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Performance of R.C. Frame Building with and without Shear Wall Based on Linear and Non-Linear Static Analysis

Jyoti Shah [a], Dinesh Kumar Gupta [b], Sailesh Adhikari [c]

[a, b, cc] *Department of Civil Engineering, Pashchimanchal Campus, IOE, Tribhuvan University, Nepal*
Corresponding Email: [a] shahjty@gmail.com, [b] replydinesh@ioe.edu.np, [c] sailesh.adhikari@pasc.tu.edu.np

Abstract

Shear wall construction is practiced to oppose the consequences of the lateral forces. Seismic and wind forces are the foremost ordinary lateral loads particularly designed to hold in multistory buildings. This paper used five models of 5 story building with & without shear walls at various locations. The dimension of the building is 16.5m * 16.5m. The building is sited in Nepal having soil type soft soil and features a role of commercial building. The goal of this research is to perform linear and non-linear static analysis. The linear static results of the story drift & story displacement for this study was within permissible limit concluding that introduction of shear walls are efficient structural means to decrease the value of story drift & displacement. Base shear increases with the inclusion of shear walls however it depends upon the position of shear walls. Similarly, the results for the non-linear static analysis was obtained that buildings with the introduction of shear walls are efficient in terms of ductility and strength as it is capable of reducing deflection at performance point. In X-direction, Model-2NL showed decrease by 28.36%, in Model-3NL by 35.10%, in Model-4NL by 32.49%, in Model-5NL by 36.90% as compared to Model-1NL (Bare Frame). Performance point for Model-1NL has the lowest Base Shear followed by Model-2NL, Model-4NL, Model-3NL, Model-5NL along X-direction. Model-3NL possesses the lowest number of plastic hinges till the last step.

Keywords

pushover analysis, plastic hinge, base shear, story drift, story displacement, performance point

1. Overview

Nepal is a seismically active country as it lies in subduction zone of Indo-Australia & Eurasian plate [1]. After studying the earlier records of earthquake in Nepal, it's now necessary to specialize in design of earthquake resistant buildings. Not only in Nepal but has become necessary in all over the world. For the fulfillment of earthquake resistant buildings, provision of shear wall system within the building have become one in all the foremost popular methods. Buildings with the introduction of shear walls when properly designed and detailed, it showed magnificient performance in earlier earthquakes. The enormous victory of the buildings with the introduction of shear walls in withholding strong earthquakes is summarized within the quote: " It is difficult to prevent the buildings from seismic forces without the aid of shear walls." as mentioned by Mark Fintel, a famed consulting engineer in United States America [2]. Buildings with shear walls are favoured choice in many earthquake liable countries, like Chile, New Zealand and USA. It is effortless to create, because reinforcement detailing of walls is analogously uncomplicated and thus comfortably applied at the location. Shear walls are fruitful, both in view of construction cost and successful in reducing the structural and non-structural (like glass windows and building contents) damages caused by the earthquake [2].

In this research, R.C. building structures with and without shear walls were investigated with linear and pushover analysis. The building was 5 story located in soft soil condition. Each floor has 3m height. There are five models of building, i.e. Bare Frame, Column size Increased and three variations of shear wall in different positions.

The goal of this research is to perform linear and non-linear static analysis, to see performance point, plastic hinge state and determine best position of shear walls supported pushover analysis.

Pushover analysis can be considered as a static non-linear analysis where seismic effect to the building is treated as static load and the values are increased gradually to find plastic hinge formation at various locations inside the building. This analysis targeted to foresee the utmost load, maximum deformation occurred, and position a censorious part of a building. Some studies show that pushover static analysis gave faultless result than non-linear dynamic analysis. Pushover analysis produced curve capacity which narrated the interrelation between base shear and deformation on the roof. The graphical interrelation between base shear and roof deformation can be witnessed in Fig. 1 [3].

IO(Immediate Occupancy), LS(Life Safety) and CP(Collapse Prevention) are the different states through which a structure undergoes at incremental levels of earthquake loading while conducting pushover analysis. Untill the displacement is sufficient enough to reach at IO, the structure doesn't experience severe damage and retains similar strength & ductility to that of pre-earthquake time. Further progress in displacement pushes the structure to LS state where few components of the structures collapse but the whole of the building doesn't collapse. At CP state, the structural and non-structural components of the building completely collapse and the structural strength is reduced drastically [3].

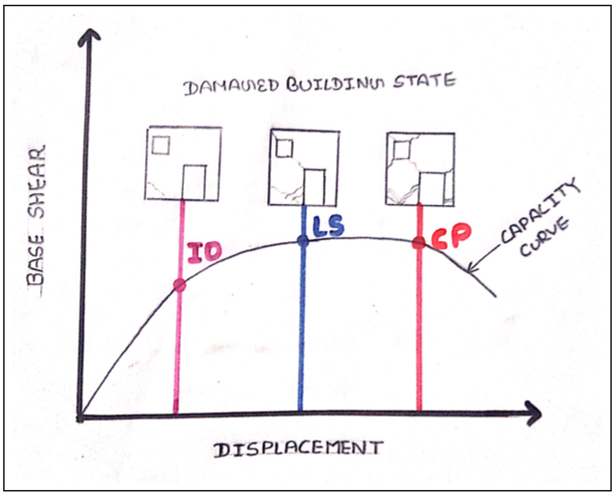


Figure 1: Capacity Curve

2. Modelling by SAP2000

2.1 Description of the Work Under Study

For this study, five models are modeled and analyzed. Both linear and non-linear static analysis were carried out for the Models. First of all Linear Static Analysis was conducted followed by Non-linear Static Analysis. Models analyzed with static linear analysis approach are represented with L at the suffix and those with the non-linear analysis approach are suffixed with NL (i.e. Model-1L indicates Model-1 is analyzed using static linear analysis approach and model-1NL indicates Model-1 is analyzed using static non-linear analysis approach).

2.1.1 Description of Linear and Non-linear Static Analysis

Linear static analysis is a design approach where equivalent static story forces, due to wind or earthquakes, are enforced to the structure. The calculation of story forces is prescriptive, and formulations for determining these forces are provided within the building code provided by the government. The static method is the easiest one because it needs less calculation effort and is predicated on formula given within the building code. This linear static analysis displays more precision in structure with bounded height [4]. Linear analysis isn't a sufficient concept within the realm of structural engineering because it's been experimented and practically observed that the building materials possess enough strength and ductility beyond its linear state [5].

Although different theories have acquired existence to justify the non-linearity, the non-linear static analysis, also referred to as pushover analysis, is taken into account to be a convenient method for evaluating the building performance. It's become a popular tool as its results help scrutinize and fine tune the seismic design based on Linear Seismic Analysis. A non-linear static analysis can help to spot members likely to reach critical states during an earthquake for which attention should incline during design and detailing.

3. Methodology

The R.C. structures are modelled employing analysis software SAP2000. Five story with 4 bay symmetric in both X and Y-direction structures are considered. Model of the considered buildings are shown in fig. 2, 3 and 4. The properties used in the structures are shown in Table 1.

Table 1: Properties of structures

Specification	Size
Concrete Grade	M20
Steel Grade	Fe-415, Fe-500
Slab Thickness	125mm
Zone Factor	Zone-V (0.36)
Importance Factor	1.2
Response Reduction Factor	5
Soil Type	III
Stiffness Modifier	
For Column	0.7
For Beam	0.35
Beam Size	300mm*400mm
Column Size (Model-1)	
For Four Columns	350mm*350mm
For Twelve Columns	450mm*450mm
Column Size Increased (Model-2)	
For Four Columns	550mm*550mm
For Twelve Columns	600mm*600mm
SW in Periphery (Model-3)	
Column Size	Same as Model-1
SW Length	1.5m
SW Thickness	250mm
SW in Corner (Model-4)	
Column Size	Same as Model-1
SW Length	1.5m
SW Thickness	250mm
SW in Core (Model-5)	
Column Size	Same as Model-1
SW Length	2m
SW Thickness	250mm

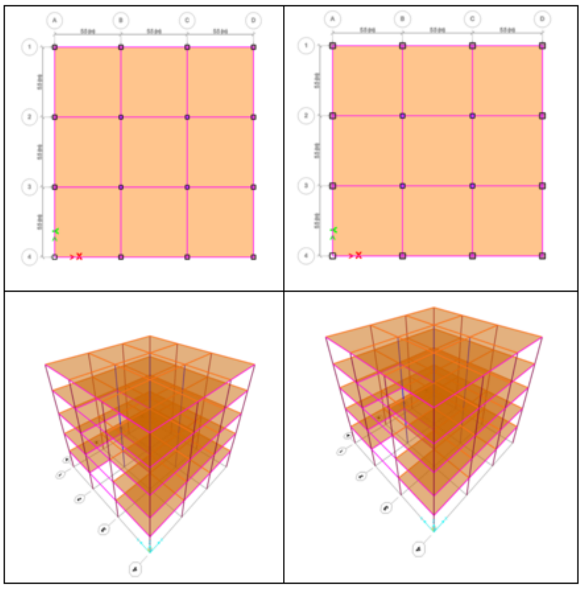


Figure 2: Plan & 3D view of Model-1 and Model-2

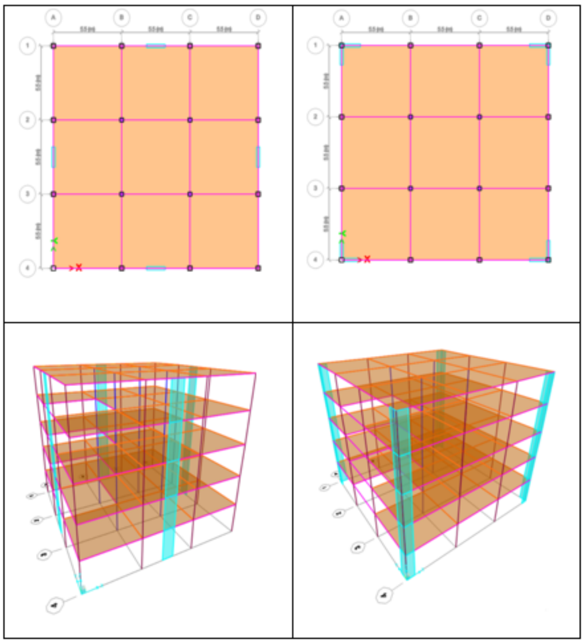


Figure 3: Plan & 3D view of Model-3 and Model-4

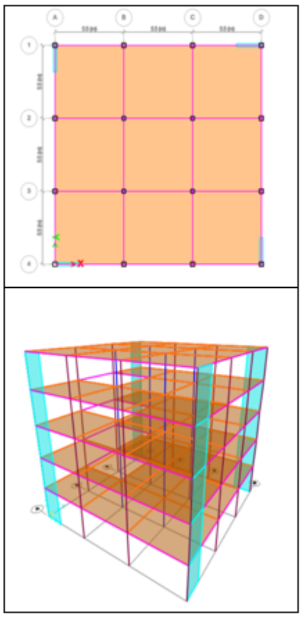


Figure 4: Plan & 3D view of Model-5

4. Results and Observation

The end results of the linear analysis were obtained in the form story displacement, story drift and base shear while the results of (pushover) non-linear analysis were obtained in the form of calculation of building performance based on the performance point and plastic hinge distribution.

4.1 Story Drift

Fig. 5 and Table 2 shows the story drift of each story that are obtained from SAP 2000 for Model-1L , Model-2L , Model-3L , Model-4L and Model-5L. The plot of Drift Ratio versus Story shows us that Model-1L has highest drift ratio among all the models. The presence of shear wall has highly helped to drop the value of drift ratio within the code prescribed permissible limit i.e., 0.004.

Table 2: Story Drift

Story	Bare Frame	Column Size Increased	Shear wall in Periphery	Shear wall in Corner	Shear wall in Core
	Model-1NL	Model-2NL	Model-3NL	Model-4NL	Model-5NL
5	0.00453	0.0024	0.00156	0.0013	0.00107
4	0.0072	0.0036	0.0033	0.0031	0.0024
3	0.0089	0.0039	0.0037	0.00389	0.0034
2	0.0089	0.0039	0.00328	0.0039	0.0035
1	0.0051	0.0023	0.0026	0.0038	0.0033
Base	0	0	0	0	0

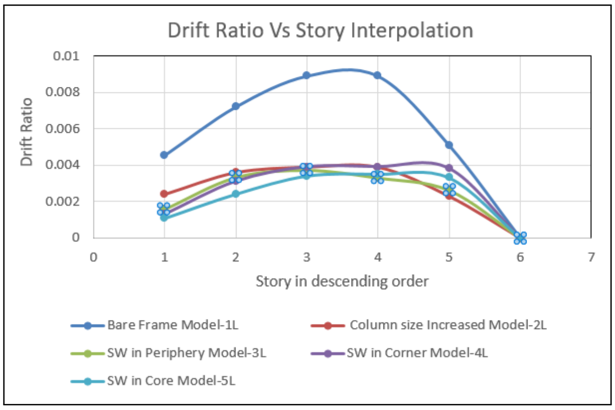


Figure 5: Story Drift

4.2 Story Displacement

Fig. 6, Table 3 and Fig. 7, Table 4 shows the value of maximum Story Displacement in X and Y-direction respectively obtained from SAP 2000.

Story displacement is high in case of Model-1L. Model-5L shows the least story displacement followed by Model-3L, Model-4L and Model-2L. The presence of shear wall has highly helped to drop the value of story displacement within the code (IS code 1893:2016, Part-1) prescribed permissible limit [6].

Table 3: Story Displacement in X-direction

Story	Bare Frame	Column Size Increased	Shear wall in Periphery	Shear wall in Corner	Shear wall in Core
	Model-1NL	Model-2NL	Model-3NL	Model-4NL	Model-5NL
5	103.83	51.04	43.2	48.33	41.07
4	90.24	43.71	35.47	36.94	31.04
3	68.75	32.83	25.63	24.85	20.64
2	42.06	19.65	14.6	13.16	10.32
1	15.29	6.86	4.66	3.88	3.22
Base	0	0	0	0	0

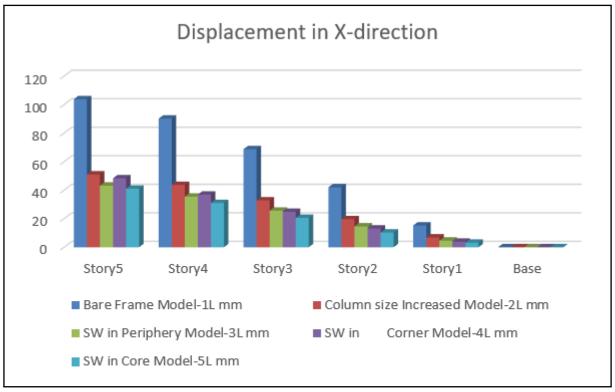


Figure 6: Story Displacement

Table 4: Story Displacement in Y-Direction

Story	Bare Frame	Column Size Increased	Shear wall in Periphery	Shear wall in Corner	Shear wall in Core
	Model-1NL	Model-2NL	Model-3NL	Model-4NL	Model-5NL
5	110.38	48.05	42.04	49.98	39.78
4	95.69	41.22	34.61	38.15	30.11
3	72.74	31.02	25.05	25.64	20.05
2	44.42	18.59	14.28	13.55	10.54
1	16.11	6.51	4.57	3.99	3.14
Base	0	0	0	0	0

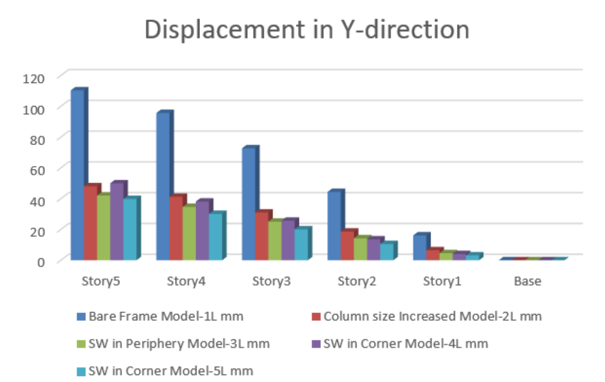


Figure 7: Story Displacement in Y-Direction

4.3 Base Shear

Fig. 8 and Table 5 shows the comparison of base shear of each models. The value of base shear in case of Model-2L is highest of all. This value might be quite misleading because higher value of base shear means higher lateral resistance by the building during the time of earthquake which is not true for Model-2L. The higher value of base shear has come out of the fact that it has higher seismic weight due to increase in the size of the column in contrary to others. If the base shear of Model-1L is compared with the shear walled models, it is found that the value of base shear increases with the placement of shear wall.

Moreover, it can be inferred that the position of shear wall is quite instrumental in producing the base shear value. Due to position of shear wall, the earthquake forces increase in the building. This indicates that the stiffness of the building is increased by placing shear wall. This is in turn giving more force absorption in the structure. Thus in this manner, the buildings are able to resist moderate earthquake with very less damage to the structural elements.

Table 5: Base Shear

Model Type	Base Shear	Unit
Bare Frame Model-1L	1651.36	KN
Column Size Increased Model-2L	1812.06	KN
SW in Periphery Model-3L	1706.02	KN
SW in Corner Model-4L	1738.82	KN
Sw in Core Model-5L	1724.24	KN

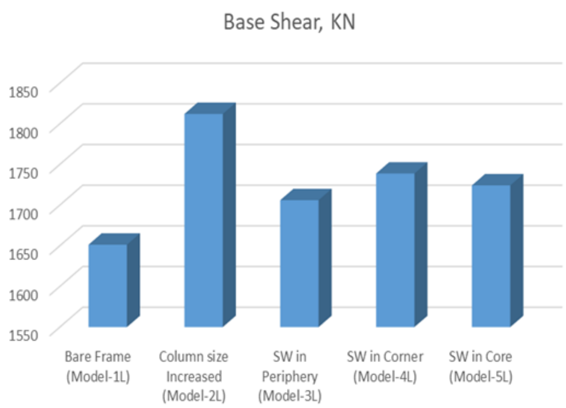


Figure 8: Base Shear

4.4 Pushover Analysis

The pushover analysis is achieved as per the provision in the ATC-40 [7] and FEMA 440 [8] using the software SAP2000. It is explained with the aid of spectral acceleration (g) vs. spectral displacement plot also known as Capacity Spectrum Method. The reduced acceleration displacement response spectrum intersects the capacity curve at a unique point called performance point. Performance point gives the global behavior of the structure while the development of plastic hinge shows the real behavior of the structure and their elements [9].

Table 6 displays the curve capacity, the interrelationship between base shear and displacement that takes place in all models slowly when pushover analysis is performed. Performance point for Model-1NL has the largest displacement followed by Model-2NL, Model-4NL, Model-3NL and Model-5NL along X-direction. It exhibits that building without shear wall is more liable to failure.

Depending on the ability to withstand the lateral load, Model-1NL lies on the bottom (see table below) and Model-5NL lies to the top. The displacement in Model-2NL showed decrease by 28.36%, in Model-3NL by 35.10%, in Model-4NL by 32.49%, in Model-5NL by 36.90% as compared to Model-1NL.

Table 6: Base Shear & Displacement for Performance Point

Model	Output Model	Base Shear (KN)	Displacement (mm)
Model-1NL	Push-X	2500.39	122.10
	Push-Y	2470.28	123.57
Model-2NL	Push-X	3529.22	87.48
	Push-Y	3470.85	88.63
Model-3NL	Push-X	4583.03	79.25
	Push-Y	4490.96	84.35
Model-4NL	Push-X	4494.11	82.43
	Push-Y	4488.20	82.97
Model-5NL	Push-X	4837.06	77.04
	Push-Y	4834.92	76.82

Formation of plastic hinge can also be seen with the increasing load and their performance levels. The hinge state can be viewed in the Fig. 20, 21 & 22, and can be known whether it I in IO, LS and CP. Models have similar plastic hinge distribution in X and Y directions due to symmetricity in shear walls [5]. Plastic hinges gradually develop in a structure with increasing earthquake loads beginning from IO to CP state/levels.This distribution can be spotted from the following Fig. 9 in supplement with Table 7.

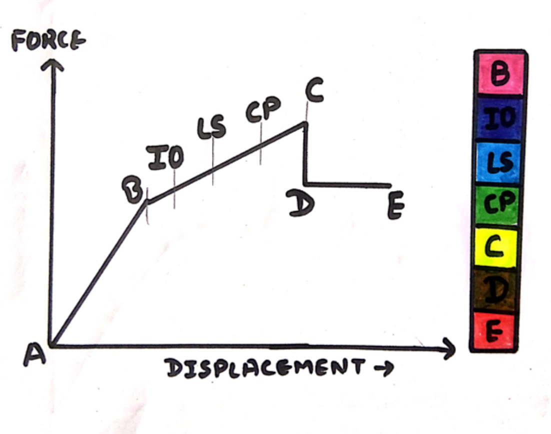
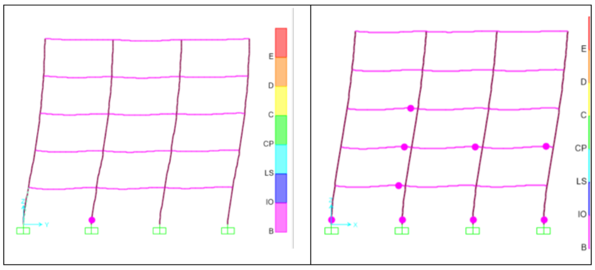


Figure 9: Force vs. Displacement

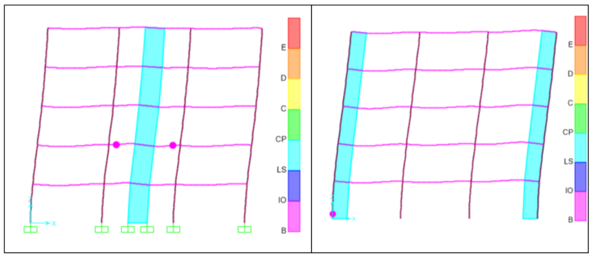
Table 7: Building Performance Level

S.N.	EXPLANATION
B	Shows the linear limit accompanied by primary melt on the structure.
IO	Tiny damage appears & the structure ductility is approximately identical as before the earthquake .
LS	Damage appears from small to medium extent. Structural ductility is reducing yet have huge possibility to pass out. .
CP	Significant damage appears on the structure therefore strength & ductility declines enormously
C	The largest restriction of base shear was still capable to tolerate building.
D	Huge deterioration of structural strength occurs, so that structure is unstable & nearly passed out.
E	Structure is disqualified to tolerate base shear & destroyed.

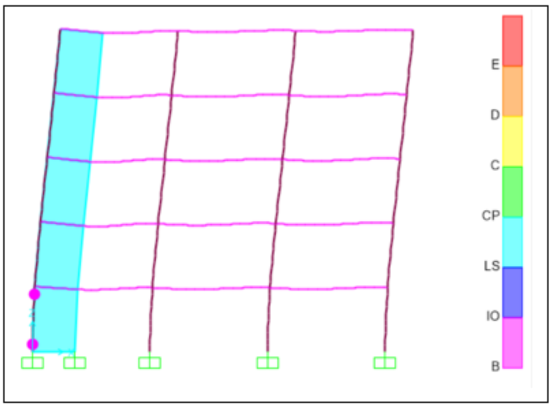
Fig. 10 (a)- Fig.10 (e) displays the formation of platic hinge in all five models. The first plastic hinge model-1NL rises on the column of ground floor and the formed hinge shows that the building is still usable. As shown in Fig, 10(b) on model-2NL the formation of plastic hinge occurs on ground, first and second floor. formation of first plastic hinge rises on second floor on beam. Similarly, Fig. 10 (d) & (e) dispays the formation of first plastic hinge rises on ground floor in case of model-4NL & model-5NL. Fig. 11 (a) shows the first collapse on column of ground floor on model-1NL. Similarly, Fig. 11 (b) shows the first failure on column of ground floor on model-2NL. In Fig. 11 (c), (d), & (e) there is no formation of any collapse hinge. In model-3NL, model-4NL & model-5NL, all the columns showed the building performance are in immediate occupancy and only small damage on the structure occurred. Fig. 12 shows the formation of plastic hinges in last step of pushover analysis. In model-1NL, column collapsed occurred on ground and first floor (Fig. 12 (a)). In model-2NL, column collapse was on ground floor and other hinges were in immediate occupancy (Fig. 12 (b)). We know that collapse of column is very much dangerous as it can cause the total collapse of structure. While in (Fig. 12 (c) & (d)) Model-3NL & Model-4NL the columns and beams still showed the building performance operational with no collapse hinge formation. Meanwhile in Model-5NL (Fig. 12 (e)), the column collapse was on ground floor. Model-3NL and Model-4NL had no collapse hinge as compared to model-1NL, model-2NL and model-5NL. After employing the target displacement pushover analysis was performed and it was seen that building with shear wall performed well than bare frame and building with column size increased and when comparison was made between the various location of shear wall, once more, shear wall in periphery and in corner proved superior as it increased the global stiffness and hold out against the applied load. Depending on plastic hinge distribution model-3NL & model-4NL was the efficient model in lessening plastic hinge collapse than other models. The process of plastic hinge formation is listed in Table 8.



(a) Model-1NL (b) Model-2NL

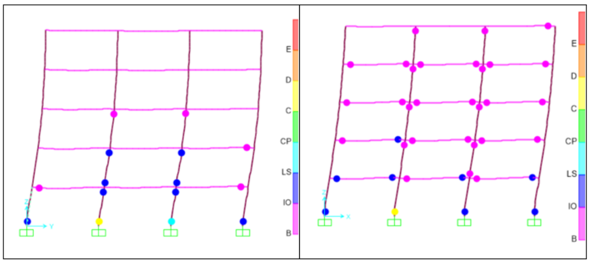


(c) Model-3NL (d) Model-4NL

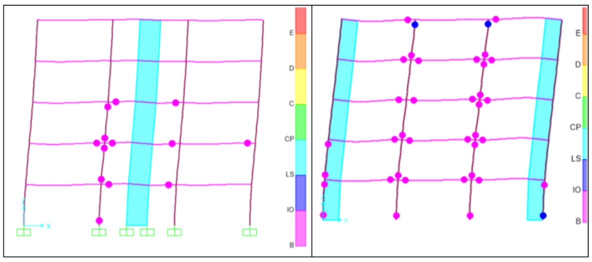


(e) Model-5NL

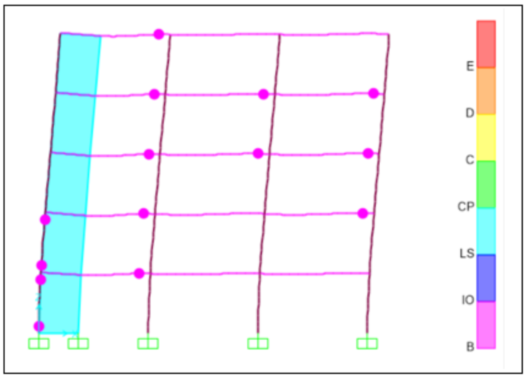
Figure 10: Formation of First Plastic Hinge



(a) Model-1NL (b) Model-2NL

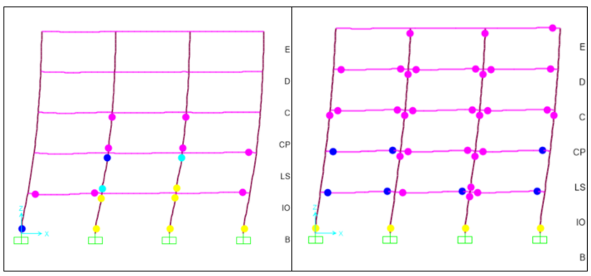


(c) Model-3NL (d) Model-4NL

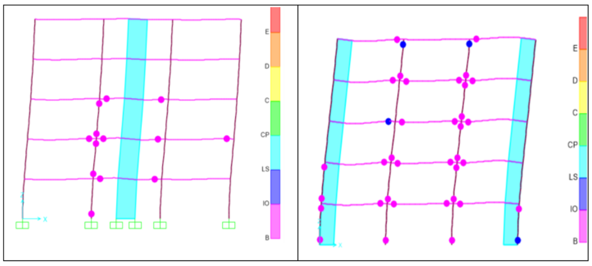


(e) Model-5NL

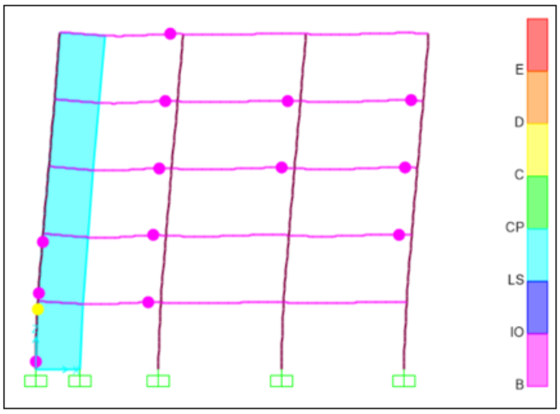
Figure 11: Formation of First Collapse Hinge



(a) Model-1NL (b) Model-2NL



(c) Model-3NL (d) Model-4NL



(e) Model-5NL

Figure 12: Formation of Plastic Hinge in Last Step

Table 8: Plastic Hinge Progression

Parameter	Model-1NL	Model-2NL	Model-3NL	Model-4NL	Model-5NL
The first plastic hinge occurs	Story 1	Story 1-3	Story 2	Story 1	Story 1
The first collapse	Story 1	Story 1	No collapse hinge formation	No collapse hinge formation	No collapse hinge formation
The collapse in the last step of pushover	Story 1-2	Story 1	No collapse hinge formation	No collapse hinge formation	Story 1

5. Conclusion

Pushover analysis helps us recognize weak structural elements by forecasting the failure mechanism and acknowledges the redistribution of forces during progressive yielding. It may help structural engineers take actions and necessary precautions during post seismic hazards. Following conclusions can be drawn from the linear and non-linear analysis:

1. Introduction of shear wall generally results in decreasing the drift and the displacement because the shear wall increases the stiffness of the building and sustain the lateral forces. The preferable performance is observed in

model-5L with respect to diaphragm displacement because it has low displacement but when compared with respect to base shear, model-3L showed better performance.

2. Performance based seismic design achieved by above method, pushover analysis satisfied the acceptance norm for immediate occupancy for various intensities of earthquake for building with shear wall.
3. The displacement in Model-2NL showed decrease by 28.36%, in Model-3NL by 35.10%, in Model-4NL by 32.49%, in Model-5NL by 36.90% as compared to Model-1NL.
4. Based on the Plastic hinge distribution, model-3NL was most efficient in reducing the seismic effect. Plastic hinges appeared on model-3NL was less than the other models and were in Immediate Occupancy.
   Hence, building with shear wall in Periphery can be concluded best among all other configurations.

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