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PERFORMANCE BASED SEISMIC ANALYSIS OF AN UNSYMMETRICAL BUILDING USING PUSHOVER ANALYSIS

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ABSTRACT

The study summarizes state-of-the-art of the review in the performance based seismic analysis of unsymmetrical building. Earthquakes can create serious damage to structures. The structures already built are vulnerable to future earthquakes. The damage to structures causes deaths, injuries, economic loss, and loss of functions. Earthquake risk is associated with seismic hazard, vulnerability of buildings, exposure. Seismic hazard quantifies the probable ground motion that can occur at site. Vulnerability of building is important in causing risk to life.

In the present study, analytical investigation of an unsymmetrical building (SMRF Type) situated in seismic zone v of India, in accordance with IS 1893-2002(part-1), is taken as an example and the various analytical approaches (linear static and nonlinear static analysis) are performed on the building to identify the seismic demand and also pushover analysis is performed to determine the performance levels, and Capacity spectrum of the considered, also Base shear is compared for G+3 and G+5 storey building models in both X and Y directions by using finite element software package ETAB's 9.7 version.

Key words: Earthquake, Pushover analysis, Unsymmetrical building, Performance levels, Capacity, Demand, Performance point.

INTRODUCTION

Earthquakes result from the sudden movement of tectonic plates in the earth's crust. The movement takes place at fault lines, and the energy released is transmitted through the earth in the form of waves that causes ground motion many miles from the epicenter. Regions adjacent to active fault lines are the most prone to experience earthquake. These waves arrive at various instants of time, have different amplitudes and carry different levels of energy. The size of the earthquake can be measured by Magnitude (M) which was obtained by recording the data of motions on seismograms. This can be measured by MMI scale (Modified Mercalie Intensity).

The Buildings, which appeared to be strong enough, may crumble like houses of cards during earthquake and deficiencies may be exposed. Experience gained from the Bhuj earthquake of 2001 demonstrates that the most of buildings collapsed were found deficient to meet out the requirements of the present day codes.

PERFORMANCE BASED SEISMIC APPROACH

Performance based seismic engineering is the modern approach to earthquake resistant design. The promise of performance-based seismic engineering (PBSE) is to produce structures with predictable seismic performance. Two key elements of a performance based design procedure are demand and capacity.

Capacity: The overall capacity of a structure depends on the strength and deformation capacity of the individual components of the structure. In order to determine capacities beyond the elastic limits, some form of nonlinear analysis, such as the pushover procedure, is required.

Demand: Ground motion during an earthquake produces complex horizontal displacement patterns in the structures. It is impractical to trace this lateral displacement at each time-step to determine the structural design parameters

METHODS OF SEISMIC EVALUATION

There are different methods of analysis provides different degrees of accuracy. Currently seismic evaluation of buildings can be divided into two categories

- Qualitative method
- Analytical method

QUALITATIVE METHODS

The method generates a Structural Score 'S', which consists of a series of 'scores' and modifiers based on building attributes that can be seen during building survey. The Structural Score 'S' is related to probability of the building sustaining life-threatening damage should a severe earthquake in the region occur. A low S score suggests that the building is vulnerable and needs detailed analysis, whereas a high 'S' score indicates that the building is probably safe for defined earthquake loads. Thus, the expression for structural score is:

(Structural score) = (Basic Structural Hazard) + (Performance Modification Factor)

S = BSH + PMF

ANALYTICAL METHODS

Analysis methods are broadly classified as linear static, linear dynamic, nonlinear static and nonlinear dynamic methods.

LINEAR STATIC ANALYSIS OR (EQUIVALENT ANALYSIS)

Here the total design lateral force or design base shear along any principal direction is given in terms of design horizontal seismic coefficient and seismic weight of the structure. Design horizontal seismic coefficient depends on the zone factor of the site, importance of the structure, response reduction factor of the lateral load resisting elements and the fundamental period of the structure. The procedure generally used for the equivalent static analysis is explained below:

(i) Determination of fundamental natural period (Ta) of the buildings $Ta = 0.075h^{0.075}$ Moment resisting RC frame building without brick infill wall.

$Ta = 0.085h^{0.075}$ Moment resisting steel frame building without brick infill walls

$Ta = 0.09h\ /\sqrt{d}$ All other buildings including moment resisting RC frame building with brick infill walls.

Where,

h - Is the height of building in meters.

d- Is the base dimension of building at plinth level in m, along the considered direction of lateral force.

(ii) Determination of base shear (V_B) of the building

$V_{B} = Ah \times W$

Where,

Ah=ZISa/2Rg is the design horizontal seismic coefficient, which depends on the seismic zone factor (Z), importance factor (I), response reduction factor (R) and the average response acceleration coefficients (Sa/g). Sa/g in turn depends on the nature of foundation soil (rock, medium or soft soil sites), natural period and the damping of the structure.

(iii) Distribution of design base shear

The design base shear V_B thus obtained shall be distributed along the height of the building as per the following expression:

$$Q_i = V_B \frac{W_i h_i^2}{\sum_{i=1}^{n} W_i h_i^2}$$

Where, Qi is the design lateral force, Wi is the seismic weight, hi is the height of the i^{th} floor measured from base and n is the number of stories in the building.

NONLINEARSTATIC ANALYSISOR (PUSHOVER ANALYSIS)

Pushover analysis is one of the methods available to understand the behavior of structures subjected to earthquake forces. As the name implies, it is the process of pushing horizontally with a prescribed loading pattern incrementally until the structure reaches a limit state (ATC-40 1996).

The Various Performance levels are tabulated below in Table 1, with their effects on both Structural and Non-structural elements.

MODELING AND NUMERICAL STUDY OF AN UNSYMMETRICAL BUILDING USING PUSHOVER ANALYSIS

In this study, nonlinear static pushover analysis was used to evaluate the seismic performance of the structures. The numerical analysis was done using ETABS 9.7 and guidelines of ATC-40 and FEMA 356 were followed. The overall performance evaluation was done using capacity curves, storey displacements and ductility ratios. Plastic hinge hypothesis was used to capture the nonlinear behavior according to which plastic deformations are lumped on plastic hinges and rest of the system shows linear elastic behavior. The building parameters considered for the study are tabulated in Table 2

Table 1: Performance levels

Performance levels	Structural performance	Non-structural performance
Operational (O)	Very light damage No permanent drift Substantially original strength and stiffness	Negligible damage. Power & other utilities are Available
Immediate Occupancy(IO)	Light damage, No permanent drift, Substantially original strength & stiffness, Minor cracking, Elevators can be restarted, Fire protection operable.	Equipment's & content secure but may not operate due to mechanical/utility failure
Life Safety (LS)	Moderate damage, Some permanent drift, Residual strength & stiffness in all stories, Gravity elements function, Building may be beyond economical repair.	Falling hazard mitigated but extensive systems damage.
Collapse Prevention (CP)	Severe damage, Large permanent drifts, Little residual strength & Stiffness, Gravity elements function, Some exits blocked, Building near collapse.	Extensive damage

Table 2: Parameters considered for the study

STRUCTURE TYPE	SMRF	
RESPONSE REDUCTION FACTOR	5	
SEISMIC ZONE	ZONE-V	
SEISMIC ZONE FACTOR	0.36	
HEIGHT OF THE BUILDING	3.0 m	
SOIL CONDITION	Medium	
PLAN SIZE	35.25 m X 34.21 m	
THICKNESS OF SLAB	0.125 m	
BEAM SIZE	300 mm X 500 mm	
COLUMN SIZE	500 mm X 500 mm	
LIVE LOAD	3.5 kN/m^2	
FLOOR FINISH	1k N/m^2	
WALL LOAD	12Kn/m	
MATERIAL PROPERTIES	Concrete grade	Steel grade
	M 30	Fe 415

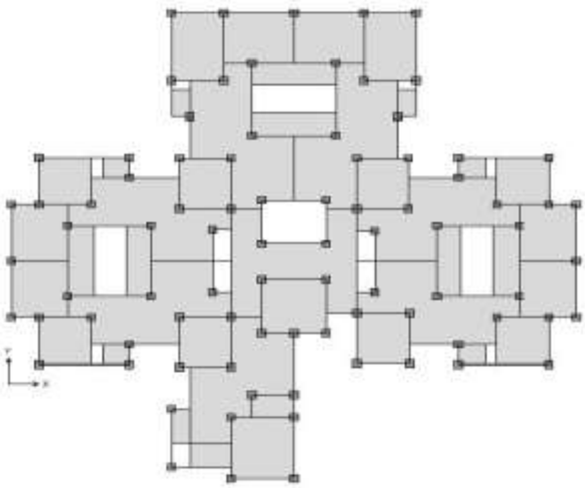

Fig 1 Plan of unsymmetrical building model

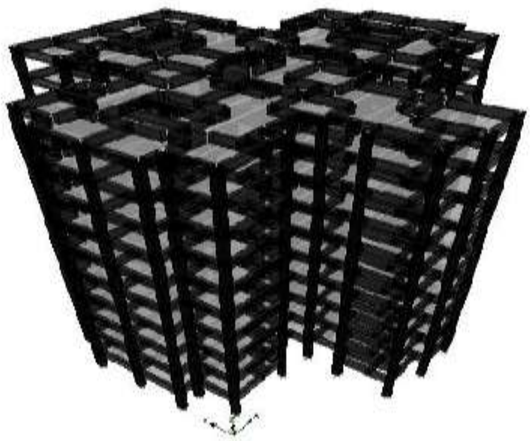

Fig 2 3-D view of unsymmetrical building model

The plan layout and 3D view of all storey building are as shown in the below Fig 2 and Fig 3 respectively

ANALYSIS AND RESULTS

PUSHOVER ANALYSIS PROCEDURE

1. Create a 3D model for the Building.
2. Define all the material properties, frame sections, load cases and mass source.
3. Assign hinge properties available in ETABS Nonlinear as per ATC-40 to the frame elements. For the beam default hinge that yields based upon the flexure (M3) and shear(V2) is assigned, for the column default hinge that yields based upon the interaction of the axial force and bending moment (P M2 M3) is assigned, and for the equivalent diagonal strut default hinge that yields based upon the axial force (P) only is assigned.
4. Define three static pushover cases. In the first case gravity load is applied to the structure, in the second case lateral load is applied to the structure along longitudinal direction and in the

third case lateral load is applied to the structure along transverse direction.

5. After the linear static analysis, design of the building as per IS-456 2000, is performed for the defined load combinations, so that the hinge properties are generated for the assigned frame elements.

6. After the design of the building, the static pushover analysis is carried out to establish the performance point.

7. Push over curves and Performance levels for G+3 and G+5 storey building models in PUSH X direction

The capacity of the building is determined by pushover curve. That is the overall capacity of a structure depends on the strength and deformation capacities of the individual components of the structure. In order to determine capacities beyond the elastic limits, some form of nonlinear analysis is required.

Table: 3 Performance levels for G+3 building model in longitudinal direction PUSHX

Step	Displacement	Base Force	A-B	B-IO	IO-LS	LS-CP	CP-C	C-D	D-E	>E	TOTAL
0	0	0	2288	4	0	0	0	0	0	0	2292
1	0.0045	2766.9111	2120	172	0	0	0	0	0	0	2292
2	0.0103	5268.6465	1943	349	0	0	0	0	0	0	2292
3	0.025	7918.5913	1797	190	293	12	0	0	0	0	2292
4	0.0584	11007.5176	1766	206	302	18	0	0	0	0	2292
5	0.0619	11196.4248	1755	211	303	23	0	0	0	0	2292
6	0.0636	11245.9756	1711	115	142	323	0	1	0	0	2292
7	0.1126	12005.5195	1711	115	140	325	0	0	1	0	2292
8	0.1126	11870.6475	1711	115	139	326	0	0	1	0	2292
9	0.1127	11879.5352	1711	115	138	327	0	0	1	0	2292
10	0.1128	11890.2793	1711	115	138	327	0	0	1	0	2292
11	0.1129	11894.8975	1711	115	137	328	0	0	1	0	2292
12	0.1133	11902.5	2292	0	0	0	0	0	0	0	2292

- The highlighted yellow colour column in the above Table 3 indicates the range of overall performance level of G+3 storey building model in PUSH X direction which lies in LS-CP.
- The highlighted green colour row represents the ultimate capacity of G+3 storey building model in PUSH X direction.

Table: 4 Performance levels for G+5 building model in longitudinal direction PUSHX

Step	Displacement	Base Force	A-B	B-IO	IO-LS	LS-CP	CP-C	C-D	D-E	>E	TOTAL
0	0	0	3818	2	0	0	0	0	0	0	3820
1	0.0071	2311.2998	3585	235	0	0	0	0	0	0	3820
2	0.0162	4380.1021	3275	544	1	0	0	0	0	0	3820
3	0.046	6814.8833	3071	274	438	37	0	0	0	0	3820
4	0.1063	8916.5547	2971	281	323	245	0	0	0	0	3820
5	0.1347	9574.8281	2964	285	313	258	0	0	0	0	3820
6	0.1368	9605.626	3820	0	0	0	0	0	0	0	3820

- The highlighted yellow colour column in the above Table 3 indicates the range of overall performance level of G+5 storey building model in PUSHX direction which lies in LS-CP.
- The highlighted green colour row represents the ultimate capacity of G+5 storey building model in PUSH X direction

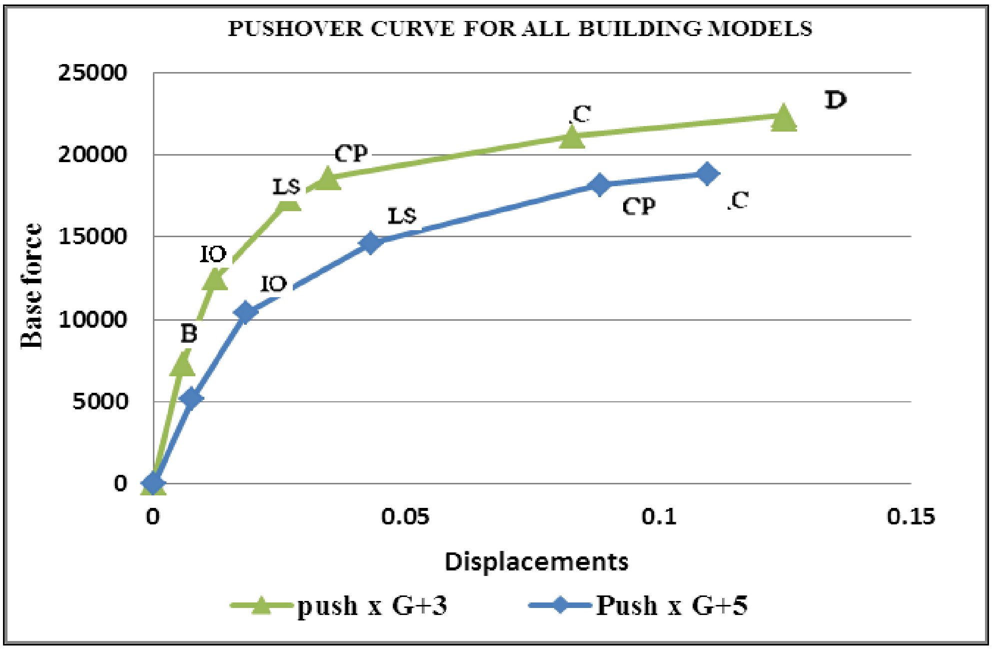

Fig: 3 Pushover curve in longitudinal direction PUSHX

Here the Fig 5 shows the obtained pushover curve or capacity curve for G+3 and G+5 storeys models with their performance levels marked in PUSH X direction.

In the above Fig 5 the notations indication: A & B – Operational level, IO – Immediate occupancy, LS – Life safety, CP – Collapse prevention, C – Ultimate capacity for pushover analysis, D – Residual strength for pushover analysis

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LOCATION OF HINGE STATUS

- From the Table 3 and Table 4, where in performance levels and location of plastic hinges are observed in G+3 and G+5 storey building models, it is seen that the pushover analysis was including twelve steps. It has been observed that, on subsequent push to building, hinges started forming in beams first. Initially hinges were in B-IO stage and subsequently proceeding to IO-LS and LS-CP stage. At performance point, where the capacity and demand meets, that is at fourth step, out of 2292 assigned hinges 1766 were in A-B stage, 206, 302, and 18 hinges are in BIO, IO-LS and LS-CP stages respectively. As at performance point, hinges were in LS-CP range, overall performance of building is said to be within Life safety and Collapse prevention, for G+3 storey building model for PUSH X direction.
- Similarly for G+5 storeys building model pushover analysis was including six steps. Here at performance point, where the capacity and demand meets, that is at fourth step, out of 3820 assigned hinges 2971 were in A-B stage, 281, 323, and 245 hinges are in B-IO, IO-LS and LS-CP stages respectively. As at performance point, hinges were in B-IO range, overall performance of building is said to be within Life safety and Collapse prevention, for PUSH X direction

Performance point of the building using capacity spectrum method.

Performance point can be obtained by superimposing capacity spectrum and demand spectrum and the intersection point of these two curves is performance point. Fig 6 shows superimposing demand spectrum and capacity spectrum.

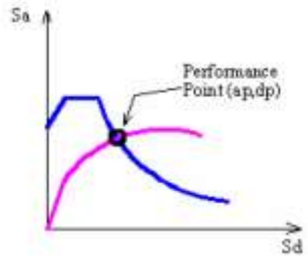

Fig: 4 Performance point

The Table 4 shows the Data for Performance point in longitudinal direction (PUSH X) for G+3 and G+5 storey building models

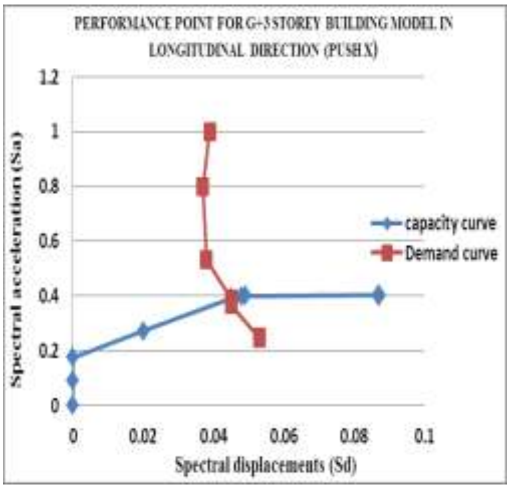

Fig: 5 Performance point for G+3 storey building model by combining capacity spectrum curve and demand spectrum curve in Push X direction

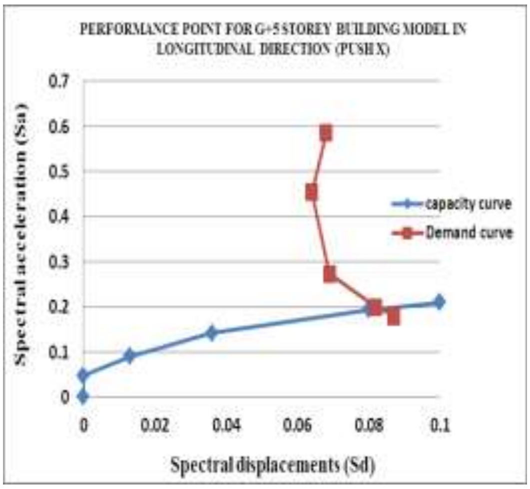

Fig: 6 Performance point for G+5 storey building model by combining capacity spectrum curve and demand spectrum curve in push x direction

Table: 5 Data for Performance point in longitudinal direction (PUSH X) for G+3 and G+5 storey building models

STOREY NUMBERS	PERFORMANCE POINT FOR PUSH X	
	Performance point in (kN)	Displacements in (meters)
G+3 Storey	10964.22	0.058
G+5 Storey	9006.722	0.110

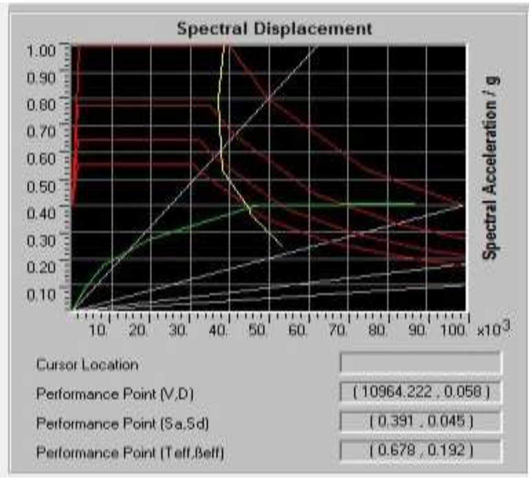

Fig: 7 Capacity spectrum for G+3 building model In PUSH X direction

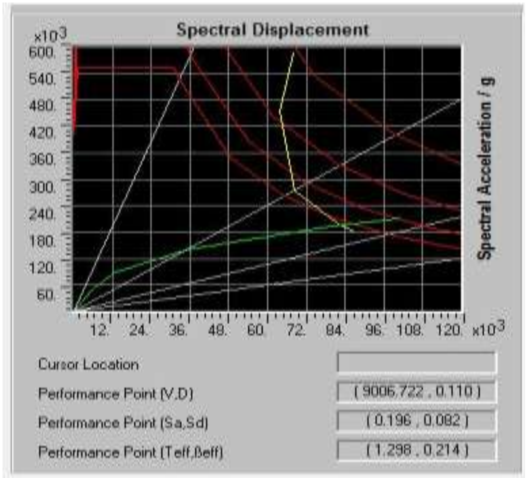

Fig: 8 Capacity spectrum forG+5 building model in PUSH X direction

Table 6 Data for capacity spectrum curve for G+3 storey building model in PUSH X direction

Step	T_{eff}	β_{eff}	Sd(C)	Sa(C)	Sd(D)	Sa(D)	ALPHA	PF*ϕ
0	0.394	0.05	0	0	0.039	1	1	1
1	0.394	0.05	0	0.092	0.039	1	0.805	1.257
2	0.432	0.087	0	0.175	0.037	0.797	0.802	1.261
3	0.538	0.158	0.02	0.272	0.038	0.532	0.777	1.279
4	0.68	0.193	0.045	0.393	0.045	0.391	0.747	1.292
5	0.695	0.201	0.048	0.399	0.045	0.376	0.749	1.293
6	0.704	0.207	0.049	0.4	0.045	0.368	0.751	1.293
7	0.929	0.276	0.087	0.404	0.053	0.248	0.793	1.299
8	0.935	0.279	0.087	0.399	0.053	0.245	0.793	1.299
9	0.935	0.279	0.087	0.4	0.053	0.245	0.793	1.299
10	0.935	0.279	0.087	0.4	0.053	0.245	0.794	1.299
11	0.935	0.279	0.087	0.4	0.053	0.245	0.794	1.298
12	0.937	0.279	0.087	0.4	0.053	0.245	0.794	1.298

Table 7 Data for capacity spectrum curve for G+5 storey building model in PUSH X direction

Step	Teff	β eff	Sd(C)	Sa(C)	Sd(D)	Sa(D)	ALPHA	PF*ϕ
0	0.683	0.05	0	0	0.068	0.585	1	1
1	0.683	0.05	0	0.047	0.068	0.585	0.782	1.293
2	0.753	0.09	0.013	0.09	0.064	0.454	0.783	1.285
3	1.006	0.177	0.036	0.142	0.069	0.273	0.768	1.286
4	1.284	0.212	0.08	0.194	0.082	0.2	0.735	1.335
5	1.386	0.224	0.1	0.21	0.087	0.181	0.731	1.345
6	1.395	0.225	0.102	0.21	0.087	0.179	0.732	1.346

The above shown Table 5 and Table 6 where in the first two columns shaded in blue colour are Sa(C) and Sd(C) gives the Capacity curve. Thus by plotting spectral acceleration (Sa) versus spectral displacement (Sd) we obtain capacity curve as shown in Fig 7 and Fig 8 above. Similarly the next two shaded red ascent colour columns are Sa (D) and Sd (D) gives the Demand curve. Thus by plotting spectral acceleration (Sa) versus spectral displacement (Sd), we obtain demand curve as shown in Fig 7 and Fig 8 above. Thus by combining these Capacity and Demand curves we obtain the Performance point at their intersections. Also we have obtained the capacity spectrum for G+3 and G+5 storey models in PUSH X direction as shown in Fig 9 and Fig 10 as shown above

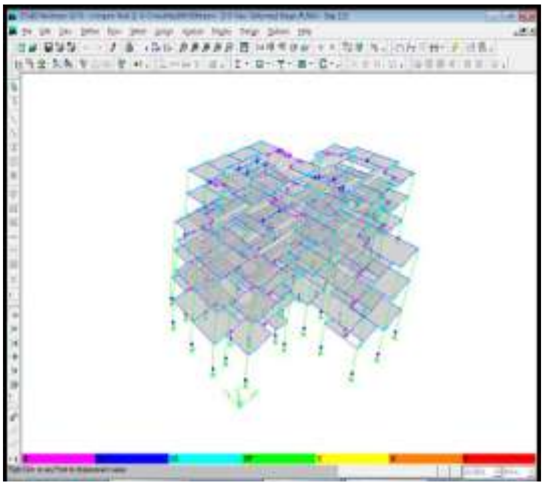

Fig: 9 Location of plastic hinges formed for G+3 building model

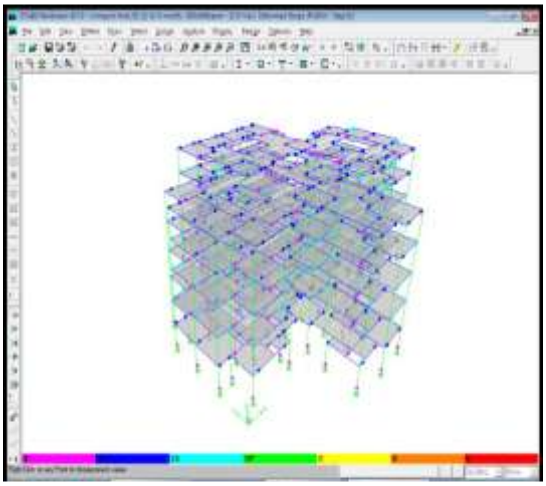

Fig: 10 Location of plastic hinges formed for G+5 building model

The above Fig 9 and Fig 10 shows the location of plastic hinges formed for different performance levels in their final step of analysis for PUSH X direction.

Table 8 Comparison of Base shear for all three building models in both longitudinal and transverse direction for both equivalent static analysis and pushover analysis

STOREY NUMBERS	BASE SHEAR IN (kN)			
	EQX	PUSH X	EQY	PUSH Y
G+3 Storey	3299	11902.5	3298.98	12512.41
G+5 Storey	5546.68	9605.63	5546.68	10564.92

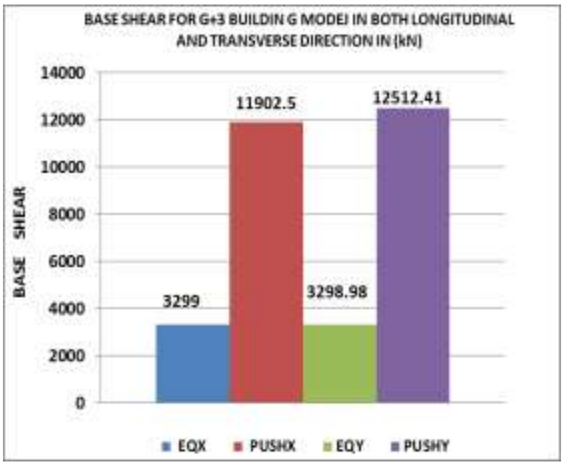

Fig: 11 Comparision of Base shear for G+3 building model for both linear static and non-linear static analysis

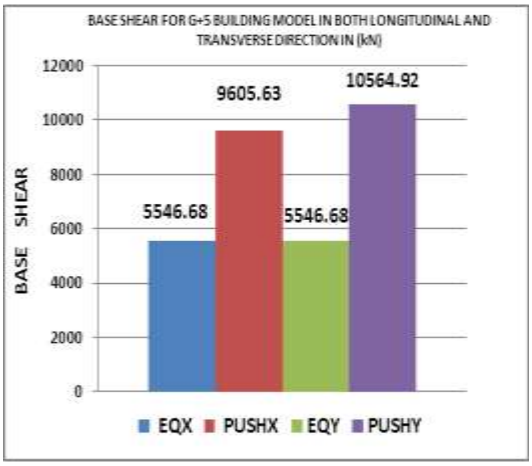

Fig: 12 Comparision of Base shear for G+5 building model both linear static and non-linear static analysis

The above table 8 shows comparision for Base shear values which is plotted in Fig 11 and Fig 12.

CONCLUSION

1. The results obtained in terms of pushover demand, capacity spectrum and plastic hinges gave an insight into the real behavior of structures.
2. The overall performance level for G+3 and G+5 storey building models were found between LS-CP (life safety to collapse prevention). The hinge status and location has been determined and it is noted that most of the hinges begin to form in B-IO range onwards.
3. The performance point is determined for G+3 and G+5 storey building models in PUSH X direction.
4. The result also shows that, Capacity of the buildings may be significant but the seismic demand varies with respect to the building height.
5. Base shear increases with the increase in mass and number of storeys of building, also base shear obtained from pushover analysis is much more than the base shear obtained from equivalent static analysis.

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