Comparative Study for the Effect of Rigid and Semirigid Diaphragms on Reinforced Concrete Walls

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Author’s contribution

The sole author designed, analysed, interpreted and prepared the manuscript.

ABSTRACT

Rigid diaphragm is generally an acceptable option in most of the seismic design codes in which the in-plane deformability is not permitted because of the infinite in-plane stiffness properties. Several building configurations may exhibit significant flexibility in floor diaphragms and accordingly using the semirigid diaphragm is recommended as significant in-plane deformation does occur. In this study, a comparative study by using rigid and semirigid diaphragms is performed to identify the related effect on the reinforced concrete (RC) walls. In this study, a numerical study for a twelve-story building with dual system of RC columns and walls is performed. All geometrical and loading properties have been kept constant while using two types of diaphragm as rigid (RD) and semirigid (SRD). The seismic performance of the studied two structures was evaluated in terms of the fundamental period, maximum inter-story drift, maximum base shear and stresses on RC walls. Generally, RD produce results nearly identical to those of SRD for base shear, story displacements and inter-story drifts as the slab is sufficiently thick and membrane deformation due to lateral loading is negligible. Compared to SRD, using RD led to increase the internal moment and shear forces resulted from the seismic loads and acting on the RC walls while the resulting vertical loads are nearly identical.
Keywords: Rigid diaphragm; semirigid diaphragm; base shear; pier stresses; story displacements.

1. INTRODUCTION

Effect of the diaphragm type and flexibility is one of the controlling parameters on the resulted internal forces in the RC walls. Relative displacements of building joints differ according to the diaphragm flexibility. The diaphragm is defined as a horizontal roof/floor system or other membrane acting to transfer the lateral forces to the vertical resisting elements [1-3]. Floor diaphragms are required to distribute seismic forces to the main elements of frames and shear walls and to tie the structure elements together to act as a single unit during an earthquake. Diaphragm types are designated as rigid diaphragm (RD), semirigid diaphragm (SRD) and flexible diaphragm (FD) [4-7]. The RD represents a plane with infinite in-plane stiffness properties which distribute lateral loads to vertical connecting elements according to the relative stiffness of these elements by tying all the joints within the plane of diaphragm together for both translation and rotation. The diaphragm may be considered as rigid when the diaphragm midpoint displacement under lateral load is less than twice the average displacements at the ends [8]. The SRD simulates actual in-plans stiffness properties and behaviour. SRD distributes the lateral load based on both the stiffness of the connecting elements and the stiffness of the diaphragm. SRD have considerable deformation under lateral load but with sufficient stiffness to distribute a portion of this load to the vertical elements and RC walls in proportion to relative stiffness of the vertical resisting elements [5-8]. Accordingly, SRD should be modelled when significant in-plane deformation is expected to occur or when required by code.

Flexible diaphragm (FD) distributes loads to vertical connecting elements which according to the tributary area of the element within the plane of the diaphragm [9-10]. A diaphragm may be considered as flexible when the midpoint displacement under lateral load exceeds twice the average displacement at the end supports. RDs and SRDs are considered in the current study as both are the most commonly used diaphragms. For most RC slab systems, in which the slab is sufficiently thick and membrane deformation due to lateral loading is negligible, RDs produce results nearly identical to those of SRDs [11-13]. To identify the effect of using RD and SRD on the stresses of RC walls, two models having the same geometrical and loading properties are considered keeping the only variable as the diaphragm type (RD and SRD). The evaluation parameters include the base shear, story displacement and internal stresses on the RC walls.

2. RESEARCH METHOD

Since the diaphragm type may affect the values of internal forces acting on the RC walls of the building, so it is mandatory to elaborate the corresponding structural response resulting from changing diaphragm type from RD to SRD (the most commonly used diaphragms in engineering practice) under lateral seismic loads. For better comparison of the effect of the diaphragm type on the internal forces of RC walls, all geometrical and loading properties of the building were fixed keeping the only variable as the diaphragm type (RD and SRD). The seismic analysis of a structure shall be performed according to one of the following methods; Equivalent Static Analysis, Response Spectrum Analysis (RSA), or Time History Analysis. Equivalent Static Method in all design codes has some restrictions and limitations of application, while the RSA could be conducted for any structure with an acceptable level of accuracy. Geometrical and loading properties of the studied buildings are illustrated here.

Linear dynamic analyses were conducted for the two building cases with the two types of diaphragms using ETABS software (Computers and Structures, 2017) [14]. ETABS software is a full-featured program that can be used for the simplest problems or the most complex projects and considers as the most commonly available software for the lateral analysis of the buildings. The program creates design output in different formats: graphical display, tabular output, and member specific detailed design information. All graphical output can be printed. The tabular output can be saved in a file or printed. The tabular output includes most of the information that can be displayed and is generated for added convenience to the designer.

2.1 Description of Buildings

To evaluate the major differences in the resulted internal forces of RC walls by changing the diaphragm type from RD to SRD, building with
the same geometrical and loading parameters was analyzed twice by RD and SRD. Selecting a building with lateral stability system as RC shear walls with RC frames is the most proper system for the current study. The building usage is offices and located at UAE. The building is twelve-story high with the same floor plan which consists of three equal bays in both directions, where the bay width equals to 6.0 m. Typical story height is 3.6 m keeping the first-floor height as 4.0 m and the total height of the buildings is 43.6 m. Technical specifications of the building is illustrated in Table 1. Additionally, Model of the building under study is illustrated in Fig. 1.

2.2 Building Parameters

2.2.1 Material properties

The compressive strength of concrete has been assumed to be of value $f_c' = 30.0$ MPa. The value of concrete density was considered as 25 KN/m$^3$ and the concrete Poisson's ratio as 0.2. Similar assumptions have been previously considered in [15]. The modulus of elasticity for concrete ($E_c$) was considered as 25.74 GPa ($E_c = 4700 (f_c')^{0.5}$ [8]).

2.2.2 Considered vertical loads

The floor was assumed to support a total vertical super imposed dead load of value 7.0 KPa (floor cover of 2.0 KPa, mechanical services of 0.5 KPa and equivalent wall loads from interior partition of 4.5 KPa). The live loads are considered with constant value of 3.0 KPa. The exterior line load due to external walls and cladding is considered as 15.0 KN/m.

2.3 Response Spectrum Properties

The considered response spectrum curve is shown in Fig. 2 according to ASCE-10 [8] and the properties of this spectrum are given below:

$$S_i = 0.869 \, g$$

The values of $F_a$ as a function of site classes and mapped short periods spectral response acceleration $S_s = 2.29 \, g$, for site Class = C and $F_a = 1$.

| Building overall dimensions (m) | Typical column dimensions (mm) | Typical beam dimensions (mm) | Typical slab thickness (mm) | Typical wall thickness (mm) | Support condition | Diaphragm type |
|---------------------------------|-------------------------------|-----------------------------|---------------------------|---------------------------|------------------|---------------|
| 18x18                           | 800x800                       | 300x600                     | 180                       | 400                       | Pin              | RD/ SRD       |

Table 1. Technical specifications of the building under study

Fig. 1. ETABS model for the building under study
Fig. 2. The considered response spectrum curve

The Values of $F_v$ as a Function of Site Classes and Mapped Spectral Response Acceleration at Period $S_1=0.869 \, g$ and $F_v=1.3$.

$$S_{MS}= F_a S_s = 1.0 \times 2.29 \, g = 2.29 \, g$$  \hspace{1cm} (2)

$$S_{M1}= F_v S_1 = 1.3 \times 0.869 \, g = 1.1297 \, g$$  \hspace{1cm} (3)

$$S_{DS}= 2/3 S_{MS} = 2/3 \times 2.29 \, g = 1.5267 \, g$$  \hspace{1cm} (4)

$$S_{D1}= 2/3 S_{M1}= 2/3 \times 1.1297 \, g = 0.7531 \, g$$  \hspace{1cm} (5)

3. RESULTS AND DISCUSSION

The dynamic analysis of the two cases of the buildings (using RD and SRD) showed that the buildings produced nearly identical results of the seismic parameters as illustrated in Table 2. This table shows the results of the modal and dynamic analyses of the two cases. As can be concluded from the table, the two building cases exhibited very close results of the time period, base shear values in both X and Y directions and the displacement of the diaphragm centre of mass at roof. Additionally, no major difference can be drawn for the inter-story drifts or building maximum drifts. Accordingly, it was concluded that a negligible difference is introduced between the performance of RDs and SRDs for the studied cases regarding the modal seismic investigated parameters. These findings are in the same line with [15].

Effect of using RD and SRD on the behaviour of RC walls will be introduced in this section. Only the major affected results will be presented. Fig. 3 shows the pier labels for the reinforced concrete walls.

For pier P1-A and P1-B, the internal shear force ($V_2$) and bending moment ($M_3$) along the major axis are plotted in Figs. 4 and 5 respectively for SPECX and SPECY. Compared to SRD, using RD led to an increase in ($V_2$-SPECX) by 22.7% and a decrease in ($V_2$-SPECY) by 41.0% and this is due to that the main direction of the shear wall P1-A and P1-B is in the X-direction. Additionally, there was an increase in ($M_3$) by 7.1% and a decrease in ($M_3$-SPECY) by 21.2% for the case of RD when compared to the case of SRD.

Table 2. Seismic results for the two building cases

| Time Period (Sec.) | Base shear SPECX (KN) | Base shear SPECY (KN) | Diaphragm CMD SPECX (mm) | Diaphragm CMD SPECY (mm) | Roof story drift SPECX (mm) | Roof story drift SPECY (mm) |
|-------------------|-----------------------|-----------------------|--------------------------|--------------------------|----------------------------|----------------------------|
| Building with RD  | 1.385                 | 7387                  | 8742                     | 88.08                    | 78.96                      | 0.00239                    |
| Building with SRD | 1.396                 | 7377                  | 8711                     | 88.38                    | 79.41                      | 0.00240                    |

CMD = Centre of mass displacement at roof floor
Fig. 3. Pier labels for the reinforced concrete walls for the building under study

Fig. 4. Results of shear force and bending moments in X-direction for P1-A and P1-B at different floor levels

Fig. 5. Results of shear force and bending moments in Y-direction for P1-A and P1-B at different floor levels
The internal shear force (V2) and bending moment (M3) along the major axis of SPECX and SPECY are respectively presented in Figs. 6 and 7 for pier C-B and C-C. Major difference in these forces is noticed along the X-direction. Using RD led to increase the moment (M3-SPECX) by 49.3% and decrease the shear force (V2-SPECX) by 42.0% at the first floor level when compared to the SRD. In addition, no major difference has been noticed in both (V2-SPECY) and (M3-SPECY) for the results of RD and SRD.

Figs. 8 and 9 shows the internal shear force (V2) and bending moment (M3) along the major axis of SPECX and SPECY respectively for pier C-A. For SPECX, both the shear force (V2-SPECX) and the bending moment (M3-SPECX) at the first floor showed an increase by 12.1% and 6.4%, respectively for the SRD option when compared to the RD option. Moreover, for SPECY, an increase of 8.3 and 3.8% was recorded respectively for (V2-SPECY) and (M3-SPECY) by using the SRD instead of the RD.

Comparing the analytical results of the RD and SRD for piers P2-A, P2-B, P2-C and P2-D, there is minor difference in the internal forces (V2) and (M3). For all piers, the resulted vertical forces from the lateral seismic forces (SPECX) and (SPECY) is almost identical and no major difference can be recorded for both RD and SRD.

### 3.1 Discussion

Most of the previous studies have been considered the RD as a basic assumption. Consequently, distribution of the lateral forces between the vertical resisting elements of the structure is depending only on the mass, stiffness and strength distribution. In many cases, selection of RD is not realistic as the structure can exhibit various degrees of flexibility [16]. Based on the analytical results in this research, there are no major differences on the structural response parameters such as displacements, story drifts and base shear values when compared the results of the RD with SRD.
On the other hand, there were considerable differences between the two types of diaphragms regarding the resulted internal forces on the RC walls of the building as concluded before in [10]. Accordingly, and as long as the RD is considered not realistic, there is a need to change our vision towards the use of SRD as a realistic replacement for the RD. SRD is considering the relative displacement between structure joints which mainly affect the resulted internal stresses in the vertical elements. Additionally, SRD counts for the building distortions that expected to occur due to the acting lateral loads.

4. CONCLUSION

Based on the modal seismic results of the dynamic analysis, the following concluded points can be drawn:

(1) The two building cases exhibited very close results of the time period, base shear values in both X and Y directions and the displacement of the diaphragm centre of mass at roof. Additionally, no major difference can be drawn for the inter-story drifts or building maximum drifts.

(2) A negligible difference is introduced between the performance of rigid and semirigid diaphragms for the studied cases regarding the modal seismic investigated parameters. Based on the pier results of internal forces, and in most cases, using a rigid diaphragm led to increase the internal shear forces and bending moments along the major axis when compared to the semirigid diaphragm.

(3) For all piers, the resulted vertical forces from the lateral seismic forces (SPECX) and (SPECY) is almost identical and no major difference can be recorded for both RD and SRD.
COMPETING INTERESTS

Author has declared that no competing interests exist.

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