columns are reduced while the induced axial forces are increased.

4.3. Open First Story Building Model

In the open first story building shown in Figure 6, similarly to the fully infilled framed building model, full brick infill masonry walls are distributed throughout the whole stories except for the first story.

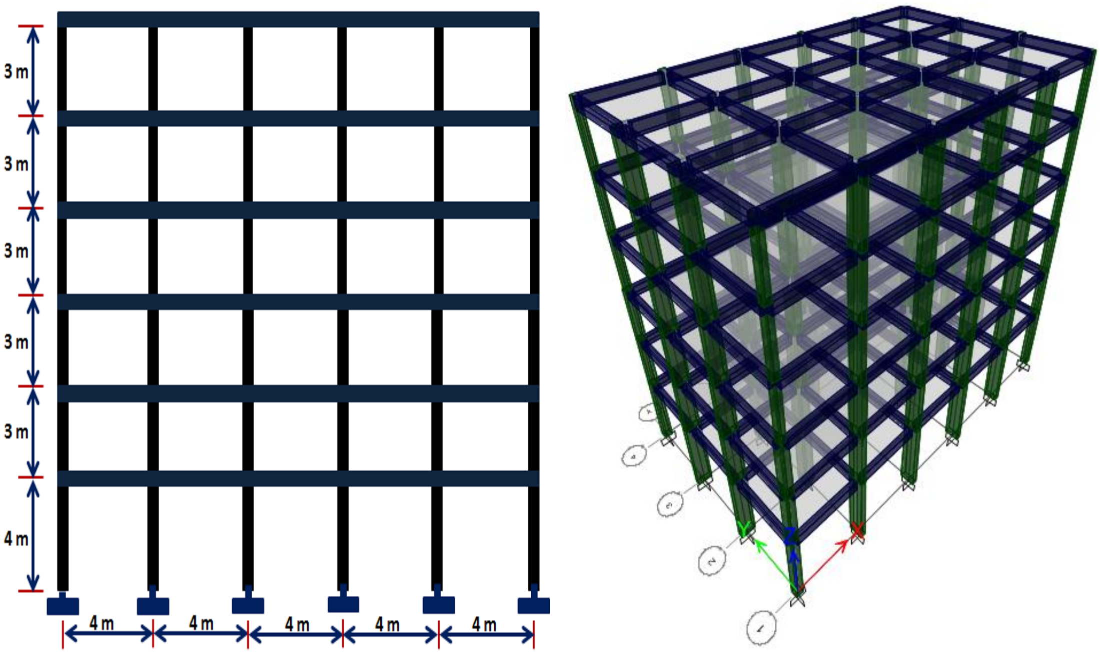


Figure 4. Schematic representation of typical front view and 3-D view of the bare frame building model for the 6-story residential building

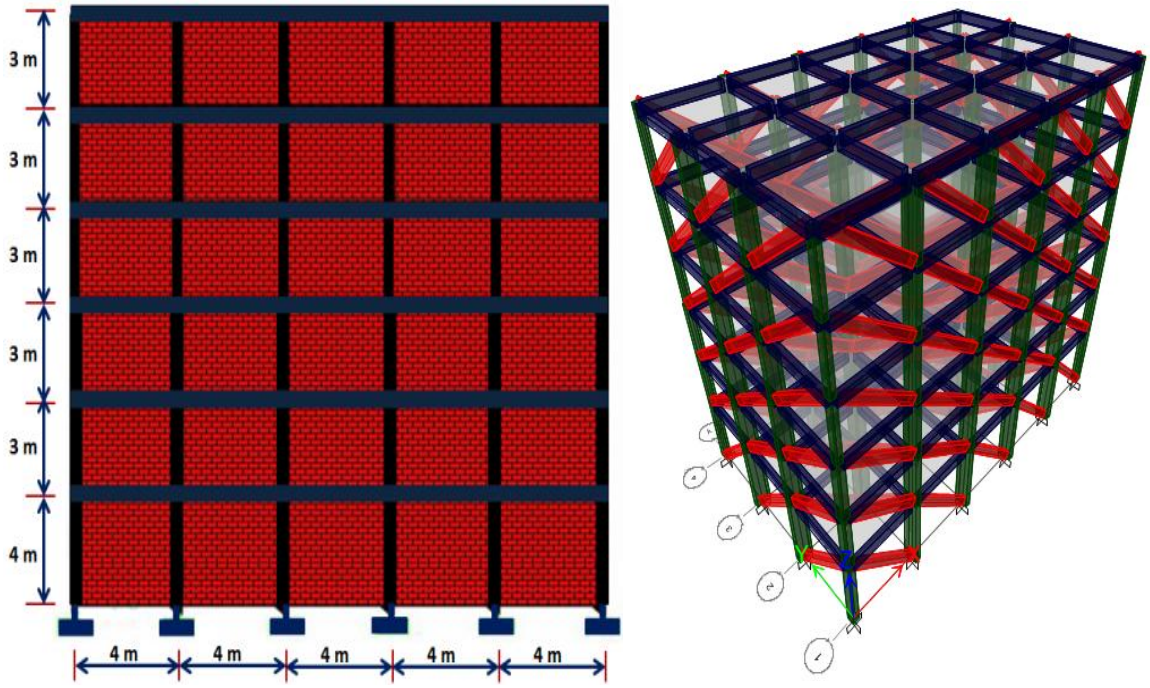


Figure 5. Schematic representation of typical front view and 3-D view of the fully masonry infill frame building model for the 6-story residential building

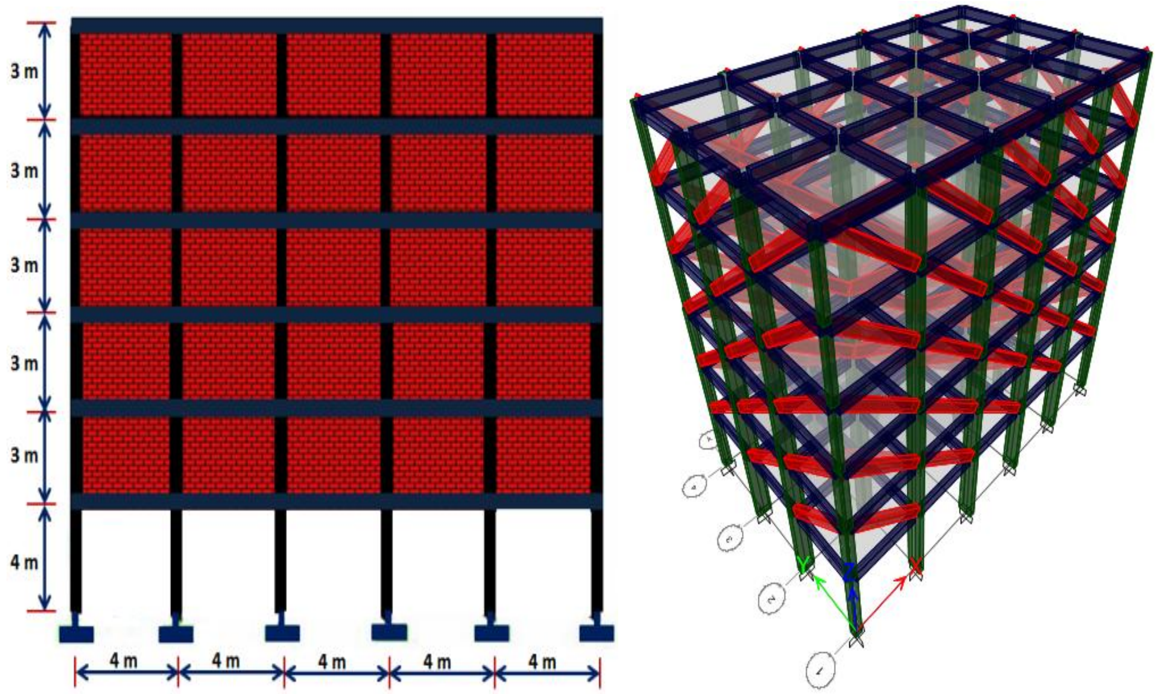


Figure 6. Schematic representation of typical front view and 3-D view of the masonry infill frame building model with open first story for the 6-story residential building

5. Earthquake Modelling

In this investigation, the horizontal ground motion records of the El Centro have been selected for performing the nonlinear dynamic TH analysis. The Characteristics of the selected earthquake motion in terms of peak ground acceleration (PGA), moment magnitude (M), and site-source distance (Dss) are 0.34g, 7.2 and 8.3 km respectively. For more characteristics about the selected records see [21]. The ground motion records of the El Centro earthquake were scaled to match the requirements of the Egyptian Code (EC) for loads. Such scaling technique of the ground motion reasonably represent the recommended PGA by the design code to fit the seismicity level of the targeted zone (see Figure 7a). Moreover, such scaling procedure facilitate the comparison of the obtained numerical results from the ground motion with those obtained employing the RS analysis (see Figure 7b).

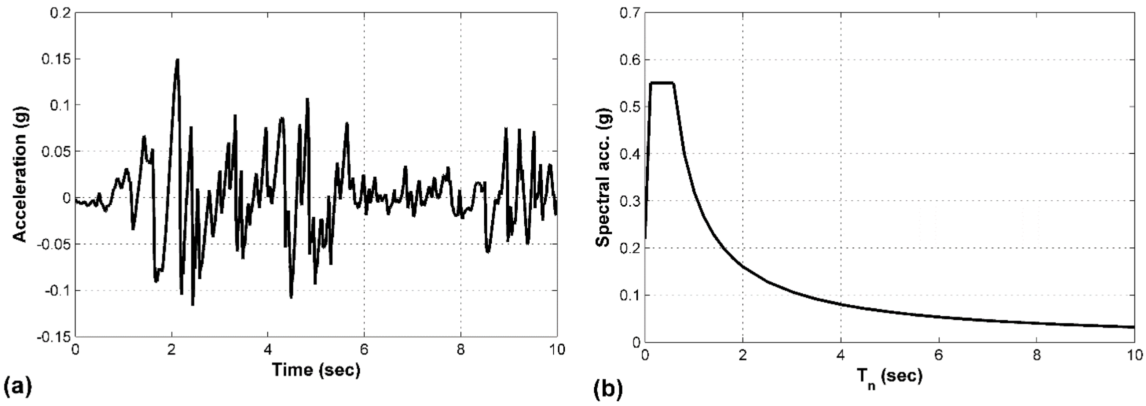


Figure 7. (a) Scaled El Centro ground motion (b) targeted response spectrum curve

6. Methods of Analysis

All structures, when excited during an earthquake, behave dynamically where the applied loading and expected responses are varying with time. The behaviour of these structures under this type of dynamic loading needs to be determined in order to evaluate the dynamic responses developed in the structure. From structural design standpoint, the peak response values are considered as ones of particular interest for performing design stages. The methods of analysis used in the current research study are based on modal response spectrum as a linear dynamic analysis and the TH as a nonlinear dynamic analysis.

6.1. Response Spectrum Method

Response spectrum analysis, sometimes called modal method or modal summation technique, is considered as a representative for the linear dynamic techniques. In this method not only the fundamental mode is considered in the analysis but also the higher modes that contribute and significantly affect the dynamic response of structure. In general, response spectra are used to analyze structures that respond within elastic-linear limits. The response in each natural mode of vibration can be computed independently of the others, and the modal response analysis is performed to identify the modes. The mode responses can be picked employing the response spectrum and the peak responses can be combined to determine the total response. For a structural model with n degrees of freedom, n corresponding mode shapes are expected. Figure 8. presents a graphical representation of the mode shapes of a building model with n stories. Each of the corresponding mode shapes is an independent and may be amplified and superimposed to create a resultant response pattern, as shown in the Figure 8.

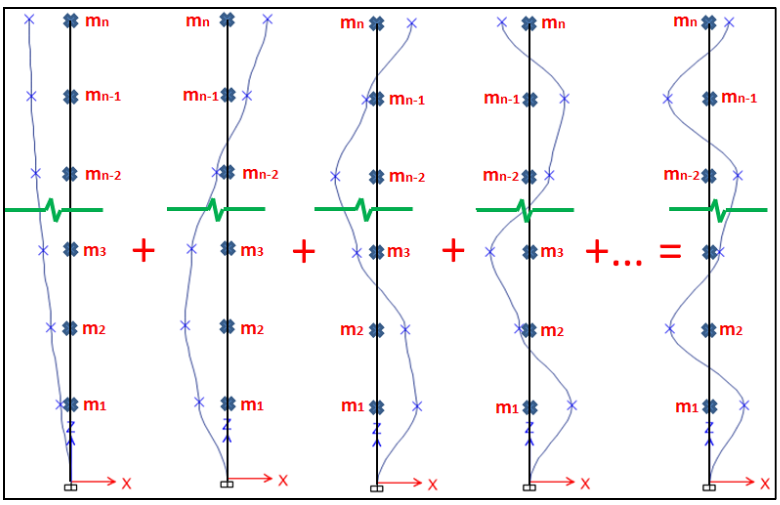


Figure 8. Mode shapes corresponding to the degrees of freedom of a structural model

6.2. Time History Analysis

The nonlinear dynamic time-history analysis is accepted as the best method to determine seismic behavior of structures. In this method of analysis a step by step technique for evaluating the dynamic response of a structural model subjected to a dynamic loading varies with time is needed. The dynamic response analyses can be performed by direct integration method, which requires greater computational efforts and gives the most reliable results. In order to incrementally apply the dynamic earthquake load to the targeted structural model, a time interval Δt needs to be defined for performing the step-by-step integration technique. The nonlinear TH analysis is carried out using real acceleration time-history records. The difficulty to perform the time-history analysis is directly proportional to the model degrees of freedom where it becomes very difficult to perform the time-history calculation manually when the number of degrees of freedom gets increase and the need for structural software packages to perform the analysis becomes necessary.

7. Response Analysis and Discussions

Linear and nonlinear dynamic analyses, namely linear RS and nonlinear TH, are performed for the developed three building models using ETABS structural software package. The seismic lateral load generated by ETABS corresponds to Cairo seismic zone II and the 5% damped response spectrum given in UBC97. For performing the nonlinear dynamic analysis, ETABS enables the user to input the scaled records of the El Centro earthquake. The results deduced from the conducted analyses are presented for bare frame, infill frame and open first story frame models subjected to the aforementioned linear and nonlinear dynamic methods including the observed overall response of each frame model. Special attention has been paid to natural period, story shear, deflection and drift responses of the multistory frame building models. Furthermore, results for the story overturning moment, stiffness and energy responses are also calculated and commented upon.

7.1. Fundamental natural period

The fundamental natural period, as one of the most important dynamic characteristics of a structure, is defined as the elapsed time by the structure to undergo one cycle of oscillation. Fundamental period as an inherent property of the structure is mainly controlled by the mass and stiffness. From structural design point of view, this inherent property is used to define acceleration spectra and consequently base shear force is obtained. The computed fundamental periods for the considered herein building models in terms of bare frame, masonry infill and open first story building models in X-direction have been found to be 0.958 sec, 0.505 sec and 0.648 sec respectively. The corresponding values in Y-direction are 0.973 sec, 0.553 sec and 0.655 sec. It is noticed from the results that modeling of infill with equivalent diagonal struts significantly affects the fundamental natural period of the building. Bare frame model, in which the masonry infill walls are ignored overestimates the induced natural period as compared to the other two models with masonry infill walls. It can be observed from the numerical results that the bare frame model provides almost twice the value of the natural period provided by the fully infilled frame model. This obtained results for the natural periods clearly indicate that considering the masonry infill action enhances the stiffness of the structure. In addition, the captured results indicate that the open first story building model, which is considered as a partially infilled frame model, provides natural period a bit higher than the corresponding value of the fully infilled frame model. This can be due to the presence of an opening at the base where masonry infill is ignored at that level leading to a reduction in the lateral stiffness. On the other hand, applying the approximate method proposed by design codes provide constant natural periods for all the considered models in both X and Y loading directions. This can be due to the approximate method independent of the structural properties of building and the deformational characteristics of the resisting elements. However, it is mainly depending on an empirical formula influenced by the total height as well as the type of the structure as the key factors influencing the method. The empirical expressions for the approximate method provide computed natural periods of 0.444 sec which is significantly shorter than those provided by the Rayleigh method. From structural design point of view, ignorance of the contribution of masonry infill to the stiffness of the structure may cause an overestimation of the calculated period leading to a decrease in the design base shear force and an increase in the calculated deflections as well. These variations in responses considerably affect the dimensions of the designed structural members.

7.2. Shear force

Seismic shear forces in terms of shear at base and shear force at each story level are considered as important parameters in seismic design stages. The calculated values of shear forces considering and ignoring the effect of masonry infill walls are presented in Figure 9. The shear values for building model with open first story are also presented in the same figure. Scaling the induced base shear due to the application of RS method is a procedure required by seismic design codes in order to ensure minimum strength of a structure designed using the RS method. The targeted strength should not less than 90 percentage of the strength that would be required from a designed structure employing the equivalent static method (ESF). For this reason and in order to calibrate the seismic base shear due to RS analysis, the ESF method is employed. The induced shear forces using ESF in both X and Y-directions are presented in the upper row of Figure 9. In addition the obtained non-scaled shear forces using dynamic RS method in both X and Y-directions are presented in the second row of Figure 9. As it can be seen from the figure, the dynamic RS analysis produces shear at base of lower values than those obtained applying the static force procedure. This may be due to the basic assumption of using ESF is that only first mode of vibration of building governs the induced responses and the contributions from the other higher modes are ignored. Contrary to ESF method, the use of RS method considers the contribution from all modes leading to shear values at base lower than those induced by the ESF. Following the design code requirements, rescaling the dynamic base shear provides results shown in the upper row of Figure 10. It is worth noting that maintaining RS base force values to be close to the static one does not necessarily lead to similar distribution of story shear forces. The TH analysis produces story shear forces of higher values than those obtained by RS analysis for the infill and open first story models (compare upper and lower rows of Figure 10). The induced shear at the base of the bare frame model is almost same under either RS or TH methods where it has been found to be of 2.15×103 and $2.25 \times 103\ kN$ for the application of RS and TH respectively in X-direction. The corresponding values in Y-directions are 2.15 x10^3 kN and $2.16 \times 103\ kN$. As it can be seen from the presented figures, the bare frame model, in which the masonry infill action is ignored, significantly underestimates the produced values of shear at base regardless the applied method of analysis. From earthquake resistant design point of view, this may cause unsafe design where the shear at base is considered as one of the main parameters during design stages. From percentage point of view and based on the induced shear values at the base of the models, ignorance of masonry action underestimates the shear force at the base of bare frame model with about 19% as compared to the produced base shear of infill model under seismic RS method in X-direction. Similar percentage has been obtained with application of seismic RS in Y-direction. The corresponding percentage due to the application of non-linear TH analysis in both X and Y-directions have been found to be of 51% and 53% respectively. The aforementioned percentage results show that the application of time-history analysis amplifies the induced base shear as compared to response spectrum analysis.

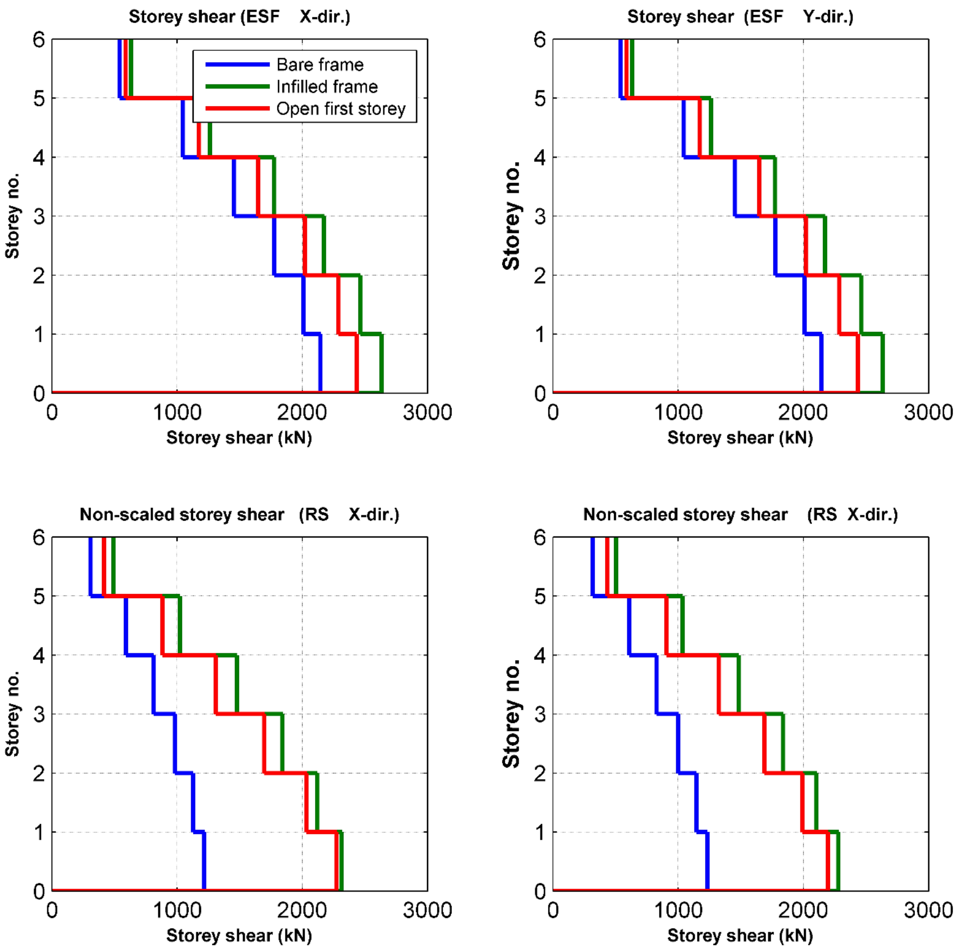
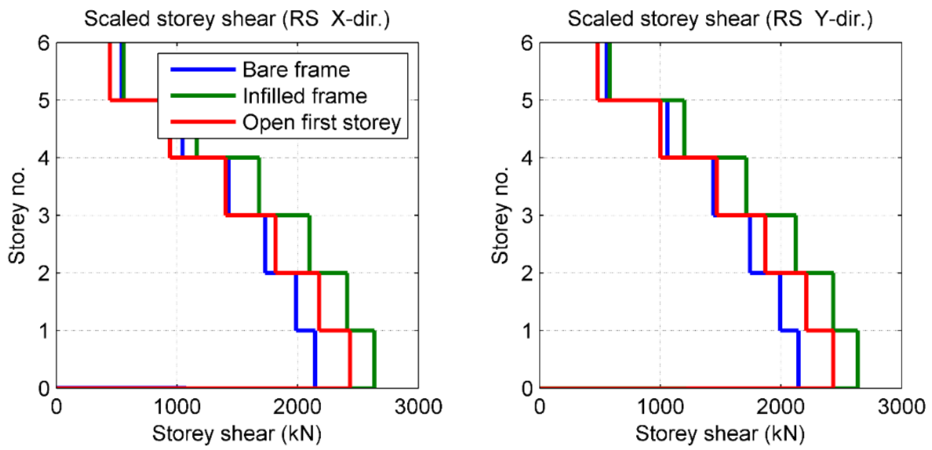


Figure 9. Story shear forces in X and Y-directions for the considered different models under ESF (upper row) and RS (lower row)



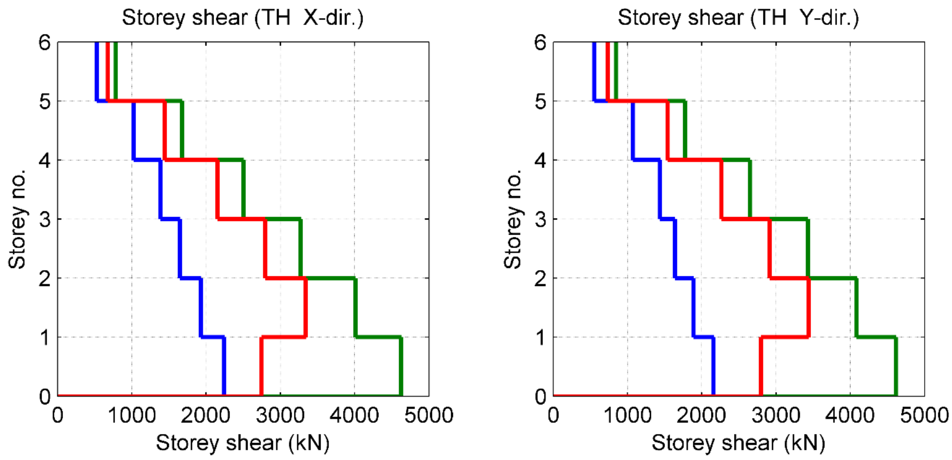


Figure 10. Story shear forces in X and Y-directions for the considered different models under RS (upper row) and TH (lower row)

7.3. Story Displacement

One of the typical ways to illustrate the behavior of building structures is to study the variation of stories displacement along the height of the building. In order to investigate the effect of incorporating masonry infill action as well as the existence of a soft story at the first floor on the obtained story peak displacement response versus the story heights under linear and nonlinear dynamic analysis, numerical simulations for the three different models in terms of masonry infill, open first story and bare frame building models have been carried out for X and Y-directions. Figure 11. shows the obtained peak displacements of each story of the developed building models in both X and Y-directions under RS (upper row) and TH (lower row). From these plotted curves, it is clear that the induced peak displacements under TH records slightly differ from the induced values by RS method in the considered two directions of analysis regardless the building model type. Incorporation of masonry infill significantly reduces the induced peak displacement as compared to the bare frame model under the same seismic excitations in X-direction. Similar trend has been observed in Y-direction. Obviously, the story displacement profile increases non-linearly as the story level gets higher regardless the type of the dynamic analysis. The plotted curves for the peak displacements associated with the open first story model employing the RS analysis method show similar trend after passing soft story level for X and Y-directions.

The time-history analysis has been found to produce similar trends as well. The tendency of the open first floor model in reducing the stories peak displacements in a similar way to the infill model can be observed (see Figure 11). However, the existence of a soft story at first floor clearly force the model to behave similarly to the bare frame model showing identical values of peak displacements at that floor. The abrupt change in the displacement profile of the model with soft story as compared to the smooth displacement profiles for the bare frame and infill frame models can be due to the stiffness irregularity. The gap difference between the captured peak displacements for the bare frame models and the other two models gets widen with the increase in building height regardless the loading direction and type of analysis as well. Clearly, the lower the stories the smaller the divergence between the plotted curves. The captured maximum displacements using RS method applied in X-direction for bare frame, infill frame and open first story models are 34.2, 10.2 and 13.1 mm respectively. The corresponding values using TH analysis are 37.5, 13.5 and 15.7 mm respectively. These presented peak results show slight increase in the obtained peak displacement values with the use of TH to perform the analysis in the X-direction. Similar trend of results have been found with the applications of seismic loadings in Y-directions. Comparing the peak displacement results of the infill frame model with the bare frame one clearly indicate that such inclusion of masonry infill action in the RC frame significantly reduces the lateral displacement considerably due to corresponding increase in lateral stiffness.

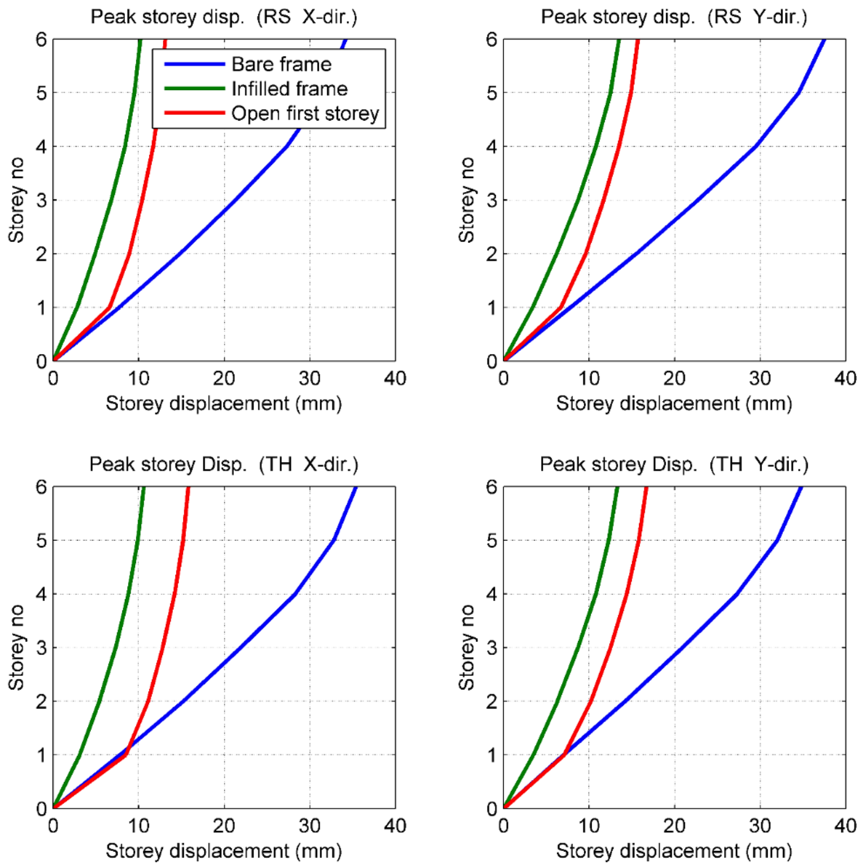


Figure 11. Story displacements in X and Y-directions for the considered different models under RS (upper row) and TH (lower row)

7.4. Story Drift

Story drift, which is defined as lateral displacement of one level relative to the level above or below normalized by floor height, is considered as an important indicator of structural behavior in performance-based seismic analyses which are used to judge the damage of structures. This can be due to the fact that story drift beyond certain levels may cause damages to the structural elements. In order to investigate the effect of the masonry infill action and the existence of a soft story at the first floor on the induced seismic stories drift, dynamic RS and TH analyses are used to excite all the considered bare frame, masonry infill frame and open first story frame building models. Curves of stories drift for the three different building models are displayed in Figure 12. under response spectrum (upper row) and time-history (bottom row) in both X- and Y-directions. As it is shown from the figure, under linear and nonlinear seismic analysis and in the considered two directions of loading, the drift distribution reached its maximum value at almost one-third the height of the building models considered except for the open first story which occurs at the first story level. The bare frame model exhibits a very major change in the induced story drift due to the effect of ignorance the masonry action as compared to the other two models with masonry infill action. For masonry infill and open first story models, slight change has been found in their seismic drift response apart from the first soft story. The obtained maximum drift response of bare frame, masonry infill and open first story models applying RS analysis in X-direction are 0.0024, 0.0007 and 0.0016 respectively and the corresponding values in Y-direction are 0.0026, 0.0009 and 0.0017 respectively. The application of TH analysis in X-direction produces peak drift response of 0.0025, 0.0008 and 0.0021 respectively. The corresponding peak values in Y-direction are 0.0024, 0.0009 and 0.0018 respectively. These presented results clearly identify that the inclusion of masonry action minimizes the peak story drift. However, the existence of a soft story significantly increases the peak story drift even with the inclusion of masonry action. In addition, the peak story drift calculated by TH analysis are almost identical to those obtained by RS method. It has also been noted that an abrupt changes in the slope of the drift profile of the model with a first soft story. This may be due to stiffness irregularity which also can be a reason of failure of structures under earthquake excitations where the columns in soft story case are imposed to large deformation and formed plastic hinges at top and bottom of the vertical elements.

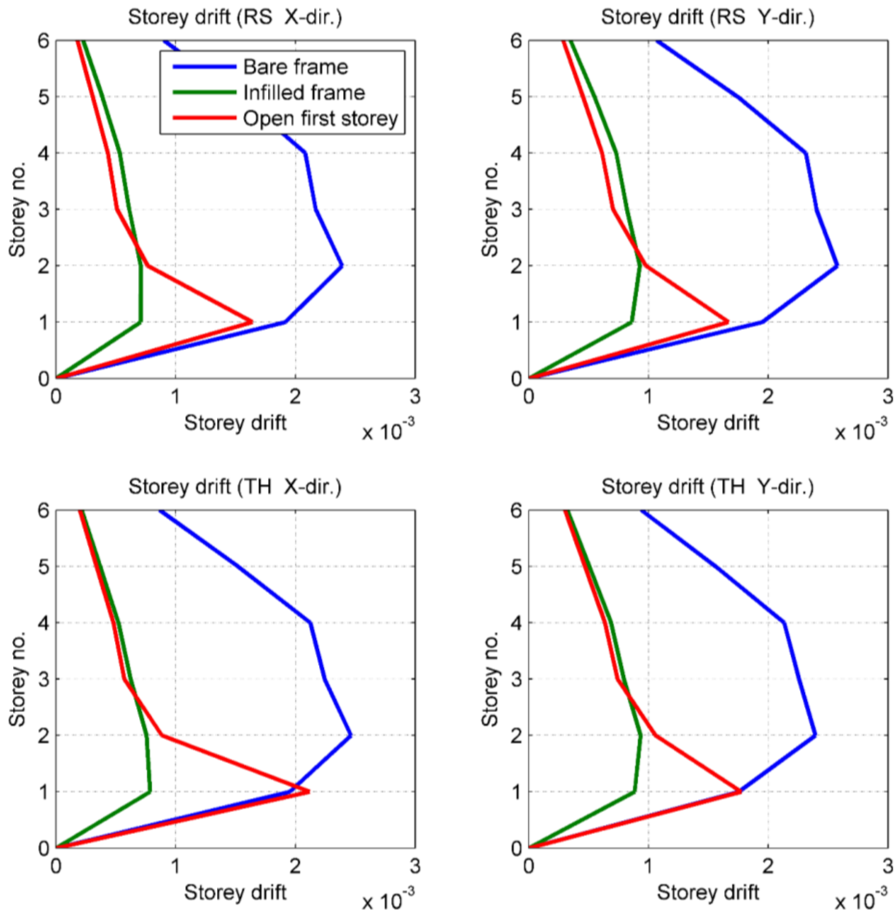


Figure 12. Story drifts in X and Y-directions for the considered different models under RS (upper row) and TH (lower row)

7.5. Story Overturning Moment

The building frame models are analyzed as bare frame, infill frame and with open first story frame under seismic actions applied separately in two orthogonal directions and the corresponding results are obtained. The curves in Figure 13. are showing the variation in story overturning moments throughout the height of building for three different building models in X and Y direction. The results by the linear dynamic RS analysis are introduced in the upper row of the figure. The lower row presents the results by the non-linear dynamic TH analysis. As it can be observed and irrespective of the type of seismic analysis, the infill frame model produces the highest moment values while the bare frame one produces the lowest moment values. The plotted curves of the overturning moment values for the bare frame model and associated values for the open first story model seems to be identical in values under RS analysis except at the first story where slight difference can be observed (see upper row of Figure 13). While the application of TH analysis show slight differences between the plotted curves of the infill model and the open first story model (see lower row of Figure 13). It can also be noted that, the lower the story the higher moment obtained under the earthquake load. The divergence between the obtained results is highly pronounced at the base of the building models. Regardless the direction of loading, the performed analysis using TH analysis shows higher moment values as compared to the corresponding values employing the RS analysis to perform the simulation. The peak moment values due to the application of RS analysis in X-direction have been found to be $2.8256 \times 104\ kN.m$, $3.4121 \times 104\ kN.m$ and $3.0141 \times 104\ kN.m$ for the bare frame, infill frame and open first story frame models respectively. While the corresponding values for the TH analysis have been found to be $3.1340 \times 104\ kN.m$, $5.3858 \times 104\ kN.m$ and $4.1496 \times 104\ kN.m$. These recorded results clearly indicate that considering masonry infill action considerably increase story moments. Moreover, the use of non-linear dynamic analysis highly magnifies the dynamic overturning moment response of the structures as compared to the linear dynamic one. Comparing the plotted curves using RS analysis shows that the direction of loading, X-direction and Y-direction, does not have a significant influence on the captured floor moments. The plotted curves under the application of TH analysis in X-direction seems to be identical to the corresponding results obtained in Y-direction.

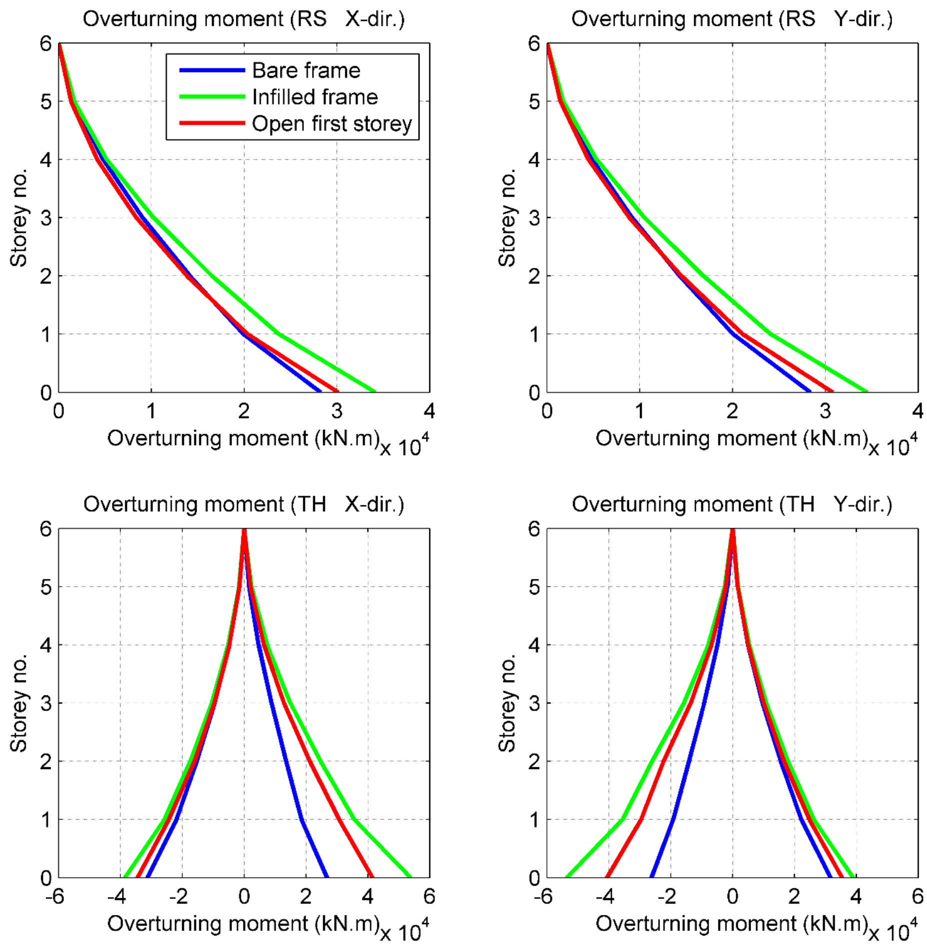


Figure 13. Story overturning moments in X and Y-directions for the considered different models under RS (upper row) and TH (lower row)

7.6. Story Stiffness

It is evident from Figure 14 that interaction between infill walls and frames have pronounced effect on the overall strength of the structure. Generally, the presence of masonry infill walls increases the stiffness of the building. Masonry infill walls applied to the considered building models highly increase the maximum stiffness in X direction four times the corresponding values of bare frame model. Similar trends can be observed in Y-direction. There is a notable reduction in the stiffness due to absence of masonry infill from first floor. This may be due to the first floor does not comply with the stiffness criteria and perform as a soft story. As it can be seen from the figure, identical agreement between the results of story stiffness for the infilled frame model and those for the open first story model just after passing the effect of existence of open story. The effect of such reduction in the induced stiffness at lower stories followed by coincidence with the story stiffness of infilled frame building model can be clearly seen in the induced story responses. For clarification, the induced drifts at lower stories of open first story and infill frame building models show significant divergence followed by nearly identical drifts at higher stories for the employed two methods of analysis.

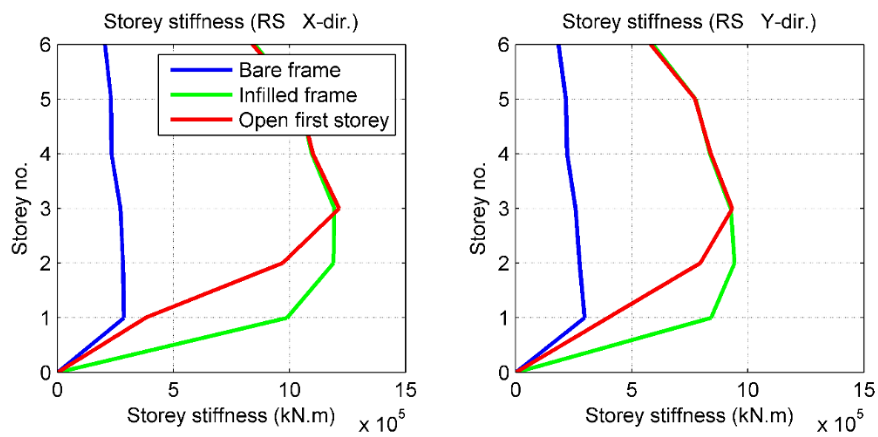


Figure 14. Story stiffness in X and Y-directions for the considered different models under RS

7.7. Energy Response

Energy is imparted to building structures when they are subjected to an earthquake excitation. Part of this imparted energy is temporarily stored in the affected structure. The kinetic and potential or strain energy are clear forms of these absorbed energies. The rest of the imparted energy is dissipated by both damping energy and yielding deformation in the elements of the structure. The energy time history curves for the input energy to the structures due to the applied El Centro earthquake, the kinetic energy and potential or elastic strain energy (the available energies in ETABS) are presented in Figure 15. for bare frame, infilled frame and open first story frame models in both X and Y-directions. As it can be seen from the figure, the input energy to bare frame building model are overestimated as compared to the other models considered. The absorbed kinetic energy time-history shows similar trend as the input energy. However, the potential energy show slight difference with the trend of input and kinetic energy. It is worth noting that the input energy to the structure must equal the absorbed energy. From the calculated results in X-direction, it has been found that the input energy values to the considered bare, infill and open first story models are 318.77 $kN.m$, 222.60 $kN.m$ and 256 $kN.m$ respectively. The corresponding calculated results for the absorbed energies have been found to be 160.78 $kN.m$, 117.36 $kN.m$ and 113.57 $kN.m$ for kinetic energies and 121.14 $kN.m$, 98.67 $kN.m$ and 138.03 $kN.m$ for the potential energies. Regardless the building model considered, these captured values clearly indicates that the input energies almost equal the absorbed energies. The captured numerical results in Y-direction prove the same as those presented for X-direction. From structural design point of view, the capacity of a structure to absorb energy must exceeds the input energy minus the dissipated energy through damping. The use of a damping ratio of about 5% of the critical, commonly used value during dynamic analysis, is able to dissipate a substantial amount of input energy to the structure.

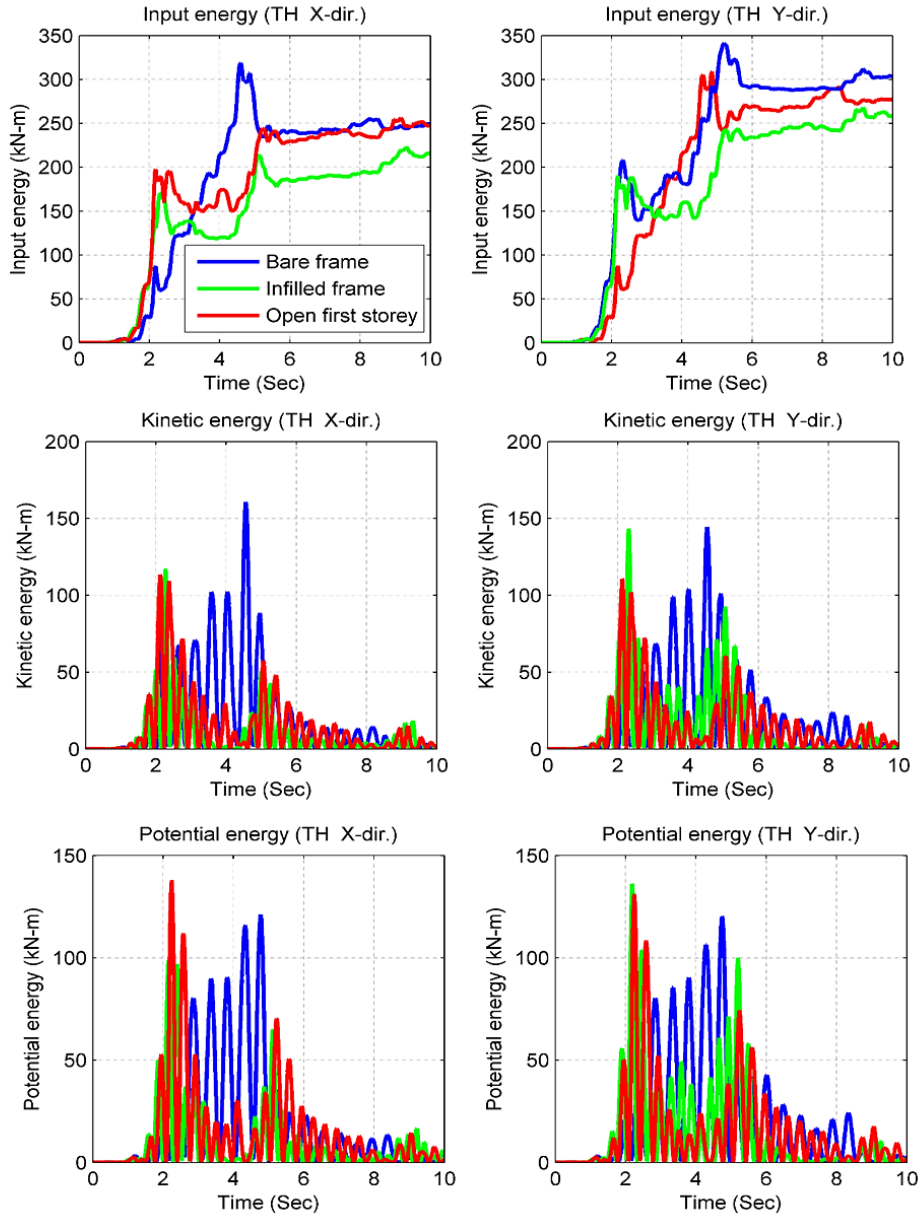


Figure 15. Input, kinetic and potential energies in X and Y-directions for the considered different models under TH

8. Conclusion

This research investigates the performance of reinforced concrete frame building models under earthquake load. The influence of factors related to building models such as masonry infill action and existence of a soft story are analyzed. Factors related the type of dynamic analysis in terms of linear and nonlinear dynamic analysis are also considered. It is concluded that, the inclusion of masonry infill action significantly changes the dynamic response behavior of the building model as compared to the bare frame model. Moreover, the existence of a soft story shows dramatic variation in the dynamic behavior of the infilled frame model as compared to the corresponding one without such soft story. In addition, the use of either linear or nonlinear analysis provides similar trends for the numerically simulated responses considered herein regardless the direction of loading. More specifically, ignorance of masonry action significantly underestimates some of the obtained responses in terms of design base shear and design base moments which crucially affect the requirements of for earthquake-resistant design. On the other hand, some other responses in terms of story displacement and story drift have been overestimated due to such ignorance of infill action leading to cost effective design due to the precautions required to prevent structural damages caused by the drift and deformation exceeding limits. Moreover, the overestimated energy especially the input energy to the structure can oblige the designer to enable the building to absorb such overestimated energy leading to costly designed structure. The fundamental natural period of the building model is highly influenced by the inclusion of the masonry infill action where the fully infilled model shows a significant decrease trend in the obtained natural period as compared to the bare frame model. However, the natural period of the infilled model with a soft story increased as compared to the full infilled one. According to the analysis of the results, the seismic design requirements are met when the masonry infill action is considered.

9. References

[1] Flanagan, R.D., Bennett, R.M. "In-plane Behavior of Structural Clay Tile Infilled Frames" Journal of Structural Engineering, 125 (1999): 590-599.

[2] Hao, H., Ma, G., Lu, Y. "Damage Assessment of Masonry Infilled RC Frames Subjected to Blasting Induced Ground Excitations " Journal of Engineering Structures, 24 (2002): 799-809.

[3] S. Sattar and A. B. Liel, Seismic Performance of Reinforced Concrete Frame Structures With and Without Masonry Infill Walls: Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering, 2010a.

[4] Colombo, A., Negro, P., Verzeletti, G. Infilled Frames Certainties and Uncertainties: Proceedings of the 11th European Conference on Earthquake Engineering, Paris, France, 1998; Balkerna: Rotterdam, The Netherlands, 1998.

[5] Varum, H. Seismic Assessment, Strengthening and Repair of Existing Buildings. PhD Thesis, Department of Civil Engineering, University of Aveiro 2003.

[6] Rodrigues H, Varum H, Costa A. "A non-linear masonry infill macor-model to represent the global behaviour of buildings under cyclic loading" Int J Mech Mater Des 4 (2008): 123–135.

[7] Rodrigues H, Varum H, Costa A. "Simplified Macro-Model for Infill Masonry Panels" Journal of Earthquake Engineering 14 (2010): 390-416.

[8] Uva G., Porco F., Fiore, A. "Appraisal of masonry infill walls effect in the seismic response of RC framed buildings: A case study" Eng. Struct. 34 (2012): 514–526.

[9] Porco F., Fiore, A., Uva, G., Raffaele, D. "The influence of infilled panels in retrofitting interventions of existing reinforced concrete buildings: A case study" Struct. Infrastruct. Eng. doi:10.1080/15732479.2013.8627 (2014).

[10] C V R Murty and S K Jain, Beneficial influence of masonry infills on seismic performance of RC frame buildings: Proceedings of the 12th World Conference on Earthquake Engineering, New Zealand, 2000.

[11] Kaushik, H.B., Rai, D.C., Jain, S.K. "Code Approaches to Seismic Design of Masonry-Infilled Reinforced Concrete Frames: A State-of-the-Art Review" Journal of Earthquake Spectra 22(2006): 961-983, 2006.

[12] Fajfar, P., Dolsek, M. "Soft Storey Effects in Uniformly Infilled Reinforced Concrete Frames" Journal of Earthquake Engineering 5(2001): 1-12.

[13] Arslan, M.H., Korkmaz, H.H. "What Is to Be Learned from Damage and Failure of Reinforced Concrete Structures During Recent Earthquakes in Turkey" Journal of Engineering Failure Analysis 14(2007): 1-22.

[14] Dogangun, A. "Performance of Reinforced Concrete Buildings during the May 1, 2003 Bingol Earthquake in Turkey" Journal of Engineering Structures 26 (2004): 841-856.

[15] Teguh, M. "Experimental evaluation of masonry infill walls of RC frame buildings subjected cyclic loads" Procedia Engineering, 171 (2017):191-200.

[16] Furtado, A., Rodrigues, H., Arede, A. and Varum, H. "Influence of the in-plane and out-of-plane masonry infill walls interaction in the structural response of RC buildings" Procedia Engineering, 114 (2015): 722-729.

[17] Furtado, A., Rodrigues, H. and Arede, A. "Modelling of masonry infill walls participation in the seismic behaviour of RC buildings using OpenSees" Int J Adv Struct Eng, (2015): 7:117-127.[18] FEMA - 306: "Evaluation of Earthquake Damaged Concrete and Masonry Wall Buildings - Basic Procedures Manual" Federal Emergency Management Agency (1999).

[19] Holmes, Malcolm. "Steel frames with brickwork and concrete infilling." Proceedings of the Institution of Civil Engineers 19, no. 4 (1961): 473-478.

[20] Mainstone, R. J. "Supplementary Note on the Stiffness and Strength of Infilled Frames. " Building Research Station, Garston, Watford (1974).

[21] Moustafa, Abbas, and Sayed Mahmoud. "Damage assessment of adjacent buildings under earthquake loads." Engineering Structures 61 (2014): 153-165.