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Seismic assessment of slender high rise buildings with different shear walls configurations

Ahmed Abdelraheem Farghaly*

Civil and Architectural Constructions, Sohag University, Faculty of Industrial Education, Egypt

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Abstract. The present study dictates the behavior of shear wall under a seismic event in slender high rise buildings, and studies the effect of height, location and distribution of shear wall in slender high rise building with and without boundary elements induced by the effect of an earthquake. Shear walls are located at the sides of the building, to counter the earthquake forces. This study is carried out in a 12 storeys building using SAP2000 software. The obtained results disclose that the behavior of the structure is definitely affected by the height and location of shear walls in slender high rise building. The stresses are concentrated at the limit between the shear wall region and the upper non shear wall especially for shear walls without columns. Displacements are doubled between the shear wall region and the upper non shear wall especially for shear walls without columns.

Keywords: shear walls; stress concentrations; SAP2000; general building capacity; stiffness; shear wall distribution/position; time history analysis; high rise building

1. Introduction

Shear walls are used in many buildings primarily to resist efficiently the action of lateral loads to participate as much as possible in carrying gravity loads. They are usually conceived as vertical plates supported at the foundation and are expected to function only under the action of in plane horizontal and vertical forces. The walls are cast between two columns leading to I or dumbbell shapes (As in this study the shear wall ended by the columns of the building at the full width of the pay). RC walls with boundary elements have substantially higher bending strength and horizontal shear force carrying capacity. The height to width ratio (H/W) of shear walls vary considerably, ranging between 0.5 to more than 30 for low to high rise buildings, respectively.

The wall density per floor (d/n=0.001), indicates the building resistance in case of predominant shear behavior; d denotes wall density and n number of stories in a building.

Sri Sritharan *et al*. (2014) investigated potential causes of less obvious wall failures and identifying means to improve their performance. At least 40% of the total longitudinal reinforcement is used in the web. Minimum wall thickness calculation directly based on Eq. (1)

*Corresponding author, Associate Professor, E-mail: khodary20002000@yahoo.com

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$$\in_{sm} \leq \frac{\pi}{2}\left(\frac{b}{l_0}\right)^2 \xi_c + 3 \in_y \quad (1)$$

b wall thickness, l_0 is the buckled length of the wall, ϵ_y is the yield strain of the reinforcement; ξ_c calculated from Eq. (2)

$$\xi_c = 0.5(1 + 2.35m - \sqrt{5.53m^2 + 4.70m}); \quad (2)$$

m calculated from Eq. (3)

$$m = \rho_{end} \frac{f_y}{f_c^{'}} \quad (3)$$

Esmaili *et al.* (2008) concluded that using shear walls for both gravity and bracing system is unacceptable neither conceptually nor economically.

Murali Krishna and Arunakanthi (2014) concluded that the structures with shear wall shows that the center of mass and center of rigidity getting closer, the shape of shear wall and its position has decreased the diaphragm displacement compared to the structure without shear wall, and for the columns located away from the shear wall has the high bending moment and less shear force when compared with the columns connected to the shear walls.

Misam *et al.* (2012) argued the importance of shear wall as a one of the efficient approach to eliminate seismic failure of soft story in high rise building, and for existing high rise building by adding different arrangement of shear wall in building helps for retrofitting of structure to resist the major portion of lateral load induced by earthquake.

Ravikanth and Ramancharla (2014) concluded that lateral forces are reducing when the shear walls are added at the appropriate locations of frames having minimum lateral forces, in an irregular structure, and they can be used to reduce the effects of torsion.

Mukundan and Manivel (2015) concluded that the moments in the columns reduced when shear wall is introduced in the structure. The maximum storey displacement of the building is reduced by 50% when shear wall is provided. Shear wall with openings and with varying thickness is still strong and stable enough to resist seismic loads. For safer design, the thickness of the shear wall should range between 150 mm to 400 mm.

Mukesh and Danish (2015) concluded that shear walls reduced story displacement to about 80% when provided at corners in outer perimeter and to 60-65% when provided inside the building. The percentage reduction is more than that obtained from bracings hence shear walls are more effective in reducing story displacements.

Suresh *et al.* (2015) considered the shear walls as wide columns of high moment of inertia and following the same procedure as for columns.

Thorat and Salunke (2014) concluded that the location of shear-wall and brace member has significant effect on the seismic response of the shear-wall frame and braced frame respectively (central location of shear-wall and brace member). Addition of shear-walls at all or unfavorable locations do not effectively in reduces the actions induced in frame, so it is advisable to provide one shear-wall in frame instead of multiple shear-walls.

Xinzheng *et al.* (2015) provided a numerical model system, integrating the fiber-beam elements for beams/columns and the multi-layer shell elements for shear walls/core tubes, to simulate tall and super-tall buildings using OpenSees.

Junfeng *et al.* (2015) advised that the shear wall must has enough stiffness, bearing capacity and ductility to the seismic design, also it must ensure the overall stability and the local stability (flange and web).

Ali *et al.* (2015) analyzed shear stress variation in an L shaped reinforced concrete wall with different heights and thickness. It was shown that the shear stress increased until reaching a peak stress and after that decreased undependably of the walls thickness, increasing the length of the shear walls increased the value of the shear stress for buildings. The thickness of the walls increases the value of the peak stress shift toward lower values of the ratio (*thickness / length*).

Simonini *et al.* (2012) examined the shear forces in cantilever wall systems with wall lengths ratio =1.5. The numerical analysis of cantilever wall systems, models with lumped plasticity beam elements are recommended when the system's response is sought, but for walls with length ratio =1.5, for short wall, lead to unwarranted interventions if they are used for seismic assessment purposes.

Ö zmen *et al.* (2013) recorded some remarkable points about collapsed buildings with shear-walls, heavily damaged buildings despite adequate concrete strength due to detailing mistakes, undamaged two-story adobe buildings close to totally collapsed RC ones and undamaged structural system in buildings with heavily damaged non-structural elements, this is on the contrary of the common belief that buildings with shear-walls are immune to total collapse among civil engineers.

Inel *et al.* 2013 observed that the confinement reinforcements were insufficient due to large spacing and improper embedment in concrete core so, heavily damaged and collapse were happened if the earthquake had been a little more destructive

Mo *et al.* (2014) compered the seismic response of reinforced engineered cementitious composite (ECC) with RC shear walls under monotonic and cyclic loading, and concluded that the reinforced ECC shear walls can have superior seismic performance to traditional RC shear walls.

Farhad *et al.* (2014) compared performance of a typical shear walls designed by different standards (ACI-318-11, NZS3101:2006 and Eurocode 8). The confinement requirements of NZS3101:2006 resulted in a section that was almost the same as ACI318-11 wall model and the only difference was a smaller value of the transverse reinforcement spacing.

Julian *et al.* (2015) summarized the experimental behavior of lightweight shear walls comprised quasi-static cyclic tests and shake table tests of twenty walls. Test results indicate that shear strength, drift ratios and energy dissipated at different limit states of lightweight concrete walls were larger in comparison to walls made of normal weight concrete.

Anuj (2012) discovered that among different location of shear wall (F- shear wall at end of "L" section) gives best results because of the end portion of flange oscillate more during earthquake, hence reduce overall bending moment of building.

Rui and seyed (2012) investigated two adjacent concrete frame models with and without shear wall. The shear wall systems provide at the link element stronger impact forces than for other structural systems so, is able to absorb more energy (than moment resisting frames) and present higher resistance against destructive earthquakes.

Chandurkar and Pajgade (2013) concluded that large dimension of shear wall is not effective in 10 stories or below 10 stories buildings, the position of shear wall will affect the attraction of forces, so that wall must be in proper position in high rise building.

Anshul *et al.* (2014) concluded that for frame with shear walls at mid-sides performs best for earthquake in z direction. The reduction in response is as high as 83% and the reduction in B.M. is approximately 70 to 85% for interior and perimeter columns respectively.

In this study a slender high rise building subjected to earthquake with different shear walls arrangement and heights tested to show the effects of the position and height of shear walls on straining actions.

2. Models description

A slender high rise building consists of frame elements as beam and column the column dimension is 550×550 mm and the beam section is 250×500 mm as frame elements and the shell element as slabs and walls, the slab and shear wall thickness are 120 and 250 mm respectively with fixed thickness. Three models used in this study, the first model was a building of 12th stories with story height 3 m the length of the building is 20 m and 10 m width (length/width=2) (Fig. 1).

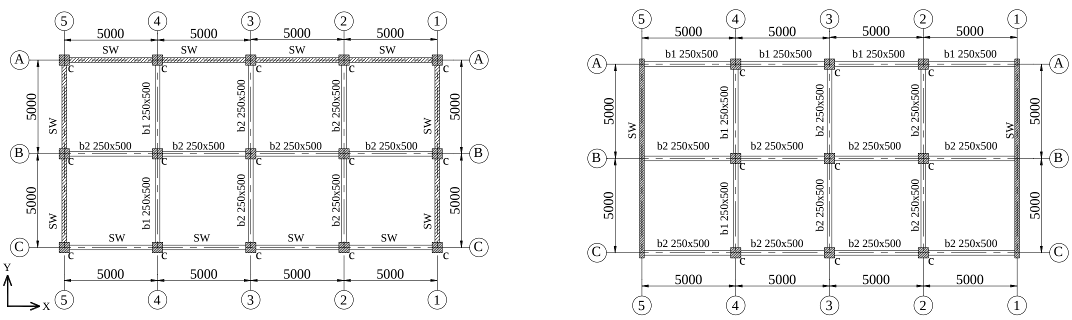
The first model (length/width=2) building consists of 4 bays in *x* direction each 5m and two bays in *y* direction each 5 m, the second model (length/width=2.5) building consists of 5 bays in *x* direction each 5 m and two bays in *y* direction each 5 m, and the third model (length/width=1) building consists of 4 bays in *x* direction each 5 m and 5 bays in *y* direction each 5 m. The shear capacity and displacements of the building found in the three models in both directions (*X*, *Y*) for different cases.

To study the effect of the earthquake on the selected models and give the best performance of the building to resist the earthquake force, four cases of study were selected:

1. Shear wall with full height of the building (36 m) (all).
2. Shear wall at ¾ height of the building (27 m) (¾).
3. Shear wall at ½ height of the building (18 m) (½).
4. Shear wall at ¼ height of the building (9 m) (¼).

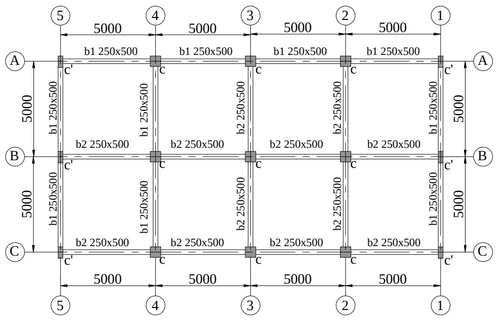
These previous four cases applied for the building’s shear wall with columns and without, the shear walls placed in the buildings as follows (for each study cases):

• Shear walls are in long and short side of the building (both).
• Shear walls are in long side only. (Long).
• Shear walls are in short side only. (Short)
• Shear walls are as stripes lengths 5 m between two columns, in both sides of the building. (strip both)
• Shear walls are as stripes lengths 5 m between columns, in short side only. (strip short)

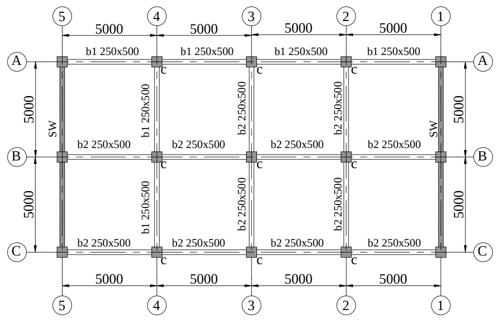


i) Shear wall with columns at each side ii) Full and half shear wall without columns

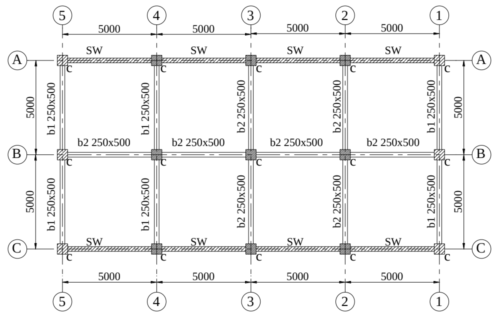
Fig. 1 Model (1) Rectangularity Ratio=2 (dimension in mm)



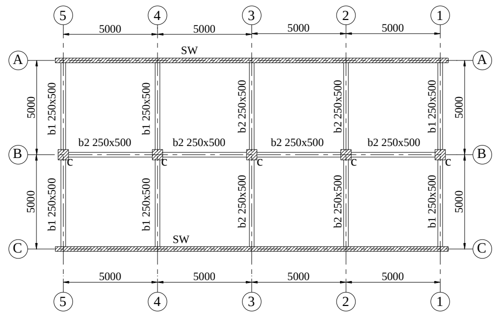
iii) Plan floor above shear wall



iv) Shear wall with columns at Short side



v) Shear wall with columns at long side



vi) Shear wall without columns at long side

(a) Cross sectional plans models

i) Full SW with col. ii) Half SW with col. iii) SW only iv) Half SW only

(b) Elevation of the models in short direction

Fig. 1 Continued

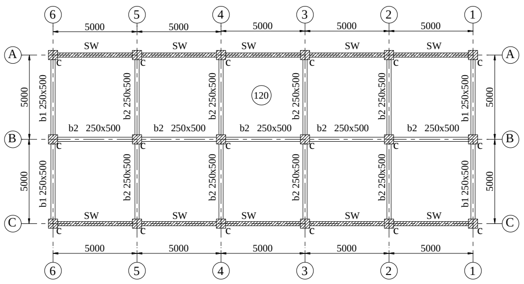
• Shear walls are as stripes lengths 5 m between columns, in long side only. (strip long)

A three-dimensional model of each building is created in SAP2000 to carry out NL time history analysis. Beam and column elements are modeled as NL frame elements with live load and cover on the slab equals to 3.5 KN/m^2, and distributed load on beams equals to 6.5 KN/m'.

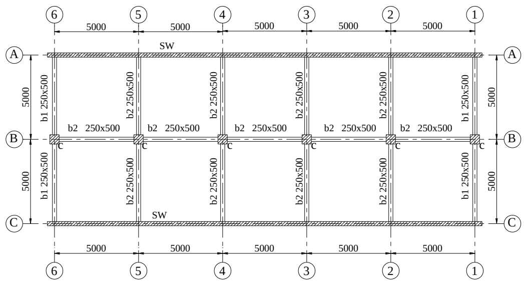
The second model was 25 m length and 10 m width (length/width=2.5) (Fig. 2).

The third model was 20 m length and 20 m width (length/width=1) (Fig. 3).

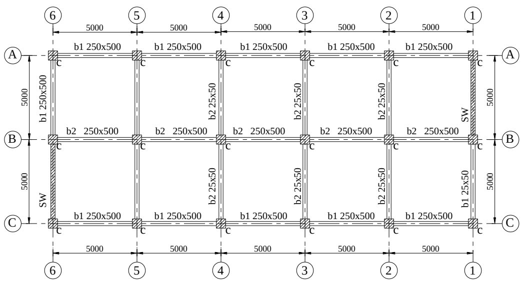
Nonlinear time history analysis is carried out considering the factor of acceleration 0.5 g (El-Centro earthquake used as shown in Fig. 4), the earthquake will affect in both directions of the building (*x*, *y* directions) for all studied cases. The time history corresponding to 5% damping is considered which is reasonable for concrete structure.



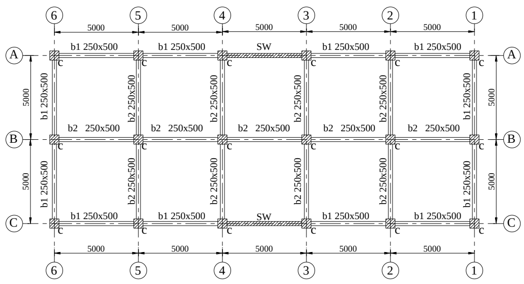
i) Shear wall with columns at long side



ii) Shear wall without columns at long side

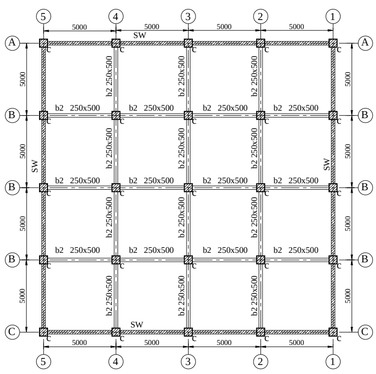


iii) Shear wall strip with columns at short side

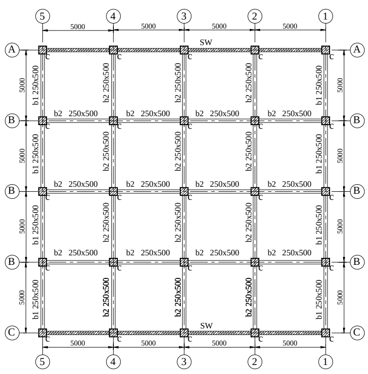


iv) Shear wall strip with columns at long side

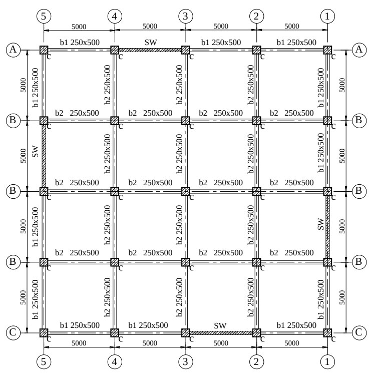
Fig. 2 Model (2) Rectangularity Ratio=2.5 (dimension in mm)



i) All sides with columns

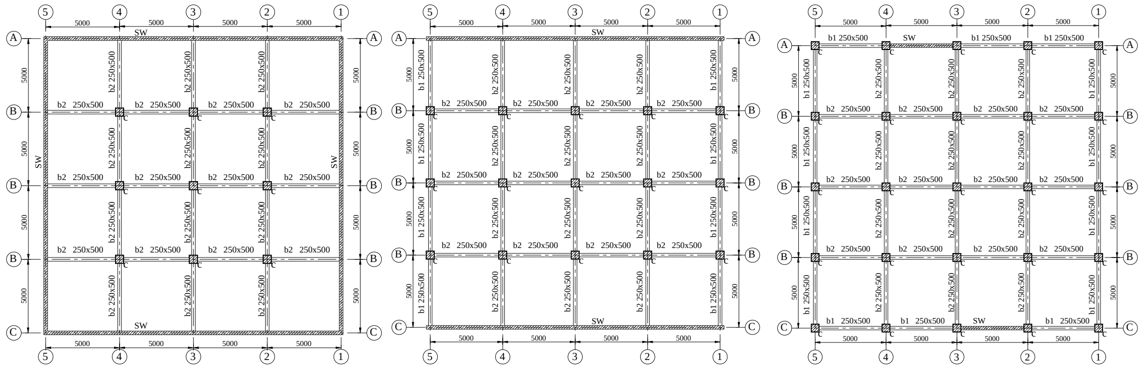


ii) One side with columns



iii) Strip one side with columns

Fig. 3 Model (3) Rectangularity Ratio=1



iv) All sides without columns   v) One side without columns   iii) Strip both sides with columns

Fig. 3 Continued

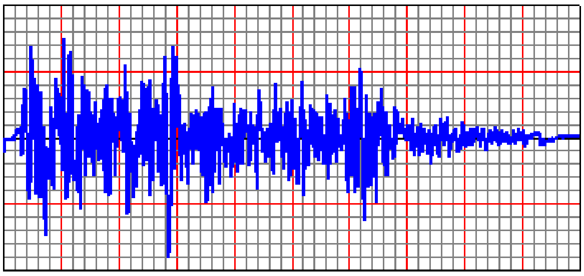


Fig. 4 The El-Centro Earthquake Excitation

Inel and Özmen (2006) investigated the possible differences between pushover analyses of the default-hinge and user-defined hinge models and they showed that the user-defined hinge model is better than the default-hinge model in reflecting nonlinear behavior compatible with element properties and the user should be aware of what is provided in the program and should definitely avoid the misuse of default-hinge properties.

In this study the default hinge properties were used.

3. Results and discussions

The main intent of this parametric study is to assess the behavior of shear wall which is encompassed with varied size, height and location on straining actions in frame slender high rise building.

Frame members primarily serve to carry the majority of gravity loads in a building, but also serve as part of lateral resisting systems. Floor system in high-rise buildings functions not only provides gravity load resistance, but also provides constraints between frames, and shear walls with great contribution to spatial components interactions.

Table 1 shows the shortcuts used in the graphs and its definitions.

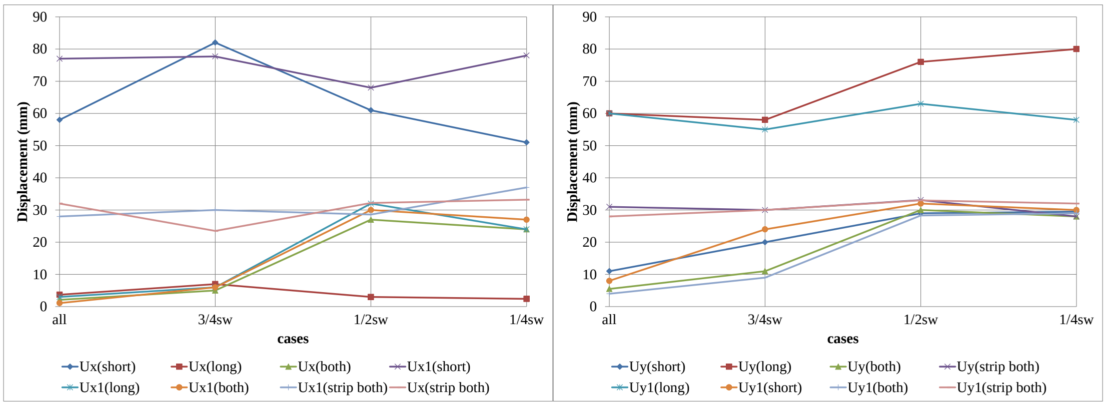
Fig. 5 shows the straining actions of building with rectangularity ratio equals to 2 (length/width=2). Fig. 5(a) shows the displacement of the building in *x* direction (long direction) in different cases of height and location of shear walls, it is noted that using shear walls along the short side of the building did not affect on the displacement for shear wall without columns, but shear walls with columns the values decreased for all, ½ sw and ¼ sw. using strip shear wall in both direction decreased top displacements in the *x* direction by 2.6 times than using shear wall at all over the short side of the building, using a shear wall with columns at all over the long side of the building decreased the top displacements by nearly 16 times than the cases of long, long1, and both these correct for all and ¾ sw cases and shear walls placement in long.

Fig. 5(b) shows the top displacement in y direction for the building in different shear wall configurations. In case of shear wall with columns the top displacement of the building increased than the case of using shear wall without columns, where it decreased the top displacement by nearly 50% than the previous two cases. Using ½ sw or ¼ sw also reduced the top displacements by 50% than the first two cases. The all and short cases decreased top displacements by nearly 33% than the rest cases.

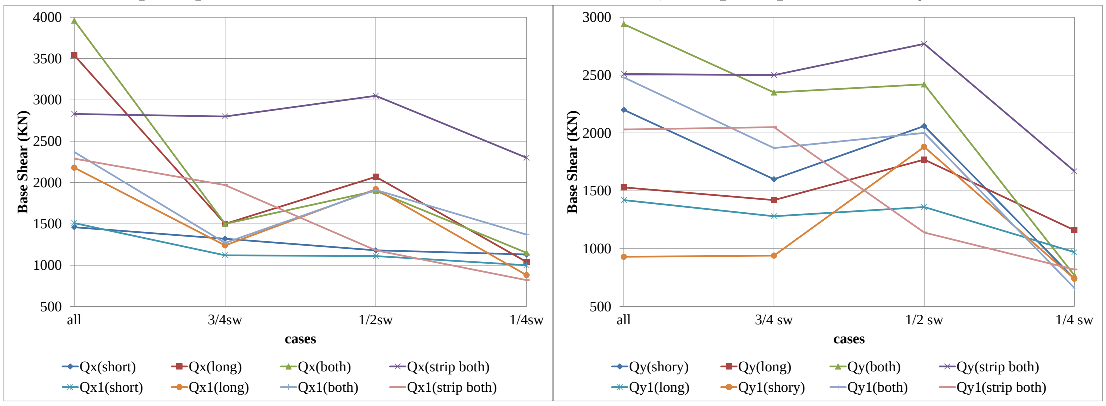
Fig. 5(c) shows the base shear in *x*-direction for different cases of shear walls configurations. All cases of shear walls configuration at case ¼ sw decreased base shear force of the building than the rest cases. Maximum base shear force showed with shear wall all over the height of the building, the case of ½ sw (with columns) strip in both sides showed a good performance of the base shear force in *y* direction, the corresponding case without columns showed decreased

Table 1 Symbol definitions

Symbol	Definition	symbol	Definition	symbol	Definition
Ux(long)	Top displacement in *x* direction with shear walls at long direction	Qy(short)	Base shear in *y* direction with shear walls at short direction.	Qx(one strip)	Base shear in *x* direction with one strip shear wall.
Uy(long)	Top displacement in *y* direction with shear walls at long direction	Ux(both)	Top displacement in *x* direction with shear walls at both directions	Qy(one strip)	Base shear in *y* direction with one strip shear wall.
Ux(short)	Top displacement in *x* direction with shear walls at short direction	Uy(both)	Top displacement in *y* direction with shear walls at both directions	Ux(strip both)	Top displacement in sx direction with strip shear walls at both directions
Uy(short)	Top displacement in *y* direction with shear walls at short direction	Qx(both)	Base shear in *x* direction with shear walls at both directions	Uy(strip both)	Top displacement in *y* direction with strip shear walls at both directions
Qx(long)	Base shear in *x* direction with shear wall at long direction	Qy(both)	Base shear in *y* direction with shear walls at both directions	Qx(strip both)	Base shear in *x* direction with strip shear walls in both directions.
Qy(long)	Base shear in *y* direction with shear wall at long direction	Ux(one strip)	Top displacement in *x* direction with one strip shear wall.	Qy(srip both)	Base shear in *y* direction with strip shear walls in both directions.
Qx(short)	Base shear in *x* direction with shear wall at short direction	Uy(one strip)	Top displacement in *y* direction with one strip shear wall.	Mz	Torsion



(a) Top Displacement in *x* direction (b) Top Displacement in *y* direction



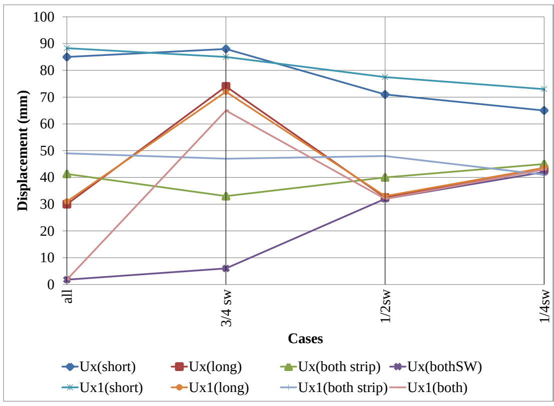
(c) Base Shear Force in *y* direction (d) Base Shear Force in *x* direction

1 refers to shear wall without columns

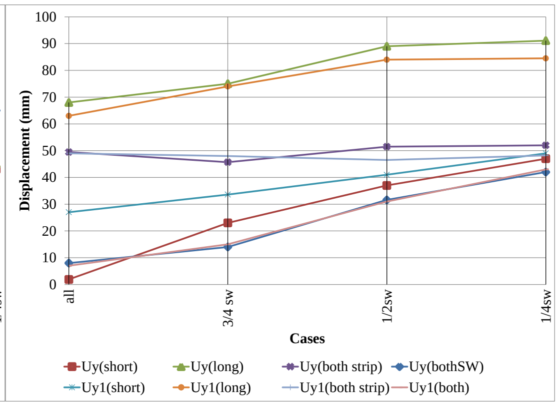
Fig. 5 Straining actions of the building (20 m×10 m) rectangularity ratio 2

in base shear force by nearly 1.25 time, but in ¾ sw case. Shear walls without columns show reduction in base shear force values than the corresponding case of shear wall with columns. Even for shear wall with columns in short direction the shear force did not reach the value of strip shear wall in both directions. Shear wall in short direction without columns on all over the height of building decreased base shear force by 3 times than use strip shear wall in both directions. Fig. 5(d) shows the base shear force in *x* direction with different shear walls. The maximum base shear force appeared with stripe shear wall in both directions (nearly constant values in all shear wall heights), minimum values in base shear force record when using ¼ sw nearly in all cases of shear walls configurations, and shear walls without columns recorded the minimum values of base shear force than all cases.

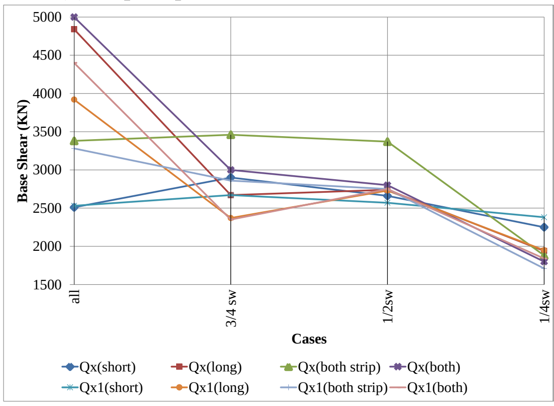
Fig. 6 illustrates the straining action of slender high rise building (rectangularity ratio 2.5) with different shear walls configurations. Fig. 6(a) shows top displacements of the building in *x* direction, maximum top displacements appeared when using shear wall in short direction in cases with columns and without columns. The minimum top displacements recorded when using shear walls in both directions followed by strip shear walls in both directions case, which decreased by 60% than the case of using shear wall in short direction only. Fig. 6(b) illustrates top



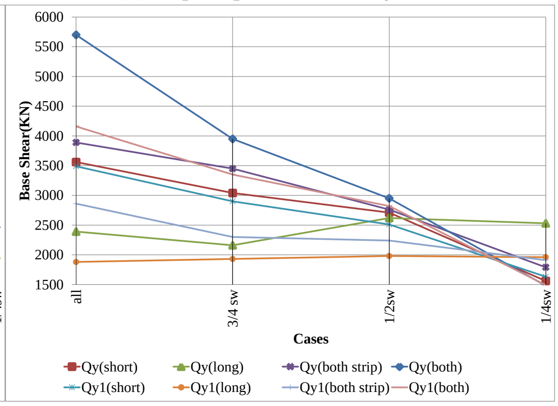
(a) Top displacements in *x* direction



(b) Top displacements in *y* direction



(c) Base Shear force in *x* direction



(d) Base Shear force in *y* direction

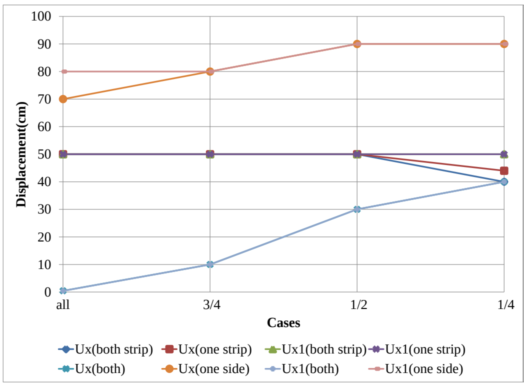
1 refers to shear wall without columns

Fig. 6 Straining actions of the building (25 m×10 m) rectangularity ratio 2.5

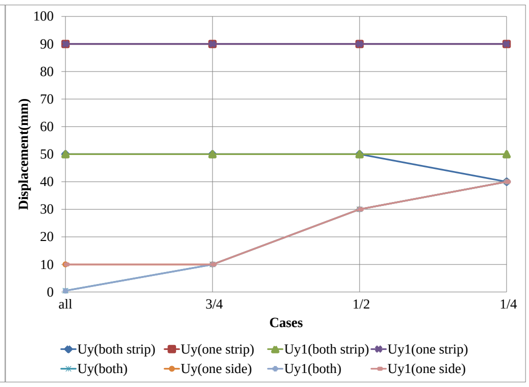
displacements in *y* direction; the maximum top displacements appeared in usage shear walls in long direction only whenever shear wall with columns or without, shear walls with columns performed well in reducing top displacements in *y* direction as shown in shear wall in short direction only. Strip shear walls in both directions of the building performed well, which reduced top displacements by nearly 40% than the maximum top displacements case.

Fig. 6(c) shows base shear in *x* direction under seismic load with different shear walls configurations. Maximum base shear appeared when using shear walls in both directions of the building for all cases of shear wall placements and shape, all cases converge in all conditions except for strip shear walls in both directions the values of shear force nearly constant in all, ¾ , and ½ sw cases, the minimum values of shear force found in the case of ¼ sw. The ratio between shear force in case of strip shear wall in both directions and the rest cases was nearly 16%. Fig. 6(d) shows base shear force in y direction of the building with different shear walls configurations. Base shear decreased dramatically for all cases when decreased the shear walls height from the full height of the building to ¼ sw case, except shear walls in long direction only which produced constant base shear for all height of shear wall. Base shear force in shear walls in long direction with columns increased by nearly 20% than without.

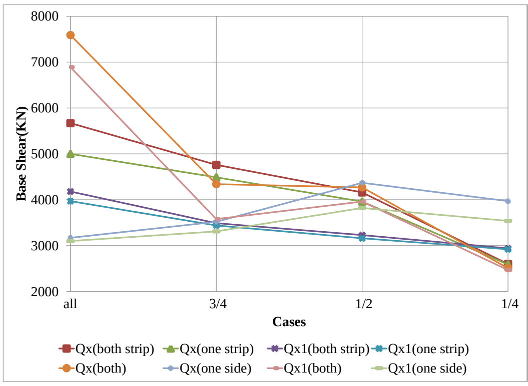
Fig. 7 shows the straining action of square building subjected to earthquake under different shear walls configurations. Fig. 7(a) illustrates top displacements in *x* direction of the building with different shear walls configurations, as shown there is no different in the top displacement if shear walls coupled with columns or not, in square building using one strip and two strip in both



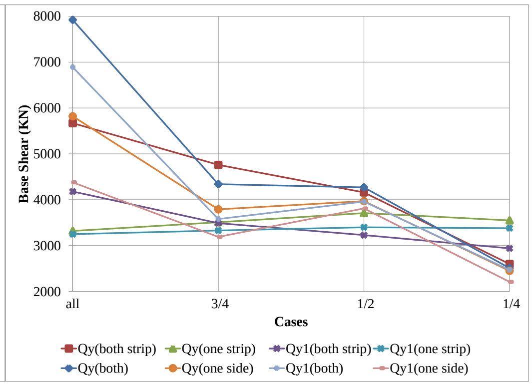
(a) Top displacements in *x* direction



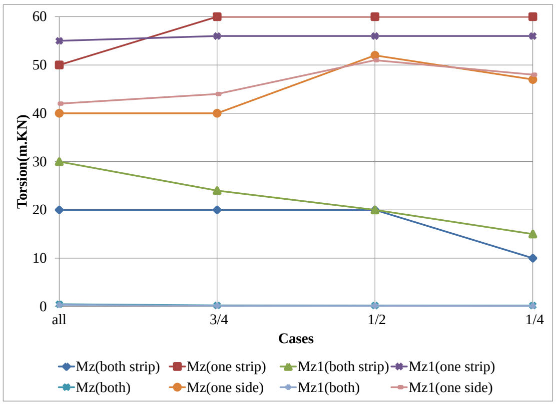
(b) Top displacements in *y* direction



(c) Base Shear forces in *x* direction



(d) Base Shear forces in *y* direction



(e) Torsion

1 refers to shear wall without columns

Fig. 7 Straining actions of the building's (20 m×20 m) rectangularity ratio 1 sides with columns and without are identical cases with constant top displacements values equals to nearly 40% less than the maximum top displacements case. The minimum values of top displacements appeared when using shear walls in both sides, but if the height of shear walls decreased the top displacements in *x* direction increased until reach the corresponding values of top displacements in case of one strip (in *x* direction) or two strip in both sides. Fig. 7(b) shows top displacements in *y* direction; strip shear walls in both directions give a moderate top displacement in *y* direction and less than the maximum case by nearly 40%.

Fig. 7(c) illustrates base shear in *x* direction. Maximum base shear in x direction appeared when using shear walls in both directions at all height of the building, and then the base shear decreased dramatically with decreased shear walls height, one strip of shear wall decreased base shear at all height of the building by nearly 25 times than maximum case, using strip shear wall in both directions at all height of the building decreased base shear by nearly 1.4 times than the maximum case, using shear walls at ¾ height of the building increased base shear by 1.1 times than maximum case and identical in the rest of heights. Base shear in y direction is identical with the corresponding case of *x* direction.

Fig. 7(e) shows torsion of the building subjected to earthquake. The unsymmetrical distribution of shear wall on the circumference of the building increased torsion on the building under bidirectional earthquake, whenever symmetrical distribution on the perimeter give the less torsion, as shown in using shear wall on one side or one strip in one side of the square building torsion increased by 5 to 4 times than using symmetrical shear walls. Shear wall with columns performed well to resist torsion than shear walls without columns. One strip shear wall in both sides of the square building increased torsion by nearly 2.5 times than usage shear wall in both sides at all sides.

It is not preferable to select unsymmetrical distribution of shear walls on the perimeter of the building as it generates additional torsion, but sometimes the engineers do that, therefore they should not resort to this solution.

These models are exposed to undesirable additional torsion when they subjected to earthquakes.

6. Conclusions

A better understanding with regard to the performance of shear walls with different arrangements, placement, and height in the slender high buildings under seismic excitation is confirmed in this study. Such understanding will benefit construction industry and put such design buildings on rational foot. The following conclusion can be extracted from the present investigation:

• The results revealed that arrangement, placement and height of shear walls can effect on the top displacements and base shear of the buildings. Top displacement of strip symmetrical arrangement shear walls with full height of the building equals to half values with that induced in both sides shear walls.

• Position of shear wall with columns (strip in both sides) has a pronounced effect on the base shear values.

• Top displacements are affected by the direction of the shear wall in the slender high rise building.

• In slender high rise buildings with rectangularity ratio less than 2.5, the walls placed in the mid-rise of the building will be sufficient.

• When the shear walls are not in the entire building height, the results shows high values of stresses at the ends of the shear walls, however the increase of stresses in the shear walls with columns are small related to that in the shear walls without columns with the same configurations.

• The designer must conduct a numerical analysis of such buildings subjected to permanent and seismic loads taking into account the symmetrical arrangement of the shear walls around the interior parameter of the building and choose the suitable dimensions, placement and height in the different structural elements and the necessary reinforcement around the shear walls connected to columns.

• Even so, the building is square in-plane torsion happened if the shear walls distributed unsymmetrical in the parameter of the building will increase torsion by 2.5 times.

• By increasing rectangularity ratio of the building the more length of the strip shear walls in long direction of the building need to be increased to make the straining actions more acceptable in values, and the height of the shear wall not less than ¾ height of the building.

• The following table concludes the results of ratio of shear wall length on the outer perimeter of the different kinds of buildings:

Kind of building	Long side shear wall ratio (both sides)	Short side shear wall ratio (both sides)
Slender building rectangularity ratio≥2.5	40%	50%
Slender building rectangularity ratio<2.5	25%	50%
Square building	33%	

• The square high rise building sustain base shear more than the slender high rise building for all shear walls configurations.

• Unsymmetrical distributions of shear wall at the parameter of the high rise building give a noticeable twist (torsion).

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