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Effect of Shape and Size of Openings in Shear Walls on Lateral Deformations in Shear Walled Framed Structures

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Abstract

Due to the high density of occupancy of multi-storey structures, structural safety becomes of utmost importance. Shear walls are structural walls which assist the framed structure in resisting lateral forces due to wind and earthquake. Providing the shear walls in multi-storeyed buildings decrease the necessity of providing heavier frames thereby increasing the floor area available in the structure. Generally, openings are provided in shear walls for architectural and functional requirements of the building structure. It is well known that providing openings in shear walls significantly decrease its stiffness and tension/Compression coupling mechanism. Codes of various origins restrict the percentage of openings in shear walls, however, remain silent about the shape of opening. The Finite element analysis has become an essential method of analysis for incorporating the physical entities mathematically. This paper aims to numerically investigate the effect of opening shape and opening size on lateral deformations of a multi-storeyed framed structure. To this end various shapes of openings i.e. triangular, square, and circular are incorporated in the shear wall and for each opening shape 20% and 25% openings have been considered. A ten-storey building containing the shear walls of various configurations has been analysed using the SAP2000 under the seismic load condition and the maximum lateral deformation produced at top storey of buildings are compared.

Keywords: Shear wall, opening shape, opening size, seismic analysis, SAP2000

1. Introduction

The popularity and necessity of a multi-storied structure is well known throughout the world. Due to space constrains and security issues multi-storeyed structures are preferred over independent structures. Moreover, multi-storeyed structures are comparatively economic and give a sense of unity. With the progressively increasing population the demand for design of a unique structure also increases. This keeps the engineers and architects at their toes to stay in market. A multi-storeyed structure is most vulnerable when it is subjected to horizontal loads as the height of the structure keep increasing. The horizontal loads lead to an oscillatory motion in the structure and if the structure is not strong enough it collapses. Out of the various lateral loads, earthquake load is quite vulnerable as it is unpredictable and quite devastating. Recent earthquake in Nepal is a fresh example of the extent of devastation that earthquake can cause. One cannot be well prepared for an earthquake as the past earthquake's data only help us to modify our design of structures for the future. A simple idea of increasing the weight of the structure helps in reducing the vulnerability of the structure. This would mean heavier beams, columns, walls and slabs in order to increase the volume of the structure. However, heavier sections would mean that they would require more materials and becomes uneconomical, moreover, they need more attention and time for both construction as well as maintenance. Due to seismic activity, the ground storey of multi-storeyed buildings lead to sudden discontinuities in their lateral stiffness and strength. In multi-storeyed Reinforced Concrete (RC) frame-wall buildings, primary lateral resistance during severe earthquake depends on floor plan density of RC structural walls. Floor plan density of walls is determined as the ratio of total plan area of structural walls and the corresponding floor plan area. Shear walls are primarily vertical walls constructed to counteract the horizontal loads acting on the structure. These can either be wind loads or earthquake loads. These walls are constructed right from foundation to the top floor or any floor depending upon the amount of resistance that is required form these walls. Shear walls can be constructed as core for elevators or staircase and may also be constructed as periphery walls. If designed and planned properly, they can be provided as partitions reducing the need for the construction of non-load bearing walls. Shear walls can be designed to resist adequate vertical and horizontal loads. When constructed along with framed structures, these structures are called as shear-walled framed structures. Incorporating shear walls in a framed structure would result in thinner sections of beams, columns and slabs thereby increasing the floor area available in the structure and also decreasing the congestion happening at the beam-column

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junctions when heavier sections are used. Moreover, sometimes for the functional requirements, it becomes necessity to provide openings in the shear walls. When used as core walls for elevators, openings are provided for laying cables and utilities, in case of staircase walls. Openings are provided for provision of windows for lighting and in peripheral walls for windows, doors or ducts for utilities. Various shapes of openings can be provided in shear walls in order to improve the aesthetics and utility of the opening. Providing openings in the shear walls, decreases the strength and stiffness of the shear walls. Nowadays, it has become a trend to provide flat slabs in place of traditional beam-slab construction in the framed structures. Flat slabs do not have beams and the floor/roof slab rests on columns. The idea is to avoid beams thereby providing a flat roof thus avoiding the use of false ceiling. This reduces the construction cost and maintenance of the structure as well as the time required for construction. This paper aims to numerically investigate the effect of opening shape and opening size on lateral deformation of top storey of a multi-storeyed framed structure. To this end various shapes of openings namely triangular, square, and circular are incorporated in the shear wall and for each opening shape 20% and 25% openings have been considered. A ten-storey building containing the shear walls of various configurations has been analysed using the SAP2000 under the seismic load condition and the maximum lateral deformation produced at top storey of buildings are compared.

2. Literature Review

Incorporation of shear walls becomes inevitable in the multi-storey buildings to withstand the moments caused by lateral forces. Shear walls act as deep vertical cantilevers to provide necessary stiffness in a building. In shear walls, shear deformations are normally found negligible compared to bending deformations, therefore, they are generally neglected. With the increase in popularity of framed structures coupled with shear walls, it has led to increase in the experimental and analytical work done for the study of behaviour of shear walls when subjected to seismic activity. It is assumed that the horizontal forces act at floor levels and that the stiffness of the shear wall is very large compared to that of the columns [1], consequently, the out of plane bending of the floors is not considered. Several other assumptions considered for the analysis of shear-walled framed structures depend upon the method of analysis. In order to save the computational time and money for the analysis however, it is universally assumed that floors act as rigid diaphragms. Toutnaji [2] presented a simple and rapid method based on the continuum approach for the static analysis for interaction between shear walls and frames with planar loading. According to Toutnaji, if the frame alone is considered to take the full lateral load, it would develop moments in columns and beams to resist the total shear at each storey and the shear mode of deformation takes place in frame. If the shear wall alone is considered to resist all the lateral forces, it would develop moments at the level and the deflected shape would be that of a cantilever. Shear walls and frames both exist in the structure and they must deflect

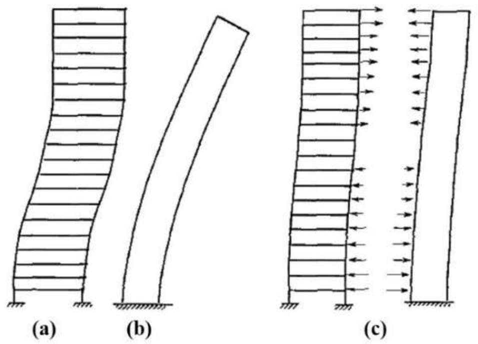

Fig 1 Typical Deformation Modes [4] (a) Free Frame (b) Free wall (c) Combined Frame and Wall

equally at every level. Because of the different lateral deflection characteristics of the frame and shear wall, the frame tends to pull back the shear wall in the upper portion of the structure and push it forward in the lower portion of the structure. As a result, the frame participates more effectively in the upper portion of the building where shear forces are relatively less, and shear wall carries most of the shear in the lower portion of the structure. Experimental work carried out by Lin et al. [3] showed that stress concentration occurs at the corners of openings which induces cracks in the wall hence reducing the strength and stiffness of the shear wall. When openings are incorporated in the shear wall, it is advisable to conduct finite element analysis for calculating ultimate strength capacity.

Equations from ACI (Eq. A7) may be used satisfactorily for the analysis of shear wall if the centre to centre distance of the boundary elements is considered as the effective depth of the wall. It is a practice to use the equations AS 3600-2001 and ACI 318- 2008 for solid load bearing walls supported at top and bottom only, certain restrictions are mandatory. In order to use these equations, higher slenderness ratio and concrete strength are used which are outside the range of these equations. Moreover, the strut and tie method may be used for solid shear walls and its use is permitted by various codes [4]. Modified equations suggested by Fragomeni et al. [5] and Saheb et al. [6] can be used based on the conditions applicable i.e. the slenderness ratio and the size of openings as suggested by them for the preparation for graphs for one-way or two-way systems. Based on experiments conducted by Daniel et al. [7] for Shear walls with central openings constructed as per UBC and ACI recommendations, interrupted vertical reinforcements to the sides of openings functions well in earthquake resistant structures. For analysis of shear walls with openings, if the size of opening is less than 10%, no reduction in stiffness is required irrespective of arrangement of the opening [8]. Yanez et al. [8] pointed out that a reinforcement ratio of 0.5 % for the shear wall has no effect on the arrangement of the openings in cyclic lateral loading. Balkaya and Kalkan [9] conducted three-dimensional nonlinear pushover analysis and carried out experimental work on shear wall dominant buildings. They observed that analytical and experimental becomes closer when the three-dimensional effects of existing transverse wall and diaphragm flexibilities are not considered. Moreover, they noticed the overall capacity of the pierced shear wall increases when interaction effects of slabs and transverse shear wall is considered. Furthermore, Balkaya and Kalkan [9] observed that with the change in the position of opening, there is a significant change in Tension/Compression coupling mechanism. Apart from these, the location of shear walls and the location of openings in the shear wall have been analysed by various authors using finite element method [10-14]. Recently, some investigations have been taken up to check the suitability of shear wall with openings for various cases of earthquake loadings [15-17]. On the basis of brief literature carried out it has been observed that that the provision of openings in shear walls is essential in a structure and the design of the structure depends on location of shear wall in the plan of the structure, its dimensions, and the presence of openings if any. Moreover, the previous studies indicate that the shear walls with openings should be sufficiently analysed and designed for earthquake loads. Furthermore, proper ductile reinforcement should be provided around openings so as to prevent propagation of cracks in the event of earthquake [18]. Ozkula et al. (2019) investigated the effect of shear wall on seismic performance of an RC buildings and concluded that Shear walls have considerable effect on seismic performance of RC buildings and performance of buildings increases with shear walls.

Hosseinia et al. (2019) conducted an experimental study to investigate the structural performances of the squat RC shear walls with the cut-out and the eccentric openings and concluded that the reduction in lateral stiffness of shear with eccentric openings was less than the cut-out openings. Moreover, they stated that the walls with openings need to be strengthened. Varma and Kumar (2021) performed the 3-D analysis of shear walled building to study the effects of size and locations of openings in shear wall and concluded that aspect ratio significantly affect the performance of shear wall and providing shear walls at the corners of the frame give good results compared to shear walls provided at the centre of the bay. Montazeri and Panahshahi (2018) carried out the failure (pushover) analysis of RC shear walls with vertically ordered and staggered openings using the ABAQUS and compared the results with the experimental data. They concluded that the walls with staggered openings have a higher loading capacity and rigidity in comparison with the walls with ordered openings.

Based on several studies carried out in past, it has been concluded that the behaviour of shear walls may be predicted either using the strut or tie method or by finite element analysis. The behaviour of shear walls with openings may be predicted analytically using the finite element analysis.

In the present investigation, using finite element analysis, suitability of the geometry of the opening in a shear wall is evaluated. For the dynamic analysis, El-Centro earthquake is considered, and the 10-storey structure is subjected to earthquake loads on two orthogonal directions to check the susceptibility of the structure.

3. Methodology

3.1 Multi-Storied Framed-Structure

In order to assess the adequacy of different empirical formulas to estimate structural period of vibration, Abdo [14] considered a shear wall (SW) dominant flat-plate 10-storey building structure. This rectangular plan building was designed according to the Egyptian code (2007) [19] and the same has been considered in the present investigation. The clear height of the ground floor is 4.4m and the repeated floors are provided at 2.8m each. In plan the structure has each bay of 7.2m × 7.2m as shown in Fig. 2. The building consists of interior columns of size 2m × 0.4m and the dimensions of exterior columns are 1.2m × 0.4m. The thickness of slab is considered as 0.3m for all the floors. In order to examine the effect of different positions of SW on dynamic behaviour and lateral response of this 10-storey building, he performed the dynamic analysis of building. For the dynamic effect considerations, Abdo [16] assumed that the building is located in cities with low seismicity (a_g = 0.10 g) and analyzed the building for dead loads plus 0.25 times live loads in conjunction with the dynamic effect according the response spectra. Based on his study Abdo [16] observed the SWs located at the periphery of rectangular building located at mid of each side performs better and the same positions of SW is considered in present study. The length and thickness of each SW is considered as 7.2 m and 0.3 m respectively. The SWs are constructed up to top storey and the thickness of columns and SWs has been assumed constant throughout the height.

In order to investigate the effect of opening size and opening shape in the present study the same 10 storey building is considered and 20% and 25% openings are introduced in shear walls at each storey and these openings are provided in three shapes namely circular, square and triangular. All the buildings have been analysed for El-Centro Earthquake effect along X-direction and along Y-direction.

3.2 Characteristics of Earthquake Considered

In the present study, the El-Centro earthquake has been considered and for this earthquake, the acceleration vs time graph is shown in Fig. 4. Every earthquake has three components – parallel to plane of rupture, normal to the plane of rupture and vertical component. The vertical component of earthquake is neglected owing to its much lowered than the gravity loads as the structure can stand well against the gravity loads. Among the parallel and normal components, the most critical case is taken for analysis. In present study the S90W component of the El-Centro Earthquake is considered and its characteristics are presented in Table1 and the time-history function is shown in Fig. 4.

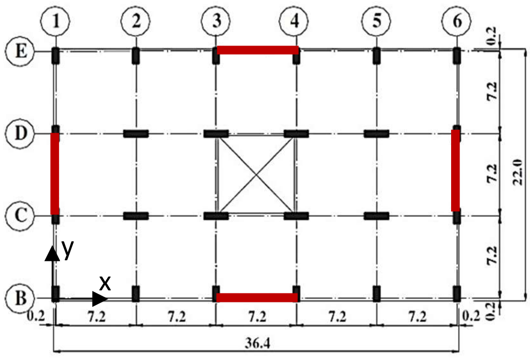

Fig 2 Plan of the structure showing the locations of shear walls [16]
(all dimensions in m)

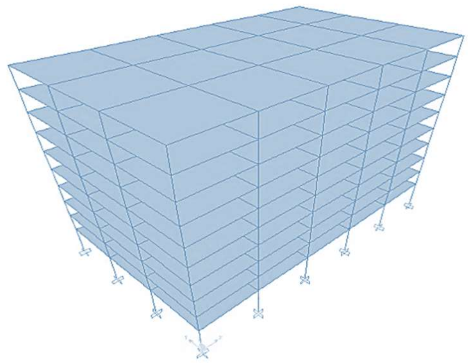

Fig. 3 A Typical Isometric view of Frames structure without shear wall

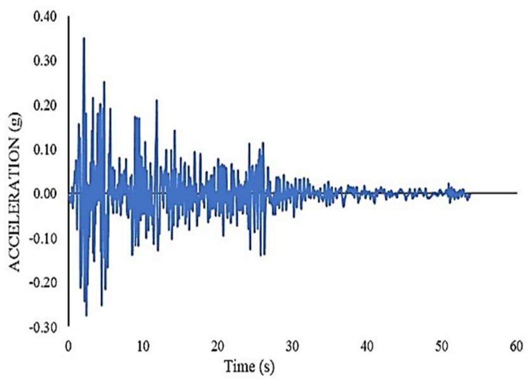

Fig. 4 Time History function of El-Centro Earthquake

Table 1 Characteristics of the Earthquake

Characteristics	El Centro
Region	California, U.S.
Year of occurrence	1940
Magnitude	6.9
Depth	8.80
Mechanism	Strike Slip
Critical component	S90W

According to IS1893:2016 [19], RC buildings must be designed for 1.5 (DL + IL), 1.2 (DL+ IL ± EL), 1.5 (DL ± EL), and 0.9 DL ± 1.5 EL, however, in the present investigation, the buildings are analysed for 1.5 (DL ± EL) only. The analysis of the building is carried out for the earthquake force components along both X-direction and Y-direction and for each case, to assess the effect of opening in shear wall, top storey drift determined using the non-linear dynamic analysis have been compared.

3.2 *Finite Element Modelling and Validation*

Initially the analysis of building structure containing no shear wall and then for building containing shear wall with no opening was carried out to check the robustness of SAP2000. The isometric view of the building continuing no shear wall is shown in Fig. 3 where the slabs are modelled as thick elements and columns are modelled as beam elements. The SAP 2000 results for building frames with and without shear walls were compared with the ETABS results [16] and found in good agreement. In order to introduce the openings in shear wall, it was observed that the SAP2000 does not have the option to incorporate openings in walls, however, it has the option to import AUTOCAD drawings for analysis.

In the present study the building models were drawn in AUTOCAD and the models were imported in SAP2000 in order to perform non-linear dynamic analysis of the building. Different shapes of openings were incorporated in the structure (circular, square and equilateral triangle) and for each opening shape the percentage opening were considered as 20% and 25% of SW area in that floor height. The openings were provided at the centre of the shear wall at each floor level. The models of the building for no-opening and for triangular opening, square opening and circular opening are shown in Fig. 6-8 respectively.

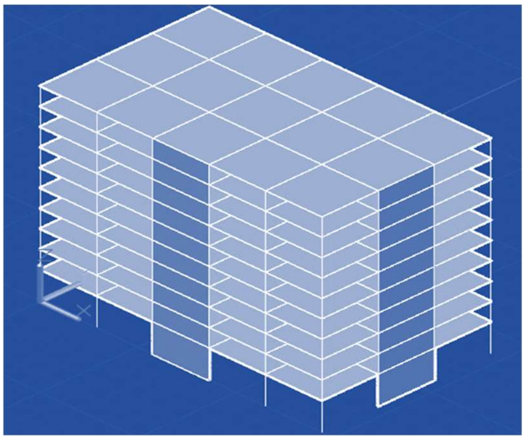

Fig. 5 Building Consisting SW without openings

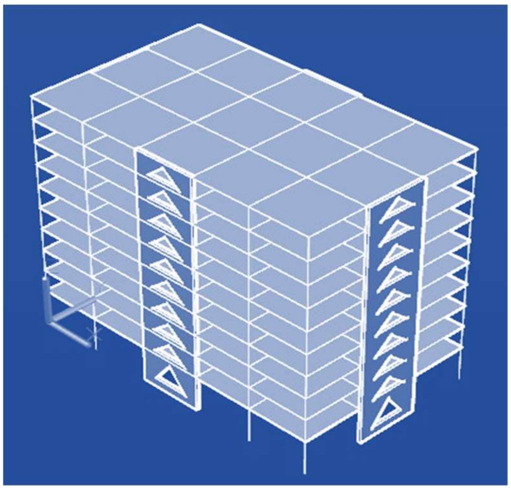

Fig. 6 Building Containing Shear wall with Triangular openings

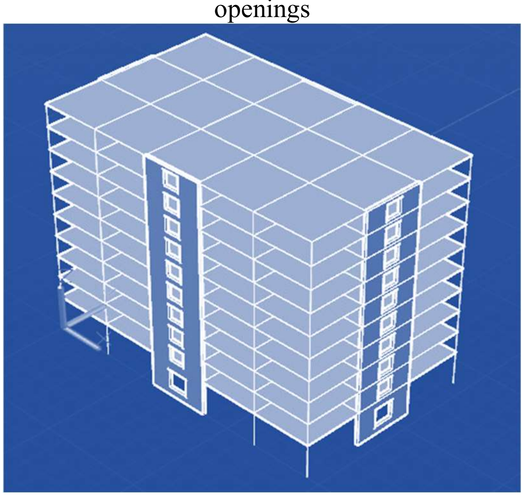

Fig.7 Building Containing SW with Square openings

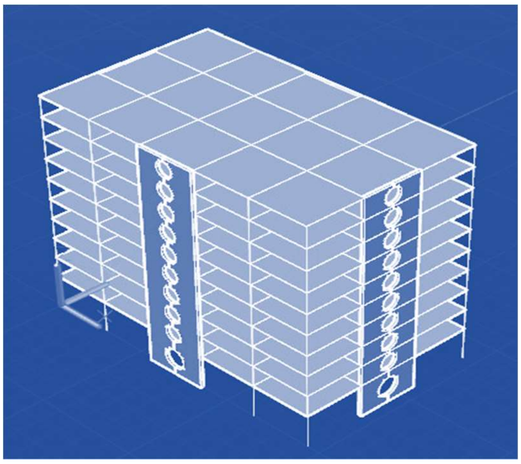

Fig. 8 Building Containing SW with Circular openings

5. Results and Discussions

Three-dimensional finite element analysis of 10-storey building with four numbers of shear walls one at each side of rectangular plan building was carried out using SAP2000. In order to investigate the effect of shear wall opening size and shape on the lateral stiffness of building, the lateral drift at top storey of buildings were determined for 20% and 25% opening in shear wall at each storey. Fig. 9(a) and Fig 9(b) show the plots of maximum top storey drift for the building when subjected to earthquake load (EL) along X-direction and Y-direction respectively.

Fig. 10(a) and Fig 10(b) shows a comparison of top storey drift of the building for when subjected to 1.5 times the combination of dead load and earthquake load considered i.e. 1.5(DL ± EL) along X-direction and Y-direction respectively. The magnitudes of lateral displacements of buildings with different opening sizes and shapes in shear walls are compared in Table 2 and 3 for EL along X- and Y-directions respectively.

It may be noticed from the Figs. 9 -10 that for the rectangular building plan considered in this study the dimension along Y-direction being smaller than the dimension along X-direction, consequently, for the EQ direction considered along Y-direction, the EL as well as 1.5(DL ± EL) cases possess higher magnitudes of Y-direction lateral deformations compared to those in X-direction corresponding to EQ direction along X-direction. This implies that the building plan side with shorter dimension is more susceptible against earthquakes. Therefore, symmetrical buildings plans are to be preferred, however, if not possible, earthquake analysis should be carried out in both the directions so as to ascertain the safety of the structure. The Tables 3-4 indicate that for 20% and 25% openings in shear wall, the triangular opening in shear wall is observed to develop maximum lateral displacements in buildings. For the EQ direction along Y-axis, the lateral displacements in Y-directions for EL and (DL ± LL) were observed for triangular opening and they were observed 19% and 24% higher compared to shear walls with no openings.

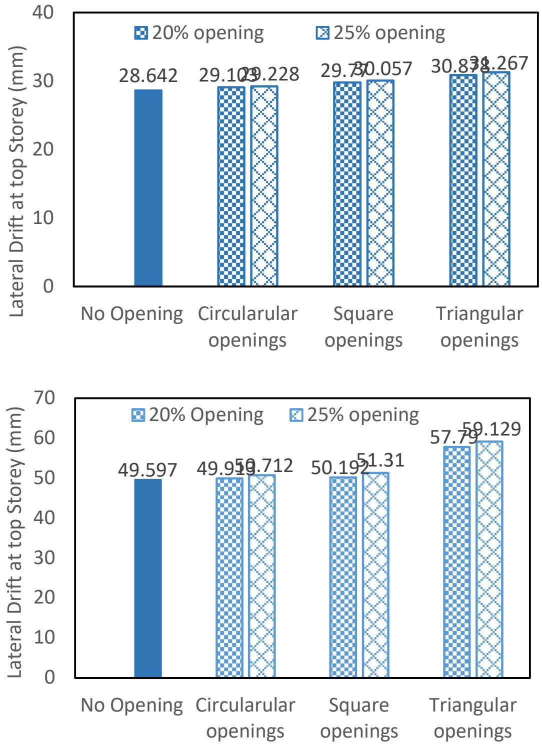

Fig. 9 Maximum top storey drift when building subjected to Earthquake Load only **(a)** EL along X-direction **(b)** EL along Y-direction

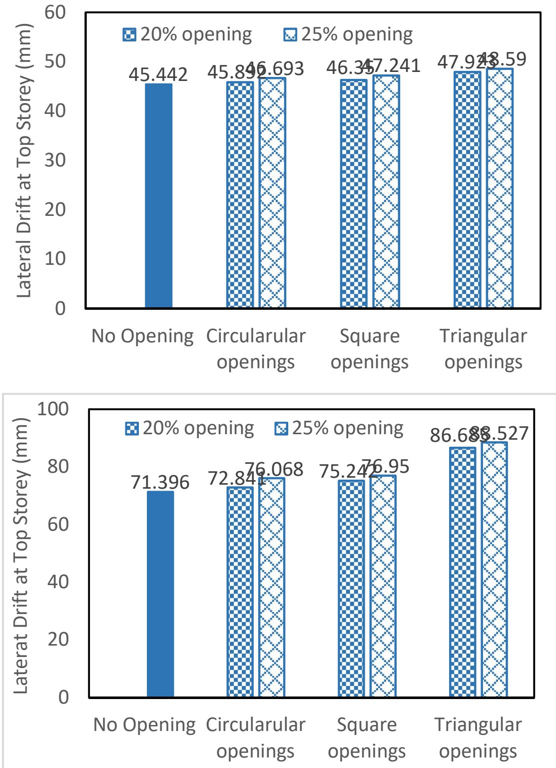

Fig. 10 Maximum top storey drift when building is subjected to Dead Load and Earthquake Load **(a)** 1.5(DL ± EL) along X-direction **(b)** 1.5(DL ± EL) along Y-direction.

Table 2: Effect of shape and size of shear wall opening on building subjected to EQ force along X-direction

Opening details	Lateral Drift (mm) for EL in X-direction for					
	EL Case only			1.5(DL±EL) Case		
	Opening size		%	Opening size		%
	20%	25%	diff.	20%	25%	diff.
No open.	28.6	28.6	-	45.4	45.4	-
Circul. Open.	29.1	29.2	0.4	45.9	46.7	1.8
square pen.	29.8	30.1	1.0	46.4	47.2	1.9
Triang. Open.	30.9	31.3	1.3	47.9	48.6	1.4

Table 3: Effect of shape and size of shear wall opening on building subjected to EQ force along Y-direction

Opening details	Lateral Drift (mm) for EL in Y-direction for					
	EL Case only			1.5(DL±EL) Case		
	Opening size		%	Opening size		%
	20%	25%	diff.	20%	25%	diff.
No open.	49.6	49.6	-	71.4	71.4	-
Circul Open.	49.9	50.7	1.6	72.8	76.1	4.4
Square. Open.	50.2	51.3	2.2	75.2	77.0	2.3
Triang. Open.	57.8	59.1	2.3	86.7	88.5	2.1

Consequently, the triangular openings were identified to produce least resistance to lateral deformation compared to circular and square shaped openings. Tables 2-3 indicate that for the EL and also for 1.5(DL ± EL) case, the opening size as well as the shape of the opening significantly affects the lateral stiffness of building. From the Tables 2-3 it may be observed that for a given opening size, the circular openings have been found to exhibit better resistance for resisting lateral loads due to EQ along X- and Y-directions. This is due to the fact that in circular openings the stresses are distributed effectively due to absence of corners in circular openings offer better resistance for the horizontal forces.

In other words, for providing the ducts for functional requirements such as pipes windows etc., of circular cross-sections is a better option than giving provisions for square/triangular shaped windows. Moreover, it may be observed from the Tables 2-3 and Figs. 9-10 that, as expected, for the EL as well as for 1.5(DL ± EL) cases, with increase in opening sixe, the magnitude of maximum lateral deformation increases. For the EL case, the circular openings are found to be least affected by rise in size of opening. size from 20 to 25%, the triangular openings result in 2.1 and 1.4% rise in lateral deformations for EQ effect considered in X- and Y-directions respectively increasing the size of circular opening from 20 to 25% the lateral deformations are merely increased by 1.6 and 0.4% for EL in X- and Y-direction respectively. On the other hand, for the 1.5(DL ± EL) case, the triangular openings are observed to perform better than circular and square openings. For the 1.5(DL ± EL) case, increasing the opening

5. Conclusions

Based on the study carried out in this paper, the following conclusions have been drawn.

- For 20% and 25% openings in shear wall, the triangular opening is observed to develop maximum lateral displacements in buildings where the lateral displacements were observed 19% and 24% higher compared to shear walls with no openings. Consequently, the triangular openings were identified to produce least resistance to lateral deformation compared to circular and square shaped openings.
- With increase in size of opening in shear wall, the magnitude of maximum lateral deformations increases. For a given size of opening, the circular opening produces minimum lateral displacement for Earthquake Load (EL) case, however, for 1.5(DL ± EL) case, the triangular shaped opening results in minimum lateral displacement.
- For the EL case, the circular openings are found to be least affected by the size of opening, on the other hand, the for the 1.5(DL ± EL) case, the triangular openings are found to less sensitive to size of the opening.

Disclosures

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