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Effect of Eccentric Shear Stiffness of Walls on Structural Response of RC Frame Buildings

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Abstract

Current research study consists of determining the optimum location of the shear wall to get the maximum structural efficiency of a reinforced concrete frame building. It consists of a detailed analysis and design review of a seven-story reinforced concrete building to understand the effect of shear wall location on the response of reinforced concrete structures when subjected to different earthquake forces. Three trail locations of shear walls are selected and their performance is monitored in terms of structural response under different lateral loads. Required objectives are achieved by obtaining design and construction drawings of an existing reinforced concrete structure and modeling it on Finite Element Method (FEM) based computer software. The structure is redesigned and discussed with four different configurations (one without shear wall and three with shear walls). Main framing components (Beams, Columns and Shear walls) of the superstructure are designed using SAP 2000 V. 19.0 whereas substructure (foundation) of RC building was designed using SAFE. American Concrete Institute (ACI) design specifications were used to calculate the cracked section stiffness or non-linear geometrical properties of the cracked section. Uniform Building Code (UBC-97) procedures were adopted to calculate the lateral earthquake loading on the structures. Structural response of the building was monitored at each story level for each earthquake force zone described by the UBC-97. The earthquake lateral forces were considered in both X and Y direction of the building. Each configuration of shear wall is carefully analyzed and effect of its location is calibrated by the displacement response of the structure. Eccentricity to the lateral stiffness of the building is imparted by changing the location of shear walls. Results of the study have shown that the location of shear wall significantly affects the lateral response of the structure under earthquake forces. It also motivates to carefully decide the center of lateral stiffness of building prior to deciding the location of shear walls.

Keywords

Reinforced Concrete Buildings, Computer aided Modelling, Shear Walls, Stiffness, Deformations

1. Introduction

Concrete structures are becoming popular in Saudi Arabia because of the rapid increase in the population. A significant number of concrete buildings were built to meet the growing population needs. A huge inventory of building is still under construction such as malls, apartments and public buildings. The concrete design and manufacturing have been growing in Saudi Arabia in the last five decades. Moreover, the concrete design plays an important role in the Saudi economy. With the technology evolution, complete model of the building could now be analyzed and designed using state of the art computer software and technologies. In designing a structure there is not only the need to consider the dead and live load of the structure, many other factors should be taken into consideration because structure faces various types of loads. The other important factors may include the location of shear walls, earthquake forces, wind loads, subsurface interaction and geometry of the building. An engineer should not only consider the self-weight, the load of the people that will inhabit the building with machinery, furniture, and appliances, but, should also consider the extent of lateral forces that the building is expected to face in the rest of his life. In this regard, earthquake forces play a vital role and most of the RC structures are highly vulnerable to the earthquakes due to higher self-weight and has shown higher destruction in the past [1]. Earthquakes are one of the major causes of the failure of RC buildings. Structural failure is not limited to structure only but it also fails, plumbing, piping system, air conditioning and electrical system of the building. Moreover, the structure should not be considered in isolation as it would also affect its surroundings and could play a vital role in the major destruction. In order to address it, many researchers have come forwarded and contributed to making RC structures stable and safe during earthquake events. Ashour and Rahman [2] performed the seismic risk analysis of the Western region in Saudi Arabia and found the eastern region is vulnerable to earthquakes. Ahmed Yakut did the seismic assessment of existing RC structures in Saudi Arabia [3]. Sadek and Sobaih carried out the inelastic analysis of asymmetric structures and Karayannis *et al.* determined the degradation of beam-column joint of infilled RC frames under intense seismic forces [3] [4]. Kalkan and Kunath had assessed the nonlinear static procedure for seismic evaluation of the building [5]. Luca et al did the assessment of various heritage structures using Eurocode [6] and Lee and Woo evaluated the seismic performance of a 3-story RC building structure [7]. The most noteworthy work in this regard is done by Shuaraim *et al.* [8] who proposed the seismic building provisions in the Saudi Building Code.

Shuaraim also performed the pushover analysis on RC frame structures to check the adequacy of these structures [9]. Ashraf Habibullah and Stephen Pyle did the practical three-dimensional pushover analysis of structure whereas Chan and Zou optimized the drift design under later loads [10] [11]. Dhileep *et al.* conducted the modal analysis of building under high seismic forces [12] and Whittaker *et al.* evaluated the displacement response for the seismic design of structures. After going through the literature review, it has been found that very few researchers had worked to determine the optimum location of the shear wall in RC frame structures [13] [14].

In this study, an RC frame building is selected and four different configurations of shear walls are modeled. Each configuration of RC frame building and the shear wall was subjected to earthquake forces based upon UBC seismic zone of 2A to 4. Displacement of the building was recorded at peak story height. Four different building models were prepared and carefully analyzed. Out of four building models, one was without shear wall (case-1) whereas the other three models carry the different location of shear walls (case-2, case-3 and case-4).

2. Building Model Details

2.1. Project Overview

The structure that is under consideration is a new building for the Sumou Real Estate Co. which is located in Riyadh. The structure has to be used as the residential building. **Figure 1** shows the plan view of the building. The building consists of seven floors. Each floor has a height of 3.1 m. Two shear walls are used in building to resist the horizontal forces from wind and earthquake loads. The size of the building is 46.98 m × 18.70 m.

The maximum span of the building in each direction does not exceed 6.7 m. The beam and column-framing layouts of the building are shown in **Figure 1**. The building has seven numbers of stories with the average story height of 3.1 m except for the ground floor, which has the ceiling height of 4.0 m.

2.2. Material and Geometrical Properties

Table 1 and **Table 2** show the material and geometrical properties of members used in this study. Two different sizes of columns were used in the study. Size of the column from ground story to the third story was 700 mm × 350 mm whereas the column size from 4th to the seventh floor was maintained 600 mm × 300 mm as given in **Table 1**. Each column carries 12 number of rebars uniformly distributed along the periphery of the column. Two different beams sizes (Beam-1 and Beam-2) were adopted for the study and provided based upon the span and location of the beam. Thickness and slab and shear walls were kept 200 mm and the clear cover was maintained at 40 mm for beam and column and 20 mm for slab and walls.

Table 2 gives the material properties employed for modeling of the building. The 28-days strength was kept as 28 MPa for all the reinforced concrete

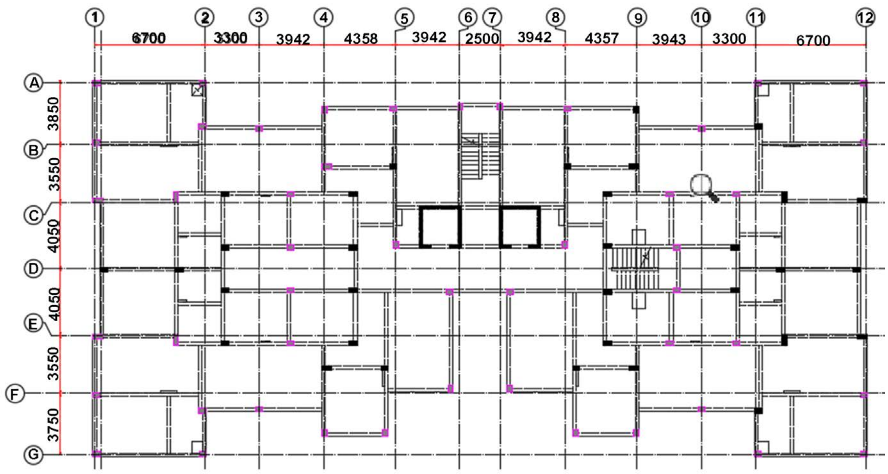


Figure 1. Layout of the building.

Table 1. Geometrical properties.

Parameter	Description	Value
Col 1	Strory-1 to Story-3	700 × 350 mm
Col 2	Strory-4 to Story-7	500 × 300 mm
Beam-1	Exterior beams	500 × 300 mm
Beam-2	Interior beams	600 × 300 mm
Slab	Thickness of slab	200 mm
SW	Shear wall thickness	200 mm
C_c	Clear cover for RC Frame	40 mm

Table 2. Material properties.

Parameter	Description	Value
f_c'	28 days compressive strength of concrete	30 MPa
f_y	Yield strength of steel rebar	420 MPa
R	Response modification factor	5.5
E	Modulus of elasticity of concrete	25,742 MPa
υ	Poison ratio	0.15
	Coefficient of thermal expansion	9.9×10^{-6}
G	Shear Modulus	11193 MPa
C_t	Time period constant of structure	0.03
S_c	Soil profile with dense soil and soft rock	360 m/s vs 760 m/s
I	Importance factor	1.25

structural members. A yield strength of 420 MPa was considered for all rebars used in beams, column, slab and walls for both flexure and shear. The elastic and shear modulus of concrete were 25,742 MPa and 11,193 MPa respectively.

Similarly, the value of poison ratio, thermal coefficient, soil profile type and building importance category factor are given in **Table 2**.

2.3. Loads

A dead load of slabs has been calculated and required densities and partition loads values are decided based upon the UBC-97 [15] and ACI-318-14 Code [16]. Slab thickness is decided using ACI-318 Code for two-way solid slab system. Moreover, loads of floor tiles, water pipes, air-conditioning, and other collateral were also considered. According to the provisions of Saudi Building Code (SBC) [17], the live load value of 5.0 kN/m^2 was adopted for public rooms whereas the value of live load for parking, filling storage places and for private rooms is 3.0 kN/m^2, 5.0 kN/m^2 and 2.0 kN/m^2 respectively. For the topmost roof, the access condition was considered with a live load value of 2.0 kN/m^2. A live load value of 5.0 kN/m^2 was considered for HVAC equipment.

This type of load depends on many factors such as zone factor, occupancy importance factor, response modification factor (R) in X and Y directions and soil type that should be known in order to define the seismic load on ETABS. The factor R is representative of the inherent over strength and global ductility capacity of lateral force-resisting system of the building under consideration. For strong and ductile building frames, the value of R is comparatively high. Importance factor is decided based upon the significance of structure. For normal or ordinary structures the value of I is taken as 1.0. However, for important structures such as nuclear power plants, hospitals, schools, the values of I will be greater than 1.0. The Uniform Building Code [15] has been used to find the zone factor, response modification factor (R) and occupancy importance factor. **Table 2** gives the values of R_w used in both X and Y direction. The soil profile type C was considered with a time period constant of 0.03 for reinforced concrete structures.

The wind load for buildings was calculated based upon UBC-97 [15]. A wind speed of 155 km/hr for Riyadh region was considered with the occupancy category III for the calculation purposes.

2.4. Design Standards

All of the concrete frame members were designed as per ACI 318-14 (American Concrete Institute) design specifications [16]. Material strengths were conforming to ASTM (American Standard of Testing Material) standards and the live load was decided based upon the SBC (Saudi Building Code) [17]. Wind load and Earthquake Loads for buildings were calculated based upon UBC-97 [15].

2.5. Computer Model

A computer model of the building was prepared using Structural Analysis Program (SAP 2000 V. 19.0) which has Finite Element Method solver to calculate the response of the building. In order to see the effect of the shear wall on the response of building, four types of building models were prepared. Figure 2 shows the 3-D model carrying shear walls at the different location. Based upon the shear walls four different cases were considered for this study.

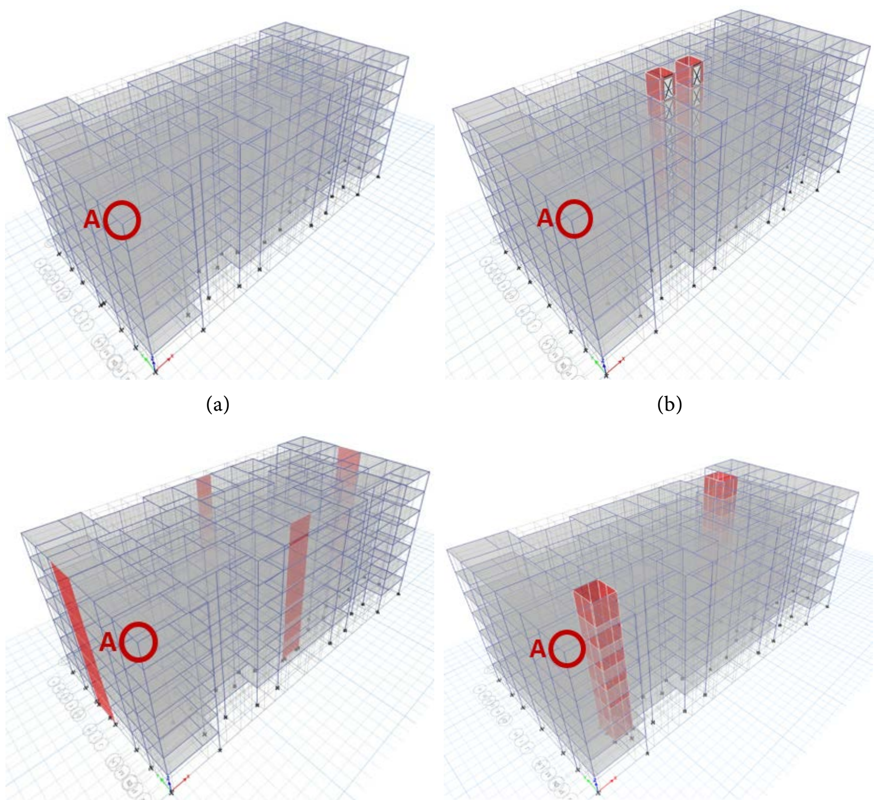
Case-1: No shear walls were considered and building response was monitored in the absence of shear walls as shown in Figure 2(a).

Case-2: Two shear walls were considered close to the geometric centroid of the building which has minimum eccentricity between the center of mass and center of stiffness of the building as shown in Figure 2(b).

Case-3: The total stiffness of the two shear walls is equally distributed on all four faces of the buildings as shown in Figure 2(c).

Case-4: Two shear walls were located at the two opposite corners of the buildings with the locations as shown in Figure 2(d).

Each case of the building was subjected to constant parameters except earthquake zone. Each case was subjected to different earthquake forces based upon the seismic zones of UBC-97. These zones vary from the mild earthquake 1 to the most hazardous earthquake forces of zone 4. Table 3 gives the earthquake zone and its zone factors considered for this study. Zone 1 forces are very small has no significant effect that's why the forces from Zone 2 to 4 are considered.



(a) (b) (c) (d)

Figure 2. Different layouts of shear walls in the RC building. (a) No shear wall (Case-1); (b) Shear wall located near the center(Case-2); (c) Shear Walls distributed around the building (Case-3); (d) Shear wall located at two opposite corners (Case-4).

Table 3. Material properties [UBC-97].

Zone	1	2A	2B	3	4
Factor	0.075	0.15	0.20	0.30	0.40

3. Results and Discussion

This part includes the results for the building structure when subjected to earthquake forces in EQX direction. Results are presented in the form of story height vs displacement curves. The reference point for the displacement is the building corner under point A. Analysis has ensured that structure is stable within allowable limits given by the aforementioned building codes.

Figures 3(a)-(d) show the maximum displacement undergone by each case with respect to the story height. Figure 3(a) shows the displacement profile of the building model under different seismic earthquake zone when no shear walls were provided in the building. The response of the building is similar to SDOF (single degree of freedom system). No significant change in the building displacements was observed when the forces were applied for Zone 2A, 2B and 3. But, at zone 4 a significant increase in the displacement of the building is observed and these displacements correspond to the nonlinear behavior of the structure. Up to 6 meters of height, a similar displacement value for zone 2A, 2B and 3 was observed but after this height, these values have started deviation till the maximum height of the building. 23.9 mm, 39.5 mm, 34.7 mm and 71.9 mm are the peak displacement values found at a story height of 21.5 m for zone 2A, 2B, 3 and 4 respectively. Figure 3(b) shows the displacement profile of the building at each story level when shear walls were provided close to the geometric centroid or center of the mass of the building (case-2). By providing the shear wall in the building with the arrangement shown in Figure 2(b) has drastically reduced the story displacement at each story level. A peak displacement of 6.8 mm, 14.9 mm, 24.4 mm and 29.5 mm was observed for Zone 2A, 2B, 3 and 4 respectively. Around 4 to the six-time reduction in displacement is observed depending upon the earthquake zone when the shear walls were provided in the building. It shows those shear walls are taking care of a major portion of the lateral forces. It has been also observed that increase in displacement for this case-2 was proportional to increase in zonal forces as shown in Figure 3(b). Figure 3(c) shows the displacement profile of the building at each story level for case-3 when shear walls were distributed along each face of the building as shown in Figure 2(c). The peak displacement values of 19 mm, 20.6 mm, 29.7 mm, and 56.4 mm was found for zone 2A, 2B, 3 and 4 respectively. In this case, displacement values are reduced as compared to case-1 but still these values are higher than the displacement values found for case-2. For instance, the maximum displacement at zone 4 for case-2 was 24.4 mm which is less than the half of the displacement found for case-3. Like case-1 and 2 response of the building was SDOF system. No significant increase in displacement was found when the forces were increased from zone 2A to 2B as shown in Figure 3(c). Figure 3(d)

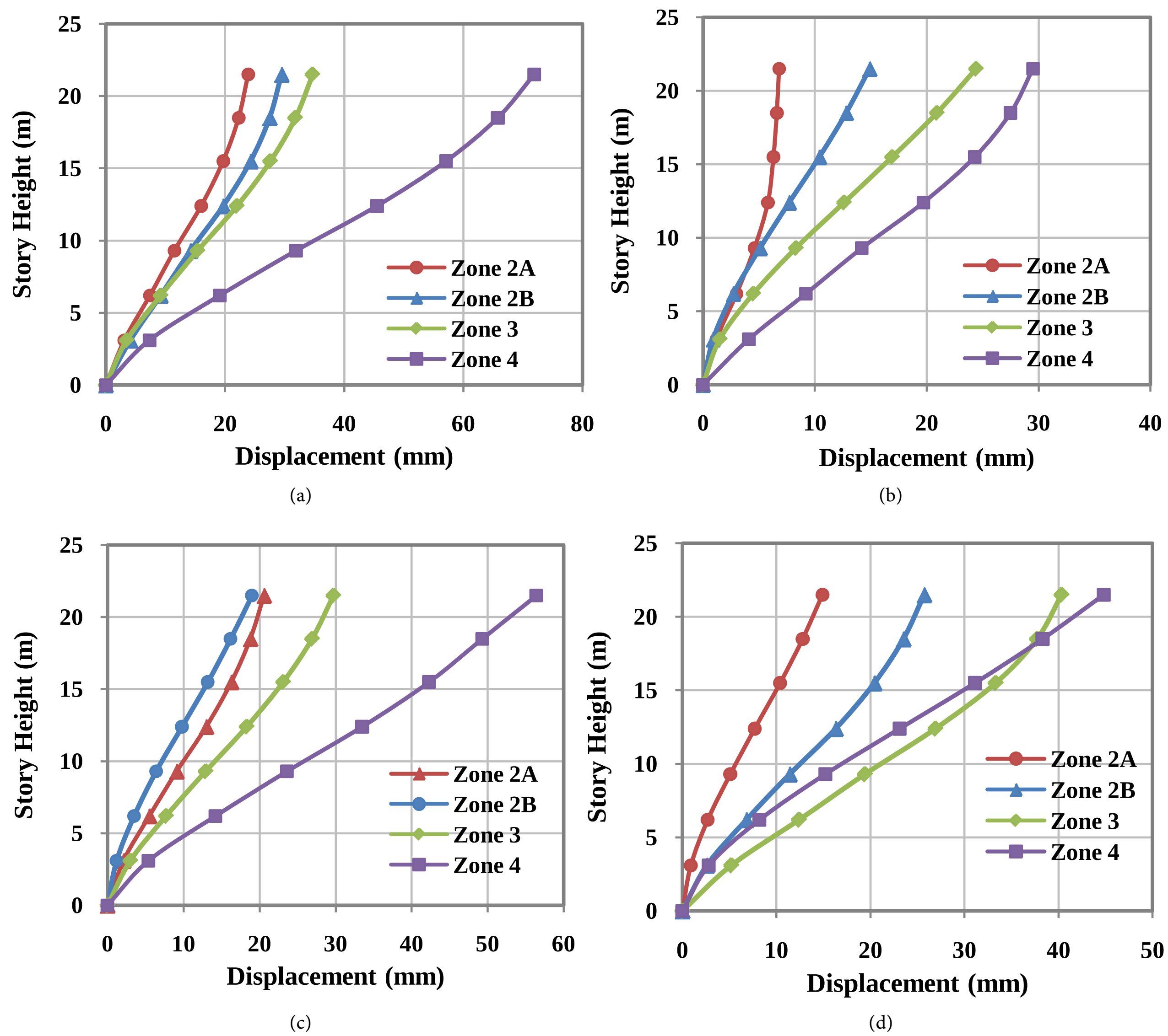


Figure 3. Displacements of various building models under different earthquake zone factors. (a) Case-1; (b) Case-2; (c) Case-3; (d) Case-4.

shows the displacement profile of the building at each story level for case-3 when shear walls were located at two opposite corners of the building as shown in Figure 2(d). In this case, a different behavior of the structural response was observed as zone-3 forces have shown more displacement compared to zone -4 forces till the story height has reached to 18.0 m. Beyond that, the displacements are proportional to the earthquake forces. A peak displacement value of 14.9 mm, 25.7 mm, 40.3 mm and 44.8 mm was observed for zone 2A, 2B, 3 and 4 respectively. It was also observed that the difference in displacement of zone-3 and 4 was much lower than that of its corresponding difference for case-1 and 2.

4. Effect of Shear Wall

Side sway in each case at corner A is compared in both (X) & (Y) direction and presented in Figure 4(a) and Figure 4(b) respectively. Figure 4(a) and Figure 4(b) show the maximum displacement of each analyzed case under different zone factors for earthquake forces acting in X-direction and Y-direction respectively. These plotted displacements are the maximum values obtained at point A for each case when the building is subjected to earthquake forces at a particular zone factor. Figure 4(a) shows that the case-1 (no shear walls) has shown the maximum displacement value at each of the applied zone factors. The maximum displacement of 71.9 mm was found at zone factor 4 for case-1. However, when the shear walls were located near the geometric center of the building as in case-2 this displacement was found the minimum. Again the maximum displacement of 29.5 mm was found at zone-4. But this value was significantly lesser than that of its corresponding value for case-1. Case-3 has shown better structural response then case-1 and case-4 but not better then case-2. Case-3 has shown the maximum displacement of 56.4 mm at zone factor of 0.4 which was even greater than case-4. When the shear walls were located at two opposite corners of the building (case-4) the displacement response was better than case-3 for only zone 1 and zone 4. But, at zone 3 the displacement was even higher than all of the cases. It could be due to the eruption of torsional forces developed because of the eccentricity of stiffness and mass center of the building.

Figure 4(b) shows the spectral response of building models when the earthquake forces were applied in the Y-direction (EQY). The overall response of the building models was similar to that of the EQX. Case-1 (no shear walls) has shown the highest displacement values but these displacement values were higher than those of its corresponding values in EQX direction. As like EQX direction, case-2 (shear walls located near the center of mass) has shown the best performance among all and displacement values are significantly lower than

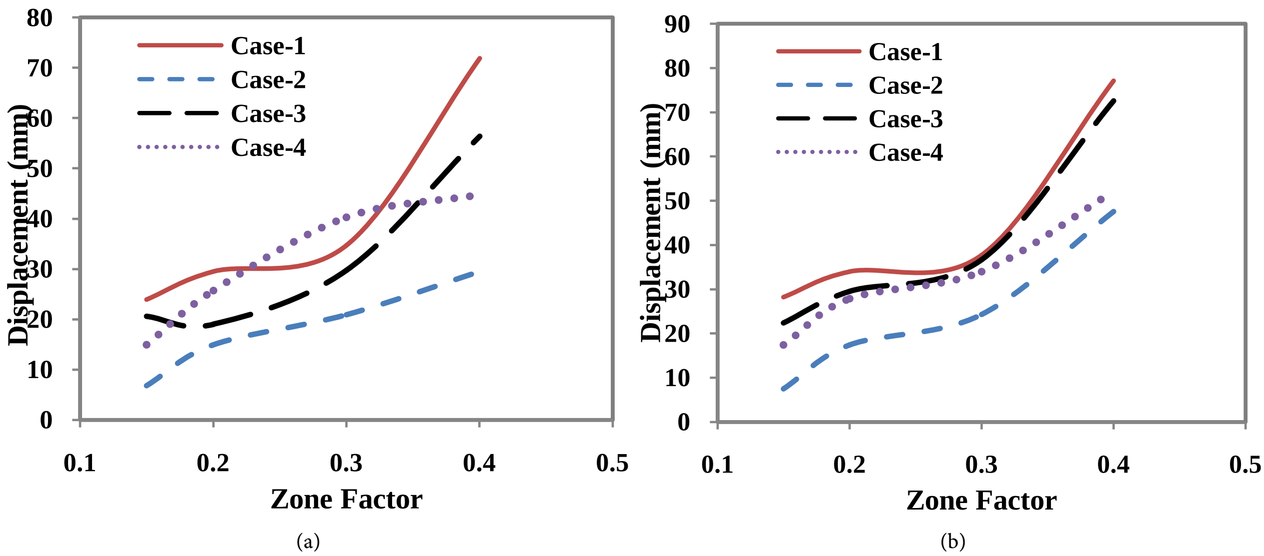


Figure 4. Spectral displacements of RC buildings under different earthquake zone factors. (a) Spectral Response for EQX; (b) Spectral Response for EQY.

case-1. No significant improvement in structural behavior was found in case-3 when the earthquake forces were applied in the Y direction as the displacement values are close to case-1. When shear walls were located at two opposite corners (case-4) comparatively better response was observed particularly at zone 1 and 4 as shown in **Figure 4(b)**.

Structure in all four alternatives has minimal deformation in X and Y direction when shear walls were provided at the middle of the structure. Case 2 had more significance displacement (in the Y direction) than (X direction). Although Case 3 showed more displacement, the general stability increased and defection was uniform in all corners. Case-1 gave relatively good results, it is an economical choice and has shown lesser deflections (shear walls in middle). It has been concluded that placing shear walls in middle is the most suitable case in design as it enhances over all stability at all corners of the building and it acts as a backbone for the structure.

5. Conclusion

After analyzing the test results, it is found that presence of the shear wall in the buildings plays a vital role in reducing the displacements and resisting the seismic forces in case of an earthquake event. However, it requires a careful analysis and understanding regarding the placement of shear walls. Building geometry plays an important role. Even sometime presence of shear wall has less significant effect or even no effect as in case of EQY direction when shear walls were provided at the opposite corners of the building. As the center of the stiffness of the building changes and eccentricity from the center of mass increases, it may produce the torsional effect and even the presence of shear wall has no effect or even adverse effect on the performance of the building. Another important parameter is the mode of vibration of the building. In all cases, the building has vibrated as a Single Degree of Freedom oscillation system. When the shear walls were located close to the center of the building a 4 to the 6-time reduction in displacement was observed as compared to case-1 when no shear walls were present. In case of EQX, a different behavior of displacement response was observed for case 3 and 4 and even the presence of shear walls could not contribute much in restoring the structural displacements. It is also observed that the structural response was linear for all the cases till the small displacement ranges but for higher earthquake forces the structural response became non-linear. It motivates to study the collapse behavior prior to the failure special when the material is in inelastic range and geometry of structure in also transforming due to permanent deformations. The current study deals with a specific given geometry of the building, which is very close to a regular one. However, it is required to further explore the irregular building shapes for future studies, which are becoming more popular for lucrative architectural designs.

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