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Seismic Performance Study of R.C. Buildings having Plan Irregularity using Pushover Analysis

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Abstract— The past earthquakes in which many reinforced concrete structures were severely damaged have indicated the need for evaluating the seismic adequacy of buildings. In particular, the seismic rehabilitation of older concrete structures in high seismicity areas is a matter of growing concern and an acceptable level of safety must be established. To make such an assessment, simplified linear-elastic methods are not adequate. Thus here we carried out the project using non-linear elastic method called as Pushover analysis which helps to assess the damage vulnerability of buildings. Earthquakes are most devastating natural hazards in terms of life and property of any region. The behavior of the structure greatly depends on size, shape and geometry of that structure i.e, vertical and horizontal irregularities and path of load transferring to the supporting ground. Irregularity in building attracts forces which lead to stress concentration at the point of irregularity; subsequently it leads to localized failure of that structure. The present study focuses on seismic performance of irregular RC models having irregularities i.e. plan re-entrant corner irregularity. For this purpose ETABS a finite element software has been used. Here 3-D RC models are modeled and analyzed for seismic zones IV and V. Roof displacement; Base shear carried; performance points; number of hinges formed are the parameters used to quantify the performance of the structure.

Key words: Plan Re-Entrant Corner, Irregularity, Pushover Analysis, Performance Point

I. INTRODUCTION

An earthquake is a manifestation of the rapid release of stress in the form of waves during the process of brittle rupture of rock. Earthquakes are the natural disasters of a generally unpredictable nature. A major earthquake is usually rather short in duration, often lasting only a few seconds. Although the magnitude of the earthquake is measured in terms of the energy released at the location of the ground fault, its critical effect on any given structure is determined by the ground movements at the location of that structure. The effect of these movements is affected mostly by the distance of the structure from the epicenter, but they are also influenced by the geological conditions prevalent directly beneath the structure and also by the nature of the entire earth mass between the epicenter and the structure [1].

The complexity of earthquake ground motion is primarily due to the factors such as the source effect, path effect and local site effect. Earthquake causes the ground to vibrate and in turn the structures supported on them are subjected to motion. Thus, the dynamic loading on the structure during an earthquake is not an external loading, but a loading arising due to the motion of support. Some of the factors contributing to the structural damage during earthquakes are plan and vertical irregularities, irregularity in strength and stiffness, mass irregularity, torsional irregularity, plan and vertical geometric irregularities etc. Therefore, it is very important to design the structure to resist moderate to severe earthquakes depending on its site location and importance. If the existing building is not designed to resist earthquakes, then its retrofitting becomes important [2].

Fig. 1.1: Ground storey collapse of a 4-storey building with open ground storey at 240 Park avenue south in New York, US. [12]

The procedures to determine lateral forces in the code, IS 1893 (Part 1): 2002 are based on the approximation effects, yielding can be accounted for linear analysis of the building using the design spectrum. This analysis is carried out either by modal analysis procedure or dynamic analysis procedure. A simplified method may also be adopted that will be referred as lateral force procedure or equivalent static procedure. The main difference between the equivalent static procedure and dynamic analysis procedure lies in the magnitude and distribution of lateral forces over the height of the buildings. In the dynamic analysis procedure, the lateral forces are based on properties of the natural vibration modes of the building, which are determined by distribution of mass and stiffness over height. In the equivalent lateral force procedure, the magnitude of forces is based on an estimation of the fundamental period and on the distribution of forces as given by a simple formula that is appropriate only for regular buildings. The following sections will discuss in detail the above-mentioned equivalent static and the dynamic procedure to determine the design lateral forces in detail [3].

In U.S itself, open ground storey structures collapsed as in Fig. 1.1. Although plan re-entrant corner irregularity did not lead to collapse of buildings, they did contribute to building damage. In Bhuj itself the plan irregularity which distributes the loads unevenly to the adjacent structural members of the building leads to the collapse of the building as in Fig. 1.2.

Many buildings with an open ground storey accommodated for parking were collapsed or severely damaged in Gujarat during 2001 Bhuj earthquake because of discontinuity in load path at lower, upper stories suggested by clients, architects due to site requirement and improper planning as shown in Fig. (1.1, 1.2).

Fig. 1.2: Ground storey collapse of a 4-storey building with plan irregularity at Bhuj. [14]

The following objects are defined to analyze the reason for failures from the past earthquakes and how these failures could be minimized in design consideration.

- To study the stiffness and ductility of the structure with plan re-entrant corner irregularity.
- To carry out non-linear static (pushover) analysis to evaluate the capacity and access the performance of reinforced concrete framed structure with plan re-entrant corner irregularity under ground motion using non-linear inelastic method called pushover analysis.
- To understand the seismic behavior of structures having irregularities in plan (Re-entrant corner irregularity) in different zones (i.e. IV and V).

II. METHODOLOGY

The present study is carried out to understand the non-linear behavior of reinforced concrete structures under earthquake loading of much higher magnitude that takes the structural frame to a level beyond the elastic limit and upto failure. For this purpose, incremental lateral load is applied to the RC model and pushover analysis is carried out using a suitable analysis and design software such as ETABS. The capacity curve is plotted which indicates the capacity of the model. The seismic demand curve is plotted depending on the magnitude of shaking. This graph suggests the seismic performance of a system and its adequacy against the design earthquake. Later an attempt has been made to understand the seismic behavior of some structures having plan re-entrant corners irregularity using pushover analysis in different zones (i.e. IV and V).

III. STRUCTURAL MODELING

A. Building With Plan Re-Entrant Corner Irregularity

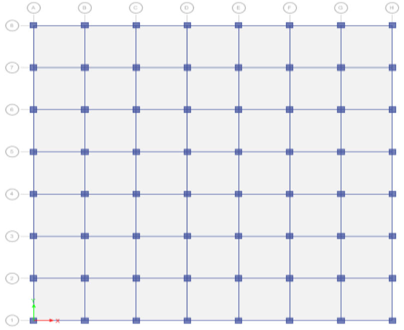
In the present study, buildings having different percentage of plan re-entrant corner irregularity have been considered. The modeling is carried out in ETABS v9.6 finite element software. The models are analyzed for different combinations of gravity and lateral loads and for different zones. Here all the buildings initially are 35m x 35m in plan having 7 bays of 5m each in both directions and later they are converted into L-shaped buildings stage by stage, by removing bays in both directions in a certain manner as shown in Fig. 3.1. The building parameters and earthquake parameters are shown in Table 3.1 & Table 3.2.

The plan configuration consists of

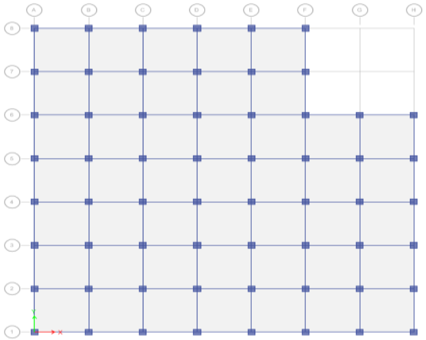
- Model 1- Building in square shape regular building
- Model 2- Building having Re-entrant corners with the projection of 28.5% in X-direction and 28.5% in Y-direction.
- Model 3- Building having Re-entrant corners with the projection of 57.14% in X-direction and 57.14% in Y-direction.
- Model 4- Building having Re-entrant corners with the projection of 71.4% in X-direction and 42.85% in Y-direction.
- Model 5- Building having Re-entrant corners with the projection of 42.85% in X-direction and 57.14% in Y-direction.
- Model 6- Building having Re-entrant corners with the projection of 71.4% in X-direction and 28.5% in Y-direction.

Parameter	Type / Value
Number of storey	Ground + 8 storey
Dimension of building	35m × 35m
Storey height (typical)	3.2m
Ground storey height	2m
Wall thickness	0.23mm
Imposed load (all floors)	4kN/m^2
Imposed load (terrace)	1.5kN/m^2
Materials	Concrete M30, reinforcement Fe500
Super dead load	2kN/m^2
Specific weight of wall	20 kN/m^3
Specific weight of RCC	25 kN/m^3
Size of column	0.65m × 0.65m
Size of beam	0.3m × 0.6m
Thickness of slab	0.150m

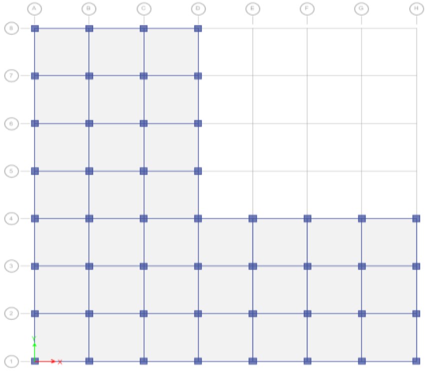
Table 3.1: Building Parameters Considered For Plan Irregular Models



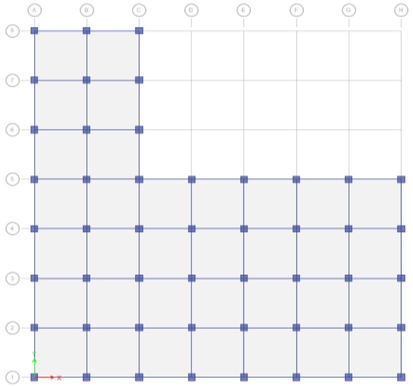
(Model-1)



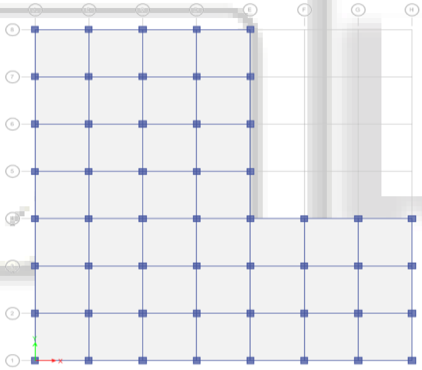
(Model-2)



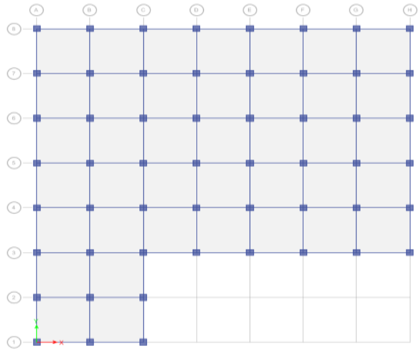
(Model-3)



(Model-4)



(Model-5)



(Model-6)

Fig. 3.1: Typical plans of plan irregular models considered for the study (M1-M6)

Parameter	Type / Value
Type of structure	Special RC moment resisting frame
Seismic zone	IV, V
Zone factor	0.24, 0.36
Importance factor	1
Damping	5%
Response reduction factor	5
Type of soil	Medium soil

Table 3.2: Earthquake Parameters Considered For Irregular Models

IV. RESULT AND DISCUSSION

A. *General*

The modeling and design is carried out, default plastic hinge properties available in ETABS 9.6 as per ATC-40 are assigned to the frame elements, and then the models are subjected to pushover analysis in sismic zone IV and V. The target displacement for pushover analysis is taken as 4% of the total height of the frame. Base shear (in terms of the pushover curves), roof displacement (in terms of the collapse displacement of the model), number and status of plastic hinges formed in the models are some of the parameters used to judge the performance of the building models.

B. *Performance Study of Plan Irregular Models*

1) *Pushover Curve Variation*

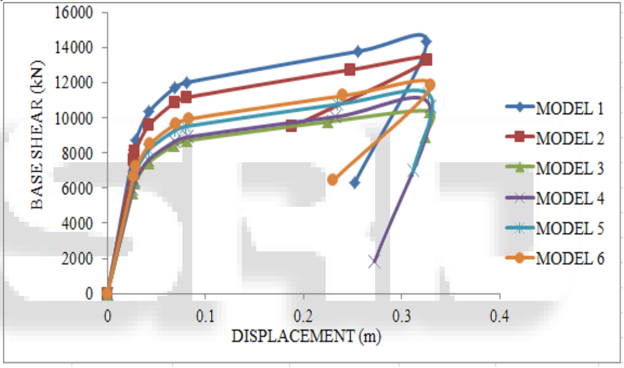


Fig. 4.1: Pushover curves for models with plan irregularity in push –X direction for zone IV.

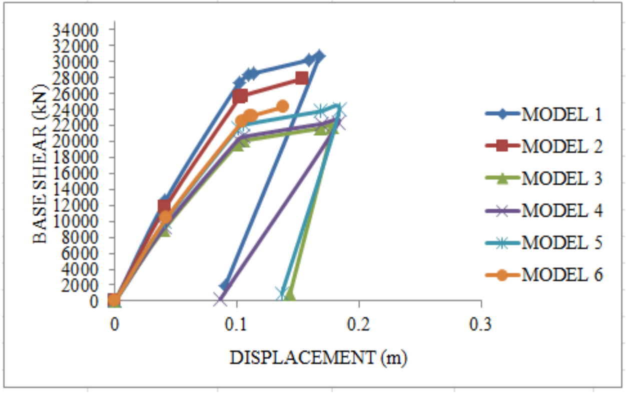


Fig. 4.2: Pushover curves for models with plan irregularity in push-X direction for zone V.

The pushover curves for the six models having plan irregularity are shown in Fig 4.1 and Fig 4.2 in X-direction for seismic zones IV and V respectively. The curves show similar features, as they are initially linear but start to deviate from linearity. The six curves from six models show a decrease in the lateral load carrying capacity, increase in the collapse displacement of the buildings well before the target displacement i.e 1.232m is reached, indicating the need for seismic retrofitting. From Fig. 4.1 and Fig 4.2, it is observed that the lateral load carrying capacity of the models reduces and collapse displacement increases as the building becomes more and more asymmetric in plan. Initial stiffness of the buildings is more in the seismic zone IV than the seismic zone V. The plan irregular models show higher displacements for lower base shears when compared to model 1 in both seismic zone IV & V. This shows that plan irregular models can deform largely for less amount of forces.

2) *Table of results from pushover analysis*

Model No	Pushover base shear V_{po} (kN)	Elastic base shear V_e (kN)	Ratio V_{po}/V_e	Collapse Disp. D (m)	Performance point	
					Base shear V (kN)	Roof disp.d (m)
1	14306.2	10937.7	1.30	0.325	12495.9	0.129
2	13296.7	10120.3	1.31	0.326	11608.7	0.129
3	10376.4	7668.1	1.35	0.328	9035.34	0.126
4	10619.3	7872.4	1.34	0.329	9246.84	0.126
5	11344.8	8485.5	1.34	0.327	9888.16	0.127
6	11833.6	8894.2	1.33	0.329	10316.7	0.129

Table 4.1: Pushover Analysis Results For Plan Irregular Models In Push-X Direction For Seismic Zone Iv

The results obtained from the pushover analysis of plan irregular models of seismic zone IV and V are represented in the Table 4.1 and Table 4.2 respectively.

Model 1 is taken as the benchmark as it is regular building, the pushover base shear for the models decreases and collapse displacement increases as the irregularity increases. The percentage decrease in pushover base shear for model 2, model 3, model 4, model 5, model 6 in comparison to model 1 in seismic zone IV are 7.05%, 27.46%, 25.77%, 20.69%, 17.28% respectively (Table 4.1). The percentage of decrease in pushover base shear as compared to model 1 is 9.27% for model 2, 29.17% for model 3, 27.08% for model 4, 21.91% for model 5, 20.75% for model 6 in seismic zone V (Table 4.2). From the Table 3.1 & Table 3.2 it was also noticed that model 1 shows less collapse displacement as it has more base shear compare to other irregular models respectively in seismic zone IV & V.

The elastic base shear for all the models is obtained from the equivalent static analysis as per IS-1893-Part I: 2002 and compared with the pushover analysis base shear. The results are presented in Table 4.1 and Table 4.2. For model 1 in seismic zone IV shows a collapse displacement of 0.3253 m and the pushover base shear of the structure was 14306.18 kN which is equivalent to 1.30 times that of the structure under elastic seismic design. For model 1 in seismic zone V shows a collapse displacement of 0.1674m and the pushover base shear of the structure was 30723.26 kN which is equivalent to 1.87 times that of the structure under elastic seismic design. It shows no large difference in lateral load carrying capacity of the buildings, indicating good structural behavior.

From Table 4.1 and Table 4.2 it is observed that, as the building becomes more and more asymmetric in plan, there is a decrease in the lateral load carrying capacity and a large amount of reserve strength of the structure will remain unutilized as indicated by the increase in the ratio (Vpo /Ve) from model 1 to model 6. This indicates that the models with plan irregularity fail earlier than the regular models.

From the Table 4.1 & Table 4.2 for the seismic zone IV & V respectively the base shear at performance point from model 1 to model 6 decreases as the irregularity increases. The percentage of variation of the base shear at performance point as compared to model 1 is 7.09% for model 2, 27.69% for model 3, 26% for model 4, 20.8% for model 5, 17.43% for model 6 for seismic zone IV. The percentage of variation of the base shear at performance point as compared to model 1 is 28.67% for model 3, 26.80% for model 4, 21.5% for model 5 in seismic zone V. It shows the performance point base shear decreases as the offset increases. The model 2 and model 6 didn't achieve the performance point as the capacity of the building doesn't meet the seismic demand. Hence among all the models considered above model 2 and model 6 in seismic zone V are more vulnerable.

For the building models considered in the study the base shear at performance point is 1.14, 1.15, 1.17, 1.17, 1.16 and 1.15 times higher in seismic zone IV for model 1 to model 6 respectively and 1.83, 1.86, 1.86 and 1.85 times higher in seismic zone V for model 1, 3, 4 and 5 respectively than the design base shear. Hence the building models are capable of resisting more base shear than it is designed to resist.

Model no	Pushover base shear V_{po} (kN)	Elastic base shear V_e (kN)	Ratio V_{po}/V_e	Collapse Disp. D (m)	Performance point	
					Base shear V (kN)	Roof disp d (m)
1	30723.3	16406	1.87	0.1674	30093	0.165
2	27874.9	14860	1.88	0.1540	N/A	N/A
3	21760.6	11502	1.89	0.1777	21464	0.161
4	22400.7	11808	1.90	0.1831	22026	0.162
5	23989.3	12728	1.88	0.1838	23617	0.163
6	24345.4	12941	1.88	0.1382	N/A	N/A

Table 4.2: Pushover analysis results for plan irregular models in push-X direction for seismic zone V

3) *Hinge Status*

HINGES	MODEL NO											
	1		2		3		4		5		6	
	NO	%	NO	%	NO	%	NO	%	NO	%	NO	%
A-B	4759	82.6	4356	81.2	3385	81.3	3466	81.3	3708	81.3	3870	81.3

B-IO	369	6.40	320	5.97	247	5.93	253	5.93	272	5.96	284	5.96
IO-LS	112	1.94	104	1.94	80	1.92	82	1.92	88	1.92	92	1.93
LS-CP	472	8.19	554	10.3	414	9.95	409	9.60	445	9.75	479	10.1
CP-C	0	0	0	0	0	0	0	0	0	0	0	0
C-D	0	0	5	0.09	0	0	1	0.02	1	0.02	0	0
D-E	48	0.83	21	0.39	34	0.81	49	1.15	46	1.0	35	0.73
>E	0	0	0	0	0	0	0	0	0	0	0	0
TOTAL	5760		5360		4160		4260		4560		4760	
PL	IO-LS		LS-CP		IO-LS		IO-LS		IO-LS		LS-CP	

Table 4.3: Number and status of hinges for the plan irregular models in X-direction for seismic zone IV

Table 4.3 and Table 4.4 shows the status of plastic hinges in different performance levels for the plan irregular building models considered in the present study. The hinges change their states namely- operational, immediate occupancy, life safety, collapse prevention, collapse-Reduced hazard and non- structural damage depending on the severity of the ground motion. Most of the designs are carried out such that the plastic hinges do not exceed the elastic limit if it exceed the status will be likely to worsen.

In the present work, it can be observed that the severity of plastic hinges formed increases from model 1 to other models as the building becomes more and more asymmetric in plan. This indicates that the asymmetry in plan of the building increases the severity of lateral forces on the buildings.

The total number of hinges formed varies from model to model that is mainly because of the shape of building the structural members i.e. beams and columns are getting reduced. The percentage of the hinges formed from model 1 to other irregular models at A-B and B-IO performance levels decreases and at IO-LS and LS-CP performance levels increases. This shows the more number of hinges formed in elastic range in A-B and B-IO performance levels. As same more number of hinges formed in inelastic range in IO-LS and LS-CP performance levels.

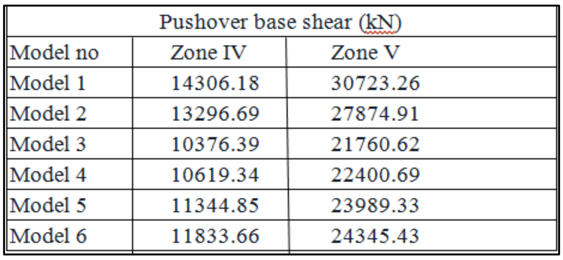
Performance level of all the building models is satisfactory and show different performance levels. Model 1 i.e. regular model shows the IO-LS performance level in both seismic zone IV and V suggesting safe under both zones. Model 3, model 4 and model 5 shows the performance levels at IO-LS in seismic zone IV and LS-CP in seismic zone V. This show the models are more severe to the lateral forces in seismic zone V than in zone IV. Model 2 and model 6 shows the performance levels at LS-CP in seismic zone IV and it doesn't reach the any performance level in seismic zone V. It shows model 2 and model 6 are the most vulnerable buildings considered in the study. Some of the frame elements have crossed the LS-Collapse Prevention (CP) performance level and are on the verge of failure and thus under incremental lateral loading the frames will undergo sufficient structural damage and thus they need to be retrofitted to perform better under increased lateral loading.

HINGES	MODEL NO											
	1		2		3		4		5		6	
	NO	%	NO	%	NO	%	NO	%	NO	%	NO	%
A-B	5272	91.5	4890	91.2	3776	90.7	3849	90.3	4137	90.7	4246	89.2
B-IO	164	2.84	82	1.52	83	1.99	98	2.30	91	1.99	155	3.25
IO-LS	171	2.96	246	4.58	161	3.87	150	3.52	162	3.55	209	4.39
LS-CP	145	2.51	141	2.63	139	3.34	161	3.77	168	3.68	149	3.13
CP-C	0	0	0	0	0	0	0	0	0	0	0	0
C-D	2	0.03	1	0.01	1	0.02	1	0.02	2	0.04	1	0.02
D-E	6	0.10	0	0	0	0	1	0.02	0	0	0	0
>E	0	0	0	0	0	0	0	0	0	0	0	0
TOTAL	5760		5360		4160		4260		4560		4760	
PL	IO-LS		Doesn't exist		LS-CP		LS-CP		LS-CP		Doesn't exist	

Table 4.4: Number and status of hinges for the plan irregular models in X-direction for seismic zone V

C. Pushover Results Comparison of Seismic Zones IV and V for Plan Irregular Models

1) Pushover Base Shear



Pushover base shear (kN)		
Model no	Zone IV	Zone V
Model 1	14306.18	30723.26
Model 2	13296.69	27874.91
Model 3	10376.39	21760.62
Model 4	10619.34	22400.69
Model 5	11344.85	23989.33
Model 6	11833.66	24345.43

Table 4.5: Pushover base shear for plan irregular models in push-X direction in seismic zone IV and V

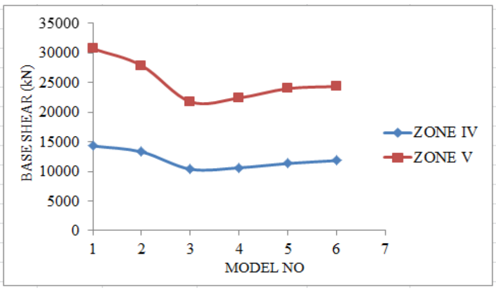


Fig. 4.3: Pushover base shear variation for models with plan irregularity in push –X direction in seismic zone IV and V

The Table 4.5 and Fig. 4.3 shows the pushover base shear for plan irregular models in seismic zone IV and seismic zone V respectively. The pushover base shear in seismic zone V are 2.14 times for model 1, 2.09 times for model 2, 2.09 times for model 3, 2.10 times for model 4, 2.11 times for model 5, 2.05 times for model 6 higher than the pushover base shear in seismic zone IV. This shows the base shear will increases when the zone changes from zone IV to zone V.

2) *Performance Point Base Shear*

Performance point base shear (kN)		
Model no	Zone IV	Zone V
Model 1	12495.91	30093.3
Model 2	11608.75	N/A
Model 3	9035.34	21464.6
Model 4	9246.84	22026.3
Model 5	9888.16	23617.2
Model 6	10316.76	N/A

Table 4.6: Performance point base shear for plan irregular models in push-X direction in seismic zone IV and V

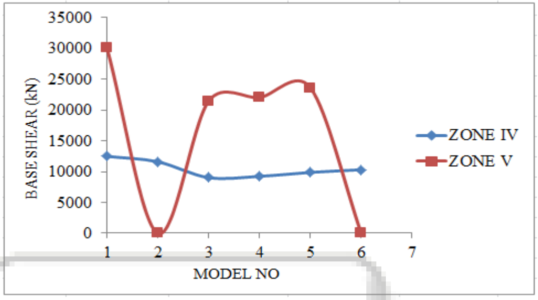


Fig. 4.4: Performance point base shear variation for models with plan irregularity in push –X direction in seismic zone IV and V

The Table 4.6 and Fig. 4.4 shows the base shear at performance point for plan irregular models in seismic zone IV and seismic zone V respectively. The base shear at performance point in seismic zone V are 2.40 times for model 1, 2.37 times for model 3, 2.38 times for model 4, 2.38 times for model 5 higher than the base shear at performance point in seismic zone IV. This shows the base shear will increases when the zone changes from zone IV to zone V. The model 2 and model 6 didn’t achieve any performance point.

3) *Collapse Displacement*

Collapse displacement (m)		
Model no	Zone IV	Zone V
Model 1	0.3253	0.1674
Model 2	0.3265	0.154
Model 3	0.3285	0.1777
Model 4	0.3291	0.1831
Model 5	0.3277	0.1838
Model 6	0.3294	0.1382

Table 4.7: Collapse displacements for plan irregular models in push-X direction in seismic zone IV and V

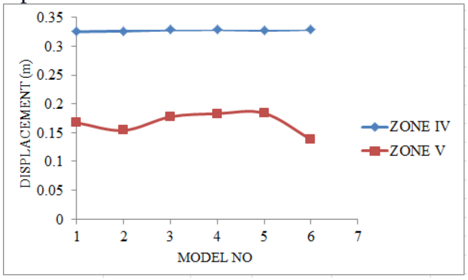


Fig. 4.5: Collapse displacement variation for plan irregular models in push –X direction in seismic zone IV and V.

The Table 4.7 and Fig. 4.5 shows the collapse displacement for plan irregular models in seismic zone IV and seismic zone V respectively. The displacements for the models in seismic zone IV are higher than the displacements in seismic zone V. This show the displacements for all the models will decreases when the zone changes from zone IV to zone V, because of the increase in the base shear. It also shows the same models in seismic zone V has less ductility compared to the seismic zone IV.

4) *Performance Point Displacement*

Performance point displacement (m)		
Model no	Zone Iv	Zone V
Model 1	0.129	0.165
Model 2	0.129	N/A
Model 3	0.126	0.161
Model 4	0.126	0.162
Model 5	0.127	0.163
Model 6	0.129	N/A

Table 4.8: Performance point displacements for plan irregular models in push-X direction in seismic zone IV and V

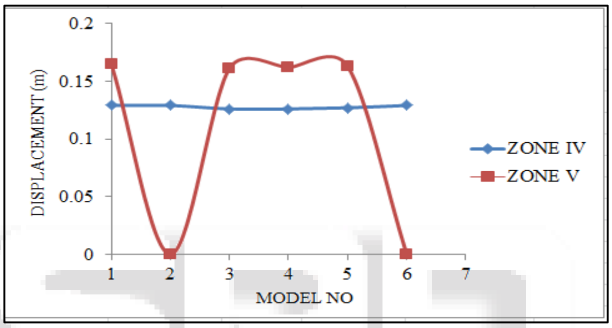


Fig. 4.6: Performance point displacements variation for models with plan irregularity in push –X direction in seismic zone IV and V

The Table 4.8 and Fig. 4.6 shows the displacement at performance point for plan irregular models in seismic zone IV and seismic zone V respectively. The displacements at performance point in seismic zone V are higher than the displacements at performance point in seismic zone IV. This shows the displacement at performance point will increases when the zone changes from zone IV to zone V.

V. CONCLUSIONS

The following conclusions were drawn from the present study:

1) As the buildings become more and more asymmetric in either plan, there is an increase in the amount of reserve strength of the buildings. This reserve strength will remain unutilized and is wasted. This means that the buildings with asymmetric plan or elevation will fail earlier than the symmetric buildings.
2) For the building models considered in the study having plan or elevation irregularity, the base shear at performance point is higher than the design base shear in seismic zone IV and V. Hence the building models are capable of resisting more the base shear than it is designed.
3) All the plan irregular models either in seismic zone IV or seismic zone V show different performance levels. This shows that, performance levels of the

buildings changes as the asymmetry increases either in plan or as seismic zones changes from IV to V.

4) The pushover base shear and base shear at performance point decreases as the buildings become more and more asymmetric in plan.
5) The collapse displacement increases as the buildings become more and more asymmetric in plan. This shows that irregular models in plan have less stiffness than the regular model.
6) The pushover base shear and base shear at performance point for the same models in seismic zone V increases than in the seismic zone IV. This shows that pushover base shear and performance point base shear increases as the seismic zone changes i.e. from zone IV to zone V.
7) The collapse displacement for the same models in seismic zone V is less than in the seismic zone IV. This shows that collapse displacement decreases as the seismic zone changes i.e. from zone IV to zone V.
8) The displacement at performance point for the same models in seismic zone V increases than in the seismic zone IV. This shows that displacement at performance point increases as the seismic zone changes i.e. from zone IV to zone V.
9) It is observed that the percentage of formation of severity of plastic hinges increases as the building becomes more and more asymmetric in plan. Thus, irregularity in plan leads to the severity of lateral forces on the building this may result in its failure.

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