Performance of Reinforced Concrete Shear Wall In Dual Structural System: A Review

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ABSTRACT

A dual structural system consists of a moment-resisting frame, and vertical reinforced concrete walls called shear walls. Shear walls used in tall buildings are generally located around elevator cores and stairwells. Many possibilities exist in a tall building regarding the location, shape, number, and arrangement of shear walls. Shear walls generally start at the foundation level and are continuous throughout the building height. Their thickness can be as low as 150mm in low-rise to medium-rise buildings or as high as 400mm in high-rise buildings. To establish an effective lateral force-resisting system, the shear walls are located in preferable positions in a structure that minimizes lateral displacements. The shear walls are situated in ideal locations to be symmetrical and torsional effects get reduced. Based on the comparison of various literature regarding the shear wall positions, the shear wall placement at the core or the corners of the structure symmetrically gives the best performance to reduce displacement and story drift. Also, lateral displacement diminishes when the shear wall's thickness increases.

Keywords: Frame-shear wall interaction; Height; Multistory building; Position; Lateral sway

1. INTRODUCTION

Shearwalls have been extensively used in mid and high-rise buildings for the past two decades. They are particularly important in tall buildings because they are more susceptible to lateral loads and seismic forces. The lateral stiffness of the building becomes more critical with increased height to resist lateral loads such as earthquake and wind loads. This stiffness may be achieved by shear wall construction, in which the walls have relatively high in-plane stiffness to resist lateral forces.

Shear wall is considered the most effective compared to all the lateral force-resisting systems, especially for tall buildings and lift cases. Shear walls are erected to counteract the impacts of lateral loads, producing the required strength and stiffness for a structure when subjected to quake tremor. When the buildings are tall, say more than twelve-story or so, beam and column size workout large, and reinforcement at the beam and column junction works out quite heavy so that there is much congestion at these joints, and it is difficult to place and vibrate concrete at these places, which does not contribute to the safety of buildings. These practical difficulties call for the introduction of shear walls in high-rise buildings (Chittiprolu & Kumar 2014).

Shear wall has high plane stiffness which can resist large horizontal loads. It significantly reduces the lateral sway of the building and thereby reduces damage to the structure and its contents. Shearwall transfers the horizontal load to the next element in the load path below it, such as floors, other shear walls, slabs, or footings. Since the shear wall carries large lateral forces, it has large overturning effects (Tarigan *et al.* 2017).

The shear wall starts at the foundation level and is unceasing throughout the structure'saltitude. The thickness of shear is in the range of 150mm to 400mm in tall structures. Shear walls resemble vertically-oriented wide beams that convey earthquake forces downwards to the foundation. Shear walls are normally located around elevators and stairwell areas in high-rise buildings. Generally, shear walls have varied cross-sections like rectangular shaped and irregular shaped sections like L, T, C, and U. Rectangular cross-sections are more frequently used over irregular sections. For resisting the lateral loads and seismic forces, the shape, location, and height of a shear wall will remarkably impact the structure's behaviour. The shear wall must be located symmetrically in a plan to reduce the adverse effects of twists in buildings. When shear walls are placed in optimum positions in the building, they form an efficient lateral force-resisting system by reducing lateral displacements under earthquake loads. Therefore it is necessary to determine the optimum location of the shear wall (Tarigan *et al.* 2017).

Moment-resisting frame(MRF) systems are inefficient for buildings over 30 stories in height because the shear racking component of deflection caused by the bending of columns and beams causes the building to sway excessively. When shear walls are combined with MRFs, a shear wall-frame interaction system results. The MRF has an approximately linear shear-type deflected profile, and the shear wall has a parabolic cantilever sway profile. When the two systems are forced to deflect in the same way by the rigid floor diaphragm, the deflection profiles are combined, resulting in a common structure shape. Each will attempt to prevent the other from attaining its natural, free, deflected shape, and as a result, there will be a redistribution of forces between the two. The upper part of the shear wall is restrained by the frame, whereas the shear wall restrains the frame at the lower part. This effect produces increased lateral rigidity of the building. The frame participates more effectively in the upper portion of the building, and the shear wall carries most of the shear in the lower portion (Ali & Moon 2007). In the lower stories, the frame relieves the load from the shear walls, while in the upper stories, the shear walls get supported by the frames. As a result, in high-rise buildings with shear wall–frame systems, the upper-story columns are likely to be overstressed.

The main objective of this paper is to find the effect of position, height, and thickness of the shear wall on the behaviour of multi-storied buildings through the study of various literature.

2. METHODOLOGY

This paper aims to determine the optimum position of shear wall such that the lateral displacement of the building is reduced. The following methodology has been followed for the fulfilment of the objective.

1. Various literature on the shear wall has been studied regarding the effect of the shear wall's position, height, and thickness.
2. Medium-rise andhigh-rise buildings are selected to study the effect of shear walls on the behaviour of buildings subjected to lateral loads.
3. Several models with and without shear walls have been analyzed in various literature. The shear walls are positioned at various locations in the building, like the central core, corners, and periphery, and the optimum position is foundto reduce the lateral displacement of the structure.
4. The shear wall's thickness varies, ranging from 150 mm to 400 mm.
5. Conclusions are made based on the study of the literature available.

3. LITERATURE REVIEW

Jiang *et al.* (2021) investigated the influence of vertical setbacks on the seismic performance of the multi-storied building through elastoplastic time history analysis on three groups of models under different levels of earthquake excitation. Different parameters, such as setback percentage, local lateral stiffness ratio, and setback position, which cause vertical irregularity in the structure, are studied in this paper. The story displacement response, shear strength, and plastic energy dissipation of three groups of models are analyzed. The nonlinear analysis software Perform-3D is used in finite element analysis. The structures are RC frame-shear wall structures with 20 stories designed according to the Chinese code GB50011-2010. The shear walls are distributed in the periphery in the floor plan layout, as shown in Fig. 1, so both the frame and shear wall area can be reduced together with setbacks. The existence of vertical setbacks causes vertical irregularity. Vertical irregularity has a sudden change of stiffness, strength, or mass between adjacent stories. The sudden stiffness change at the setback position has increased the inter-story drift ratio at the setback position. However, the maximum inter-story drift ratio is smaller than the structure without a setback. It is due to the reduced mass due to the setback. The setback percentage is highly correlated to the variation of the inter-story drift ratio. Therefore, setback percentages can be used to quantify vertical irregularity. The setback at the middle height of the building should be avoided as it gives larger inter-story drift and seismic force. The setback at the lower height produces a more prominent influence on the variation of inter-story drift.

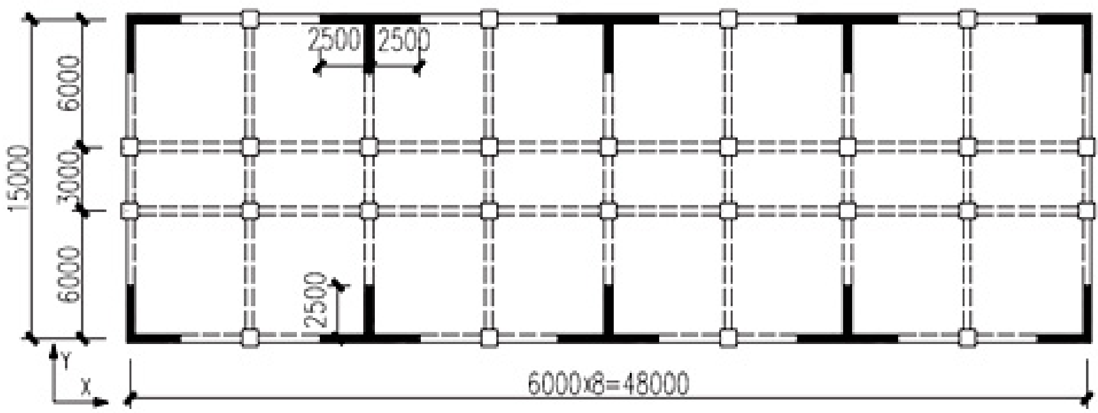

Fig. 1 Typical floor plan layout with shear walls (Jiang *et al.* 2021)

Reshma *et al.* (2021) emphasized finding the best feasible position of the shear wall in a 20-storied RCC building by conducting studies on base shear, period, drift ratio, and displacement. Four models are considered to study the behaviour of the structure under different seismic zones. The comparative analysis is done by considering with and without shear walls and placing shear walls at different locations, such as at the lift's periphery, corners, and the face. The corner position of the shear wall performed better than all other positions and is the best feasible location.

Ahamad and Pratap (2020) studied shear walls at different locations in a G + 20 multi-storied residential building. The multi-storied building is analyzed for story drift, base shear, maximum allowable displacement, and torsional irregularity by changing the structure's stiffness and height in different seismic zones of India prescribed by IS 1893 (Part I): 2016 by adopting the response spectrum analysis. It compares the behaviour of multi-storied buildings with and without shear walls by using ETABS software. Threedifferent cases are considered, i.e., building without the shear wall, building with a shear wall at one end, and building with shear walls at four ends. The building model with shear walls at four ends showed better results regarding story displacements, base shear, and fundamental period.

Jain and Sathbhaiya (2020) analyzed four cases of a tall structure G+14 considering shear walls at different positions by comparing a conventional structure with a shear wall structure considering P-delta analysis as per IS 1893 (Part I):2002. A building plan of plus shape, as shown in Fig. 2, has been analyzed considering shear walls at three different sections, i.e., at the outermost walls, at the corner edges, and at the inner close loop, to determine the most suitable position for the shear wall. This study concluded that a structure with a shear wall at the close loop in the inner periphery shows the best results when various parameters like story displacements, story shear, and bending moment are compared.

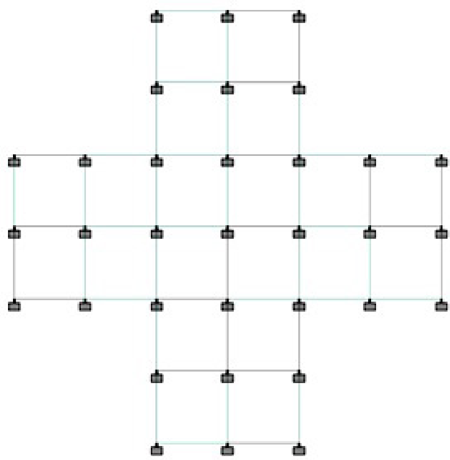

Fig. 2 Plan of plus-shaped structure (Jain & Sathbhaiya 2020)

Shreelakshmi and Kavitha (2020) identified the optimum thickness of the shear wall and its suitable position in the structure. The linear static analysis method uses ETABS 2016 software to study the G+20 story building located in seismic zone IV with soil type as a medium. Four different thicknesses of the shear wall, such as 150mm, 175mm, 200mm, and 225mm, have been considered, and again three different positions of the shear wall have been considered in the buildings, such as the shear wall at corners, shear wall at mid-span of the structure and shear wall at the core of the structure. Twelve combinations of the building were analyzed. The parameters considered are story dislocation, story drift, overturning moment, base shear, and modal period. In all cases, displacement values are higher in the shear wall of thickness of 150mm compared to other thicknesses of the shear wall. As the thickness of the shear wall increases, the displacement value decreases. In all the considered models, the shear wall placed at the corners showed the ideal results compared to the shear wall at mid-span and the structure's core. The modal period is more for a 150mm thick shear wall than a shear wall of other thicknesses. As the thickness of the shear wall increases, the period goes on to decrease. By comparing the position of the shear wall among all, the building with a shear wall at the corner showed a lesser period. As the thickness of the shear wall increases, the base shear values also increase. By comparing different positions, the shear wall at the corner showed higher base shear, and the wall in the middle of the building showed lesser base shear. It can be concluded that 150mm shear wall thickness will be adequate in the event of low rise to medium-rise buildings, which offers great cost-benefit. It can be presumed that as the thickness of the shear wall increases, the displacement diminishes. In all the considered models, the shear wall at the corners indicates the ideal location.

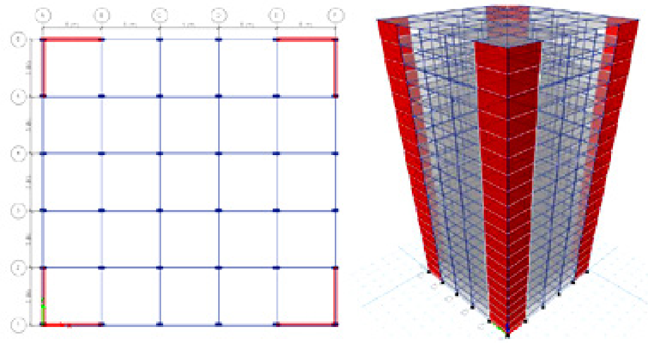

Fig.3 Shear wall at the corner of the structure (Shreelakshmi & Kavitha 2020)

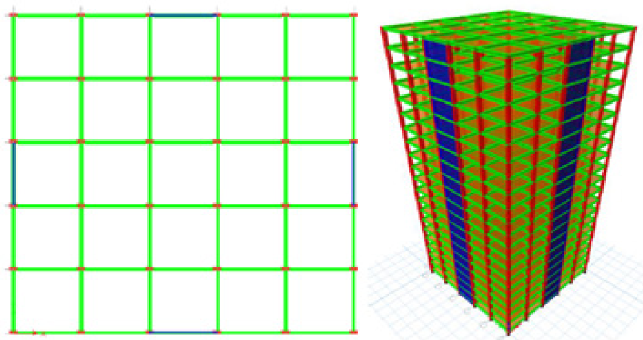

Fig. 4 Shear wall in the middle of the structure (Shreelakshmi & Kavitha 2020)

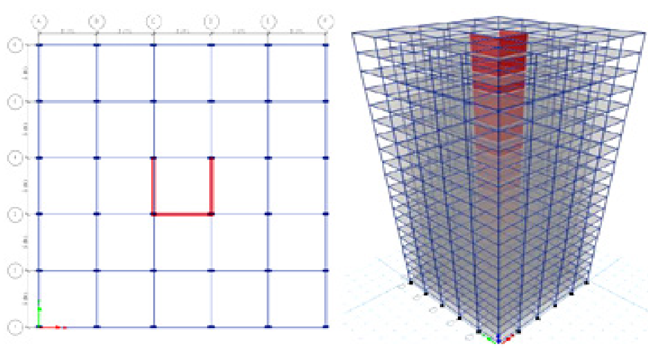

Fig. 5 Shear wall at the centre of the structure (Shreelakshmi & Kavitha 2020)

Almayah and Taresh (2019) analyzed multi-storied buildings by using time-history analysis. Base shear and floor displacements for different shear wall locations are examined under the action of ground motion records of El Centro, California, in 1940. A total of 35 combinations of building models are studied by considering different building heights cases, such as 5, 10, 15, 20, and 25 stories, and seven different shear wall locations. The building models are analyzed for story displacement, base shear, story drift, roof displacement, and fundamental period. It is found that the height of the structure and the location of the shear walls highly affect the natural period of a structure. When the shear walls are located in the corners, and the core of the building, the values of the roof and floor displacement are minimal. The effect of shear wall location is more prominent for buildings of more than ten stories.

Fares (2019) studied a 12-storied building using the Response spectrum analysis method. The position of shear walls is distributed into 3 cases: perimeter walls, intermediate walls, and central core walls. Each case is analyzed and compared to others according to three parameters: lateral stiffness, diaphragm displacement, and drift. It is found that the core walls are the best choice for the position of the walls in the buildings to resist earthquake loads. The central core showed much more stiffness than the other two models. The stiffness of the central core and the other two models is much higher at lower stories but gradually decreases in top stories. The core walls model gives the smallest floor displacement since this model gives the highest lateral stiffness values for each floor. The perimeter walls model gives the highest diaphragm lateral displacement for all floors. The core walls model gives a smaller drift than the intermediate and perimeter walls models. This conclusion confirms that the core walls model is the best choice for the distribution of walls in earthquake design.

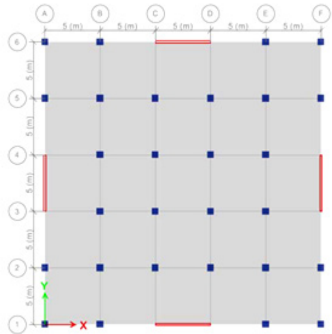

Fig. 6 Layout of the perimeter walls (Fares 2019)

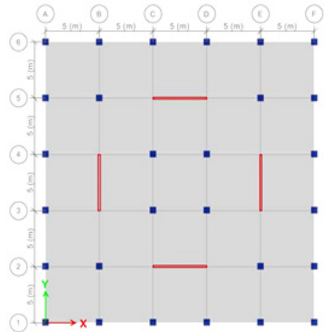

Fig. 7 Layout of the intermediate walls (Fares 2019)

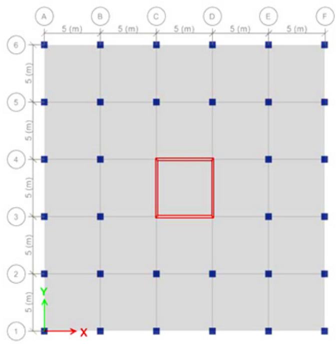

Fig. 8 Layout of the central core wall (Fares 2019)

Gupta and Bano (2019) studied the performance of various geometries of shear walls: C-shaped, L-shaped, I-shaped, and Rectangular-shaped. In this paper, G+6, G+16, and G+25 storied building is modelled and analyzed for lateral displacement, story stiffness, and story drift using ETABS-2016 software. The analysis of the building is done by using an equivalent static method. The performance of the I-shaped geometry shear wall placed at the centre of the building plan is better than other shear wall geometries.

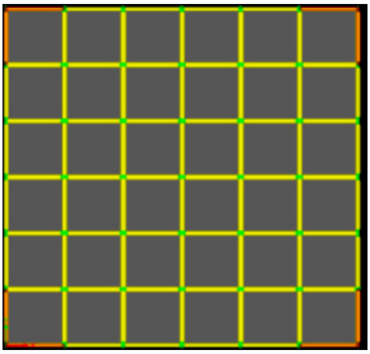

Fig. 9. L-shaped shear wall (Gupta & Bano 2019)

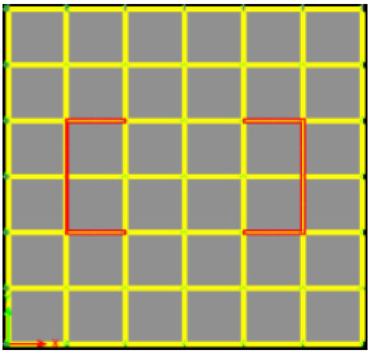

Fig. 10 C-shaped shear wall (Gupta & Bano 2019)

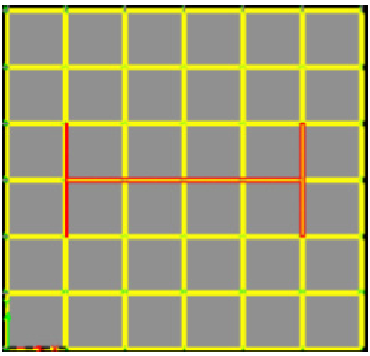

Fig. 11 I-shaped shear wall (Gupta & Bano 2019)

Yadav and Joshi (2019) analyzed a 6-storied high-rise building to find the effect of height and position of the shear wall. A total of 12 models, including both with shear and without shear walls, are analyzed using STAAD.Pro software. The models include buildings without shear walls and walls at different bay positions and buildings with varying heights of shear walls. There is no major difference in nodal displacement with different models of bay positions. With the increase in the height of the shear wall at different floor levels from the foundation to the top height of the building, there is a significant decrease in the lateral displacement of the building. The bending moment in the column increases with an increase in the height of the shear wall.

Tarigan *et al.* (2017) studied the effect of shear wall location in a 4-story building in Pekanbaru. Four different models of structures, such as open frame, the shear wall at core symmetrically, the shear wall at periphery symmetrically, and the shear wall at periphery asymmetrically, are analyzed using the response spectrum method. Based on the analysis, symmetrically placing the shear wall at the structure's core gives the best performance to reduce the displacement and story-drift. The structure without a shear wall has a maximum natural period. The existence of a shear wall gives high stiffness to the structure, thereby reducing the period of the structure. A structure with a symmetrically shear wall at the core has the shortest period and least lateral displacement. The existence of a shear wall reduces story drift below the allowable drift.

Bhattacharjee *et al.* (2017) analyzed a 15-storied high rise to find the optimum position of the shear wall. Six different models: one building model without a shear wall, and rest five models of the building having shear walls at corners were symmetrically placed at mid-span of the periphery, at the core in the form of a tube, at each side asymmetrically placed in the horizontal plane, and at corners of adjacent two sides only having a centre of mass not coinciding with the centre of rigidity as shown in Fig. 12. It is observed that the model having shear walls at the core of the building shows the best results for a square plan which is made symmetrically based on analysis of various parameters i.e., period, frequency, peak story shear, joint displacement (maximum) in both directions, and story drift in both directions. Also, shear walls placed asymmetrically do not perform effectively in the building and sometimes prove irrelevant. It shows a torsional effect in the building in asymmetrically placed shear walls, and hence poorly designed shear walls may lead to a decrease in the efficiency of the building.

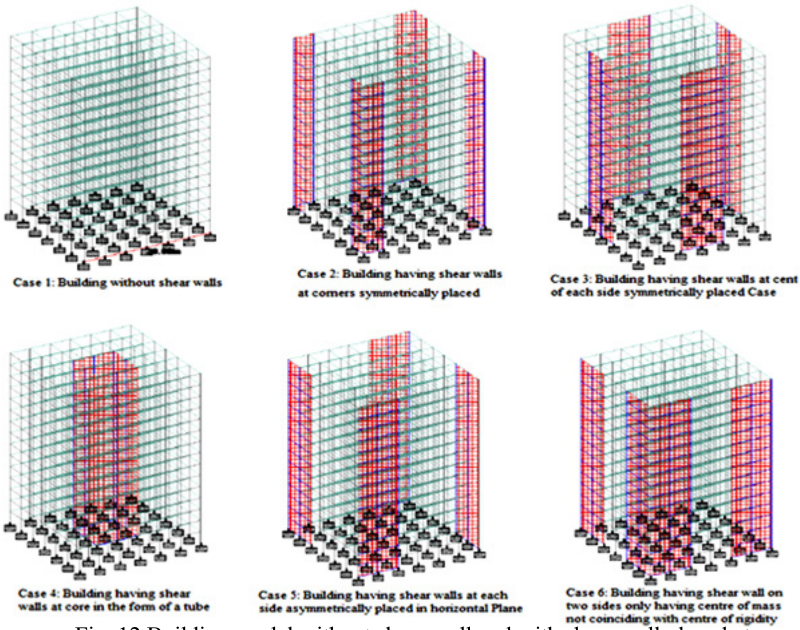

Fig. 12 Building model without shear wall and with shear wall placed at different locations (Bhattacharjee *et al.* 2017)

Aminnia and Hosseini (2015) studied the seismic behaviour of multistory reinforced concrete vertically chamfered buildings by using more appropriate shear wall form and arrangement in 7-, 10-, 12-, and 15-story buildings. The considered forms and arrangements include common rectangular walls and L-, T-, U- and Z-shaped plans located as the core or in the outer frames of the building structure, as shown in Fig. 13. Maximum roof displacement, particularly the formation of plastic hinges and their distribution in the structures, have been compared based on the results of a series of nonlinear time history analyses using a set of selected earthquake records. It is found that shear walls with a U-shaped cross-section, placed at the building's central core, give the best results. Also, walls with Z-shaped cross-sections at the corners give the building reliable seismic behaviour. However, the Z-shape cross-section may create some architectural limitations.

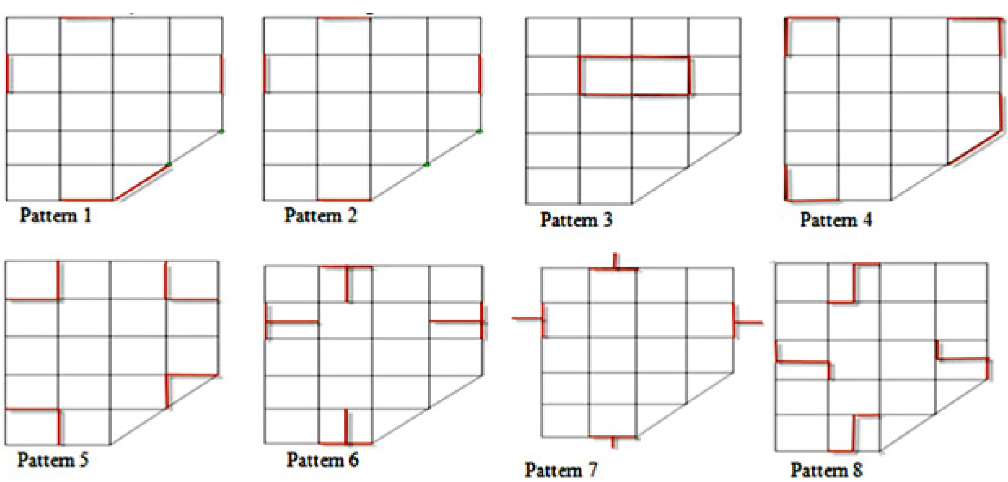

Fig. 13 Building plan with a shear wall placed at different locations (Aminnia & Hosseini 2015)

Hiremath and Hussain (2014) studied the effect of the addition of shear wall at different locations and configurations with varying thicknesses of shear walls. The results are obtained by performing pushover analysis using ETABS v 9.7.1 in the form of displacements and story drift. Four types of models have analyzed a building with a shear wall at the corner with uniform thickness, a building at mid-span with uniform thickness, a building with a shear wall in the middle mid-span with uniform thickness, and a building with a shear wall in middle mid-span channel type with uniform thickness. Building with a shear wall at mid-span (periphery) with varying thickness is ideal. The drift ratio in the upper story is more, less in the lower stories and maximum in the middle story. A model with a shear wall at mid-span having varying thickness achieves the highest reduction in displacement with base shear in the elastic region so that the building acts well within the elastic region.

Atik *et al.* (2014) determined the optimum level of wall curtailment in wall-frame structures by thoroughly analysing the continuum model. This study has revisited the related equations to study the effect of the calculation precision on determining the optimum level of wall curtailment. The optimum level of curtailment always lies between the zero wall shear and the point of inflection in the corresponding full-height wall structure. This result is very useful for finding the optimum level of curtailment. The curtailment level removes wall's negative shear by making it equal to zero at the top. At the same time, it removes the negative moment. As a result, the interruption of the shear wall at this level eliminates the reverse force applied by the shear wall on the frame, and consequently, the top deflection of the structure will be minimum. Hence the optimum level of curtailment, which results in the minimum top deflection of the structure, eliminates the negative moments and negative shear forces in the shear wall. It corresponds to a zero shear force at the top of the wall, which presents an easier alternative to working out the optimum level of curtailment.

Wang *et al.* (2001) studied the effect of shear wall height on the earthquake response of frame–shear wall structures. The paper proposed a numerical method based on the transfer matrix technique and structural modelling using wall elements. It is used to determine the natural frequencies, the shears at floor level, and the maximum displacement of the structures. Each structure is assumed to consist of nine-story, three-span frames and a central shear wall built parallel to the frames. Three structures with 1–, 4 –, and 9 – story shear wall heights are analyzed. A comparison of the maximum top displacement of the three structures does not show any significant variation, concluding that the extension of the shear wall over the entire height may not be necessary. While comparing the natural frequencies, it is found that the natural frequencies for different structures having stepped shear walls are generally identical. The frequencies and shears at floor level for different structures having shear walls discontinued are close. It indicates that the influence of shorter shear walls on the effective stiffness of the structures is marginal for some structures.

5. CONCLUSION

For resisting the lateral loads and seismic forces, the shape, location, and height of a shear wall remarkably impact the structure's behaviour. The shear wall should be placed in optimum positions in the building to form an efficient lateral force-resisting system, which reduces lateral displacements under earthquake loads. The shear wall thickness can be as low as 150mm, or as high as 400mm in tall structures. Shear walls of the thickness of 150mm will be adequate in the event of low-rise to a medium-rise building, which offers great cost-benefit. It can be concluded that as the thickness of the shear wall increases, the displacement diminishes.

Based on the comparison of various shear wall positions, the shear wall placement at the corner of the structure symmetrically gives the best performance to reduce displacement and story drift. It has been observed that the model having a shear wall at the corners of the building shows the best results based on analysis of various parameters i.e., period, frequency, peak story shear, joint displacement (maximum) in both directions, and story drift in both directions. The best results also come from shear walls with a U-shaped cross-section located at the building's central core.

The setback increases the inter-story drift ratio at the setback position due to the sudden change of lateral stiffness. The setback at the middle height gives a larger inter-story drift ratio, and seismic force and setback at the lower height produce a more prominent influence on the variation of the inter-story drift ratio. Overall, setbacks at the middle height should be avoided. However, shear wall curtailment was better prohibited, especially for buildings that should not get harshly damaged by earthquakes.

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