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Effect of Shear Wall in Seismic Performance of High-Rise Irregular RC Framed Building

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Abstract: ***"Effect of Shear Wall in Seismic Performance of High-Rise Irregular RC Framed Building" considers the effect of introduction of shear wall in a high-rise irregular building. It compares the displacement responses that come about when a high-rise building is subject to lateral loads in an earthquake prone region. Irregular building with and without shear walls with different configurations are analyzed using the IS:456 2000 and seismic code IS:1893 2016. The earthquake loads are analyzed using static (Equivalent Static Method) and dynamic (Response Spectrum) methods as per IS:1893 2016 and the time history method using acceleration time history of Bhuj 2001. Based on the comparisons done during this study, the lateral stiffness of the buildings is enhanced by the introduction of shear walls at the building which leads to better performance against lateral loads. The configuration with shear wall at the lift core gives a good performance against lateral load in both the x and the y directions and the configuration with the shear wall along the y direction gives the best performance against lateral loads in y direction. The performance of any high-rise buildings can be improved by providing shear wall of appropriate lengths at appropriate locations. The location should be such that the shear wall should help in decreasing eccentricity, and distributing gravity and lateral loads in best way possible.***

Keywords: Shear wall, Equivalent static method, Response Spectrum, Time History

1. Introduction

Earthquakes pose serious threat to life in many regions of the world. It poses engineering design problems in most civil engineering structures and the probability that a major earthquake will never affect any given structure is very low for locations near the boundary of major tectonic plates. As the Indian subcontinent lies in the boundary of the Eurasian and Indian plates the probability of earthquakes, affecting the performance of any structure is very high. Structures are susceptible to collapse during moderate to strong ground motion, which trigger huge losses to the human society in terms of lives and economy. However, the cost of engineering construction is greatly increased if we assume that a large earthquake will damage every engineering structure in every location in the Indian Subcontinent. The seismic design of building structures is typically conducted to satisfy the life safety using modern design codes. The design codes have been finalized conducting a number of studies including the seismic hazard analysis. The design codes have classified different locations considering their possibility of occurrence of a major earthquake in that location. The best engineering approach to this possibility is to design the structure to avoid a collapse in the severe conditions, thus ensuring safety against loss of human life, and accepting the possibility of damage of the structure according to the importance of the structure.

In the Indian subcontinent, most of the modern buildings are made with Reinforced Concrete. For low-rise buildings, simple beam-column frame is sufficient to take in the lateral loads subjected during an earthquake. However, for high-rise buildings the beam-column system alone is not able to take in the stressed occurring due to lateral loads. The need of high-rise buildings in urban areas is necessary now as the land area in urban centers is limited. The lateral load such as wind load, eq. load is the dominating one in tall buildings. While gravity loads increase linearly with height. In comparison, the lateral loads differ in proportion to the building's square height. Thus, the tall building should be stable, rigid and rigid according to the required codes to balance the lateral load. The rigidity and the stability of the structural system are crucial in high-rise buildings. The size of the structural members is increased to make the framework more stable while the structural configuration is altered with the use of techniques such as bracings, tubes etc. to increase the strength.

Doing all this will not guarantee a better lateral load carrying capacity of the structures as increasing the size of the members will increase the weight of the building, which consequently will increase the base shear and hence the effects due to lateral loads. To counteract the effect, introduction of shear walls is done on high-rise buildings. The size of the structural members is increased to make the framework more rigid as the structural configuration is altered using techniques such as bracings, tubes etc. to increase the strength.

There are several researches on the impact of shear wall on high-rise buildings. Most research is conducted for regular buildings. Although the research on the irregular buildings is done, the irregularity of the plan considered in this study, the building shaped "U" was not considered by any of the researcher. In addition, a 40-storied building is being considered in the research. IS 16700: 2017 defines a Tall Building as a building with a height of more than 50 meters but a height of less than or equal to 250 meters. In addition, most research is done for symmetric building and not for asymmetric building, and mostly done using IS 1893:2002 and most research is not done using the latest IS 1893:2016 seismic code.

(Naresh & Brahma Chari, 2019) concluded that "for high-rise buildings static analysis is not sufficient for the analysis and design of multistoried buildings" and (Mohan & S, 2017) concluded that "the effect of type of opening in a shear walled building is dependent on the shape of the building itself."

Therefore, as U-shaped plan irregular building is taken under consideration to find if the optimum position of shear walls under static response spectrum and time history loads.

2. Methodology

At first the problems within the realms of structural engineering was examined and various literature on the existing researches were read thoroughly. The research on high-rise buildings in earthquake prone areas was selected as the subdomain. Through further evaluation of literature, the need of shear wall on high-rise buildings was chosen as the topic of consideration of the study. Again, through literature review it was found that comparison of responses using buildings with different orientation of shear wall and building without shear wall was a topic that needed further investigation. Therefore, the study compares the responses occurring on a forty-story building subjected to earthquake loads without and with different positions of shear walls using the equivalent-static and response spectrum analysis. Displacements occurring in the multistoried structures have been compared for the equivalent-static and response-spectrum load cases according to the IS-1893:2016, along with the time history load cases.

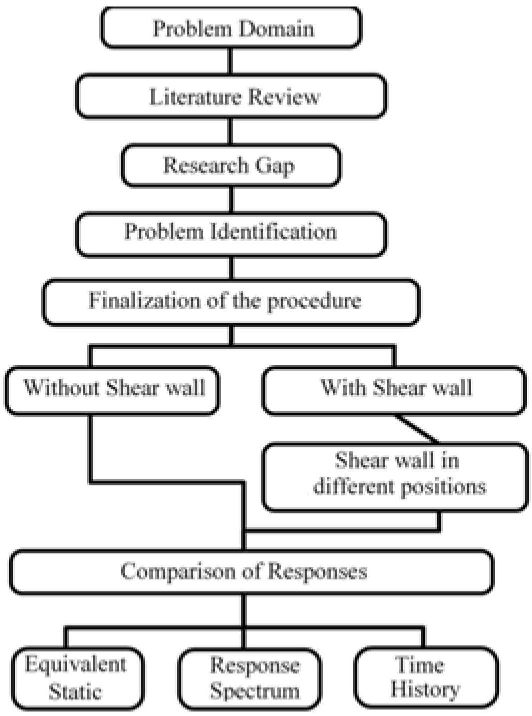

Figure 1: Outline of the methodology

General features of this model building are given by Table 1

Table 1: General features of the model

Parameters	General Description
Type of building	Commercial building
Location	Zone V
Structure system	RCC frame structure; Special moment resistant frame
Plinth area	3276 m2
No. of story	40 (Forty) story
No. of Bays	15 in X direction and 10 in Y direction
Floor to floor height	4.0 m for Ground floor & 3 m for other's
Types of Slab	150mm thick; Two way Slab
Types of Beam	Rectangular main beam (450mm×800mm)
Types of Column	Square (800×800) mm
Types of Foundation	Assumed to be Raft Foundation
Materials	Cement, Brick, Sand, Rebar etc.
Method of analysis	ETABS 2018 (Equivalent Static, Response Spectrum and Time History)

Characteristic strength of material is given by Table 2

Table 2: Materials used for modelling the structure

Parameters	General Descriptions
Concrete	M25 for slab, M40 for beam, M50 for column
Steel grade (fy)	Fe500

Loads occurring at the buildings is idealized and is according to Table 3.

Table 3: Loads occurring at the structure

Parameters	General Descriptions
Self-weight of Building	As per Software (ETABS)
Floor finish	1.5 kN/m2
Live load	4 kN/m2
Partition wall load	1 kN/m2
Earthquake Load	as per IS 1893:2016 Part I code

For the study for each code following cases were studied
1) Equivalent Lateral Force (Static) method
2) Response Spectrum (Dynamic) method
3) Time History Analysis Method

Five models were taken into consideration for carrying out the study. The placement of beams and columns is same for each of the five models. The only difference is the introduction of shear walls at different positions of the model. The first model is a moment resisting frame without shear wall. Fig 2 shows the general plan of the first model. Fig 3 is the 3D representation of that model.

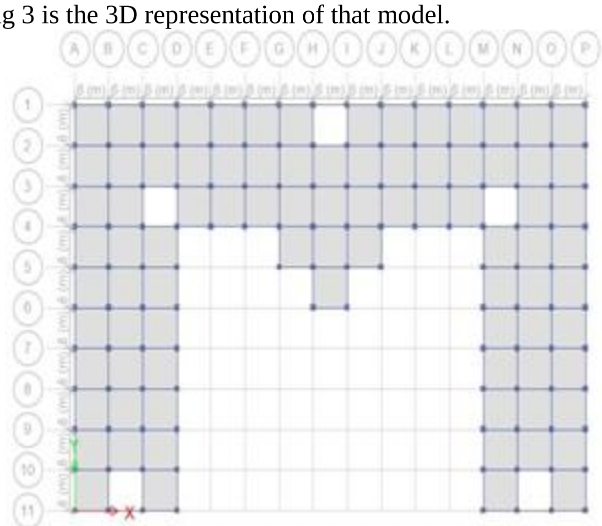

Figure 2: Model 1: Model without shear walls: Plan

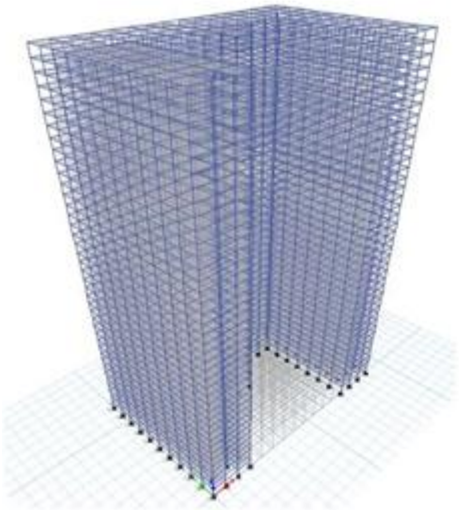

Figure 3: Model 1: Model without shear walls: 3D

The second model is the model with similar to model 1 but with the introduction of shear walls in lift core positions. This model has been shown in Fig 4.

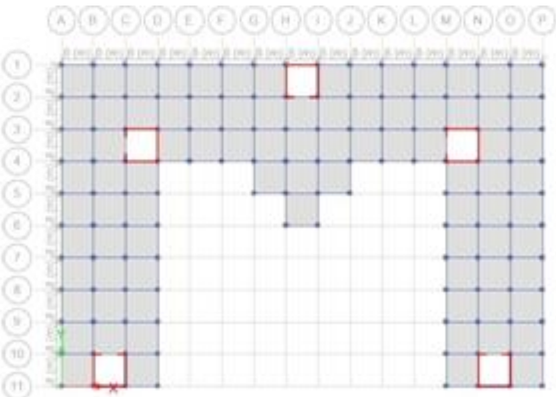

Figure 4: Model 2: Model with shear walls at lift core: Plan

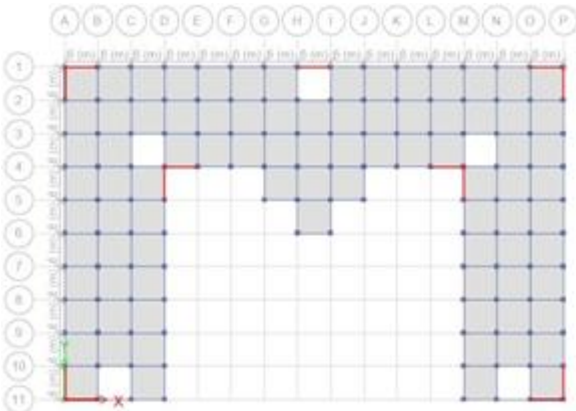

Figure 5: Model 3: Model with shear walls at outer corners: Plan

In the third model the shear walls are introduced at the outer corners of the structure. The is shown in Fig

4) In the fourth model the shear walls are introduced along the global x direction and in the fifth model the shear walls are introduced along the global y direction. The plan of fourth model and the fifth models are given by Fig 6 and Fig 7 respectively.

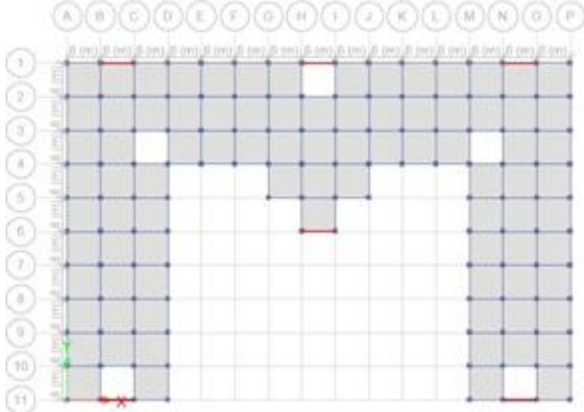

Figure 6: Model 4: Model with shear walls along x direction: Plan

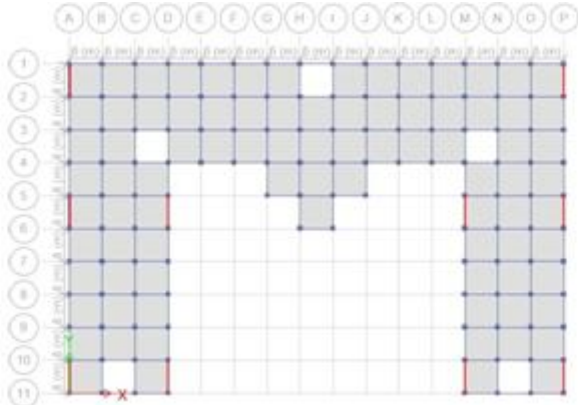

Figure 7: Model 5: Model with shear walls along y direction: Plan

The following considerations and basic characteristics were assumed to model the study building in ETABS 2018.

- Beam elements and column elements were modeled as frame elements whereas the concrete walls and floor slabs are modelled as thin shell elements.
- All (Column-Beam, Foundation-Column etc.) the joints were assumed to be rigid.
- Rigid diaphragms provide a basis in horizontal plane for the frames at each floor level.
- The consideration of staircase was not done in the model.
- All floor loads were applied to the deck which distributes uniformly the load to the beams.
- The masonry in fills were thought not to exist in the model as it is a commercial building and the infill walls are not necessarily present in the building. Uniformly distributed load of 1kN/m^2 is provided throughout the plan to take the infill walls into consideration

After the modelling of the structure, the model is checked for any shortcomings both manually and using the feature in ETABS 2018. The buildings are analyzed for the load cases mentioned along with the default load combinations given by IS 1893:2016. In the present study, the results due to individual equivalent linear static and response spectrum load cases are considered for comparison. The load cases considered for comparison are

1) Equivalent Linear Static Load Case in x direction, Ex
2) Equivalent Linear Static Load Case in y direction, Ey
3) Response Spectrum Load Case in x direction RSx
4) Response Spectrum Load Case in y direction RSy

5) Time History Load Case in x direction, THx
6) Time History Load Case in y direction, THy

"In many seismic codes, the equivalent static lateral force V is used as a reference value of the total seismic design base shear. For instance, the base shear calculated using the modal response spectrum analysis should not be less than 80 % or 90 % of the equivalent lateral base shear. This minimum base shear is provided because the computed period of vibration may be the result of an overly flexible (incorrect) analytical model (Bourahla 2013)." IS 1893:2016 suggest to scale the dynamic base shear equal to the static base shear if dynamic base shear comes out to be less than the equivalent static base shear. On the same note, the scaling of the Dynamic base shear is done according to the IS code in order to correct the flexible model established by the modelling software. Fig 4.7 shows the displacement contours for dead load case after the analysis.

Time History Analysis

Time history analysis is carried out for the models using the ground motion data of Bhuj (2001) earthquake. The data from Ahmedabad station with Latitude 23 degrees 2 minutes North and 72 degrees and 38 minutes east has been taken as the ground motion in both x and y direction for load cases THx and THy respectively. The component of earthquake occurring in Ahmedabad station is taken to be N78E as it gave the maximum peak ground acceleration of 1.0382 ms^{-2}. A total of 26706 acceleration data points at an interval of 0.005 second was considered for the time history analysis. Fig 8 shows the acceleration time history of the time history taken into consideration for the analysis.

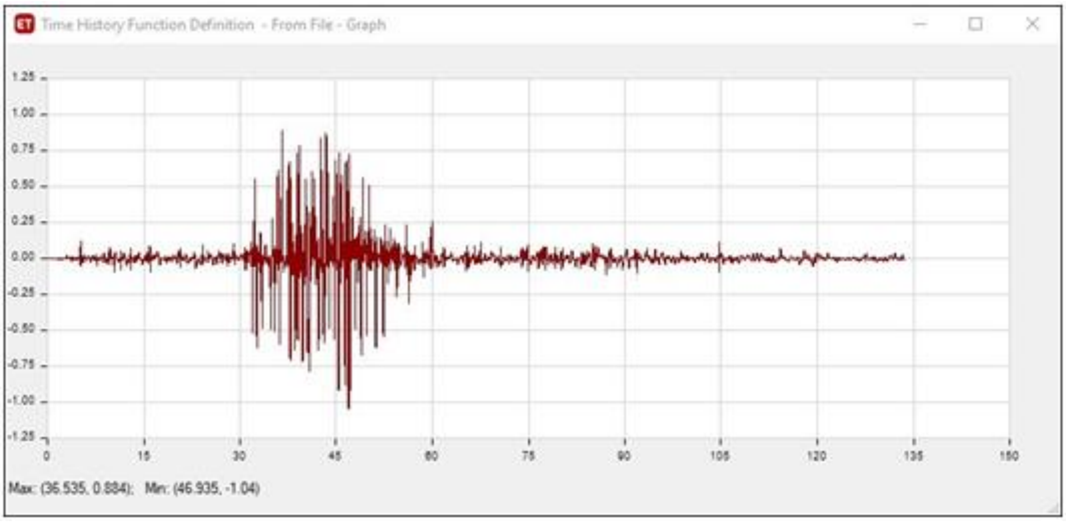

Figure 8: Acceleration Time History of Bhuj 2001 Earthquake

Factors Likely to Affect Results

There are various factors which might affect the results. The first one is the distance between the center of mass and center of stiffness. When the center of mass and center of stiffness are located near to each other the torsional forces induced in the structure are low which means that the structural elements need not resist the torsional forces and hence the responses occurring in a building due to the effect of lateral forces is low. The models with center of mass and center of stiffness close by can have a better performance as compared to the models whose center of stiffness and center of mass is far. Fig 9 shows the distance between the center of mass and center of stiffness for different models. The model with the lift core has the least distance between center of mass and center of stiffness followed by model with shear wall in x direction, model without shear wall, model with shear wall in y direction and model with outside shear walls. The second is the length of shear wall in perpendicular directions. Fig 10 shows the length of shear walls in different directions for different models.

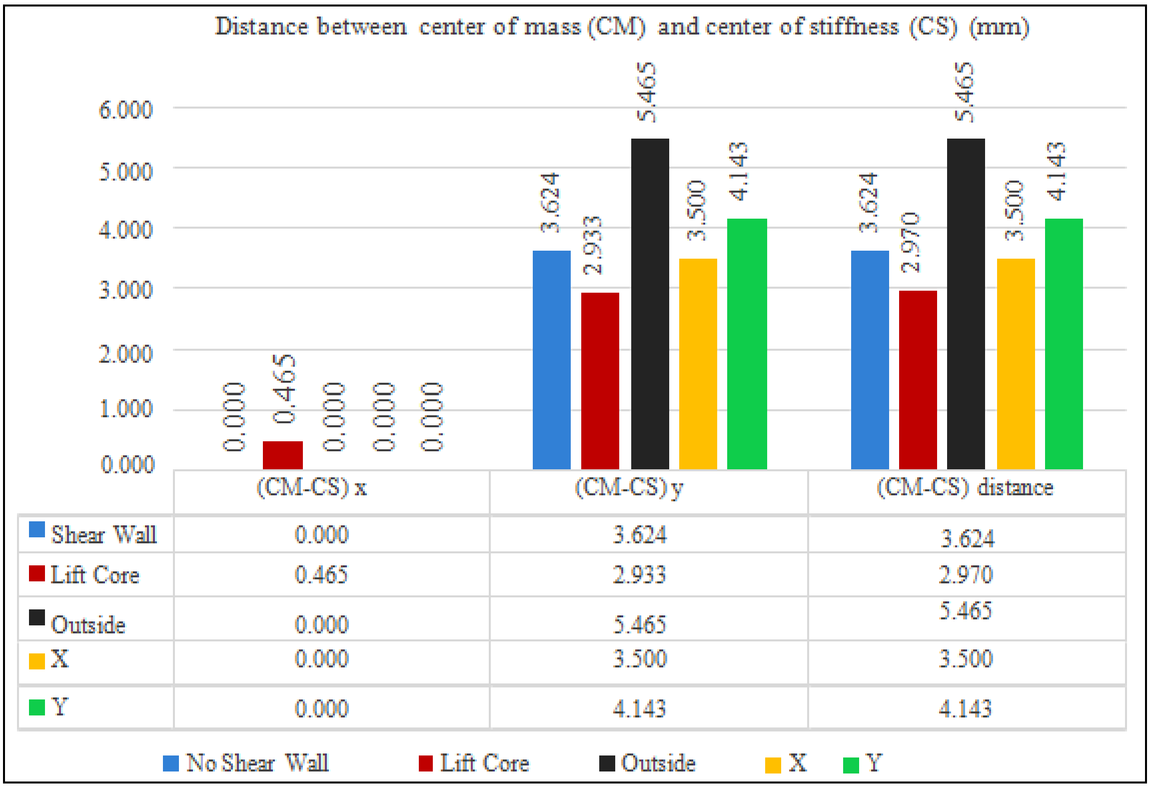

Figure 9: Distance between center of mass (CM) and center of stiffness (CS) (mm)

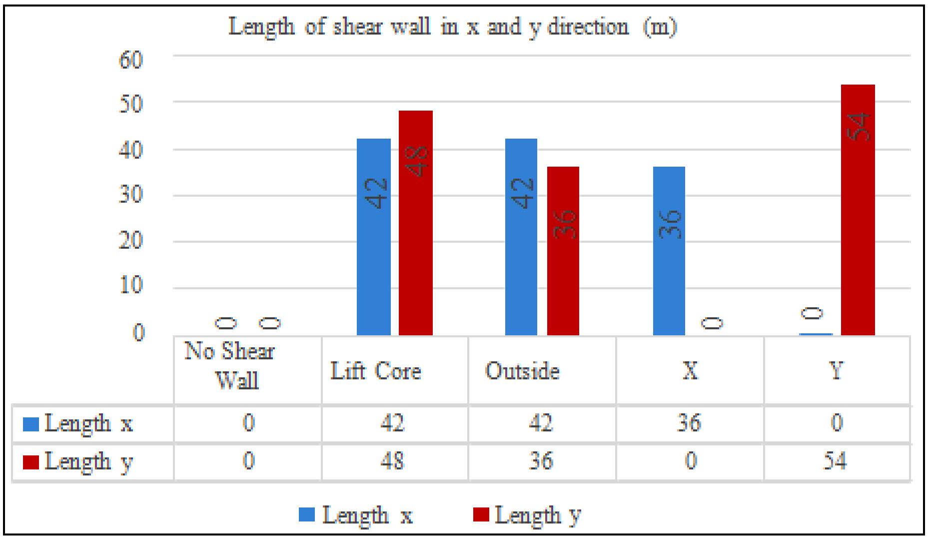

Figure 10: Length of shear wall in x and y direction

3. Results

Comparison of Maximum Story Displacement

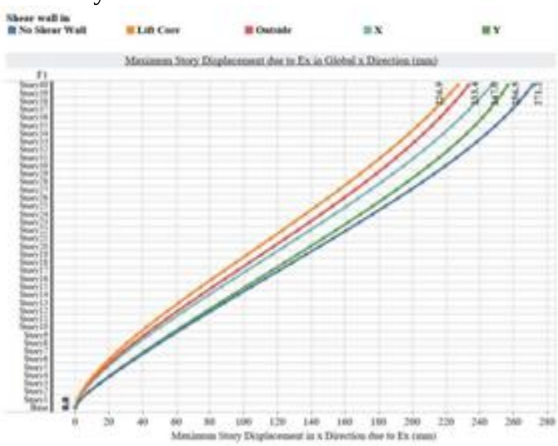

Figure 11: Maximum story displacement due to Ex in global x direction

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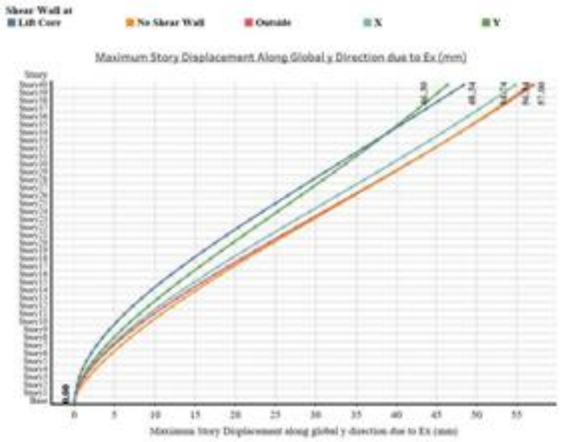

Figure 12: Maximum story displacement due to Ex in global y direction

Fig 11 and Error! Reference source not found. shows the comparison of maximum story displacement due to equivalent static load Ex in global x direction which is the direction Ex is acting. From the figure we can see that maximum story displacement has been decreased in models where shear wall has been introduced in the structure. Moreover, the lateral displacement is seen least when the lift core is used. After that the displacement is least when the shear walls are introduced at the outside corners of the building followed by shear wall aligned along X direction and then in Y direction. The introduction of lift core reduces the maximum displacement in the top story by 16%. The maximum story displacement for top story is reduced by 5%, 9%, and 14% with the introduction of shear wall in y direction, x direction, and outside corners respectively.

From Fig 12 it can be seen that there is a significant displacement in Y direction due to Ex. The displacement in Y direction is seen to be more than 25% of the displacement in X direction. The considerable displacement is due to the irregularity in the building and due to the prevalence of torsional forces due to which the building experiences force in the mutually perpendicular direction. Due to the load case Ex, the maximum top story displacement is found to be reduced by 22%, 15% and 4% if the shear wall is introduced in y direction, at the lift core, and along the x direction.

Fig 13 and Fig 14 is the graphical representation of the comparison of maximum story displacement for Ey load case in x and y directions respectively.. The results again vindicate that the introduction of shear wall decreases the lateral displacement in the structure. The displacement in y direction is least when the shear wall is placed along y direction and the displacement is x direction is minimum when the lift core is constructed using shear walls. The top story displacement caused by Ey in x direction is only 5% of the displacement in y direction. The introduction of shear wall in lift core reduces the maximum top story displacement by 25% in x direction and by 15% in y direction. The introduction of shear wall at y direction reduces the top story displacement by 18% in the y direction. Placement of shear wall in x direction does not significantly decrease the maximum story displacements in both x and y direction if Ey load case is considered.

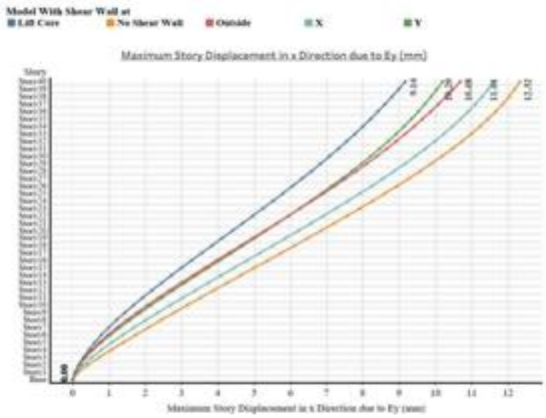

Figure 13: Maximum story displacement due to Ey in global x direction

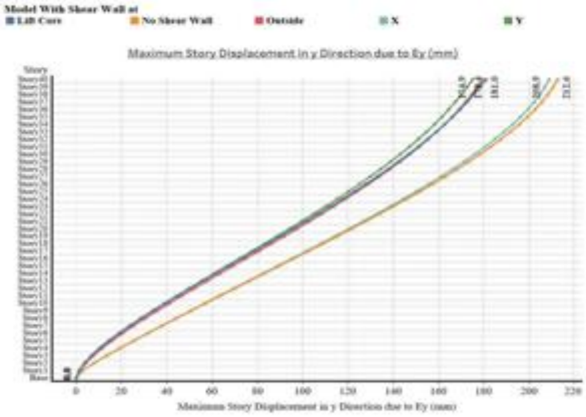

Figure 14: Maximum story displacement due to Ey in global y direction

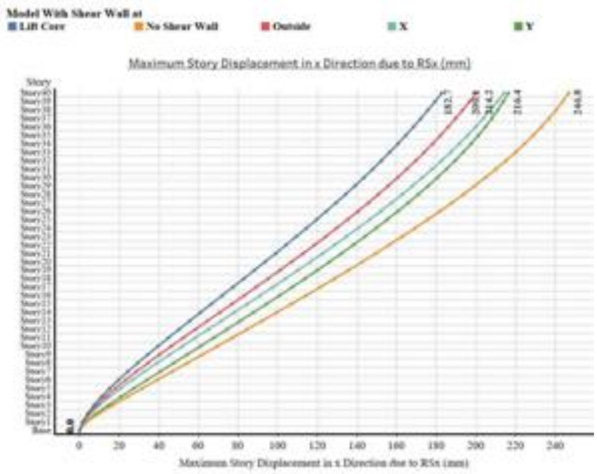

Figure 15: Maximum story displacement due to RSx in global x direction

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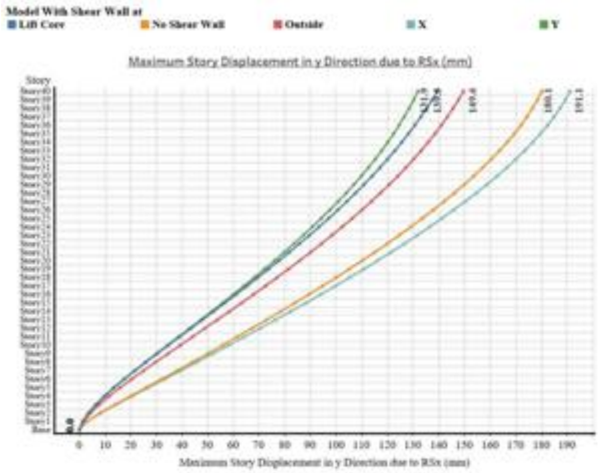

Figure 16: Maximum story displacement due to RSx in global y direction

Fig 15 and Fig 16 shows that the maximum lateral displacement is significantly affected by the Lateral force using response spectrum in x direction (RSx). Interesting observations can be seen from the plots. The maximum displacement in x direction and y direction are comparable. The lateral response spectrum force in x direction has caused a displacement of more than 75% of displacement in the mutually perpendicular y direction. The maximum story displacement of top story in x direction is 246.8mm while the maximum displacement in y direction is 191.1mm, which is about 77% of the displacement in x axis. This high value of displacement can be explained by the irregularity of the building. Furthermore, the maximum displacement in y direction is maximum when the shear wall is aligned along the x axis as the shear wall does not increase the lateral stiffness in mutually perpendicular direction but increasing the seismic weight of the structure hereby attracting more lateral earthquake force which increases displacement. We also see that the model with the shear wall at the lift core displaces the least in x direction as compared to other models. The top story displacement in x direction is reduced by 26% if the shear wall is introduced in the lift core, 19% if the shear wall is introduced in outside corners, 13% if introduced in x direction and 12% if introduced in y direction.

However, in the y direction the displacement is least in models having shear wall aligned to y direction. It reduces the maximum displacement at top story by 27%. It is because the lateral force is effectively taken by the shear wall. This model is closely followed by the model having shear wall at lift core which shows that shear wall towards the center of the building is effective in reducing lateral displacement of a multistory building. The model reduces the maximum top story displacement by 22%. The maximum top story displacement in y direction is decreased by 17 % if shear wall is introduced at the outside corners of the structure. However, the maximum story displacement in y direction due to RSx is increased by 6% if shear wall is introduced in x direction. It might be because the addition of shear wall in x direction only aids the addition of seismic mass of the building which in turn increases the seismic forces thereby increasing the maximum lateral displacement.

Fig 17 and Fig 18 also shows comparable results of that of Fig 15 and Fig 16. Although the maximum displacement in both x and y directions have decreased while the lateral load case RSy is used, the trend of the displacement with the introduction of shear walls in different locations is similar to that of the RSx load case. Due to load case RSy, the introduction of shear wall has reduced the maximum displacement in top story along x direction, by 23%, 19%, 12%, and 9% when the shear walls are introduced in lift core, outside corners, along x, and along y directions respectively. For the same load case the maximum displacement at top story in y direction is reduced by 24%, 19%, and 17% when the shear walls are introduced in y direction lift core, outside corners respectively while here is a 7% increase with the introduction of shear wall in x direction.

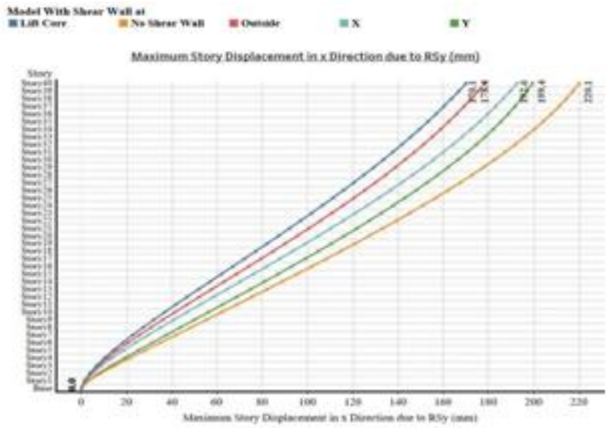

Figure 17: Maximum story displacement due to RSy in global x direction

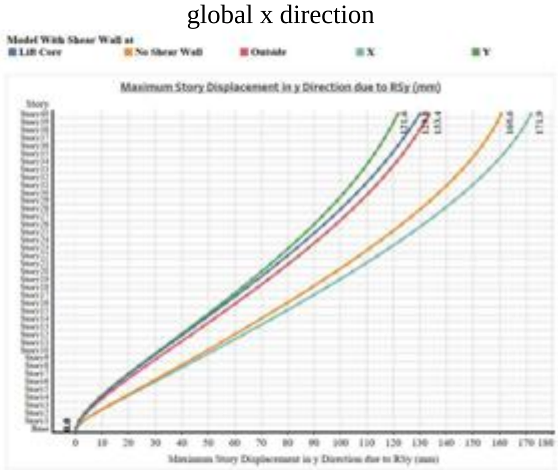

Figure 18: Maximum story displacement due to RSy in global y direction

Fig 19 shows the variation of maximum story displacement is x direction due to time history load case THx, in which the trend is consistent with the equivalent static load case Ex and response spectrum load case RSx. The maximum story displacement is seen in when in the model without the shear wall and the least displacement is seen for model with shear wall at lift core. The maximum story displacement of the top story is seen to decrease by 13%, 10%, 8%, and 5% when the shear wall is introduced in lift core, outside corners, along x direction and along y direction respectively. Similar results is seen due to THx in y direction given by Fig 20. The only difference in trend being that the introduction of shear wall in y direction has considerably reduced the maximum story displacement in y direction. The variation of maximum story displacement in y direction due to Thy be seen in Fig 21, which shows that the maximum story displacement is decreased by 17%, 16%, 14%, and 13% when shear wall is introduced in y direction, lift core, outside corners and x direction.

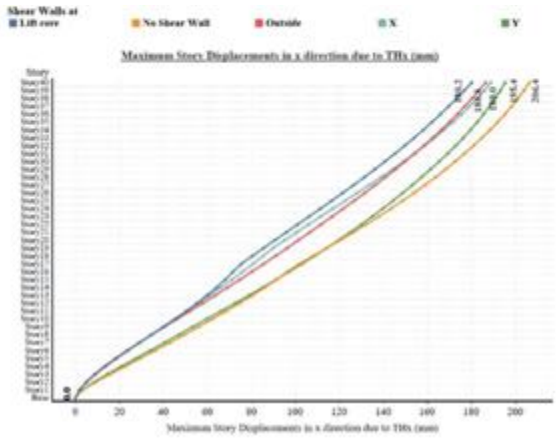

Figure 19: Maximum story displacement due to THx in x direction

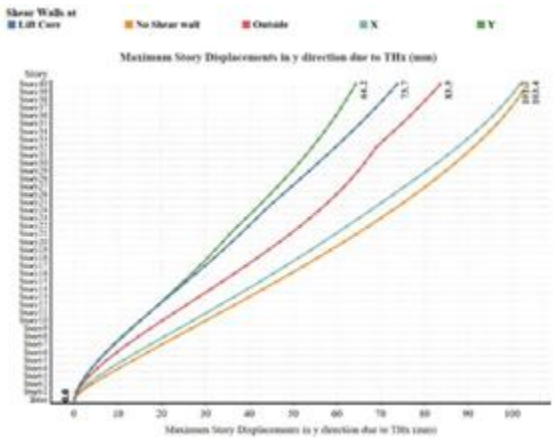

Figure 20: Maximum story displacement due to THx in y direction

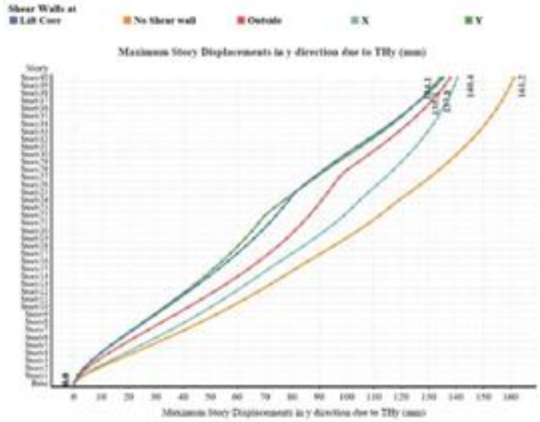

Figure 21: Maximum story displacement due to THy in y direction

This reduction of maximum story displacement is supported by Gupta and Bano (2017), Khanna and Chand (2016) and Mukundan et. al. (2015). Gupta and Bano (2015) observed that "the maximum story displacement of the building is reduced by up to 25% with the introduction of shear wall. This observation nearly matches the observations of this study." The tables of the comparison are given in the annex section of the report. The observations of the least displacements in the shear walls in cores and corners is supported by Lakshmi et al. (2014). The observation that the maximum displacement in x direction will be less when the shear wall is provided at x direction and maximum story displacement in y direction will be less when shear wall is provided in y direction was observed by Kumar et al. (2013).

Fig 22 and Fig 23 shows the average of maximum displacements across the five models while using different load cases in x and y directions respectively. It can be seen in Fig 22 that displacement along the x direction across the five models is maximum due to the equivalent linear static load case in x direction, Ex. The response spectrum load case in x direction RSx comes next causing about 85% of the displacement caused by Ex in the upper stories. The time history load case gives the least of the three methods, only about 80% of the maximum story displacements in upper stories. The response spectrum load case in y direction RSy also causes considerable story displacement in the global x direction which is more that 75% of the displacement caused by the equivalent static load case in x direction, Ex, in upper stories of the structure. The linear static load case Ey however only causes displacement of about 5% of the displacement caused by linear static load case Ex. From the observations it can be said that the equivalent linear static method does not account to the effect of the lateral force in the perpendicular direction arisen due to factors such as irregularity and torsion.

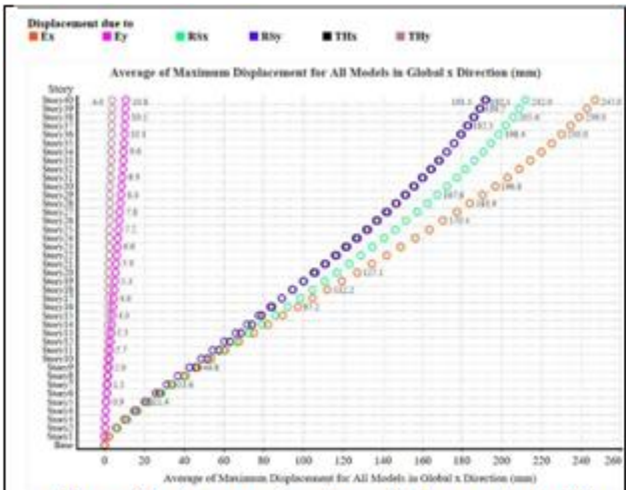

Figure 22: Average of maximum displacements for all models in global x direction

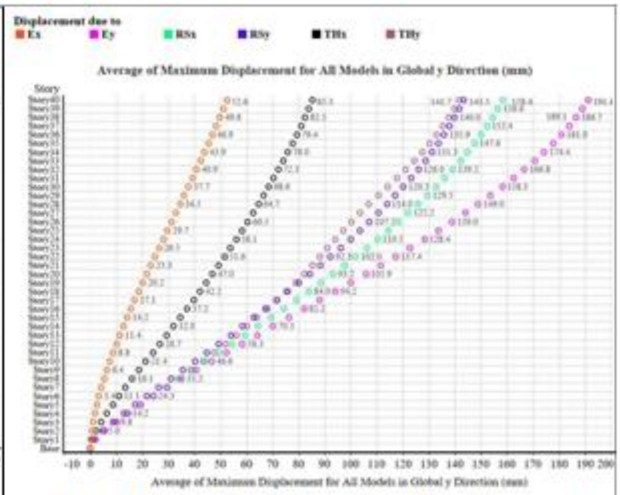

Figure 23: Average of maximum displacements for all models in global y direction

Fig 23 shows similar results to that of Fig 22 in which Ey gives the maximum displacement to the models while Ex gives the minimum displacement to the model. The displacement caused due to the dynamic load cases is considerable here too. The anomaly here is that the response spectrum load case in perpendicular direction to the direction of displacement, RSx, causes more displacement than the response spectrum load case in the same direction to that of the displacement, RSy. The same trend is observed by Naresh and Brahma Chari (2019) and Monish et al. (2015). Naresh and Brahma Chari (2019) concluded that "in both x and y directions, static analysis gives higher values for maximum displacement of stories" while Monish et al. (2015) also concludes that "displacement is more in static case than in the response spectrum case."

Comparison of Time Period

The time period of the first mode of the models are compared in Fig 24. The model without shear walls has the maximum time period of 5.03 seconds. With the introduction of shear wall, the time period of the structure has decreased due to the increased stiffness provided by the shear walls. The percentage decrease in time period is shown in Fig 25.

From Fig 24 and Fig 25 we can see that the time period has decreased by 2.2% to 4.92 seconds when the shear wall is introduced along the y direction. Moreover, the time period has decreased by 6.4% to 4.71 seconds when the shear wall was introduced along x directions. The model with the shear wall in outside corners has a fundamental time period of 4.53 secs which is 9.9% less than the model without the shear wall. The model with the lift core has the least time period among five models. The model has the time period of 4.44 seconds which is 11.7% less than the model without shear wall.

There is a decrease in time period of the fundamental mode as the shear walls are added to the structure. This observation is also seen by Khanna and Chand (2019), and Raghunandan and Kumar (2017). Raghunandan and Kumar (2017) gives the reason that "when the shear wall is introduced in the structure, the shear wall adds additional stiffness to resist against the lateral forces which consequently decreases the modal time period."

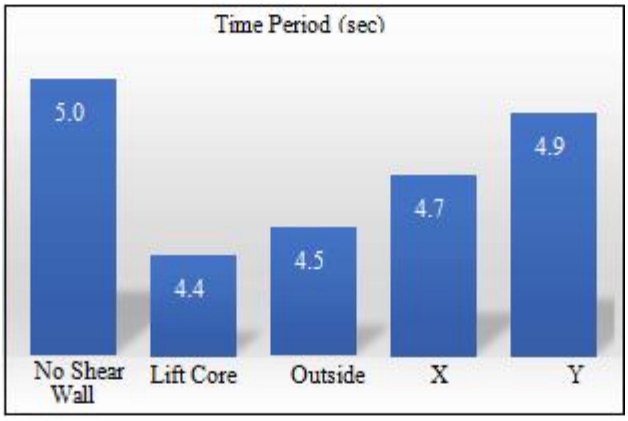

Figure 24: Comparison of fundamental time period computed by ETABS 2018

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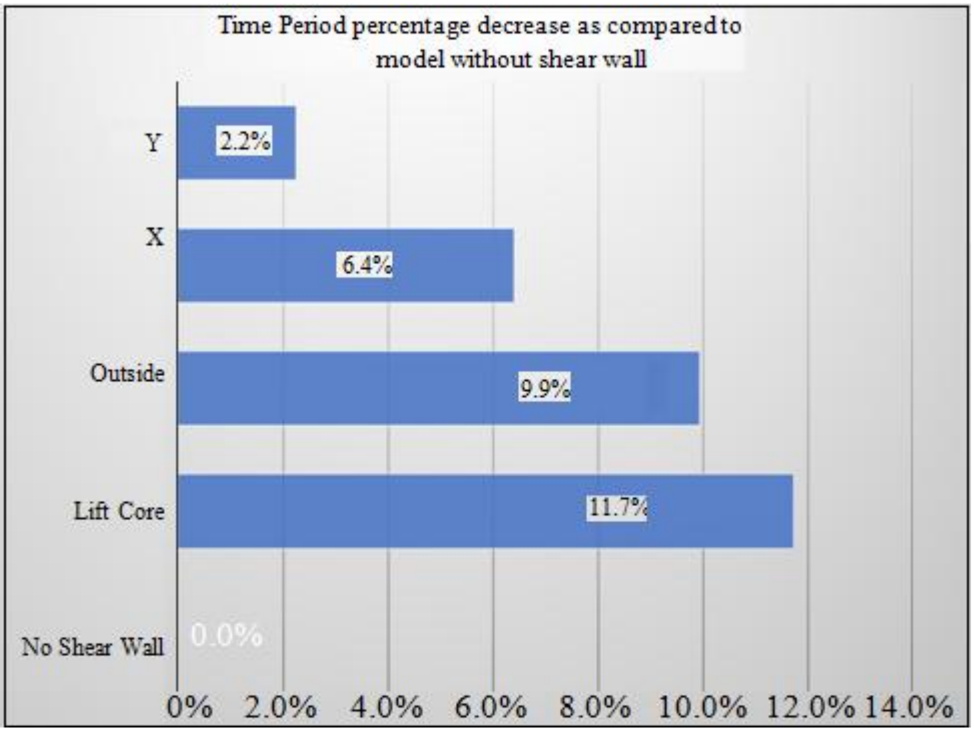

Figure 25: Time Period percentage decrease as compared to model with no shear wall

4. Summary and Conclusion

The maximum story displacements in global x direction for, linear static load case in x direction, Ex, and response spectrum load case in x direction, RSx and time history load case in x direction THx was seen for model without shear wall and the minimum story displacement was seen for model with lift core shear wall which reduced the maximum story displacement up to 16% for static case, up to 26% for response spectrum case and up to 13% for time history load case THx, while the minimum story displacements in global y direction for all three load cases, linear static load case in y direction, Ey, and response spectrum load case in y direction, RSy, and time history load case Thy was seen for model with shear wall in y direction with a decrease of up to 18% for static case, up to 24% for response spectrum case, and 17% for time history load case as compared to the maximum displacement for model without shear wall. The maximum displacement in response spectrum case in y direction is for model with shear wall in x direction. The linear load static load cases cause more story displacement (about 15%) than the response spectrum load cases in same direction of the load case. However, it is to be noted that the response spectrum load cases also cause considerable story displacements (up to 75%) in orthogonal directions of the story displacements in the same direction of the load case. The linear static load case and the time history load cases only cause about 5% and 2% of the displacements in orthogonal direction of the load case.

1) The model with the lift core has the minimum time period and the model without the shear wall has the maximum time period. The time period of the model with the lift core is 11.7% less than the model without shear wall. The time period of the structure has decreasing trend when the shear wall is provided which is due to the increased stiffness provided by the shear wall.
2) The base shear along both x and y directions are maximum for the model with shear wall at lift core and minimum for the model without shear wall.
3) The model consisting of shear wall at the lift core has shown better performance in the most of the parameters compared, which might be because of the following reasons.
    - The model has the least eccentricity as the center of mass and the center of stiffness is at the least distance of all the models.
    - The shear wall is provided along both x and y directions.
    - The shear wall is placed at the core/central location of the structure. So, this orientation effectively resists the lateral forces.
4) The configuration and the location of shear walls has substantial impact on response of the structure due to earthquake forces, in terms of story displacement. Shear walls offer large strength and stiffness to buildings in the direction of their orientation. The performance of any high-rise buildings can be improved by providing shear wall of appropriate lengths at appropriate locations. The location should be such that the shear wall should help in decreasing eccentricity, and distributing gravity and lateral loads in best way possible.

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