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Optimization of Rhombus Opening Area of Shear Walls On Tall Buildings

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Abstract: This research was designed to determine the optimum percentage and configuration of rhombus opening on shear wall of tall building. A residential tall building of 12-storeys having base size of 20m × 10m with height of floor of 3m was analyzed. In this paper, percentages of 12%, 24%, 36%, 42%, and 54% concentric rhombus opening in a shear wall in tall buildings were modeled. The effect of the opening size on the lateral displacement, base shear, and stress at the opening was determined. It was found that the opening of 12% has less lateral displacement, base shear, and stress at the opening. This indicates that this opening delivers the best performance among the other percentages. Five models with the same percentage of rhombus opening of 12% at different configuration on the shear wall in tall buildings were modeled to determine the optimum configuration of opening on shear walls. It was found that Model-1 is the optimum configuration since this model has the lowest lateral displacement and stress at the opening. It can be concluded that Model-1 with 12% opening area is the optimum size and configuration to resist lateral force on tall buildings.

Keywords: Shear wall, tall building, lateral displacement, rhombus opening, base shear force

1. Introduction

In modern tall buildings, reinforced concrete (RC) frame building with reinforced concrete shear wall (RCSW) is most common approach to satisfy the population needs and for safety of the structure under any loading conditions. RCSW are generally used as a vertical structural element to provide stiffness, strength, and stability against lateral loads which are generated by wind and earthquakes. Their thickness may be as low as 150 mm, or as high as 400 mm in high rise buildings. RCSWs act as cantilever members which support beams represented by the floor. RCSW structure in tall buildings has gained popularity in the recent years, especially for the construction of service building or office/commercial tower [1], [2].

RCSWs in tall buildings are generally provided along the both sides length and width of buildings or arranged in the form of core for use of stairs and lifts which usually makes entrance to the car parking and public lobby areas, as well as the entrance to elevators or staircases difficult. This can be overcome by providing an opening in it. RCSWs with multi-

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*Corresponding author: Agusril@uniten.edu.my openings are used at tall buildings to accommodate architectural, mechanical, and safety requirements. RCSWs may have one or more openings for functional reasons such as doors, windows, and other types of openings in the shear walls. The size and location of openings may vary depending on purposes of the openings [2], [3].

Shear walls with openings are typically called coupled walls where they act as cantilevered walls connected by coupling beams known as spandrel beams. These openings used to be simple with uniform shapes typically being rectangles and squares with a possible reason was to make the analysis stage less complicated for engineers. However, with the advancements in computing power, finite element methods and software, it is now possible to account for complex shear walls with non-uniform opening shapes or arrangements [4].

The factors which influence the capacity of seismic energy dissipation of reinforced concrete shear walls are openings by their dimensions, shape, and positioning. The openings can cause large tensile stresses and cracking around the opening of the shear wall. This could potentially lead to the decrease in load carrying capacity of the reinforcement concrete shear wall panels under lateral loads at tall buildings. Openings with various locations, size, and shape will affect its overall stiffness as compared to shear walls without openings [5], [6].

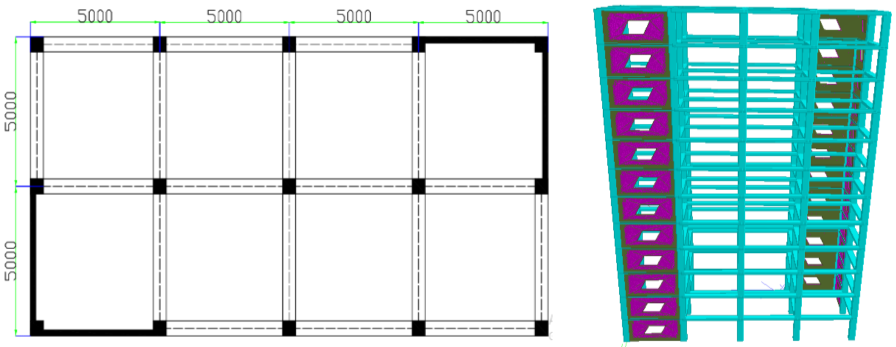
Architectural requirements typically push for more and larger openings. However, it is a structural challenge to meet those requirements while maintaining a safe and sound design for both strength and serviceability demands. Researchers found that the base shear and story drift increase with both the size and number of openings. This makes incorporating larger openings more difficult and crucial to study [7].

Tall structures offer real focal points, yet there is a serious challenge for designers within the sight of seismic and wind loading. The seismic execution depends exceptionally on the tallness of the building. One of the difficulties is that providing openings on shear wall there will be huge stresses around the opening and deflection in the wall compared to solid shear wall in structure. It will reduce the stiffness and strength of structure, which is the most regular reason for basic damage [8]. Thus, most designers provide openings in a specific location, specific arrangement, and specific shape that will produce less stresses and deflections on the structure to prevent the decrease of the strength of the structure [9].

As a rule, designers prefer to locate the opening with rectangular or square shape at center of the walls in the building since it will assure that type of shape and configuration arrangement of opening will emit less stresses and deflection in structure. However, it sometimes conflicts with the architectural requirements. It is important to note that the size, shape, and configuration of opening in shear wall play a major jab in the performance of wall under the lateral load [10], [11]. The use of rhombus opening at shear wall of tall building has not been extensively researched. Therefore, the study on rhombus opening effect on tall building need to be performed to cater the architect's requirements. In this study the effect of rhombus opening of shear wall at tall building is studied to determine its effect to lateral displacements as well as the stresses at the openings.

2. Methodology

In this paper, a 12-storey building with a 3 meters' height for each level and a base area of (20 x 10) meter as shown in Fig. 1 was modelled. The building was analyzed in accordance with the UBC 1997 code [12] and ASCE-07 [13] code for wind load in STAAD. Pro Vi8 program. The model is subjected to gravity loads as per UBC 1997, earthquake as per UBC 1997 and wind load as per ASCE-07. The building is modelled using software STAAD. Pro Vi8 and a linear analysis was performed. Square and rectangular cross sections were chosen for modeling the structural members while the base had fixed supports. The square column dimension is 50 x 50cm, the beam section is 30 x 50cm both of which were modelled as line elements including the perimeter spandrel beams. The slab thickness is 15 cm, and the shear wall has a constant thickness of 20 cm all over the height of the building. The 5 different models were studied with different positioning and size of openings on the shear wall in the building. All openings in each case were designed to satisfy the requirements of windows. It can be recognized the places of the double leg shear walls as along exterior parameter. Fig. 2 illustrated five models with various percentage area of rhombus openings (12%, 24%, 36%, 42%, and 54%) were modelled to determine the optimum size of opening on the reinforcement concrete shear wall in tall buildings.



(a) (b)

Fig. 1 - (a) Plan view of building in millimeter (mm), and; (b) side view of building

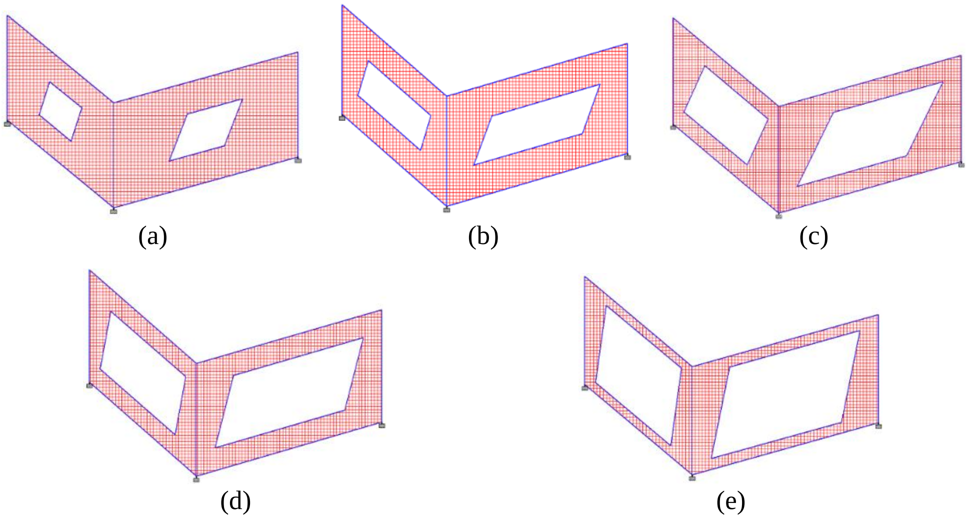

(a) (b) (c)
(d) (e)

Fig. 2 - Various percentage of rhombus opening of shear wall (a) Model-A (12%); (b) Model-B (24%); (c) Model-C (36%); (d) Model-D (42%), and; (e) Model-E (54%)

Fig. 3 and Fig. 4 show the five models with the same area opening of 12% with different configuration in order to determine the optimum configuration of rhombus opening on the shear wall at tall buildings. The horizontal distance for configurations is 0.5 m from the corners. Table 1 shows the position of the opening to the left and right side of the edges of the wall. In this study, the lateral displacement (Δ) as shown in Fig. 5 will be determined.

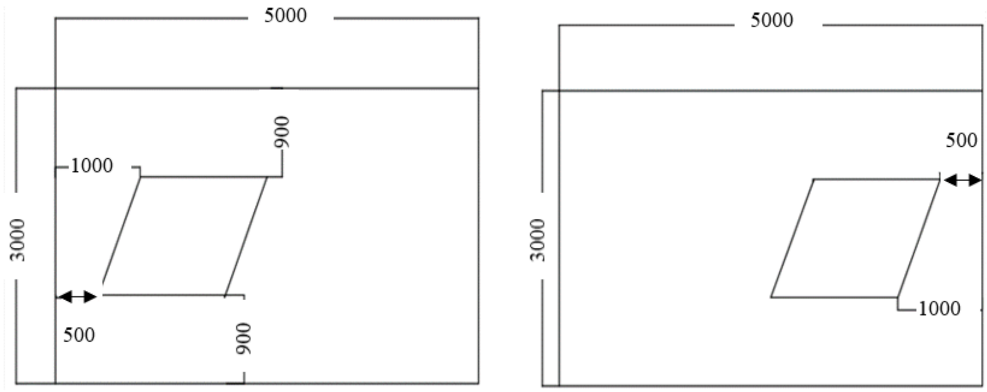


Fig. 3 - Configuration of openings in shear wall in tall building, all unit in millimeters (mm)

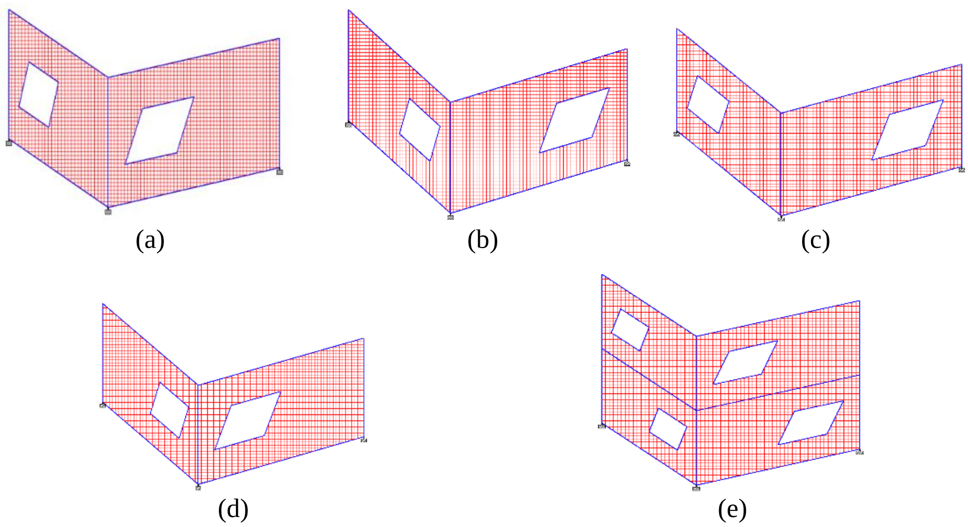

(a) (b) (c)
(d) (e)

Fig. 4 - (a) Model-1; (b) Model-2; (c) Model-3; (d) Model-4, and; (e) Model-5 in shear wall of tall building

Table 1 - Configuration of rhombus opening in shear wall

Model	Position of opening (Left opening)	Position of opening (Right opening)
1	Near to the left edge of wall	Near to the left edge of wall
2	Near to the right edge of wall	Near to the right edge of wall
3	Near to the left edge of wall	Near to the right edge of wall
4	Near to the right edge of wall	Near to the left edge of wall
5	Combination Model 1 and 2	

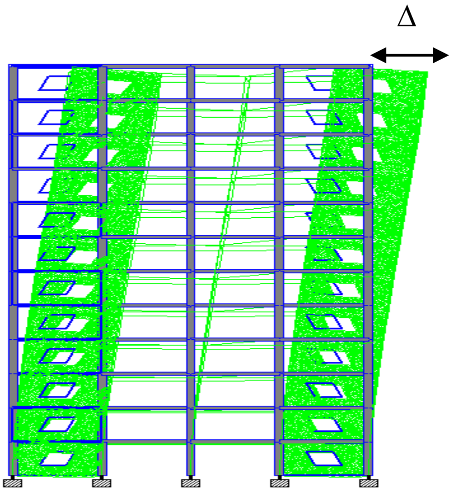


Fig. 5 - Lateral displacement of rhombus opening (Δ) of tall building

3. Results and Discussion

3.1 Optimum Size of Opening

Optimum size of the opening is determined by comparing the lateral displacements of the building at the highest floor by using 5 models with different percentage of openings. Model A, Model B, Model C, Model D, and Model E have the opening area of 12%, 24%, 36%, 42% and 54%, respectively. In Fig. 6, it is observed that displacement at top of tall building with Model-A is about 26.76 mm, Model-B is about 30.8 mm, Model-C is about 38.3 mm, Model-D is about 43.37 mm, and Model-E is about 64.83 mm. The difference between top displacement of Model-A and Model-B is approximately 15%, and for Model-C and Model-D is approximately 25%, Model-C and Model-D is approximately 14%, and Model-D and Model-E is approximately 50%. The results indicate that the rigidity of the structure decreases with the increment of opening size in the shear wall in the building. The decreasing rigidity of the structures is indicated by the increment of the lateral displacement of the building. The percentage of lateral displacement increment is relatively low for the shear wall with the opening up to 24% (Model-A and Model-B). The percentage increases rapidly for Model-C, Model-D, and Model-E. Sharma & Amin [5], which studied rectangular openings, found that the maximum lateral displacement at 12th story is 30 mm for rectangular opening. It means that Model-A and Model-B displacement with rhombus opening area of 12% and 24%, respectively have maximum lateral displacement of 26.76 mm and 30.8 mm can be considered acceptable.

Fig. 7 shows the base shear of Model-A, Model-B, Model-C, Model-D, and Model-E. It can be observed that the base shear of building with Model-A is 925.54 kN, Model-B is 925.54 kN, Model-C is 986.98 kN, Model-D is 985.94 kN, and Model-E is about 984.17 kN. It can be seen that the base shear increases proportionally up to 24% opening, however, as the percentage of opening increases, the base shear increases more rapidly. It is found that the base shear of Model-A and Model-B are less than Model-C, Model-D, and Model-E. Model-A and Model-B show the best performance as far as base shear values are concerned.

Fig. 8 shows the stress at bottom of Model-A is 5.47 N/mm^2, Model-B is 7.41 N/mm^2, Model-C is 8.57 N/mm^2, Model-D is 11.7 N/mm^2, and Model-E is 12 N/mm^2. From Fig. 9, it can be observed that the stress around the opening for Model-A is about 8.9 N/mm^2, Model-B is 9.87 N/mm^2, Model-C is 15 N/mm^2, Model-D is 15.6 N/mm^2, and Model-E is 18 N/mm^2.

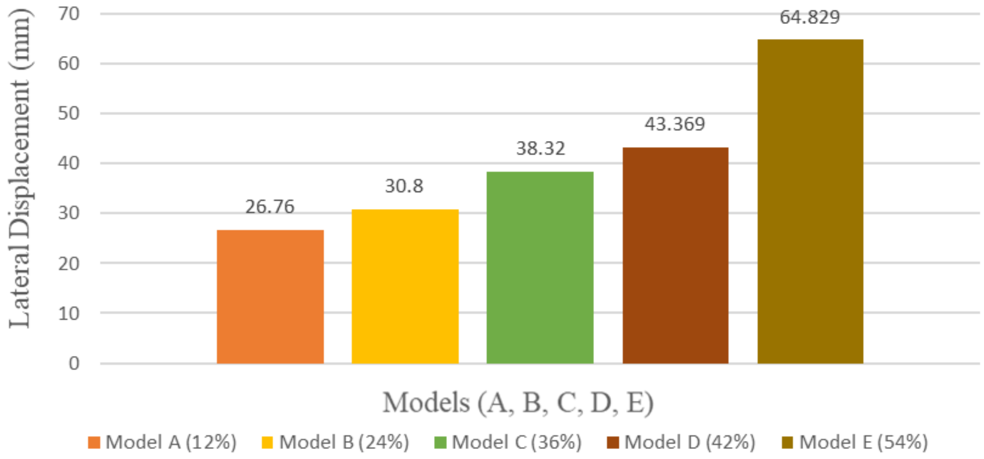


Fig. 6 - Lateral displacement versus percentage opening of shear

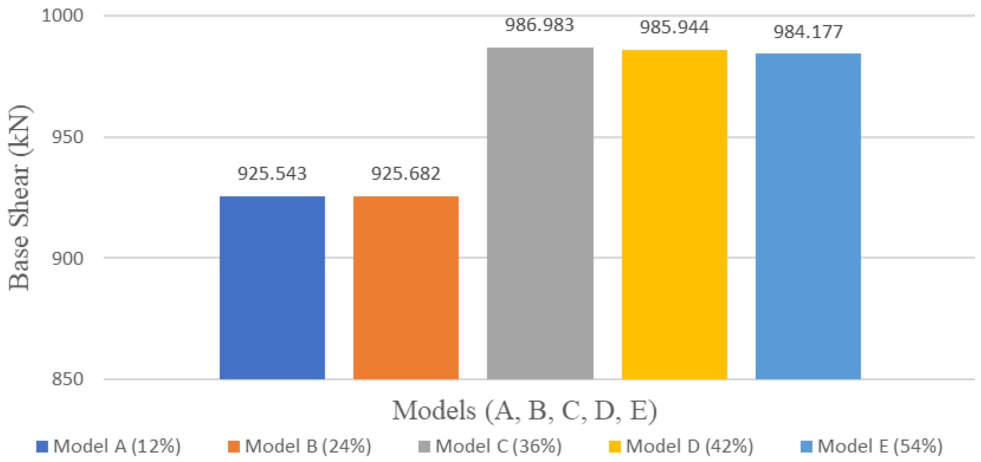


Fig. 7 - Base shear vs percentage opening in shear wall in tall building

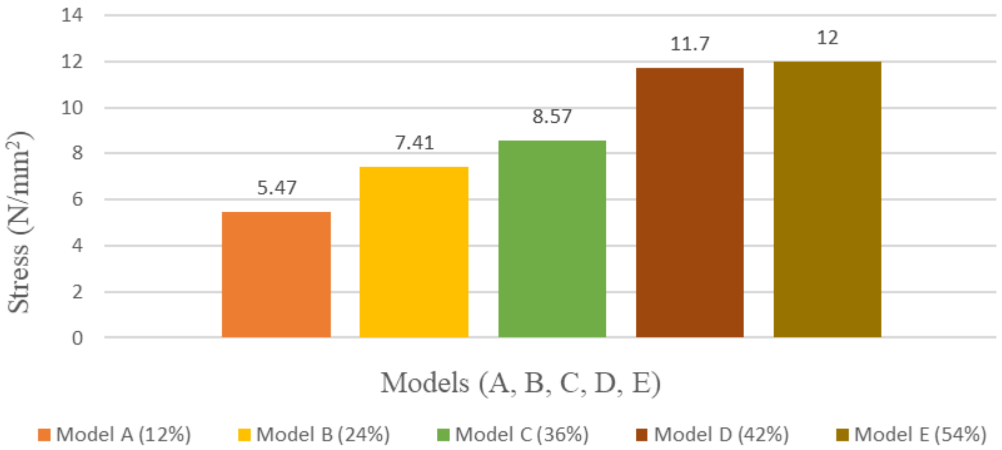


Fig. 8 - Stresses at bottom of opening vs percentage of opening in shear wall in tall building

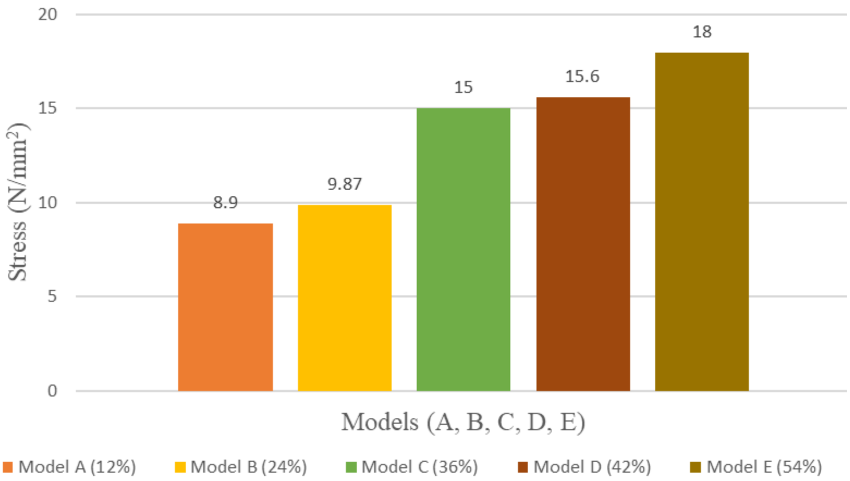
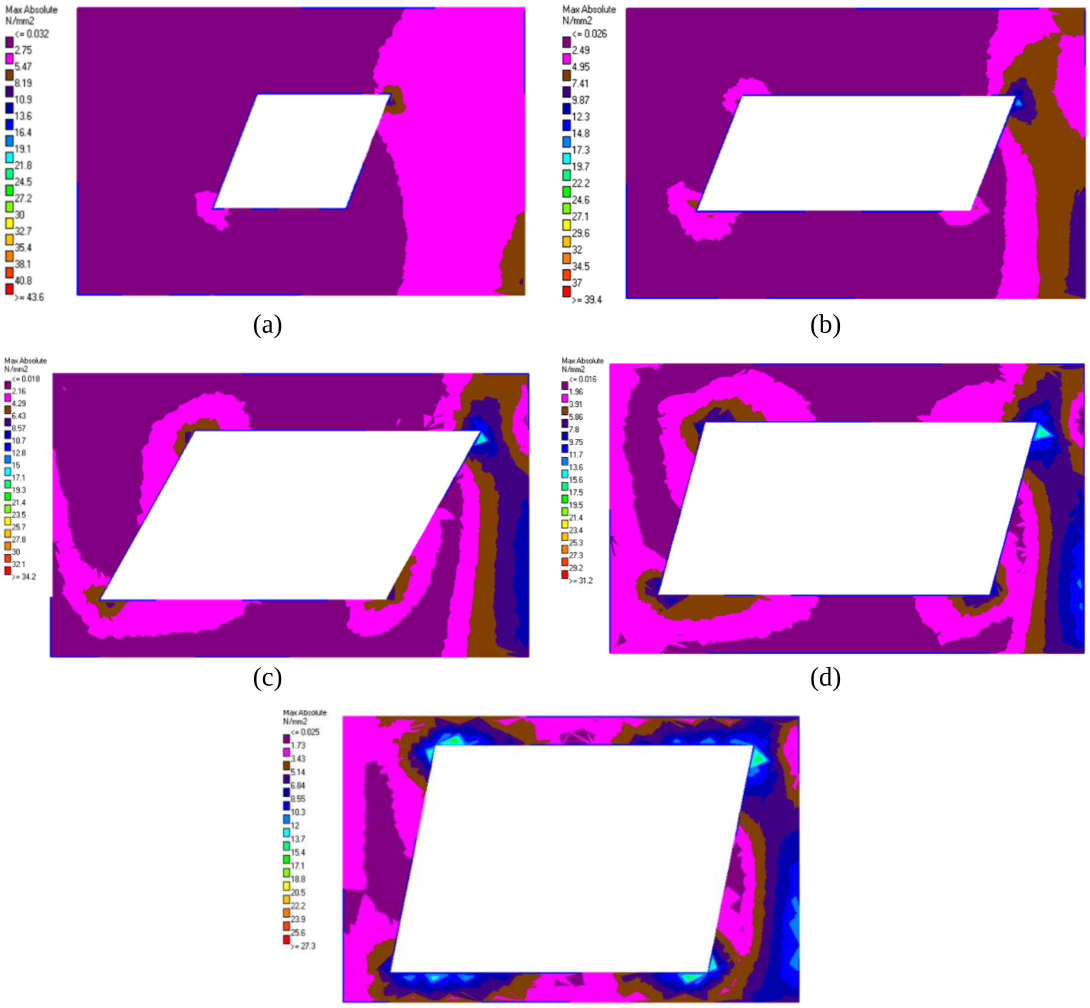


Fig. 9 - Stresses around the opening vs percentage of opening in shear wall in tall building

Stress distributions around the opening of shear wall can be observed in Fig. 10. Model-A with maximum stress of 8.19 N/mm^2 occurred at the right side of the opening edge. This maximum stress occurred at a small area at the edge of opening, while for Model-B, the stress increases to 9.87 N/mm^2 with the affected area also increases as compared to Model-A. Model-C, D, and E show similar patterns of stress distributions where the maximum stress occurred at the edges of the opening with maximum stress of 15 N/mm^2, 15.6 N/mm^2, and 18.8 N/mm^2 respectively.



(a) (b)

(c) (d)

(e)

Fig. 10 - Stresses distribution around the opening (a) 12%; (b) 24%; (c) 36%; (d) 42%, and; (e) 54% of opening in shear wall in tall building

3.2 Optimum Configuration of Opening

In order to determine the best configuration of opening, Model-A with 12% opening was chosen. For the purpose of this study, the model was labelled as Model-1 until Model-5 to represent configuration 1 to 5. Fig. 11 shows lateral displacements of Model-1 to Model-5. The top displacement of Model-1 is about 28.459 mm, Model-2 is about 29.849 mm, Model-3 is about 30.973 mm, Model-4 is about 29.69 mm, and Model-5 is about 30.269 mm. Results indicate that the opening configuration in the wall has significant effect on the lateral displacement as well as the rigidity of the tall building.

The allowable lateral displacements as per UBC 1997 must not exceed 0.025 time the height of structure where it has a fundamental period of less than 0.7 sec. For structures that have a fundamental period of 0.7 sec or greater, the story drift must not exceed 0.020 time of the height frame. The total height of building is 36 m, therefore, the allowable is 72 mm. The highest lateral displacement is 30.973 for Model 3, however this value is still under allowable value as per UBC 1997's requirements.

The base shear forces are shown in Fig. 12. It can be observed that Model-3 has the highest base shear force while Model-2 has the lowest base shear force. This is maybe due to the location of two openings at the right edge of each wall that contribute to twisting of the building that increasing the base shear of the building.

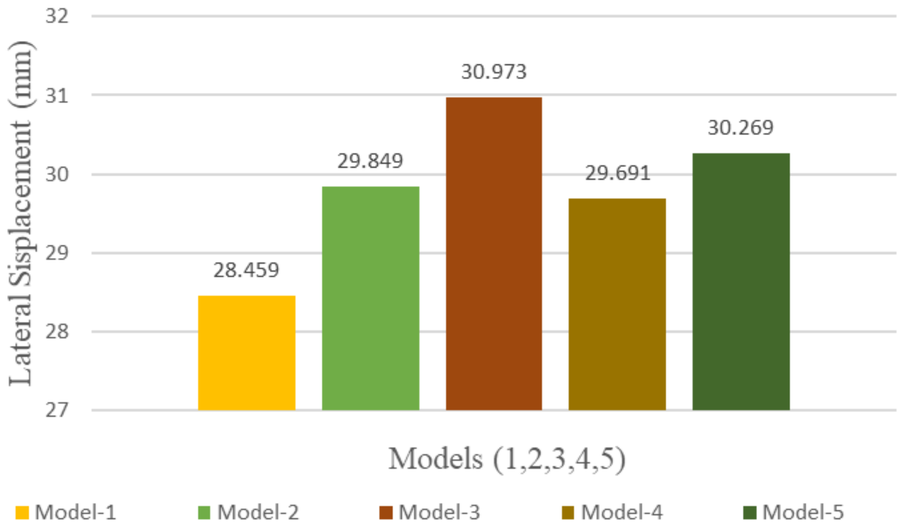


Fig. 11 - Lateral displacement vs configuration of opening in shear wall in tall building

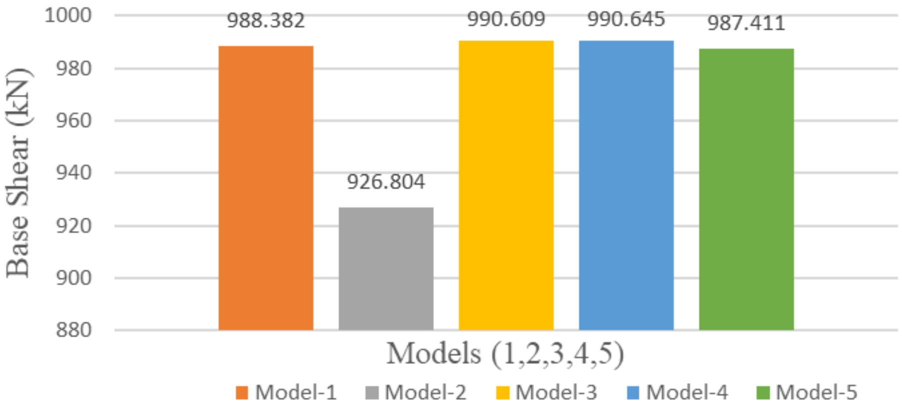


Fig. 12 - Base shear of shear walls on tall building

From the numerical analysis in Fig. 13, it is seen that the stress at bottom of Model-1 is 6.3 N/mm^2, Model-2 is 8.94 N/mm^2, Model-3 is 4.6 N/mm^2, Model-4 is 6.19 N/mm^2, and Model-5 is 7.26 N/mm^2. The stresses around the opening for Model 1 is 9.03 N/mm^2, Model 2 is 15.6 N/mm^2, Model 3 is 10.9 N/mm^2, Model 4 is 9.27 N/mm^2, and Model 5 is 16.9 N/mm^2. These stresses are less than stress which is obtained by Sharma and Amin [5] which is 18.136 N/mm^2 at shear wall opening for rectangular opening. It can be concluded that the present of rhombus opening at proper locations will produce less stress as compared to rectangular opening.

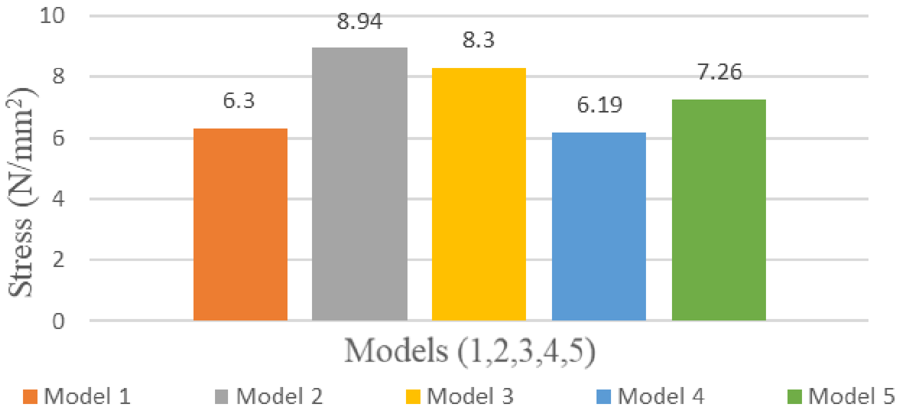


Fig. 13 - Stresses at bottom vs configuration of opening in shear wall in tall building

The stresses around the openings in the shear wall can be observed in Fig. 14. Model with configuration-5 arrangement has the maximum stresses around the opening in the wall. It was also found that the model with concentric arrangement has the minimum stresses around the opening in wall. The base shear difference between the maximum and the minimum stresses around the opening is about 89%.

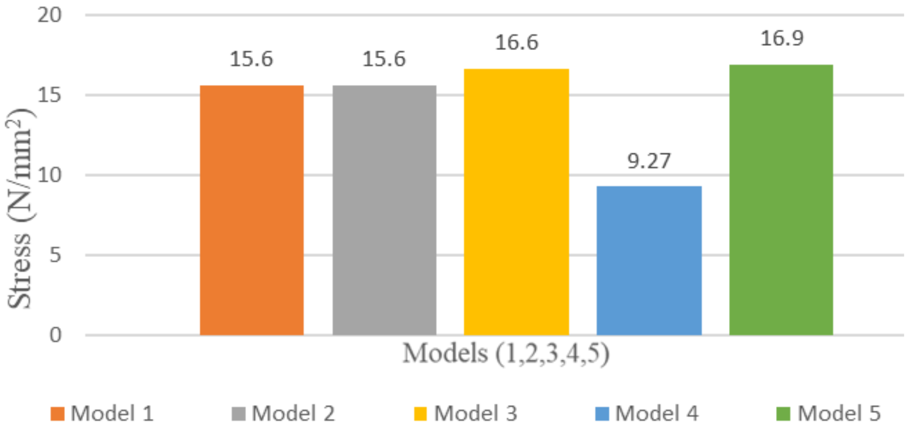
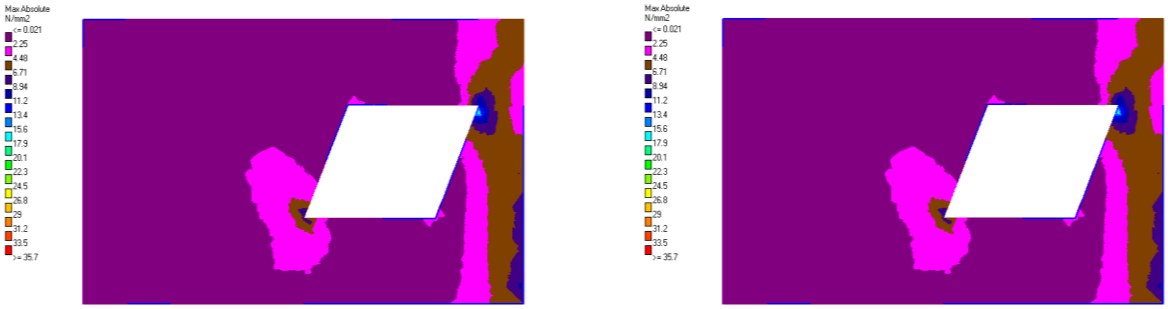
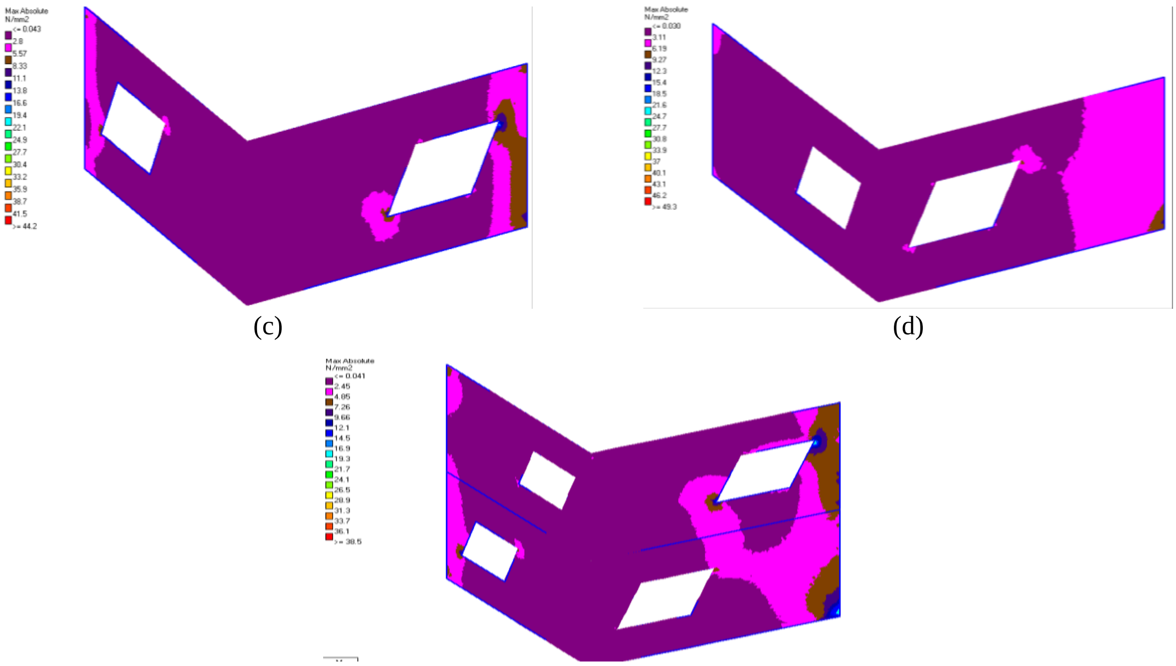


Fig. 14 - Stresses around opening vs configuration of opening in shear wall in tall building

Stress distribution around the opening of shear wall can be observed in Fig. 15 for Model-1 to Model-5. Model-1 and Model-2 have similar patterns and a maximum stress of 15.6 N/mm^2 occurred at the right side of the opening edge, with its maximum stress occurred at small area at the edge of opening. For Model-3, the stress increases to 16.6 N/mm^2 with the affected area also portraying increment as compared to Model-1. Model-4 and Model-5 have the lowest and the highest stress, respectively. It could be concluded that the higher stress in Model-5 was due to the contribution of opening from the above floor to the lower floor, which is increasing the stress. However, the stresses are still less than previous study by Sharma & Amin [5] which is 18.136 N/mm^2 at shear wall with rectangular opening. Moreover, the stresses at the shear wall still under allowable strength of concrete of 30 N/mm^2 which is consider safe.



(a) (b)



(c) (d)

(e)

Fig. 15 - Stresses at bottom and around opening with (a) Model-1; (b) Model-2; (c) Model-3; (d) Model-4, and; (e) Model-5 in shear wall of tall building

4. Conclusion

The research work was conducted in order to develop a numerical model of the reinforcement concrete shear wall with rhombus opening subjected to lateral load. To achieve the objective of this research, three-dimensional model of shear walls was produced using STAAD. Pro vi8. The effect of opening size on shear wall was studied to determine lateral displacement, base shear and stress at the opening. It was found that opening 12% (Model-A) has less lateral displacement, base shear and stress at the opening, which indicates that this opening shows the best performance among the others.

Five models with the same percentage of rhombus opening of 12% at different configurations on shear walls in tall buildings were modeled to determine the optimum configuration arrangement of openings in shear walls in tall buildings. It was found that Model-1 (configuration 1) as the optimum configuration since this model has the lowest lateral displacement and stress at the opening. It can be concluded that Model-1 with 12% opening area as optimum size and configuration to resist lateral forces on tall buildings. Future works can explore different shear wall configurations with rhombus openings and nonlinear analysis.

It should be noted that the reported results are only applicable for this specific model because different models will produce different behaviors.

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