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Seismic Response Evaluation of Moment-Resisting-Frame Multi-Story Buildings with Soft Story

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Abstract: **The current study investigates the seismic response of reinforced concrete moment resisting-frame multi-story buildings with soft story or open story located at different levels and designed according to the Egyptian Code. Different building models as (1) bare frame, (2) frame with fully infill wall panels and (3) frame models with infill panels and soft storey at base level, 3rd level, 6th level, 9th level, and 12th level have been built. In order to simulate the stiffness and structural action of masonry infill walls, single equivalent strut method has been used. The seismic response of the considered models are obtained using dynamic response spectrum analysis. The obtained response quantities are storey displacements, drifts, shear and overturning moments. In addition, the fundamental natural periods in both longitudinal and transverse directions of bare frame, frame with masonry infill, and a variety of building frame models with soft storeys have also been computed. The results obtained from the analysis for bare frame model tend to highly deviate from the results of other models confirming the usefulness and necessity of considering masonry infill wall action. Moreover, the absence of masonry infill action, i.e. existence of open or soft storey, causes significant and substantial changes in the obtained storey responses.**

Keywords: **masonry infill walls, single diagonal strut, soft storey, response spectrum analysis, moment resisting frame, ETABS program.**

I. INTRODUCTION

Many of the moment resisting frame multi-storey buildings are constructed with an adopted open storey in order to accommodate parking garages, reception lobbies or any other open air spaces which is considered now a day's as unavoidable feature. This open floor is characterized with little or no infill wall, that result to frame-infill interaction which may significantly affect both the stiffness and strength of frame building on resisting the lateral loads due to weakness of the open storey relative to the other storeys. Such multi-storey reinforced concrete buildings are often called buildings with soft storey.

In 1969, Fintel and Khan [1] introduced the concept of soft story. However, during the 1930s some other researchers focused on some aspects of an open or soft first story (see, [2-4]). The 1997 Uniform Building Code (UBC) [5] and several other codes, (see for example, IBC-2003 [6] and ASCE-2002 [7]) define the soft storey as the floor of about 70% less stiffness than the floor above it.

Masonry infill walls, which consist mainly of bricks or concrete blocks, are treated as non-structural elements and their strength and stiffness contribution are neglected during earthquake resistant design where most of the multi-storey RC frame buildings are designed without considering structural action of masonry infill walls. However, the effect of such structural action under seismic actions has been proved to have a significant impact on the seismic response of the structure through increasing both structural stiffness and strength compared to bare RC frame buildings [8,9]. Significant evidences from observations of damage of RC buildings having soft storeys and located in active seismic zones led to investigating the idea in greater details as well as realizing the potential economic advantages from the implemented concept with safety and other necessary practical provisions.

Rao et al [10] performed a response analysis in terms of floor displacement, drift and base shear employing IDARC 2D program for nonlinear analysis. Significant reductions in the considered responses have been found due to the incorporation of the infill wall effects. Seismic performance of a RC structural building with soft storey under a strong ground motion has been investigated by Amit and Gawand [11]. Sharma and Setia [12] employed the equivalent static force procedure in order to analyze the response of RC building with soft storey and having shear walls in different directions. Investigating the behavior of RC as well as the overall damage of frame buildings under dynamic loads considering and ignoring the effect of masonry infill walls can be found in [13,14]

The major aim of this research paper is to investigate the response behavior of RC framed buildings due to existence of a soft story at different storey levels. Different structural models are built with soft storey at base level, 3rd level, 6th level, 9th level, and 12th level. Due to its simplicity and suitability for large structures, the widely used single equivalent strut method is utilized to model the infill wall panels and hence representing the stiffness and the structural action of masonry infill walls. The numerical simulations will be performed using response spectrum procedures as representative to the dynamic analysis.

II. MODEL CONSIDERED FOR ANALYSIS

The building structure considered in this research study is a typical reinforced concrete (RC) framed building designed according to the Egyptian code. In order to study the effect of soft storeys and their locations on the dynamic response of reinforced concrete framed buildings, different building models with infill panels were developed. The typical plan of the considered building models has six bays of 36 m and 4 bays of 16 m in both X-direction and Y- direction respectively (see Figure 1). The floor height has been assigned to be of 3m. The buildings are modelled as moment-resisting frames having soft storeys at; base, third storey, sixth storey, ninth storey, and twelfth storey as can be seen in Figure 2. In order to avoid torsional response due to irregularity, the chosen plan of the building system ensures symmetry in both X and Y directions. The covering slab is designed as solid slab system of thickness 14 cm. The designed reinforced concrete beam are of dimensions 30x60 cm. The columns orientation as can be seen in the figure and are of cross sections 30x60 cm without reduction in dimensions throughout the building height. For the purpose of defining the lateral loads, the considered building models are assumed to be located in Cairo as well as rested on soil of medium strength. Due to its simplicity and suitability for large structures, the single strut model is used to model the infill wall. Properties of the used construction materials in terms of elastic modulus, unit weight and poisons ratio for both concrete and masonry are 24099 MPa, 25.0 kN/m3, 0.20 and 5500 MPa, 20.0 kN/m3, 0.15 respectively. ETABS the well-known software package are used for developing the models. The developed models are (i) bare frame with included masses of infill walls (ii) building model with full infill masonry (iii) building model with full infill masonry except base floor (iv) building model with open storey at 3rd floor (v) building model with open storey at 6rd floor (vi) building model with open storey at 9rd floor and (vii) Building model with open storey at 12th floor. Moreover, the ETABS software package is used to perform both the static and dynamic analysis following the Egyptian Code for loads.

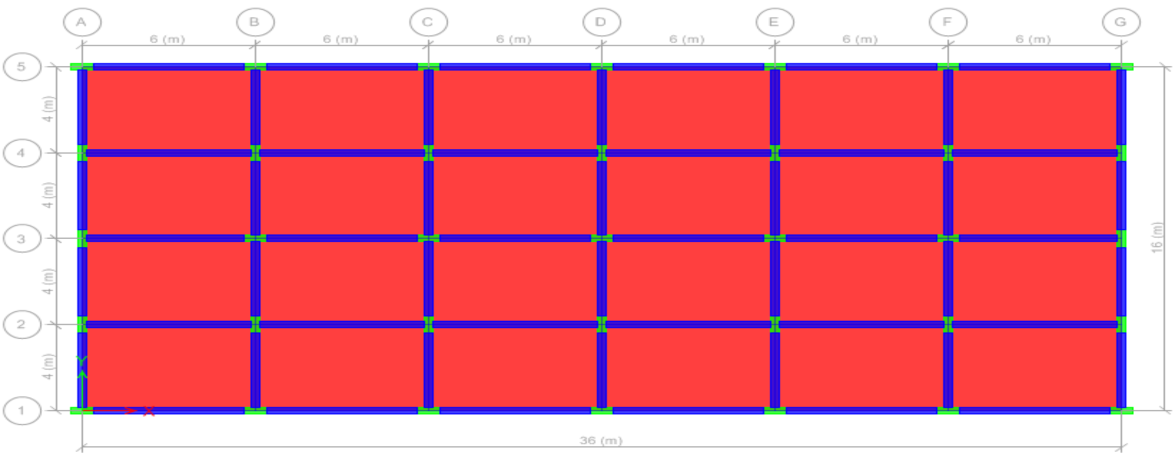

Fig. 1. Typical floor plan of the thirteen storeys frame building

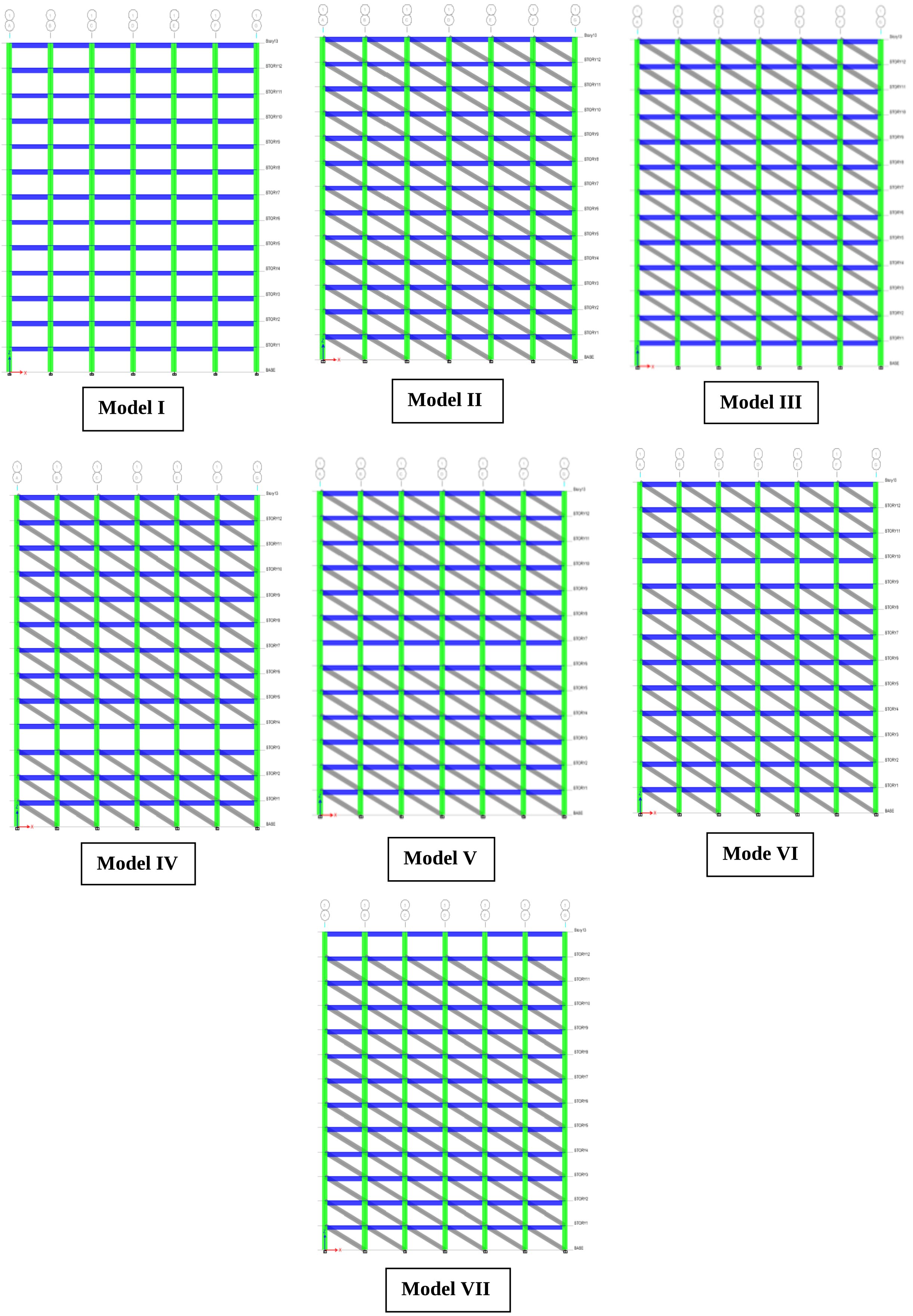

Fig. 2. Developed models with different arrangements of the open storey

III. MODELLING OF MASONRY- INFILL WALLS

Two methods have been proposed in order to properly simulate the behavior of masonry-infill walls namely, the micro model method (see for example, Morbiducci 2003) and the macro model method which has been introduced by Polyakov in 1966. Although the micro model method is producing the better results and can be used for understanding local and global response, it is rarely used due to its complexity in generating the model and the computation costs. The macro model method, also called the equivalent diagonal strut method, has been developed to study the global response of masonry-infilled frame buildings. The main disadvantage of the equivalent diagonal strut method is the deficiency in modelling the openings accurately. However, there are some advances in considering walls openings where some number of struts can be used in order to accommodate the effect of openings (Asteris 2003, Puglisi and Uzcategui 2008). In the current study, walls are modelled as panel elements without any opening. Requirements of FEMA 356 will be followed to model the masonry infill walls. According to FEMA 356, masonry-infill walls prior to cracking is modelled with an equivalent diagonal compression strut of width, a. The thickness and modulus of elasticity of the strut are same as those of the represented infill panel.

The thickness of the strut can be written in terms of the column height between centerlines of beams h_{col} and the length of panel L as:

$$a = 0.175(\lambda_1 h_{col})^{-0.4} r_{inf} \quad (1)$$

Where the value of diagonal length of infill panel r_{inf} can be calculated according to Eq. (2)

$$r_{inf} = \sqrt{(L_{inf})^2 + (h_{inf})^2} \quad (2)$$

The Coefficient λ_1 which is used to determine equivalent width of infill strut can be calculated as a function of the infill panel height h_{inf}, moduli of elasticity of both frame materials E_{fe} and material of infill panel E_{me}, columns moment of inertia I_{col}, infill panel length L_{inf} and thickness t_{inf}, according to Eq. (3):

$$\lambda_1 = \left[\frac{E_{me}\, t_{inf} \sin 2\phi^{\circ}}{4 E_{fe} I_{col} h_{inf}}\right]^{\frac{1}{4}} \quad (3)$$

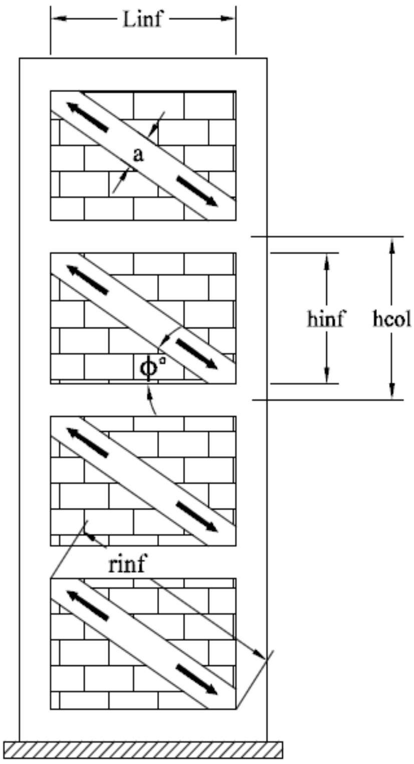

Fig. 3.Equivlent diagonal compressive strut model

IV. RESPONSE SPECTRUM METHOD

Due to its simplicity and ease of application, the equivalent static force (ESF) method is still widely used. However, the application of ESF method requires structures regular in shapes as well as limited in their heights. Moreover, the use of ESF may lead to unreasonable results in some specified cases. These restrictions minimize the use of ESF in analyzing structures under earthquake loads. The linear elastic response spectrum analysis is valid for all types of structures. Response spectrum are curves plotted between peak response of single degree of freedom system in terms of displacement, velocity, and acceleration against its natural frequency due to specified earthquake ground motion or set of earthquake ground motions. So when time period of the structural is known , the peak response of structural can be determined and then the base shear can be calculated by contribution of some important parameters. These parameters mainly depend on seismic zone factor, soil condition, important factor of building, structural system of the building (shear wall or frame system or combined) and damping factor. Another important parameter is the modal analysis in which response spectrum analysis compute the structure's response through considering modes. These modes mainly depend on structure's height. The application of Response spectrum analysis requires considering sufficient number of vibration modes in order to capture participation of at least 90% of the structure's mass in each of two orthogonal directions. For low to mid rise structural, the first three modes are enough to get accurate results. However, more than three modes have to be considered for high rise structural. In order to calculate peak response values, several methods are used to combine these major modes. One of these familiar methods is square root of some squares (SRSS) of the maximum model value, sum of the absolute of the modal response values (ABS) and the complete quadratic combination (CQC) are also methods to calculate peak response computation. Another very important parameter is rescaling the base shear that obtained from response spectrum analysis with the one obtained from ESF. Egyptian Code for seismic design defines specific equations for each range of the spectrum curve for four different

$$S_a\,(T) = a_g\,\gamma_1 S_1 \left[\frac{2}{3} + \frac{\mathrm{T}}{T_B}\left(\frac{2.5\eta}{R} - \frac{2}{3}\right)\right] \qquad 0 \le \mathrm{T} \le T_B$$

$$S_a\,(T) = a_g\,\gamma_1 S_1 \frac{2.5\eta}{R} \qquad T_B < \mathrm{T} < T_C$$

$$S_a\,(T) = a_g\,\gamma_1 S_1 \frac{2.5}{R}\left[\frac{T_C}{T}\right]\eta \;\ge 0.2\,a_g\,\gamma_1 \qquad T_C < \mathrm{T} < T_D$$

$$S_a\,(T) = a_g\,\gamma_1 S_1 \frac{2.5}{R}\left[\frac{T_C T_D}{T^2}\right]\eta \;\ge 0.2\,a_g\,\gamma_1 \qquad T_D < \mathrm{T} < 4\,Sec$$

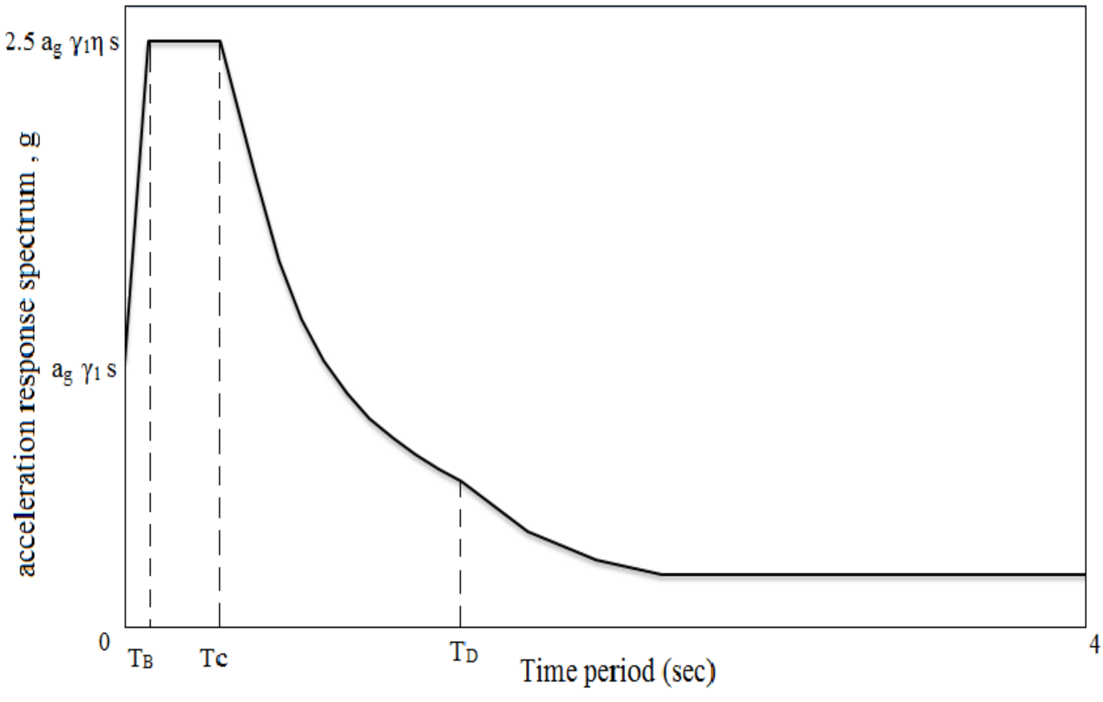

Fig. 4. Design response spectrum curve according to Egyptian Code (2008)

Where Sa (T) is the spectrum acceleration at period T, ag is the design ground acceleration. T_B, T_C, T_D are the natural period values characterize the elastic response spectrum shape. These period values are mainly depending on the ground type of the constant spectral acceleration, η is the design damping correction factor for the horizontal elastic response spectrum. S represents the soil factor, the importance of the structure is denoted by γ and the reduction factor R is mainly dependent on the structural system.

V. RESULTS AND DISCUSSIONS

In this section, the framed building shown in Figure 1 is used in order to evaluate the effect of soft storeys and their locations on the dynamic response of reinforced concrete framed buildings. The developed building models presented in Figure 2 with infill panels and soft storeys at; base, third, sixth, ninth, and twelfth floors are also used in this analysis. The dynamic response spectrum analysis has been performed following the Egyptian code requirements where the considered moment resisting frame building is located in Cairo. Accordingly, the considered seismic zone has been set to be III, and the selected soil profile type is C (medium sand). Response modification factor of 5 to suit RC moment resisting frame building has been chosen. Damping correction factor and importance factors equal unity has been utilized in the analysis. The well-known Software package ETABS has been used to perform the analysis. The used version is V.13.1.5 year 2013.

The results for the developed seven different models of the framed building, namely, bare frame building model, building model with full infill masonry, building models with soft storey at base, 3rd floor, 6th floor, 9th floor, and at 12th floor are presented in the form figures and table. The observed trends in the results are discussed in this section.

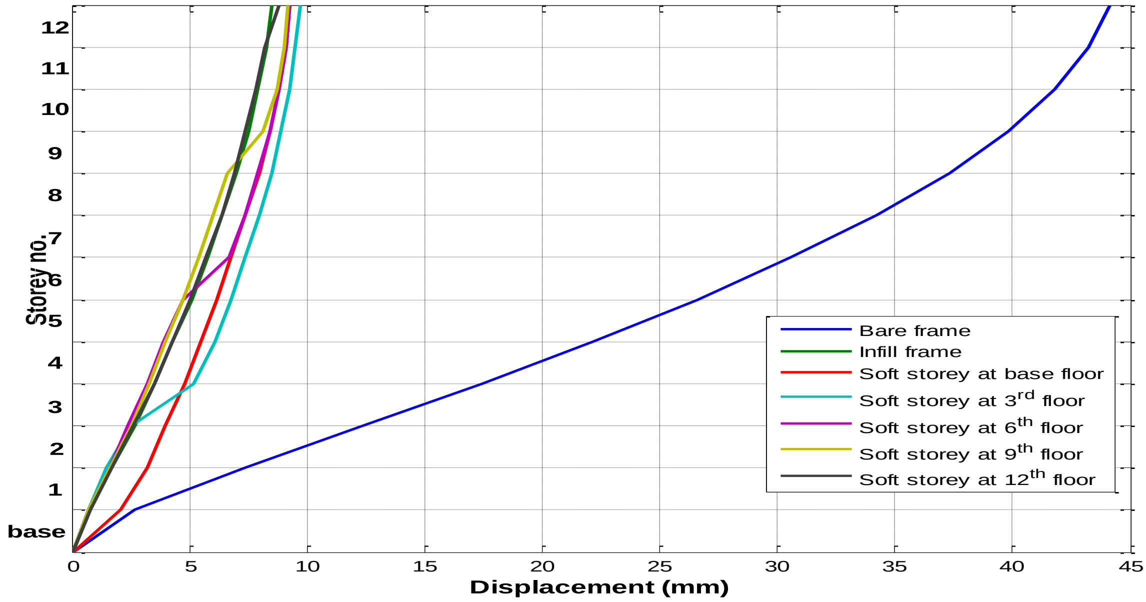

Fig. 5. Peak storey displacements versus building height for bare frame, frame with masonry infill, and framed building models with soft storey under dynamic response spectrum loading

To show the effect of considering and ignoring modelling buildings with masonry infill walls as well as the effect of considering soft storeys located at different levels on the peak displacements distribution throughout the height of building, The storeys peak displacements distribution for the cases of bare frame, masonry infill frame, and soft storey at base, 3rd, 6th, 9th, and 12th levels have been calculated using dynamic response spectrum analysis and presented in Figure 5. It can be observed from the figure that the case for bare frame, i.e., ignoring masonry infill action, significantly overestimates the obtained peak displacements at each storey level compared to the case of masonry infill wall frame especially at higher storeys of the building frame. This can be due to the increase in building stiffness with the consideration of masonry infill wall action. Comparing the plotted curve for the case of infill frame with the plotted curves for the building frame with soft storey at different levels shows that all the curves are coinciding with the curve of infill wall case and start to diverge with significant increase in displacements at these storeys for all the considered cases as can be seen in Figure 5. This sudden increase in peak displacements is due to the absence of masonry infill action at the soft storey levels. The trend in the increase in peak displacements after passing the soft storey has been found to be similar for all considered locations of soft storeys. It is worth noting that the soft storey does not affect the obtained displacement values of storeys located below. However, an increase trend in the displacement values of the storeys located above have been found.

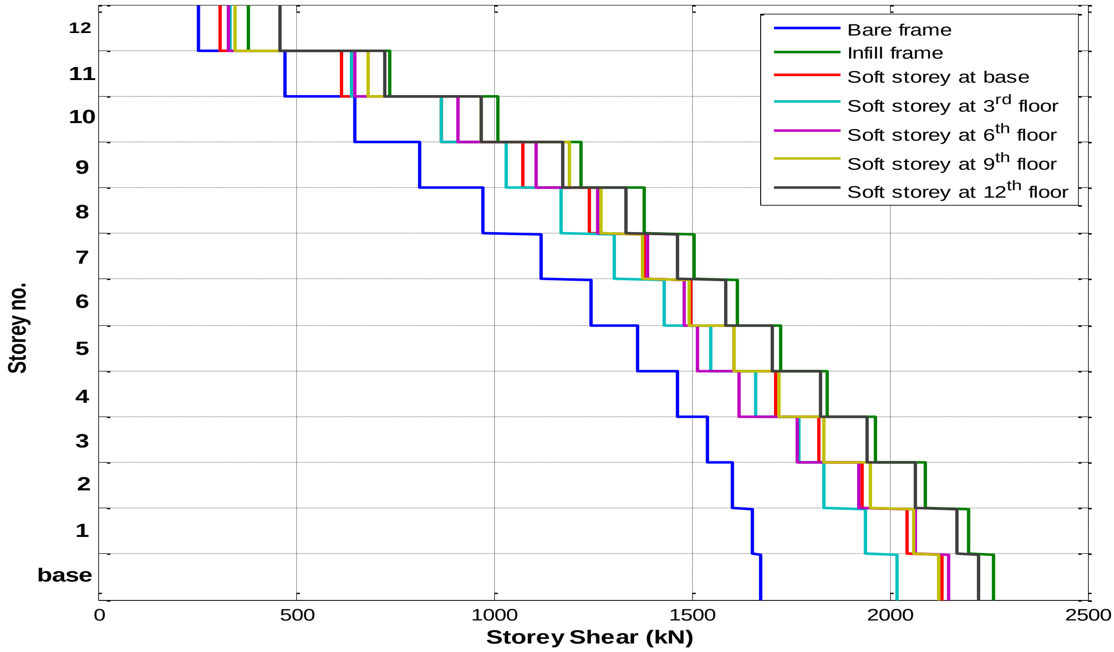

Fig. 6. Peak storey shear forces versus building height for bare frame, frame with masonry infill wall, and framed building models with soft storey under dynamic response spectrum loading

Figure 6 presents the obtained storeys and base shear forces for framed building modelled as bare frame, frame with masonry infill walls, and frame building with soft storeys. As it can be seen from the figure under dynamic response spectrum analysis and when masonry infill was not considered in the analysis (i.e., bare frame model case) the response in terms of storey shear forces shows transmission of smaller shear forces to the base and superstructure than those transmitted to the building model with masonry infill. The presence of soft storey at base or at any other level generally decreases the transmitted shear forces to the floors of the building models compared to masonry infill frame model. From earthquake resistant design point of view, ignoring masonry infill wall action significantly underestimates the shear force at the base, which is considered as one of the main parameters during design stages, and hence may lead to unsafe design.

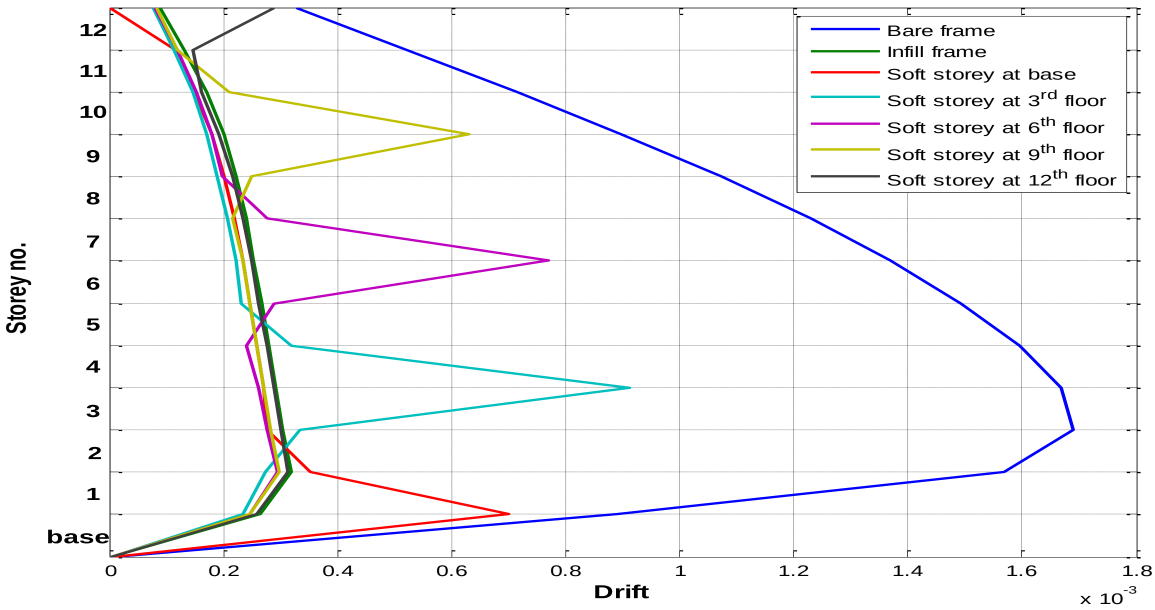

Fig. 7. Peak storey drifts versus building height for bare frame, frame with masonry infill wall, and framed building models with soft storey under dynamic RS loading

One of the objectives of this research work is to study the framed building drift response. In order to achieve this, the dynamic response spectrum analysis is used to excite all the considered models. Curves of storeys drift are displayed in Figure 7 for the all the considered building model types as bare frame, masonry infill wall frame, and masonry infill wall frame with soft storeys. From the figure one can find that; first, the storey drift induced by the bare frame model in which the masonry infill action is ignored is much higher than those obtained by the other considered cases. Second, the storey drift obtained from the analysis of the frame building modelled to consider the masonry infill action is highly lower than the case ignores such action. Third, the drift values for a building model with soft storey almost show values similar to those obtained considering masonry infill actions except at the location of soft storey where a significant increase in the drift can be observed. Considering masonry infill wall action in modelling of buildings decreases the induced drift values. However, the existence of a soft storey at any level increases the drift value at that storey and may exceed the allowable limits suggested by design codes.

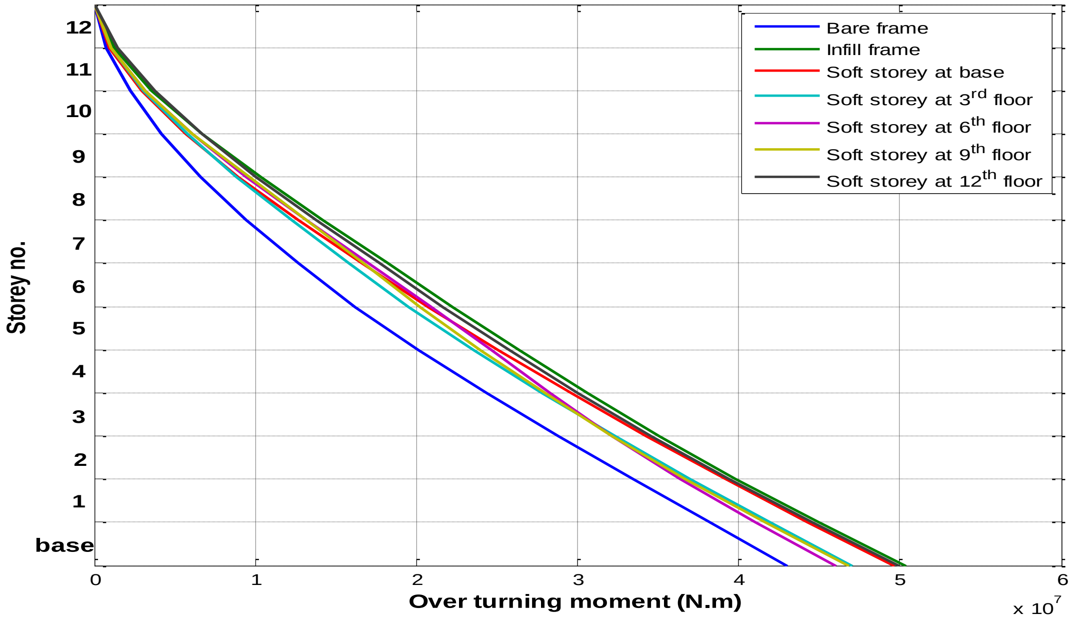

Fig. 8. Peak storey moments versus building height for bare frame, frame with masonry infill wall, and framed building models with soft storey under dynamic RS loading

Figure 8 presents the Peak storey moments at each storey level for the bare frame model, frame with masonry infill wall model, and framed building models with soft storeys in a comparative way under dynamic RS loading. As can be seen, ignoring the masonry infill wall action underestimates the obtained bending moments (see the bare frame case). The induced overturning moments for the framed building model with fully masonry infill walls and those having soft storeys at different locations show insignificant changes in the obtained values at higher storeys. However, the change in peak moments is pronounced at lower storeys.

TABLE 1: FUNDAMENTAL LATERAL NATURAL PERIODS OF BARE FRAME, FRAME WITH MASONRY INFILL, AND FRAME WITH MASONRY INFILL HAVING SOFT STOREYS

Fundamental time period (Sec.)		
Model No	ETABS Analysis (RSA)	
	Longitudinal Direction	Transverse Direction
I	1.899	1.753
II	0.745	0.770
III	0.839	0.866
IV	0.897	0.908
V	0.829	0.849
VI	0.768	0.794
VII	0.744	0.768

The change in fundamental lateral natural period obtained from the conducted analysis for 6 bay 4 bay framed building modelled as bare frame, frame with full masonry infill walls, and frame with masonry infill walls having soft storeys at different levels are presented in Table 1 for both longitudinal and transverse directions. It observed that Model I which represents the bare frame model gives higher time period compared to the other models considered in the analysis. The percentage changes in lateral natural period due to incorporation of the masonry infill walls represented by model II in the Table 1 compared to the lateral natural period of bare frame model represented by model I are of about 61% and 56% in both longitudinal and transverse directions respectively. The results for all other cases are also exhibit similar trends showing insignificant change in their fundamental lateral natural periods, irrespective of the soft storey location in both longitudinal and transverse directions respectively. Again, this observation is found to be true for both types of the bare frames, namely, the ones without tie beams as well as the ones with tie beams.

VI. CONCLUSION

In this work, the analysis of a 12-storey reinforced concrete moment resisting-frame multi-story building designed according to the Egyptian Code for seismic loading and modelled as bare frame, frame with fully infill wall panels and frame models with infill panels and soft storey at different levels has been carried out. The analysis results obtained in this work indicate the seismic performance of the analysed reinforced concrete frame building model with masonry infill wall action is much better than the performance of bare frame model. In fact, the bare frame model produces design shear forces substantially differs and less than the demand one produced with masonry infill action and this may lead to design failure. The analysis of storey peak displacements clearly highlights the effect of masonry infill action which causes substantial increase in the obtained storey peak displacement. This reflects the big gap between considering and ignoring masonry infill action. On the other hand, existence of a soft storey induces sudden increase in the drift at that storey. The presence of soft storey at base or at any other level generally decreases the transmitted shear forces to the floors of the building models compared to masonry infill frame model. Slight changes in the induced moments at higher storeys have been found for all the considered building models. At lower storeys such change in storey moments become more pronounced. Both transverse and longitudinal fundamental natural buildings of the superstructure emphasis the effect of masonry infill action.

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