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Seismic Vulnerability Assessment for Various Shapes and Types of Reinforced Concrete Shear Walls in Multi-Storey Buildings

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Abstract

To improve the lateral stiffness and economy, reinforced concrete shear walls are introduced in buildings. This study aims to conduct the seismic assessment of shear walls in a multi-storey building. In this work, various factors are investigated and their performance is compared for various shapes and types of shear walls with respect to strength, displacement, time period, etc. The building considered for the study purpose is a G+12 residential building and is situated in a high seismic zone. The response spectrum analysis of the building is carried out by using the software ETABS. The results show that shear walls not only reduce the seismic forces in a building, but also are advantageous if they are situated in proper positions.

Keywords: shear wall, seismic analysis, mode shapes, types, response spectrum analysis, multi-storey building

1. Introduction

Human fatalities and financial losses caused by natural disasters have been significantly increased in the last couple of decades. Seismic activities have been the most disastrous phenomenon among these natural disasters. Earthquakes are the vibrations caused under the earth's surface, which lead to the loss of life and damage of structures [1-3]. Many reinforced concrete (RC) buildings in urban regions lying in active seismic zones may suffer moderate to severe damage during ground motions. From the literature survey, it is found from post-quake damage evaluations that shear walls exhibit good overall performance [4-6]. Nowadays, shear walls are one of the most common elements for resisting lateral forces in high-rise construction and rehabilitation of existing structures. RC structures are ample to resist both the vertical and horizontal loads, but when these structures are designed without shear walls, beam and column sizes are quite large. This increases the weight and forces in the buildings. Due to the larger size of elements, there is congestion at the joint also. To overcome these problems, shear walls become very important structural elements in the view of the economy as well as lateral force resisting elements [7-14].

The construction of shear walls in different sizes of buildings will have more advantages than building frames in terms of load-carrying capacity and economy. Due to the provision of shear walls, the side bending of structures will be controlled better than elements like closed frames. Therefore, in multi-storey buildings, minimum stresses are induced in structural elements due to shear walls. At the same time, various shapes and locations need to be identified for better performance of shear walls. The factors

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such as symmetry, torsional resistance, redundancy, and circulation should be considered while choosing proper shapes and locations of the shear walls. Thus, researchers are motivated to investigate the structural response of the shear walls. These structures add stiffness and strength during seismic activities, which are ignored during the design of structures and construction.

The main purpose of this research is to verify the system of shear walls as well as the effectiveness of shear using various shapes like rectangular (R), channel (C), T, and L shapes. Various structural properties are investigated and their performance is compared for various shapes and types of shear walls. In past decades, several investigators worked on the analysis and design of shear walls through various approaches. Some of the research are discussed below.

2. Literature Review

El-Sokkary and Galal [15] studied the effect of preliminary selection of RC shear walls' ductility level on material quantities. Dasgupta et al. [16] studied the current design provisions of walls given in the Indian code of practice. Uttekar et al. [17] and Nayak et al. [18] studied the seismic response of RC buildings considering various methods and structural configurations. Medhekar et al. [19] discussed the behavior, modes of failure, and factors influencing the structural response of shear walls. Kumar et al. [20] discussed RC multi-storey buildings are very complex to be modeled as structural systems for analysis. Venkatesh and Bai [21] found that the seismic loads are occasional forces that may occur during the lifetime of a building. Kim et al. [22] investigated the seismic performance of a staggered wall structure designed with a conventional strength-based design. Kaveh and Zakian [23] studied the optimal seismic design of RC shear wall-frame structures. Kassem et al. [24] studied and reviewed the seismic vulnerability assessment of civil structures. Finally, the authors suggested the most general empirical and analytical methodologies for seismic assessment.

Reshma et al. [25] and Tarigan et al. [26] analyzed symmetrical and asymmetrical buildings with different configurations of shear walls using time-history analysis. The authors presented that for lateral loadings, the buildings with shear walls show more linear behavior than the buildings without shear walls. Deepna et al. [27] studied the optimization of thickness of shear walls for high-rise buildings. From the study, the authors presented the effect of varying thickness in terms of storey drift and storey shear. Asl and Safarkhani [28] studied steel plate shear walls to reduce the beam section using push-over analysis. From the analysis, the investigators concluded that plastic strains are transmitted over the steel shear walls. Shafaei et al. [29] investigated the shear walls with and without openings using a finite element model. From the investigation, the authors concluded that the shear strength of the shear walls was dependent on the positions of openings.

Bongilwar et al. [30] studied the importance of shear walls in the seismic design of multi-storey structures. From the results, the authors concluded that it was very essential to consider the shear walls in the seismic analysis, which led to a decrease in the probability of collapse. Kaleybar and Tehrani [31] investigated the seismic performance of intermediate steel moment frames using different passive control systems. The nonlinear time-history analyses were performed to examine the seismic behavior of fluid viscous dampers, viscoelastic dampers, pall friction dampers, and metallic dampers. Finally, the investigators concluded that the structures with dampers had better seismic performance compared to the original structure. Though a considerable amount of investigations has been done in the analysis of shear walls, the investigators have not paid much attention to the seismic analysis of shear walls considering various shapes, positions, and types of shear walls. Hence, this research tries to fulfill this gap.

3. Modeling and Analysis of Building

Two cases are studied by using the software ETABS to verify the effectiveness of shear walls in the seismic zone. Case I deals with the analysis of a building with R-, C-, T-, and L-shape shear walls. After the analysis, the resistance of these shear walls is compared, and the most efficient shape is decided based on the analysis results. Case II deals with the analysis of a building with shear walls using different types of structural systems (i.e., frame type and dual type). The effectiveness of RC shear walls in the seismic performance of the building is studied in terms of strength, displacement, and storey drift. The analysis data for the building are shown in Table 1.

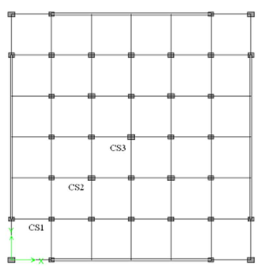
Table 1 Analysis data for a residential building

Serial number	Content	Value
1	Response reduction factor	5
2	Importance factor	1
3	Soil condition	Medium
4	Wall thickness	230 mm
5	Thickness of shear wall	200 mm
6	Thickness of slab	150 mm
7	Floor-to-floor height	3.1 m
8	Size of column	C1 = 500 mm × 500 mm C2 = 300 mm × 600 mm
9	Size of beam	300 mm × 450 mm
10	Grade of steel and concrete	Fe415 & M20
11	Floor finish and live load	1.875 kN/m^2 & 3.0 kN/m^2

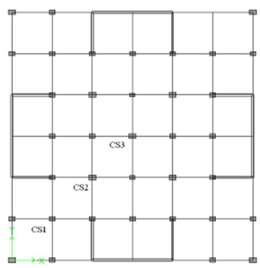
3.1. *Case I*: *Analysis of the building with shear walls in various shapes*

The building considered is a G+12 symmetrical building with dimensions 10.5 m × 10.5 m and is situated in seismic zone III. To compare the seismic resistance of the shear walls in various shapes, the number of the walls in each principal direction is arranged to be the same. Four different shapes of the shear walls, i.e., R, C, T, and L, are considered as shown in Fig. 1. The shear walls are modeled by using ETABS with shell elements as shown in Fig. 2. The shear walls are modeled as piers for the vertical elements above the openings, and are modeled as spandrels for horizontal elements. The mesh size is decided to adequately capture bending deformation. The height of the building is considered 43.3 m for the study. The earthquake forces are analyzed by using IS 1893:2016 (part I) [32-33].

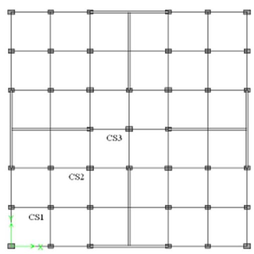
The models considered for analysis are as follows: Model I (the building with an R-shape shear wall), Model II (the building with a C-shape shear wall), Model III (the building with a T-shape shear wall), and Model IV (the building with an L-shape shear wall). In each model, the position of the shear wall is decided such that the building remains symmetrical and the principal axis is equal to the length of the wall in both directions. Also, the number of columns in each model is the same, so the stiffness of all the models remains the same.



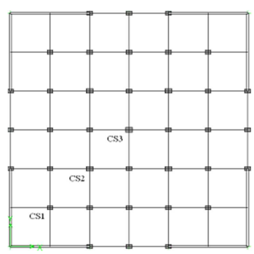
(a) Model I (R-shape shear wall)



(b) Model II (C-shape shear wall)

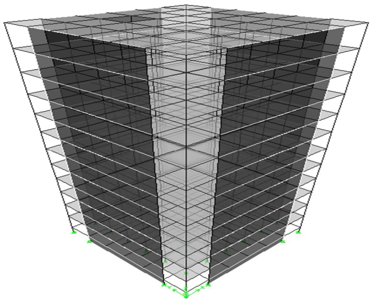


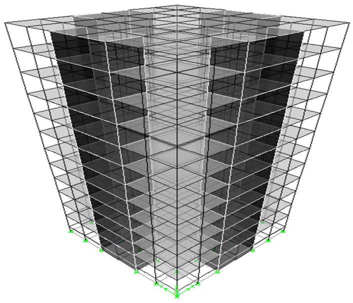
(c) Model III (T-shape shear wall)

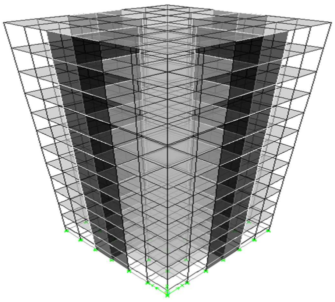


(d) Model IV (L-shape shear wall)

Fig. 1 Various shapes of shear walls


(a) ETABS model of the R-shape shear wall


(b) ETABS model of the C-shape shear wall


(c) ETABS model of the T-shape shear wall

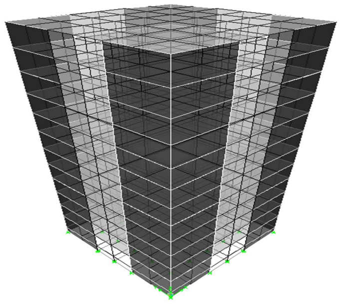
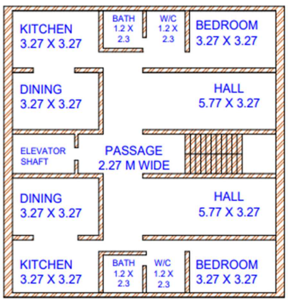

(d) ETABS model of the L-shape shear wall

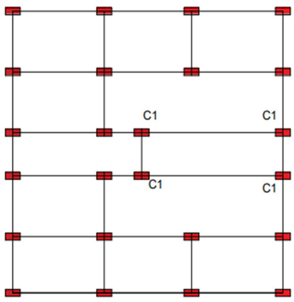
Fig. 2 ETABS models of the building with shear walls in various shapes

3.2. Case II: Comparison between the frame-type and dual-type structural systems

In this section, a G+12 residential building is analyzed for earthquake forces by considering two types of the structural system, i.e., frame type and dual type. The comparison is made between two types of systems for strength, displacement, and time period. The building is situated in seismic zone III. As shown in Fig. 3, the residential building has a plan size of 9.5 m × 16.5 m. Other details of the building are shown in Table 1. The following models are considered for analysis and are shown in Figs. 4 and 5: Model I (the frame-type structural system without shear walls) and Model II (the dual-type structural system with shear walls).

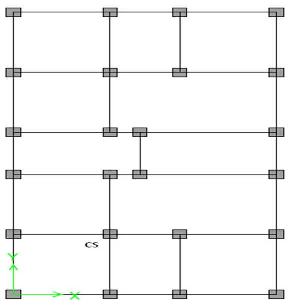


(a) Plan



(b) Line plan

Fig. 3 Plan of a residential building


(a) Model I

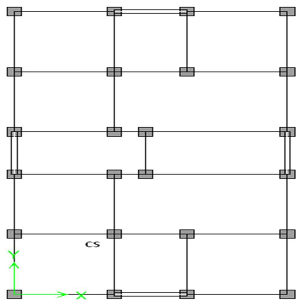
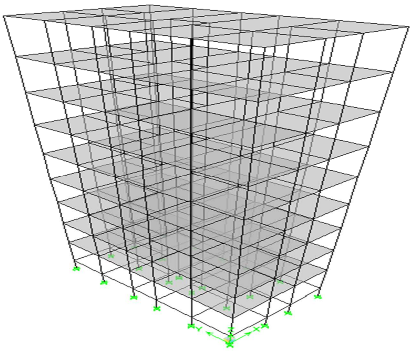

(b) Model II

Fig. 4 Building models (frame type and dual type)


(a) Without shear walls

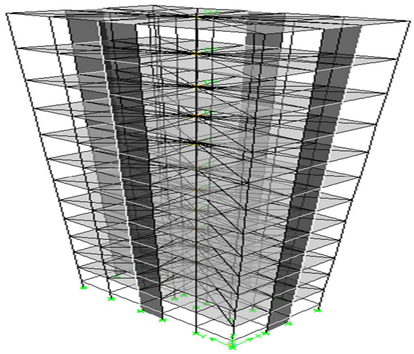

(b) With shear walls

Fig. 5 Software models of a G+12 building

4. Results

The response spectrum of any earthquake ground motion is a plot of peak (or maximum) values of response quantities (viz. displacement, velocity, and acceleration) as a function of the natural vibration period or frequency and damping ratio of a single degree freedom system. In this method, the maximum model response is obtained for each mode using the response spectrum. Mode shapes are the displacement shapes of a vibrating system corresponding to natural frequencies. The number of modes to be combined in the analysis is the sum of all modes considered, which is at least 90% of the total seismic mass. The response spectrum analysis of the building for the above two models is carried out by using the software ETABS considering all the 12 modes of vibration. The response spectra for medium soil site considering 5% damping as per IS 1893:2016 (part I) are used for the analysis. All other data for the building are the same as that for the static analysis. The comparison of dynamic analysis results for the displacement, storey drift, shear force, bending moment, and time period in Case I and Case II is shown below.

4.1. Case I: Analysis of the building with shear walls in various shapes

The difference between an initial position and any later position of a point is called displacement. For serviceability consideration, the performance of the structure can be checked by displacement. From Fig. 6, it can be seen that the displacement of the building increases with an increase in height. The minimum difference is observed in storey displacement up to the 4th floor. After that, higher displacement is observed as storey height increases. The maximum storey displacement is 6.5 mm, 7.25 mm, 8.2 mm, and 8.5 mm for the building with R-, L-, C-, and T-shape shear walls respectively. The displacement of the T-shape shear wall on the top floor increases up to 11.53%, 26.15%, and 30.79% as compared to C-, L-, and R-shape shear walls respectively.

Storey drift is the displacement of one level relative to the other level above or below. From Fig. 7, it is observed that the drift index increases from the bottom storey to the 6th storey for all shapes of shear walls and then gradually decreases for all models. The maximum storey drift is 0.79 mm, 0.76 mm, 0.635 mm, and 0.55 mm for the building with T-, C-, L-, and R-shape shear walls respectively. The maximum storey drift of the building with a T-shape shear wall is increased up to 3.94%, 24.40%, and 43.63% as compared to C-, L-, and R-shape shear walls respectively. The storey drift for a T-shape shear wall is more than that for the shear walls in all other shapes. The results indicate that the R-shape shear wall shows better performance than others in terms of the storey drift.

Fig. 8 shows the comparison of the maximum forces, bending moment, and torsion for columns CS1, CS2, and CS3 with different shapes of shear walls. An axial force is developed because of the dead load of the structure. The variation of axial force distribution for CS1, CS2, and CS3 with different shapes of the shear walls is shown in Fig. 8(a). From the results, it is shown that the axial force for CS3 is the maximum. The maximum axial force is 3720 kN for CS3 having an L-shape shear wall. At the same time, the maximum axial forces are 2790 kN and 2985 kN for CS1 and CS2 having T-shaped shear walls respectively.

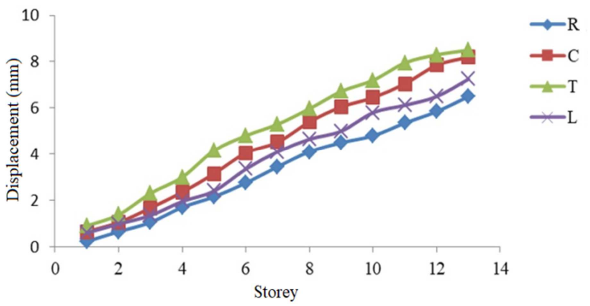


Fig. 6 Maximum displacement for different shapes of shear walls

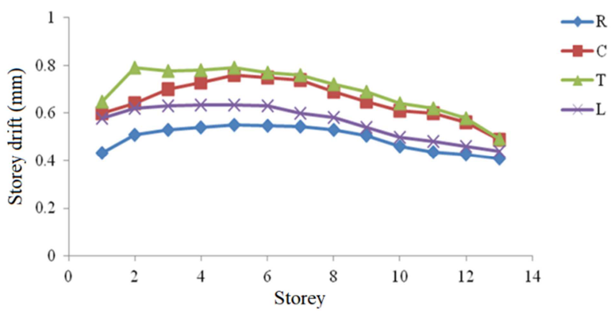
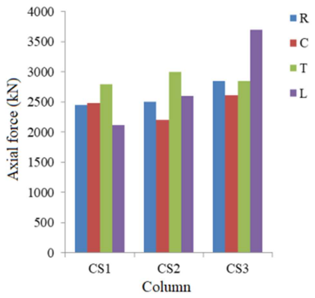
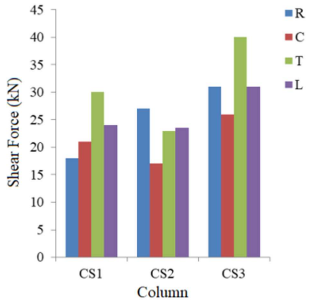


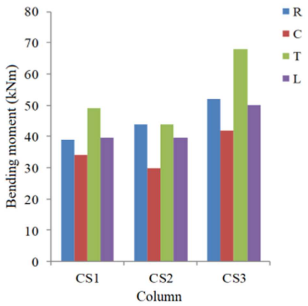
Fig. 7 Storey drift for different shapes of shear walls



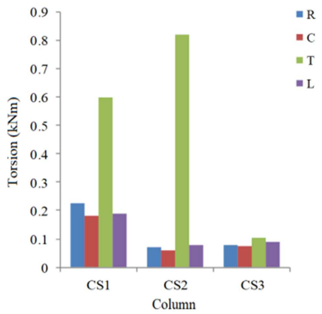
(a) Axial force



(b) Shear force



(c) Bending moment



(d) Torsion

Fig. 8 Maximum forces, bending moment, and torsion in columns for different shapes of shear walls

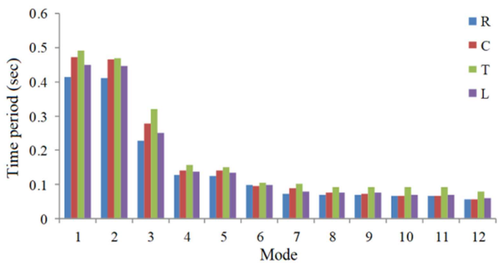


Fig. 9 Time period of vibration for different shapes of shear walls

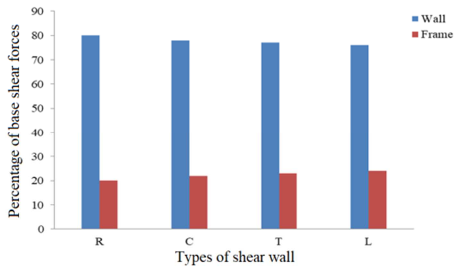


Fig. 10 Base shear distribution for Case I

From the results, it is observed that the shear force should not only be checked at extreme points, but should also be checked at intermediate points as ignorance of this may lead to cracking problems. This is interpreted from the figure that the shear force values are low at extreme columns according to the analysis results; however, they vary at the intermediate points, and greater values are at the center. The maximum shear force is observed for the column CS3 having a T-shaped shear wall. The maximum bending moment is seen at the center of the building for all types of shear walls, and the maximum bending moment is obtained for the building having a T-shape shear wall followed by R-, L-, and C-shape shear walls. According to the analysis results, the torsion force values are high at extreme columns; however, they vary at the intermediate points, and low values are at the center. The torsion force in CS1 for the T-shape shear wall is 2 to 2.5 times more than that for the R-shape shear wall. From Fig. 8, it is also clear that the forces are maximum in the T-shape shear wall. It is also seen from Fig. 8 that, due to the shear walls' position, distributed torques are increased in CS1 and CS2. The maximum forces are reduced by 30% to 50% in the R-shape shear wall than in the T-shape shear wall.

In the structural analysis and the design of the structure, the combination of modal shapes is used to assume the deflection profile. A total of twelve numbers of modes are used for the analysis purpose. From the analysis, it is found that modes 1 and 2 are in the translation mode, and mode 3 is in the third torsional mode. As shown in Fig. 9, the time period for each successive mode decreases as the mode number increases. It is noticed that the shape of the first and second modes for all cases is somewhat similar. However, the shape of the higher mode tends to differ more. Also, it can be seen that the % difference in the time period is less before the third mode. As the authors proceed towards the higher mode, it decreases by 72 to 78%. The time period of the T-shape shear wall is the longest, followed by C-, L-, and R-shape shear walls.

The distribution of base shear between the walls and frames depends upon the frequency characteristics of the structure. From Fig. 10, it is clearly seen that the walls take 75 to 80% of the base shear, whereas the frames take 20 to 24% of the total base shear.

4.2 Case II: Comparison between the frame-type and dual-type structural systems

It can be noted from the analysis that the lateral displacement is more predominant in Model I than Model II. The maximum displacement profile for Models I and II is shown in Fig. 11. The maximum displacement for Model II is less than 15% as compared to Model I. The maximum storey displacement of Model I is 12.33 mm, which is 1.15 times of Model II. Therefore, Model I will experience much damage during an earthquake. Also, it can be seen that the difference in the maximum displacement increases as the storey level increases. This implies that the presence of a shear wall increases the lateral stiffness of the building and reduces the lateral displacement of the structure.

The storey drift in the structure differs with various positions of the structure due to the torsional effect produced by lateral loads. From the results, it is observed that the storey drift is minimum at the base level, increases at the middle storeys, and then decreases at the top level for both models. The storey drift of each storey for Models I and II is shown in Fig. 12. The storey drift for Model II is less than Model I. The storey drift for Model I is about 40% to 60% more than Model II. The utilization of shear walls reduces the storey drift. It is found that the Model II structure gives the best results to reduce the storey drift.

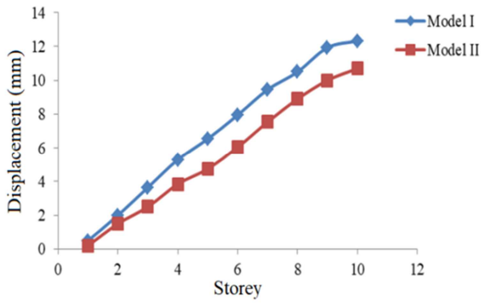


Fig. 11 Maximum displacement for Models I and II

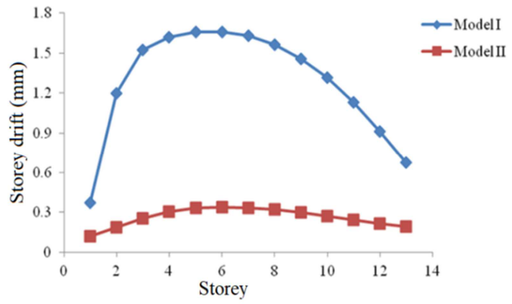
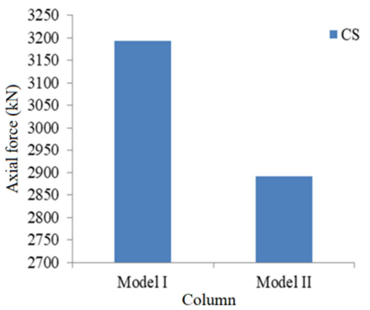
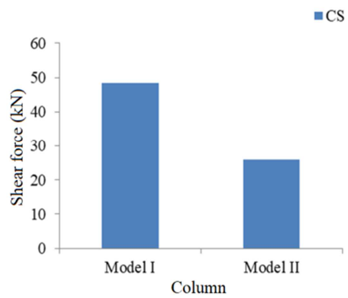


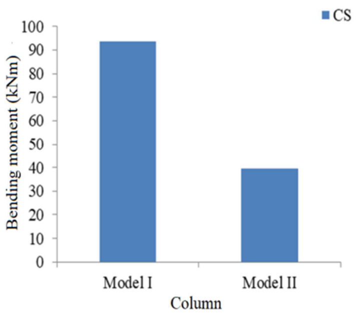
Fig. 12 Storey drift for Models I and II



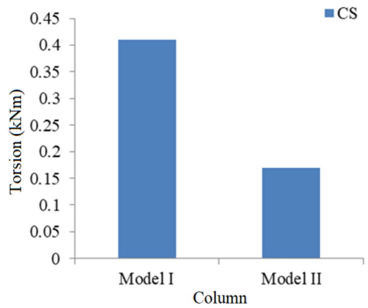
(a) Axial force



(b) Shear force



(c) Bending moment



(d) Torsion

Fig. 13 Maximum forces, bending moment, and torsion in the column CS

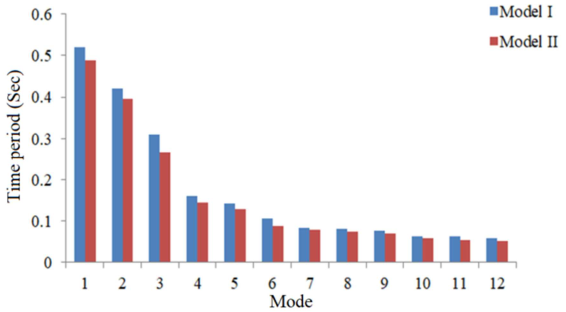


Fig. 14 Time period for the frame-type and dual-type structural systems

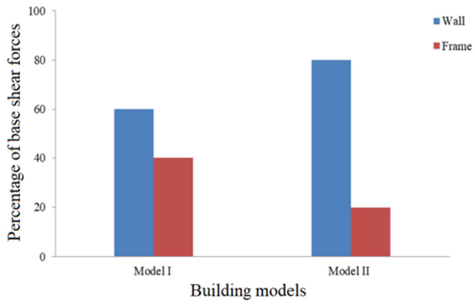


Fig. 15 Base shear distribution for Case II

The maximum forces, bending moment, and torsion in the column CS for two types of structural systems are shown in Fig. 13. Considerable reduction in shear force, bending moment, twisting moment, etc. is observed in the dual-type structural system as compared with the frame-type structural system. The axial force for CS in Model II is reduced by 20% as compared to that in Model I. The maximum shear force for Model II is decreased by 15% as compared to that for Model I. The bending moment and torsion for Model I is more than Model II. Very good control over the torsion forces can be achieved by using the dual-type structural system as compared to the frame-type structural system.

The structure moves back and forth when subjected to seismic motions. However, these motions are different in a flexible and rigid structure. The time period and frequency of vibration for the frame-type and dual-type structural systems are shown in Fig. 14. The application of shear walls in the building reduces the fundamental natural period. It is also observed from Fig. 14 that the time period for each successive mode decreases as the mode number increases. The time period for higher modes is shorter as compared to fundamental modes. Since the time period of vibration for the dual-type structural system is shorter than the frame-type structural system, the performance of the dual-type structural system is better in seismic excitation. Shear walls offer high stiffness to the structure and can decrease the period of the structure.

From Fig. 15, it is seen that in Model I, the wall takes 60% of the total base shear, whereas the frame takes 40% of the total base shear. At the same time, in Model II, the wall takes 80% of the total base shear and the frame takes 20% of the total base shear.

5. Conclusions

In this work, the factors affecting the seismic analysis of a building are studied with respect to strength, displacement, and storey drift. A comparison is made between the frame-type and dual-type structural systems to check the effectiveness of shear walls in a medium-rise building. The seismic performance of the shear walls in various shapes is also compared. The following conclusions are made from the analysis results.

(1) The displacement, storey drift, and time period of vibration for the R-shape shear wall are found to be less or fewer than those for the shear walls in other shapes.

(2) The maximum forces, bending moment, and twisting moment for the R- and L-shape shear walls are approximately equal.

(3) The maximum forces, storey drift, and time period of vibration for the T-shape shear wall are far more than those for the shear walls in other shapes. Hence, it is better to avoid the T-shape shear wall.

(4) The performance of the R-shape or L-shape shear walls is better than that of the C-shape or T-shape shear walls for earthquake forces.

(5) The seismic resistance of the R-shape and L-shape shear walls is found to be approximately equal.

(6) With better control over the displacement, the storey drift can be achieved by using the R-shape shear wall.

(7) To control the displacement and storey drift, it is preferable to place the shear walls towards the longer columns. If the shear walls are located towards the shorter columns, considerable reduction for maximum forces can be caused.

(8) The dual-type structural system with shear walls in proper locations is more effective in resisting earthquake forces than the moment-resisting frame system.

(9) The time period of vibration for the building with the shear walls located towards shorter columns is found to be shorter than that with the shear walls located at any other positions.

(10) The building with shear walls modeled gives more realistic results.

(11) It is very essential to study the seismic analysis of the structure with various shapes and types of shear walls, which considerably increase the performance of the overall structure and decrease the possibility of failure.

Conflicts of Interest

The authors declare no conflict of interest.

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