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Response Analysis of Multi-Storey RC Buildings under Equivalent Static and Dynamic Loads According to Egyptian Code

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Abstract: **The frequent occurrence of earthquakes around the world has heightened the need for studying the seismic performance of existing structures according to code of practice. This concept has become an urgent issue in Egypt especially after hitting a dramatic earthquake to Cairo in 1992. The objective of this research is to assess the seismic performance of an existing shear wall residential building located in Cairo. Both dynamic response spectrum (RS) and equivalent static force (ESF) methods are used in the seismic analysis. The design RS curve suggested by the Egyptian Code (EC) for seismic design is utilized to perform the dynamic analysis. The response analysis of the building under the acting seismic loads has been performed using ETABS, universal finite element analysis software for dynamic analysis. The entire work has been carried out in two stages in order to rescale the dynamic base shear. In the first stage, the built three dimensional building model has been subjected to the static and dynamic earthquake loading following Egyptian code guidelines and hence the obtained static and dynamic base shear are compared. The second stage is concerned with scaling the obtained dynamic base shear and reloading the model as the first stage. The considered responses are expressed in terms of floor displacements, shear forces at each floor level, base shear and base moment. Moreover, results from numerical simulations, for storey torsional irregularity ratios are presented for the considered static and dynamic analysis methods. The results of the study show significant differences in building's responses obtained using ESF and RS analysis methods. It has been found that the application of static method in a specified direction results in responses in the same direction. However, the applications of dynamic RS method induces response in both directions regardless the direction of loading.**

Keywords: **Equivalent static force, response spectrum, base shear, Egyptian code.**

I. INTRODUCTION

After the devastating 1992 earthquake in Egypt, the Housing and Building National Research Center started modifying the existing EC for loads in order to efficiently simulate expected ground motions and provide the seismic loads required for earthquake resistant design of structures [1-4]. Reconsidering the existing structure design requirements was also one of the main roles of the established committees at that time. The EC for loads issued in 1993 only considered the ESF method as sufficient to represent lateral seismic loads. In fact, this method has been permitted in most of the design codes for loads all over the world and often proves to be sufficient for regular buildings with heights range from low to medium. For high-rise structures, where more modes have to be considered, as well as structures having irregularities whether in plan or in elevation, where torsional effects may be significant, dynamic analysis rather than static one can be used for more accurate analysis. Two types of dynamic analysis namely; time-history (TH) analysis and RS analysis methods can be used to make the structures sound against seismic activity. Several major modifications were introduced to edition of

1993 Egyptian code for loads through improving the ESF method and the inclusion of the dynamic RS analysis in order to accurately determine the lateral earthquake force at base and consequently the distribution of such dynamic base shear at the storey levels.

Analysis of structures using static and dynamic analysis methods has been carried out using several authors according to the Canadian code and other codes [5-10]. Based on the National Building Code of Canada (NBCC), Patrick P. et al. [11] introduced a spread sheet for the purpose of computing the seismic design forces using the equivalent static force procedure. Saleh M. et al. [12] conducted two-dimensional analysis using four different residential steel structures with different heights and designed using the standard equivalent static procedure per the Iranian Seismic Code of practice. Qaiser Z.K. [13] performed a detailed comparison between RS and ESF analysis methods considering a 20 story building of 200 ft increased up to 400 ft height with about 40 story in order to determine the height above which RS analysis significantly affects the structure design. The lateral seismic forces and the induced deformations obtained from the ESF procedure and the dynamic RS analysis method according to the 2005 NBCC are compared for buildings with different storey heights and having structural mass irregularity [14]. An analytical study for investigating the dynamic behavior of industrial buildings modelled respectively as regular crane-supporting steel structure and irregular building housing a vertical mechanical process has been carried out by Richard J. et al. [15]. The dynamic RS analysis and ESF analysis method have been used to evaluate the seismic response of both structures. Moreover, the elastic time-history dynamic analysis was employed for comparison purposes with the other two methods of analysis as well as validating the predicted results for both structures. S. A. Raheem [16] performed a research study in order to evaluate the Egyptian code for seismic design utilizing a RC multi-story building designed as moment-resistant frame employing the TH analysis procedure together with the dynamic RS analysis procedure and the ESF procedure. Analysis of the obtained results under the application of the three different approaches has been used to evaluate the advantages, limitations, and ease of application of each approach for seismic analysis according to EC for seismic design.

A review of the above cited papers indicates that among the conducted works to evaluate the performance of the dynamic RS analysis and the ESF analysis in seismic design only the work done by S. A. Raheem evaluates the recommended two methods of analysis by the Egyptian code for seismic design. However, in his work, the base shear determined by the ESF analysis method has not been used as a benchmark to scale the design base shear obtained by the dynamic RS analysis and hence affects both the distribution of the lateral seismic forces over the height of the structure and the analysed results.

The objective of the present paper is to provide a comparative study between the two seismic design analysis methods recommended by the 2012 edition of the EC for loads namely; ESF analysis and the dynamic RS analysis. The two methods of analysis are applied to a residential multi-storey reinforced concrete building of fourteen storey and designed according to the EC provision. The results under both the static and dynamic analysis are analysed and presented in the form of storey shear forces before and after scaling. The storey deflections and drifts in the direction of both X and Y directions are also presented. Further, the induced storey moments as well as the storey torsional irregularity ratios are computed and presented under the considered methods of loading in both directions of loading.

II. MODELLING AND IDEALIZATION

A. Building Description

This research studies reinforced concrete building as a typical fourteen storey flat slab-column system located in Cairo. The building is near to be square in plan with dimensions 18.6m x 19.3m. The building is designed for residential use. Typical floors plan and isometric view are presented in Fig. 1 and Fig. 2. Typical floor height is 3m. The floors are made of concrete flat slabs supported by columns. The thickness of the floor slab is 25 cm for all storeys. The cross-section of the columns used to support the structure is determined as 30cm x 50cm for smallest column dimensions in the structure and as 30x140 for the largest ones. The designed system to resist the seismic forces consists of two elevator cores in both X and Y direction. Additional shear wall in X direction is also designed for seismic resistance purpose. The considered herein building structure has been designed according to the EC with specified characteristic compressive strength f_{cu} = 25 MPa and steel reinforcement with yield strength f_y= 360 MPa.

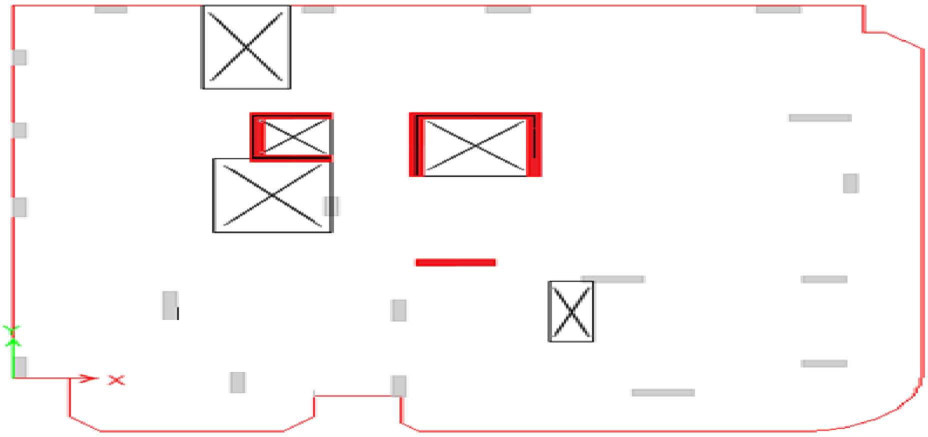

Fig. 1.Typical floors plan of the fourteen storey residential building

B. Building Model

The three dimensional RCmulti-storey building used in this study was modelled as flat slab-column system with shear walls. For the purpose of modelling the real behaviour of the slabs, they were modelled using shell elements to ensure providing stiffness in all directions and transfer mass of slab to columns and beams. A rigid diaphragm was assumed at all floor levels. In order to account for the modal damping effect, the complete quadratic combination (CQC) technique, which takes into account the statistical coupling between closely spaced modes caused by modal damping, is used for modal combination. The first modelling step with ETABS involves defining the physical properties of the used materials. Sections for horizontal and vertical elements of the considered building are defined in terms of dimensions and material properties. Consequently the defined sections are assigned to the corresponding plane elements such as slabs and beams and the corresponding vertical elements such as columns and shear walls. Choosing the correct boundary conditions through assigning supports and connections with appropriate restraints is one of the important aspects in structural modelling. Three-dimensional analysis is carried out under static and dynamic seismic analysis in both X and Y directions, which are known to be orthogonal directions.

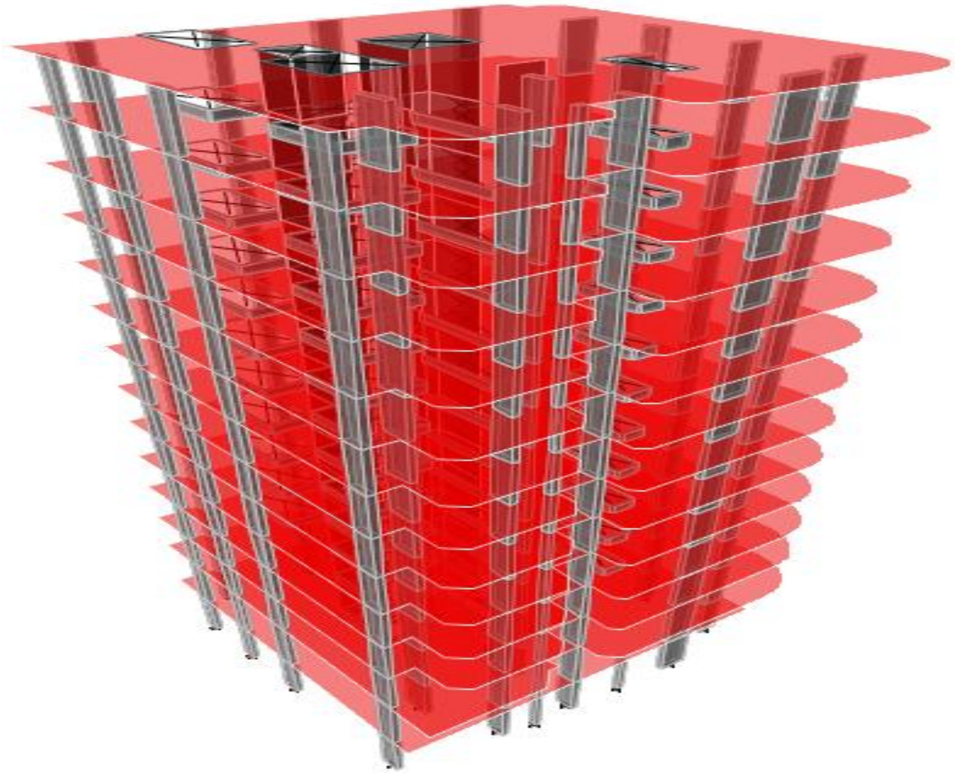

Fig. 2.Three-dimensional building model

III. EARTHQUAKE ANALYSIS METHODS

Most of the used design codes provide the minimum standards required life safety but not to insure preventing damage.There are two commonly used procedures for specifying seismic design forces namely: the linear dynamic RS analysis and the ESF analysis.

A. Equivalent Static Force Method

In this method the inertia forces are determined as static force with the use of empirical formulas. To adequately represent the dynamic behaviour of the structures, the method is highly recommended for regular structures with uniform distribution of mass and stiffness as well as uniform shape and statical system, . However, it can be applied to irregular ones with some limitations. The design base shear can be calculated as:

$$F_b = S_d(T)\lambda W/g \qquad (1)$$

Where, T represents the fundamental time period of the structure, λ is a correction factor, dependent on the fundamental period of the structure with respect to the value of T_C , W is the structure's weight. Additionally, the seismic zone factoraffects thevalue of the induced base shear. The formulas used to calculate the previously defined terms can be found in the design codes for loads. The use of the method requires defining parameters such as seismic zone factor, soil profile and seismic source type which can be calculated in accordance with the principals of the regulations used in this study. The base shear F_b, as determined from Eq. (1) is distributed over the height of the structure as a force F_i at each level in addition to a force F_t at the top of the structure according to the formula:

$$F_b = F_t + \sum_{i=1}^{n} F_i \qquad (2)$$

The extra force $F_t = 0.07TF_b$ and no more than 0.25 F_b only when $T > 0.7$ sec

The remaining portion of the total base shear $(F_b - F_t)$ is distributed over the height, including the top, by the formula:

$$F_i = \frac{(F_b - F_t)(w_i h_i)}{\sum_{i=1}^{n} w_i h_i} \qquad (3)$$

Where, w_i and h_i respectively refer tothe floor's weight and floor's heightat the i^{th} level above thebuilding's base. The point of action of the calculated storey force is acting at the storey centre of mass.

The overturning moment M at a particular storey level i is the sum of the moments of the story forces above, about that level. Hence:

$$M_i = F_t(h_n - h_i) + \sum_{j=i}^{n} F_j\left(h_j - h_i\right) \qquad (4)$$

The accidental torsional moment shall be determined through dividing the maximum displacement $\delta_{\max}$ at level i by the average displacement δ_{avg} and torsional irregularity exists if the obtained ratio exceeds 1.2. The effect of torsional irregularity at a specified storey shall be accounted for by increasing the accidental torsion at the specified level by an amplification factor, A_x determined from the following formula:

$$A_x = \left[\frac{\delta_{\max}}{1.2\delta_{avg}}\right]^2 \le 3 \qquad (5)$$

B. Response Spectrum Analysis Method

Response spectrum analysis is used for analysing the performance of structures under earthquake motions. The method assumes a single degree of freedom system to be excited by a ground motion in order to obtain the response spectrum curves for peak displacement, peak velocity or peak acceleration. Thus once the natural period of the structure is known then the response spectrum curves helps in estimating the peak responses of such structure. These estimated values are considered as the basis for calculating the earthquake forces to be resisted through earthquake resistant design stages. In order to perform RS analysis, important parameters in terms of expected earthquake intensity in the considered zone and the supporting base soil behaviour have to be considered. One of the other parameters related to the computation process is the modal analysis in which the RS analysis computes the structure's response through considering the significant modes. Mode contribution to the structure's response and flexural deformation is mainly dependent on the structure's height. For low to mid-rise structures, the first three modes are sufficient to capture accurate results where the higher modes contributions diminish very quickly. However, more than three modes have to be considered for high-rise structures. These numbers of requested modes can be selected such that their combined participating mass is at least of 90% of the total effective mass in the structure. Once the number of significant modes is established, several methods are used for the purpose of estimating the peak response values. The Square Root of Some of Squares (SRSS) of the maximum modal values is one of the popular methods. Another two methods namely: sum of the absolute of the modal response values (ABS) and the CQC are also used for peak response computation. Scaling the response spectrum curve to consider the over strength and global ductility capacity of lateral force-resisting systems is another important parameter during dynamic RS analysis. Rescaling the design base shear in accordance with the ones obtained with the ESF analysis is another important parameter. The regularity and irregularity of structures mainly govern the scaling factor of the design base shear. The design building codes in seismic regions uses the obtained pseudo acceleration values $S_d(T)$ as basis for calculating the forces that a structure must be designed to resist. The Egyptian design code for loads defines specific equations for each range of the spectrum curve for four different soil types and damping ratio as:

$$S_d(T) = a_g \gamma_I S \left[\frac{2}{3} + \frac{T}{T_B} \left(\frac{2.5}{R} - \frac{2}{3} \right) \right] \qquad 0 \leq T \leq T_B$$

$$S_d(T) = a_g \gamma_I S \frac{2.5}{R} \qquad T_B \leq T \leq T_C$$

$$S_d(T) = a_g \gamma_I S \frac{2.5}{R} \left[\frac{T_C}{T} \right] \geq [0.2] a_g \gamma_I \qquad T_C \leq T \leq T_D$$

$$S_d(T) = a_g \gamma_I S \frac{2.5}{R} \left[\frac{T_C T_D}{T^2} \right] \geq [0.2] a_g \gamma_I \qquad T_D \leq T \leq 4$$

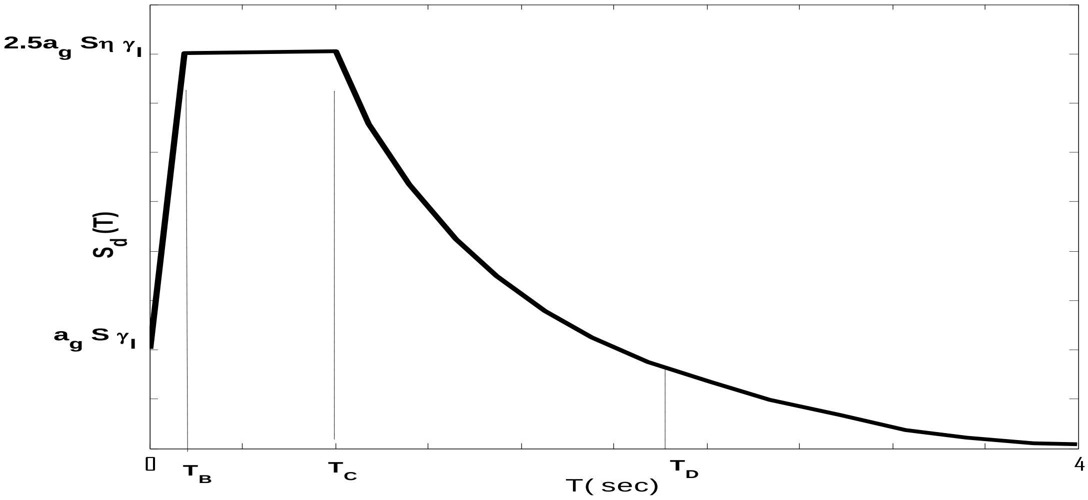

Fig. 3. Typical response spectrum curve

Where a_g, γ_I, and S respectively represent the designed peak ground acceleration, the important factor for the structure, and soil factor. R is a factor accounts for the ductility and over strength of the structural system. T_B, T_C, T_D are values for the periods describing the shape of the elastic response spectrum and depend on the ground type.

IV. STATIC AND DYNAMIC ANALYSIS RESULTS

The nonlinear finite element analysis software ETABS is employed to create the building model and run analysis. The considered software package enables the user to define the earthquake load acting on the structure as static and/or dynamic loads. Moreover, the software allows the user to perform the analysis according to several predefined codes. The adopted model for analysis is residential fourteen stories building with floor slabs as flat slabs of thickness 25 cm. Shear wall and cores of thickness 30 cm are used to resist the lateral forces. The building consists of rectangular columns with different dimensions vary from 30cmx50cm to 30cmx140cm. The foundation is designed as a raft of 1.50 m. The stories of the building are of 3.00 m height. Static and dynamic RS analysis methods which are equivalent to the seismic forces acting on the considered building structure will be calculated according to the EC for loads. Seismic zone 3 will be selected since the building is located in Cairo. The considered seismic zone is of peak ground acceleration of 0.15 g. Cairo is characterized with stiff Soil profile type and hence the soil at the site that will be used in the analysis is assumed to be of type C. The numerical coefficient R, which is a representative of the over strength and global ductility capacity of lateral force-resisting systems, is equivalent to 5 as the building is designed with shear walls to resist lateral forces. The seismic importance factor γ_I = 1. The results of the performed analysis are presented in the form of figures and tables. The induced nonscaled and scaled storey shear forces in X and Y directions under dynamic and static loads acting in X directions are presented in Fig. 4 and Fig. 5. The obtained maximum deflection at each storey level in the orthogonal directions X and Y for the considered two methods of analysis is presented in Fig. 6. In addition the variation storey moments in both X and Y directions due to applied static and dynamic load in X direction can be shown in Fig. 7. The values for torsional irregularities at each storey due to Static force and dynamic RS analysis in both directions of loadings are presented in Table 1.

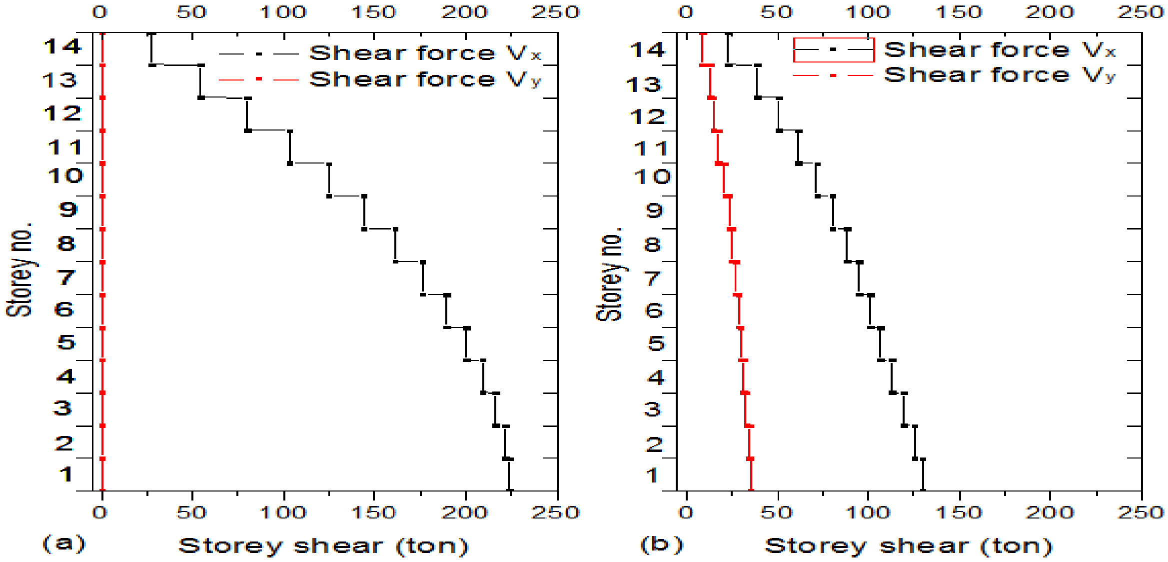

Fig. 4. Nonscaled storey shear forces under (a) ESF X-dir and (b) dynamic RS X-dir

For the purpose of comparisons and according to the EC for loads requirements, if the shear at base determined by dynamic RS analysis is less than that specified by the ESF procedure, it has to be scaled to the static base shear determined by the lateral force procedure. Similarly, if the dynamic base shear obtained from a dynamic RS analysis is of higher value compared to the static base shear, it may be scaled down.Fig.4, shows the obtained base shear using both ESF and RS procedures before scaling. From the figure, it can be seen that the dynamic RS analysis produces shear at base lower than the one obtained applying the static force procedure. Following the code requirements, rescaling the dynamic base shear through a magnification factor induces same base as the one obtained employing the static analysis (see in Fig. 5). It has to be noted that maintaining the code level of base force to be same for the static and dynamic analysis does not necessarily lead to similar distribution of storey shear forces using the ESF and the dynamic RS procedures.

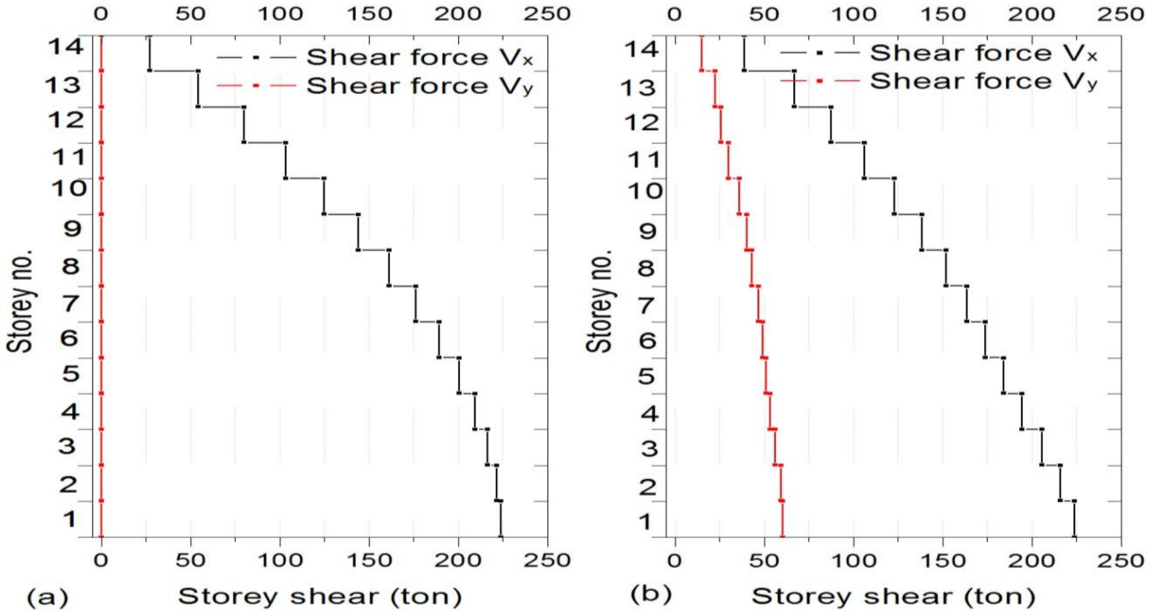

Fig. 5. Scaled storey shear forces under under (a) ESF X-dir and (b) dynamic RS X-dir

Story shear is an important parameter from the structural designer's point of view. Variation of change in scaled story shear under the equivalent static earthquake load and dynamic RS load is presented in Fig. 5. Although the direction of loading is in X-direction, the dynamic RS induced storey shear forces in both X and Y-directions. However, the ESF only induces storey shear in the direction of loading. Storey base shear in both X and Y-directions under ESF analysis as compared to the same dynamic storey base shear obtained considering RS analysis shows significant changes especially in the induced storey shear in Y-direction (V_y). Scaling the dynamic shear at base to be the same as the static shear at base does not necessarily lead to similar static and dynamic shear forces at the corresponding floor levels. As it can be seen from the figure, the use of RS procedure predicts significantly more story shear in X-direction (V_x) at higher stories as compared to those predicted due to loading the structure with ESF method. The increase in dynamic storey shear at the top storey with respect to static storey shear is of 41%. However, at lower storeys the dynamic storey shear are slightly less than the story shear of structure obtained under static force analysis with about 7%.

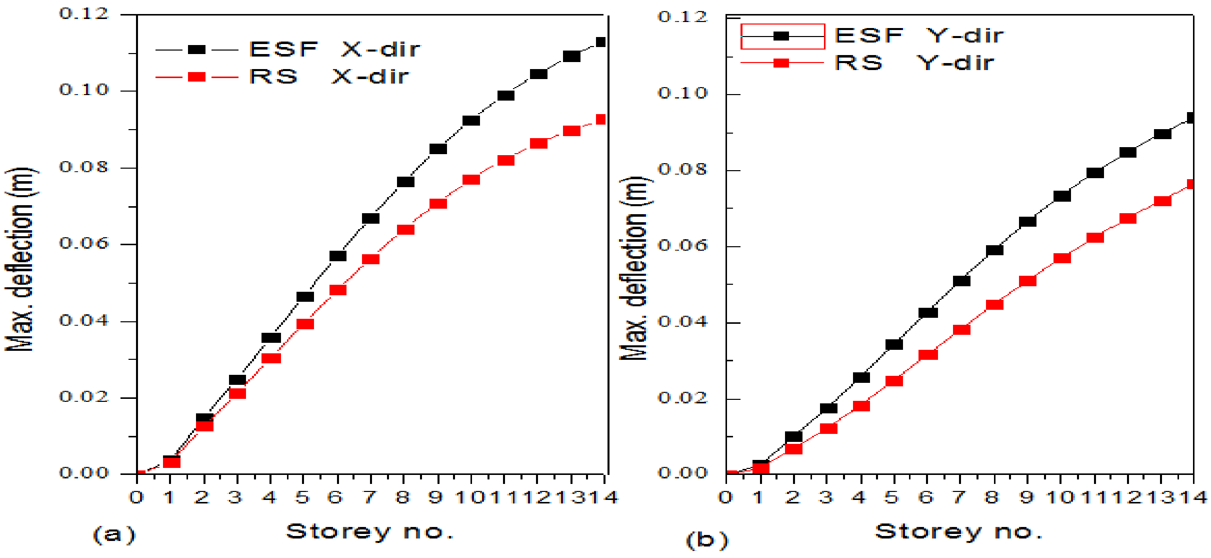

Fig. 6. Storey deflections under ESF and dynamic RS loadings in (a) X-dir and (b) Y-dir

Fig. 6 shows the max story deflection under ESF analysis and dynamic RS analysis in both X and Y directions. As it is shown, the induced max story displacement due to static loading in X direction are of higher values as compared with those obtained under dynamic RS loadings in X direction, (see Fig. 1 (a) and (b)). Similar results have been obtained when loading the building in Y direction. As it is expected the higher the storey levels the higher the induced storey deflection. Moreover, the variance in the obtained maximum storey deflections under static and dynamic earthquake loading are more pronounced at the top stories regardless the direction of loading considered. It can be seen from the figure that the induced storey displacements in X direction due to ESF and RS show significant increase in comparison with the corresponding values in Y direction. This increase in the story displacement in X direction comparable to Y direction is occurring due to the overall global stiffness in X are of lower values to the overall global stiffness in Y direction. Based on the calculated storey deformations under the two methods of analysis, it has been found that the computed percentage variations in storey deflection under static loading and the corresponding storey deflection under the dynamic analysis show nearly similar values for X and Y directions. Considering the top storey as an example, the percentage variation of the maximum deflection using the two methods of analysis is 17.98% when loading is applied in X direction and about 18.85% when loading is applied in Y direction which clearly seems to be identical. Computations of the percentage variation for the other stories under static and dynamic loading in X and Y directions show nearly identical values.

The variation in moments versus storey number is plotted in Fig. 7. For the graphs representing static loading case can be seen in Fig. (1a) and the graphs for the dynamic RS case can be seen in Fig. (1b). As it can be observed and irrespective of the type of loading, the lower the storey the higher moment obtained under the earthquake load. Regarding the type of load, loading the building with ESF method as a representative to the earthquake load produces higher moment as compared to the corresponding values when representing the earthquake load by the dynamic RS analysis method. Although, the building is loaded in Y direction, the dynamic equivalent load induces double moments around X and Y (see Fig. (1b)). On the other hand, the ESF method only induces moment around X (see Fig. (1a)). Similar results has been found when loading the building in X direction where the ESF method only produced overturning moment around Y direction while the RS dynamic loading produces overturning moments around both X and Y directions.

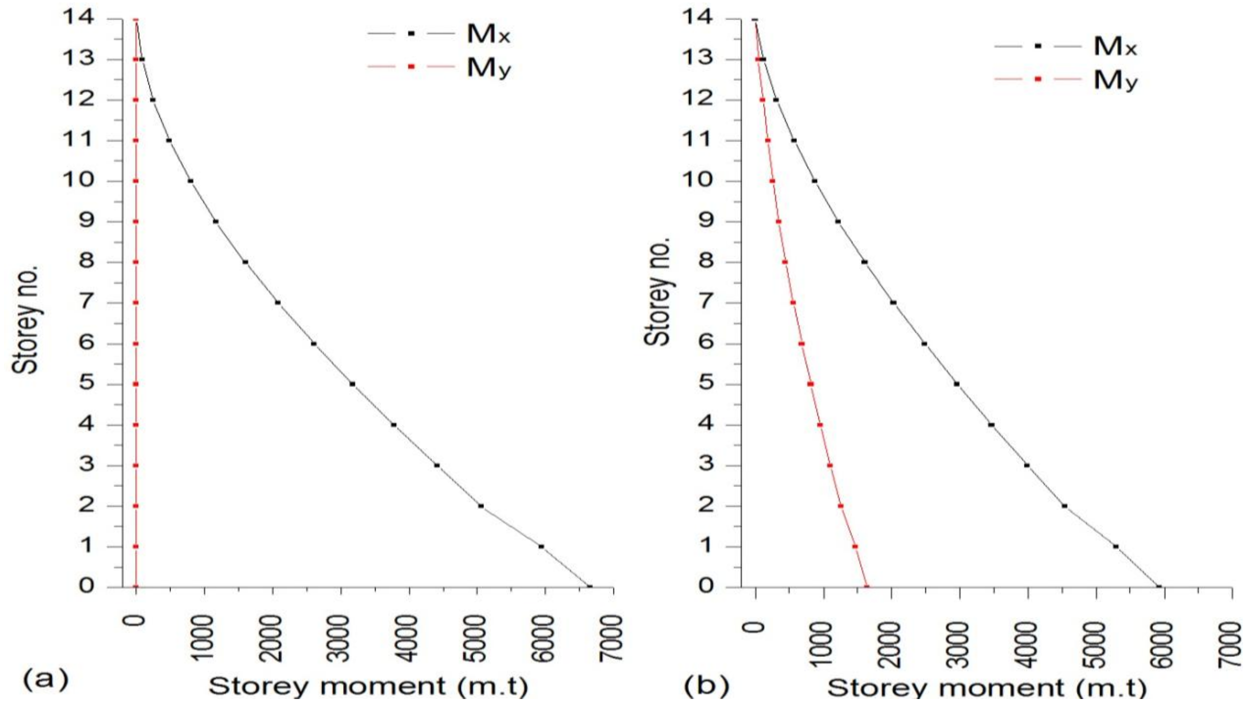

Fig. 7. Storey deflections under ESF and dynamic RS loadings in (a) X-dir and (b) Y-dir

TABLE I: TORSIONAL IRREGULARITY UNDER ESF AND RS ANALYSIS IN BOTH X AND Y-IRECTIONS

Storey	Storey torsional irregularity ratios			
	Earthquake Loading (X-dir)		Earthquake Loading (Y-dir)	
	ESF	RS	ESF	RS
14	1.558534	1.354022	1.146187	1.116105
13	1.578696	1.366195	1.155709	1.114375
12	1.598924	1.378689	1.165514	1.112959
11	1.618784	1.392262	1.175310	1.112314
10	1.638359	1.405367	1.185261	1.111671
9	1.657942	1.418082	1.195665	1.111034
8	1.677911	1.430531	1.206921	1.110414
7	1.698668	1.442843	1.219528	1.110362
6	1.720523	1.455092	1.233998	1.110582
5	1.743628	1.467281	1.250944	1.111011
4	1.767795	1.479258	1.271233	1.111999
3	1.791517	1.490282	1.295995	1.114110
2	1.811922	1.498815	1.325348	1.116480
1	1.801640	1.490606	1.362077	1.114687

Numerous studies investigated the structural damage during earthquakes concluded that torsion is one of the critical factors leading to major damage or complete collapse of buildings. ETABS software package enables the structural engineers to calculate the center of rigidity and hence the designers can perform torsional analysis. The results of the accidental torsion analysis under ESF and RS analysis are shown in Table 2. For loading in X-direction and Y-direction, both ESF and RS analysis produce torsional irregularity where all the ratios (max. deformation/avg. deformation) are more than 1.2. However for applying RS loading in the Y-direction, shows no torsional irregularity because all the computed ratios are less than 1.2. On the other hand, applying ESF loading in the Y-direction produces torsional irregularity from level 1 to level 8 of the building where the ratio of maximum to average story drift is varying from 1.206921 at level 8 to 1.362077 at level 1. According to the Egyptian Code for loads and based on the calculated results presented in Table 1 for loading in X direction, torsional amplification factors has to be determined for all the storeys of this building regardless the type of loading whether ESF or RS analysis. For loading the considered building in Y direction, specified storeys require such amplification factor under the equivalent static procedure. However, dynamic RS analysis shows none torsional irregularity in torsion and hence no torsional amplification factors are need for the building's storeys.

V. CONCLUSION

Analyses of 14-storey flat slab-column building with shear walls system, designed in accordance with the EC for loads and subjected to two different approaches equivalent to earthquake loading, has been studied in both X and Y directions. The considered two approaches are the dynamic RS and static force analysis. The dynamic and static base shear in both directions of loading are computed and compared. An amplification factor has been used to scale the dynamic base shear with respect to the static one. The building's responses in terms of scaled base shear, storey deflections, storey moments, storey drifts, and torsional irregularity ratios have been calculated under the considered two methods of analysis. It is clear from the analysis that the static analysis gives higher values for maximum displacement of the stories in both X and Y directions rather than the dynamic RS analysis method, especially in higher stories. Although scaling the base shear due to RS analysis to be of equal value to the one due to ESF, it has been found that a significant increase in the dynamic shear at higher stories. However at lower stories a slight increase in the dynamic shear compared with static shear regardless the direction of loading. The dynamic RS analysis produces storey shear in both directions regardless the loading direction while the static analysis only produces storey shear in the direction of loading. Contrary to the storey shear forces, the induced storey moments under ESF and RS analysis methods are of higher values at lower stories compared to the higher ones. Moreover, significant increase in the obtained storey moments at lower storeys under RS compared to the corresponding low levels under ESF analysis. In addition, RS analysis produces Moments in both directions regardless the direction of loading and the ESF is not. The results obtained from the structure presented herein have shown that the torsional irregularity in a structure subjected to seismic loading may be influenced by the direction of seismic loading as well the loading approach and strongly lead to analyzing irregular buildings for torsion. Even though the dynamic RS analysis method of seismic design is the prefered method due to the computional advantage in predicting response of structural systems where it involves the calculation of only the maximum values of the induced response in each mode. However, The ESF analysis method is used as a benchmark to scale the design base shear obtained by the dynamic RS analysis before the distribution of the lateral seismic forces over the height of the structure under the dynamic RS base shear.

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