ISSN: 2278-0181
ESDST - 2017 Conference Proceedings

Analytical Investigation on Retrofitting of A Multistoried R.C.C. Framed Building Using Pushover Technique

Guljit Singh
Assistant Professor,
Department of Civil Engineering,
Baba Banda Singh Bahadur Engineering College,
Fatehgarh Sahib, INDIA 140 407

Jagmohan Singh
Assistant Professor,
Department of Civil Engineering,
Baba Banda Singh Bahadur Engineering College,
Fatehgarh Sahib, INDIA 140 407

Simranpreet Singh
Assistant Professor,
Department of Civil Engineering,
Baba Banda Singh Bahadur Engineering College,
Fatehgarh Sahib, INDIA 140 407

***Abstract* - The scope of present study aims at determining the earthquake load carrying of a building and thereby improving its seismic load carrying capacity by providing certain adequate provisions of retrofitting. The performance based seismic engineering technique known has Non-Linear Static Pushover analysis procedure has been effectively used in this regard. The pushover analysis has been carried out using SAP2000, a product of Computers and Structures International. A total of 28 cases for a particular six storey building located in Zone-IV have been analyzed, considering retrofitting of different structural elements, i.e. Beams and Columns, in different combinations as well as at different storey levels. The retrofitting is started from the bottom most storey and subsequently moving towards the top most storey. The response of the building for each case at each storey level is recorded.**

The results of analysis are compared in terms of base shear and storey displacements.

Keywords: Performance-based seismic engineering (PBSE), Retrofitting, nonlinear static pushover analysis, Performance level, Finite element analysis, Sap 2000.

I. Introduction to Pushover Analysis

In Pushover analysis, a static horizontal force profile, usually proportional to the design force profiles specified in the codes, is applied to the structure. The force profile is then incremented in small steps and the structure is analyzed at each step. As the loads are increased, the building undergoes yielding at a few locations. Every time such yielding takes place, the structural properties are modified approximately to reflect the yielding. The analysis is continued till the structure collapses, or the building reaches certain level of lateral displacement.

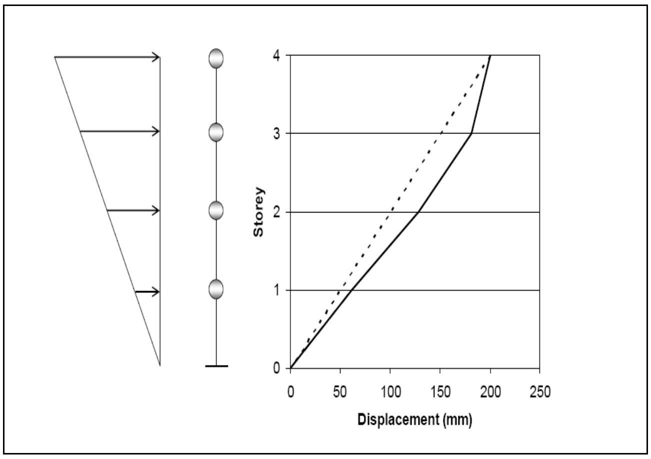


Fig. 1. Inverted Triangular Loading for Pushover

A. *Need for Pushover Analysis*

Conventionally, seismic assessment and design has relied on linear or equivalent linear (with reduced stiffness) analysis of structural systems. In this approach, simple models are used for various components of the structure, which is subjected to seismic forces evaluated from elastic or design spectra, and reduced by force reduction (or behavior) factors. The ensuing displacements are amplified to account for the reduction of applied forces.

B. *Description of Pushover Analysis*

The non-linear static pushover procedure was originally formulated and suggested by two agencies namely, federal emergency management agency (FEMA) and applied technical council (ATC), under their seismic rehabilitation programs and guidelines. This is included in the documents FEMA-273, FEMA-356 and ATC-40.

Methods and design criteria to achieve several different levels and ranges of seismic performance are defined in FEMA 273. The four Building Performance Levels are Collapse Prevention, Life Safety, Immediate Occupancy, and Operational. These levels are discrete points on a continuous scale describing the building's expected performance, or alternatively, how much damage, economic loss, and disruption may occur.[4]

The three Structural Performance Levels and two Structural Performance Ranges consist of:

S-1: Immediate Occupancy Performance Level

S-2: Damage Control Performance Range (extends between Life Safety and Immediate Occupancy Performance Levels)

S-3: Life Safety Performance Level

S-4: Limited Safety Performance Range (extends between Life Safety and Collapse Prevention Performance Levels)

S-5: Collapse Prevention Performance Level

In addition, there is the designation of S-6, Structural Performance Not considered, to cover the situation where only nonstructural improvements are made.

The four Nonstructural Performance Levels are:

N-A: Operational Performance Level

N-B: Immediate Occupancy Performance Level

N-C: Life Safety Performance Level

N-D: Hazards Reduced Performance Level

In addition, there is the designation of N-E, Nonstructural Performance Not Considered, to cover the situation where only structural improvements are made.

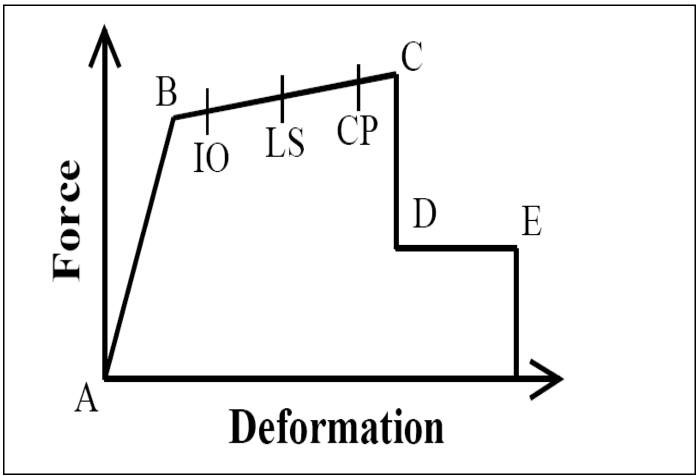


Fig. 2. Force - Deformation Curve [4]

II. PREVIOUS STUDIES

According to Jong-Wha Bai (August 2002), Seismic retrofitting is an effective method of reducing the risks for existing seismically deficient structures. Numerous intervention techniques are available for improving the seismic behavior of RC building structures. It is important to obtain accurate as-built information and analytical data to perform a seismic evaluation of the existing structure and to select the appropriate retrofitting strategy. A number of experimental and analytical studies focused on seismic retrofitting techniques and extensive seismic damage control activities in practice have contributed to the present state of development. Further research should be conducted to improve the selection of appropriate retrofit techniques using criteria based on performance, economy and constructability[16].

According to Gajjar R. K. et al (2002), pushover Analysis results from powerful softwares can be transferred to virtual reality platforms in order to make the outputs more user friendly and easy to understand, besides making it very simple to re-analayze and observe the end results any number of times, till the user is able to grasp the full impact of his final decision. Virtual reality platforms provide a fantastic opportunity as add-on modules to complex analysis software which generally need a high degree of decision and understanding of behaviour of the structure under consideration even prior to modeling it on the desktop. Instant graphical outputs in virtual reality, bring into focus the errors in primary configuration details, in modeling or in designing. The user can therefore afford to make mistakes and correct them at the touch of a few strokes on the keyboard. As the concept is still in its infancy, and as 3D graphics have been hitherto limited to the highly sophisticated domain of movie animation, the computer time and effort required in creating real-life images seem extremely daunting, but are worth the pain if the expense and amount of on-site rehabilitation and on-table interpretation from innumerable tables and numbers, is borne in mind. The concept of VR can then be extended to the web where other stake holders too sitting across the globe can interact and give valuable inputs towards an optimum and robust solution [13].

Chopra et. al (May 2003)**,** laid down the concept of modal pushover analysis (MPA). They analysisd six SAC buildings, each analyzed for 20 ground motions, and their statistical analysis leads to bias and dispersion in the procedure. The results demonstrated that by including a few "modes" (typically two or three), the height-wise distribution of demands estimated by MPA is generally similar to the "exact" results from nonlinear response history analysis. The MPA procedure estimates seismic story-drift demands to a degree of accuracy that should be sufficient for most building design and retrofit applications [15].

Jain et. al (August 2002), carried out pushover analysis for seismic retrofitting of buildings for a flat slab building. The various retrofitting techniques used by them included jacketing of columns only, providing additional beams and providing both columns jacketing and additional beams. They concluded that jacketing or retrofitting of columns result in a much higher drift capacity. The additional beams significantly reduce softening caused by sagging hinges. But they have a comparatively lower drift capacity. However jacketing of both beams and columns result into the best response of the system [12].

III. GENERAL OVERVIEW OF PARAMETRIC STUDY

The main objective of seismic design of buildings is to avoid total catastrophic damage so that structural damages caused, if any, could be repaired after the earthquake event. Static pushover analysis is an attempt by the structural engineering profession to evaluate the real strength of the structure and it promises to be a useful and effective tool for performance based design.

Finally, certain special combinations of retrofitting have been done from the results obtained from the study, so as to get a highly improved response of structure at a relatively cheaper cost.

The following cases (Table I) have been incorporated in the study:

TABLE I. Description of various cases

SR. NO.	CASE NO.	DESCRIPTION OF CASES
1		Original structure
2	1	Retrofitting beams of 1st storey only
3	2	Retrofitting columns of 1st storey only
4	3	Retrofitting beams & columns of 1st storey only
5	4	Retrofitting beams of 1st +2nd storey only
6	5	Retrofitting columns of 1st +2nd storey only
7	6	Retrofitting beams & columns of 1st +2nd storey only
8	7	Retrofitting beams of 1st +2nd+3rd storey only
9	8	Retrofitting columns of 1st +2nd+3rd storey only
10	9	Retrofitting beams & columns of 1st +2nd+3rd storey only
11	10	Retrofitting beams of 1st +2nd+3rd+4th storey only
12	11	Retrofitting columns of 1st +2nd+3rd+4th storey only
13	12	Retrofitting beams & columns of 1st +2nd+3rd+4th storey only
14	13	Retrofitting beams of 1st +2nd+3rd+4th+5th storey only
15	14	Retrofitting columns of 1st +2nd+3rd+4th+5th storey only
16	15	Retrofitting beams & columns of 1st +2nd+3rd+4th+5th storey only
17	16	Retrofitting beams of 1st +2nd+3rd+4th+5th +6th storey only
18	17	Retrofitting columns of 1st +2nd+3rd+4th+5th +6th storey only
19	18	Retrofitting beams & columns of 1st +2nd+3rd+4th+5th +6th storey only

A. *Description of a Building*

In the present work, a six storied reinforced concrete frame building situated in Zone IV, is taken for the purpose of study. The plan area of building is 12 x 12 m with 3.0m as height of each typical storey. It consists of 4 bays of 3m each in X-direction and Z-direction (3 x 4= 12m). Hence, the building is symmetrical about both the axis. The total height of the building is 18m. The building is considered as a Special Moment resisting frame. The retrofitting of frame elements, i.e. Beams and columns is done in various combinations at all the storey levels. The plan of building is shown in fig. 3; the front elevation is shown in fig. 4 and 3d view in fig. 5.

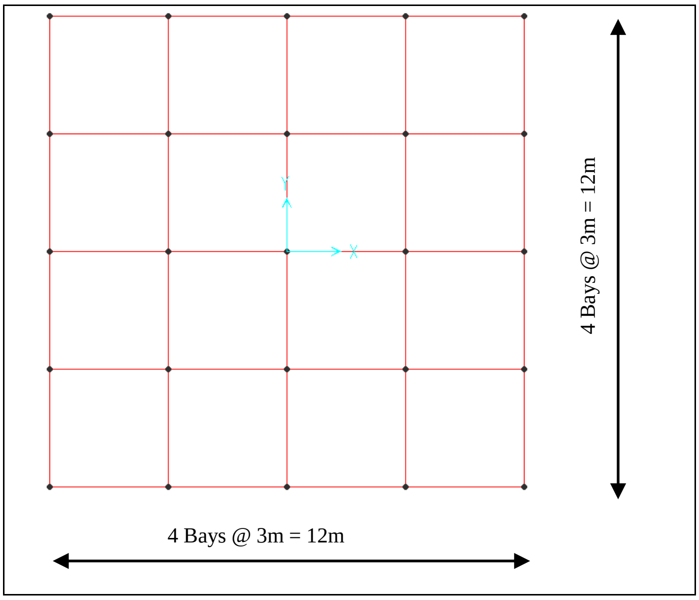


Fig. 3. Plan of Building

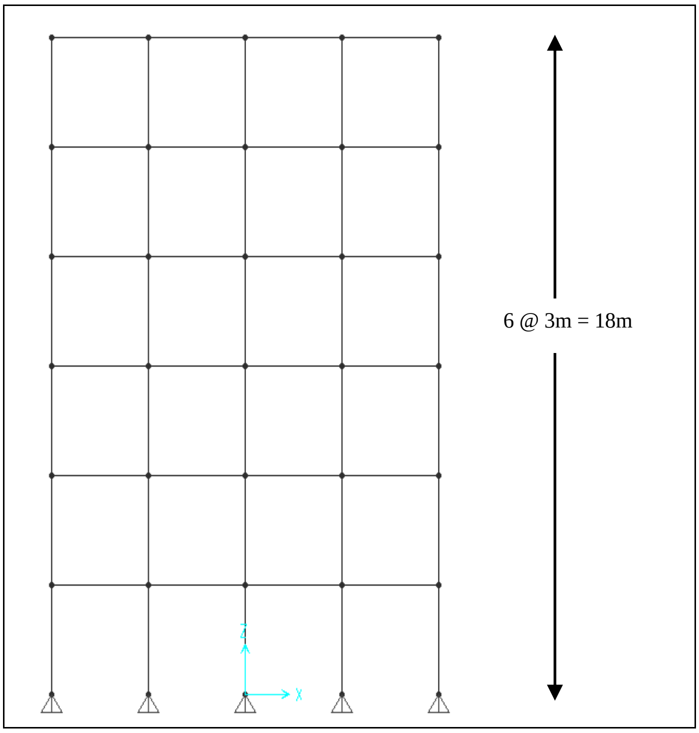


Fig. 4. Elevation of Building

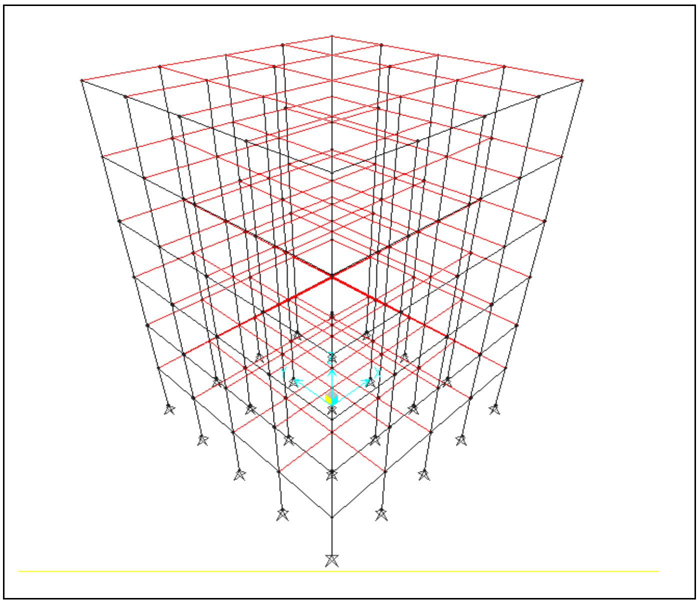


Fig. 5. 3D view of Building

B. Sectional Properties of Elements

The sectional properties of elements in case of the original structure are taken as follows:

Size of Column = 450 x 450mm, Size of Beam = 0.230 x 300 mm, Thickness of Slab = 125mm thick

When the structure was retrofitted, the size of columns was increased to 600x600mm, while that of beam was changes to 300x450mm. A nominal percentage i.e. 1% of the increased area can be provided for the retrofitting purposes.

C. Loads Considered

The following loads were considered for the analysis of the building. The loads were taken in accordance with IS:875[1][2].

D. Gravity Loads

The intensity of dead load and live load at various floor levels and roof levels considered in the study are listed below [9].

- Dead Load

At all Floor Levels

Weight of Slab: 0.125 x 25	= 3.125 kN/m^2
Weight of Screed: 0.050 x 20	= 1.000 kN/m^2
Weight of Floor Finish: 0.025 x 24	= 0.600 kN/m^2
Weight of partition Wall	= 1.000 kN/m^2
Total Dead Load	= 5.725 kN/m^2
Total Dead Load Taken	= 6.0 kN/m^2

A wall load of 12kN/m has been applied to all the outer beams at all the floor levels

- Live Load

Live load at all floor levels = 3.0 kN/m^2

This live load is reduced by 25% for calculating the seismic weight of the structure as per provisions of IS1893:2002(PART 1).

E. Seismic Loads

The design lateral force due to earthquake is calculated [11] as follows:

Design horizontal seismic coefficient:

The design horizontal seismic coefficient Ah for a structure shall be determined by the following expressions:-

Ah = Z I Sa 2 R g

Provided that for any structure with T≤0.1 sec. The value of Ah will not be less than Z/2 whatever the value of R/I.

Z= Zone factor

I = Importance factor depending upon the functional use of the structure.

R = Response reduction factor, depending upon the perceived seismic damage performance of the structure.

Sa /g =Average response acceleration coefficient for rock or soil sites.

- Seismic Weight

The seismic weight of each floor is its full dead load plus appropriate amount of imposed load. While computing the seismic weight of each floor, the weight of columns and walls in a storey shall be equally distributed to the floors above and below the storey.The seismic weight of the whole building is the sum of the seismic weights of all the floors.

Design Seismic Base Shear

The total design lateral force or seismic base shear (Vh) along any principal direction is determined by the following expression:-

Vh = AhW

Where W is the seismic weight of the building.

Fundamental Natural Time Period

The approximate fundamental natural time period of vibration (Ts) in seconds of a moment resisting frame building without brick infill panels may be estimated by the following empirical expressions:

TS = 0.075h0.75 for RC framed building

TS = 0.085h0.75 for steel framed building

Where h=Height of the building in meters

For all other buildings, it is given by:-

Tn = 0.09h/$\sqrt{d}$

Where h=Height of the building in meters

d= base dimension of the building at the plinth level,in meters, along the considered direction of the lateral force.

- Distribution of design force

The design base shear (Vh) computed is distributed along the height of the building as below:

$$Q_i = V_h \frac{W_i h_i^2}{\sum W_i h_i^2}$$

Where,

Qi = design lateral force at each floor level i

Wi = seismic weight pf floor i.

i = height of floor i measured from the base.

- Design lateral force

The design lateral force shall first be computed for the building as a whole the design lateral force shall then be distributed to the various floor levels. The design seismic force thus obtained at each floor level, shall then be distributed to individual lateral load resisting elements depending on the floor diaphragm action.

IV. PUSHOVER ANALYSIS USING SAP2000

The following steps are included in the pushover analysis. Steps 1to 4 are to create the computer model, step 5 runs the analysis, and steps 6 to 10 review the pushover analysis results.

1. Create the basic computer model (without the pushover data) as shown in Figure 6. The graphical interface of SAP2000 makes this quick and easy task. Assigned sectional properties & applies all the gravity loads i.e. Dead load and Live load on the structure [5].

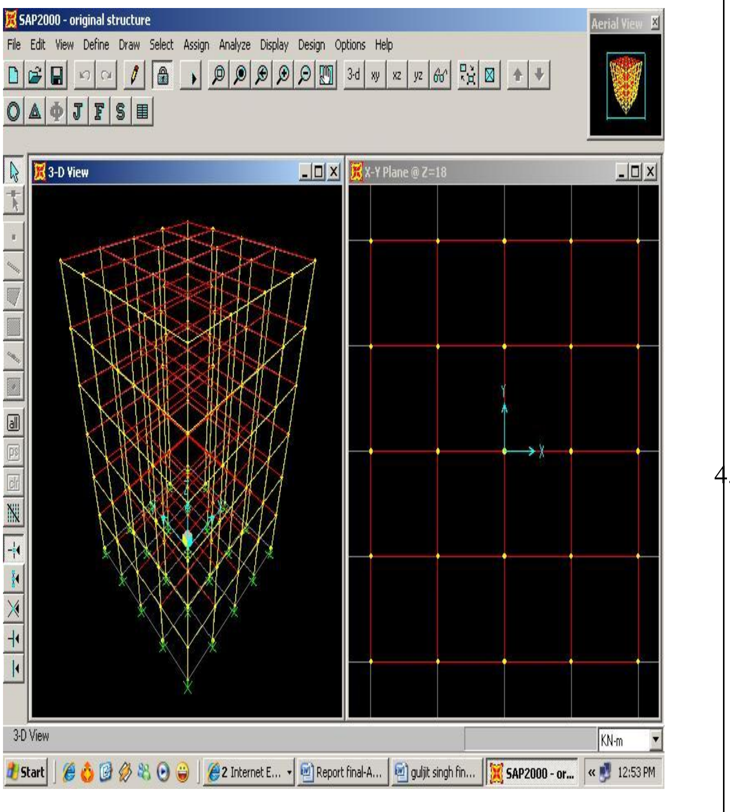


Fig. 6. Basic Model in SAP2000

2. Define properties and acceptance criteria for the pushover hinges as shown in Figure 7. The program includes several built-in default hinge properties that are based on average values from ATC-40 for concrete members and average values from FEMA-273 for steel members. In this analysis, PMM hinges have been defined at both the column ends and M3 hinges have been defined at both the ends of all the beams.

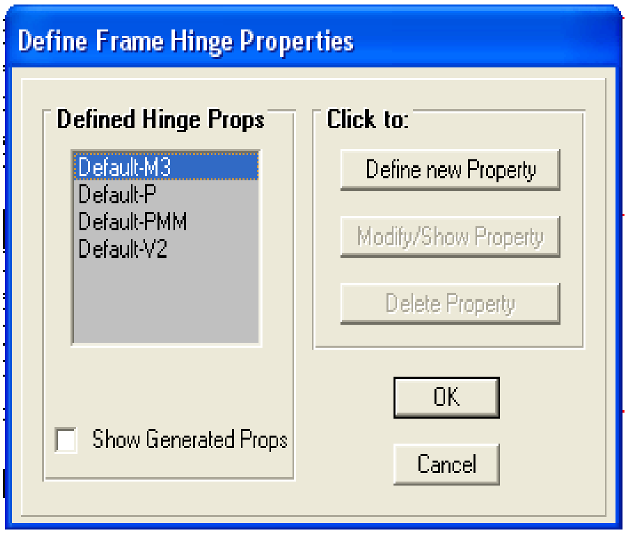


Fig. 7. Defining Hinge Properties

3. Locate the pushover hinges on the model by selecting all the frame members and assigning them one or more hinge properties and hinge locations as shown in Figure 8.

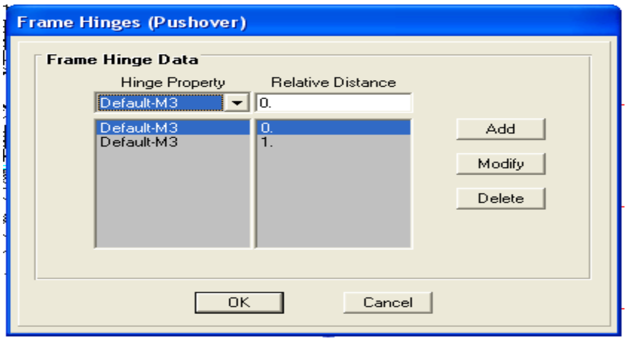


Fig. 8. Assignment of Hinges

4. Define the pushover load cases, figure 9(a) and (b). In SAP2000 more than one pushover load case can be run in the same analysis. Also a pushover load case can start from the final conditions of another pushover load case that was previously run in the same analysis. Typically the first pushover load case was used to apply gravity load and then subsequent lateral pushover load cases were specified to start from the final conditions of the gravity pushover. Pushover load cases can be force controlled, that is, pushed to a certain defined force level, or they can be displacement controlled, that is, pushed to a specified displacement. Typically a gravity load pushover is force controlled and lateral pushovers are displacement controlled. In this case a Gravity load

combination of DL+0.25LL has been used. This combination has been defined as GRAV. The lateral loads have been applied to a case called PUSHPAT.

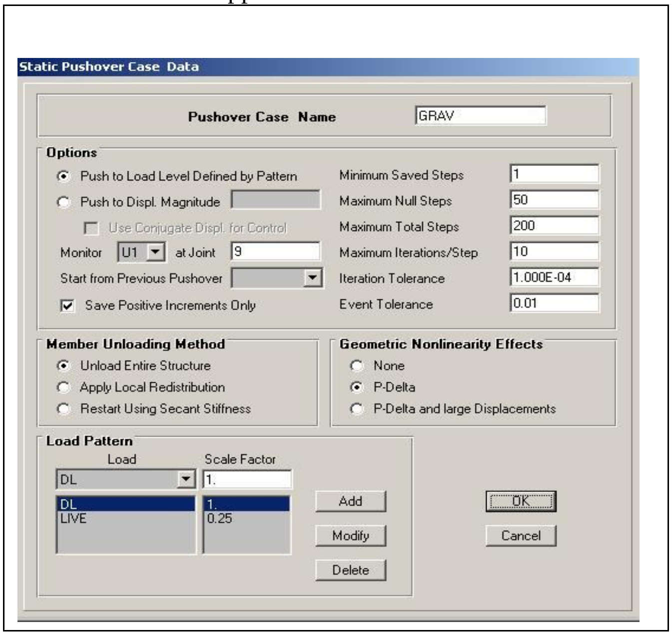


Fig. 9. (a). Defining Pushover Cases

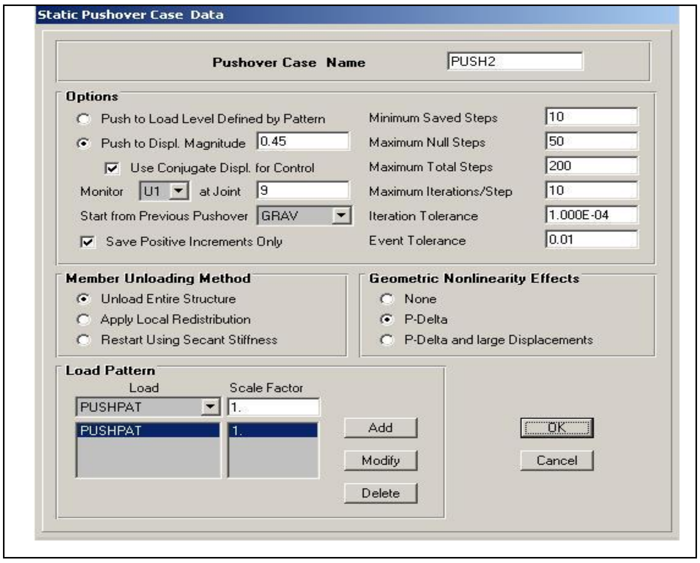


Fig. 9 (b). Defining Pushover Cases

5. Run the basic static analysis. Then ran the static nonlinear pushover analysis.
6. The Pushover curve was made for control nodes at each storey level. This was done by defining a number of pushover cases in the same analysis, and displacement was monitored for a different node in each case.
7. The pushover curve was obtained as shown in Figure 10. A table was also obtained which gives the coordinates of each step of the pushover curve and summarizes the number of hinges in each state (for example, between IO and LS, or between D and E). This table is shown in Figure 11.

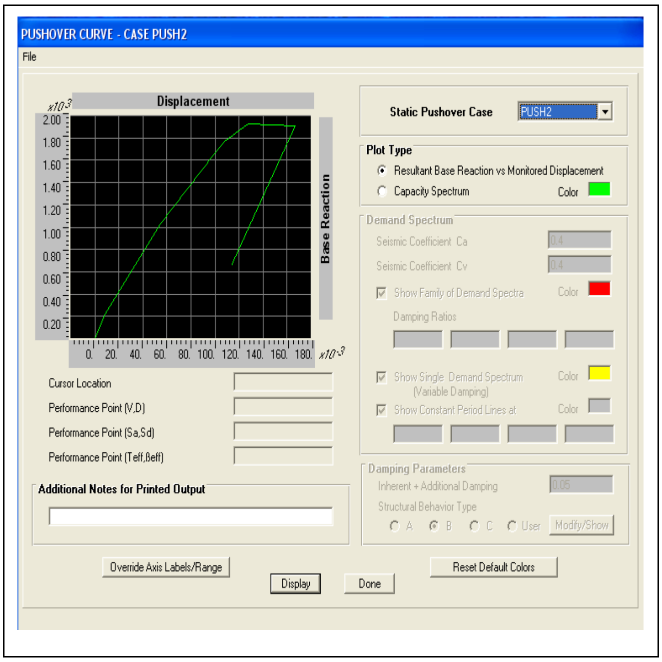


Fig. 10. Pushover Curve

PUSHOVER CURVE

Step	Displacement	Base Force	A-B	B-IO	IO-LS	LS-CP	CP-C	C-D	D-E
0	-6.374E-06	0.0000	780	0	0	0	0	0	0
1	0.0070	259.0387	778	2	0	0	0	0	0
2	0.0544	1440.7926	574	206	0	0	0	0	0
3	0.1046	2447.5491	529	169	82	0	0	0	0
4	0.1531	3100.0957	487	100	185	8	0	0	0
5	0.2000	3594.6836	424	149	124	83	0	0	0
6	0.2028	3615.9114	420	152	108	100	0	0	0
7	-0.0468	-1960.9600	420	152	108	100	0	0	0

Fig. 11. Tabular Data for Pushover Curve

8. The capacity spectrum curve obtained is shown in Figure 12. The magnitude of the earthquake and the damping information on this form can be modified and the new capacity spectrum plot can be obtained immediately. The performance point for a given set of values is defined by the intersection of the capacity curve and the single demand spectrum curve. Also, a table was generated which shows the coordinates of the capacity curve and the demand curve as well as other information used to convert the pushover curve to Acceleration-Displacement Response Spectrum format (also known as ADRS format). See Figure 13.

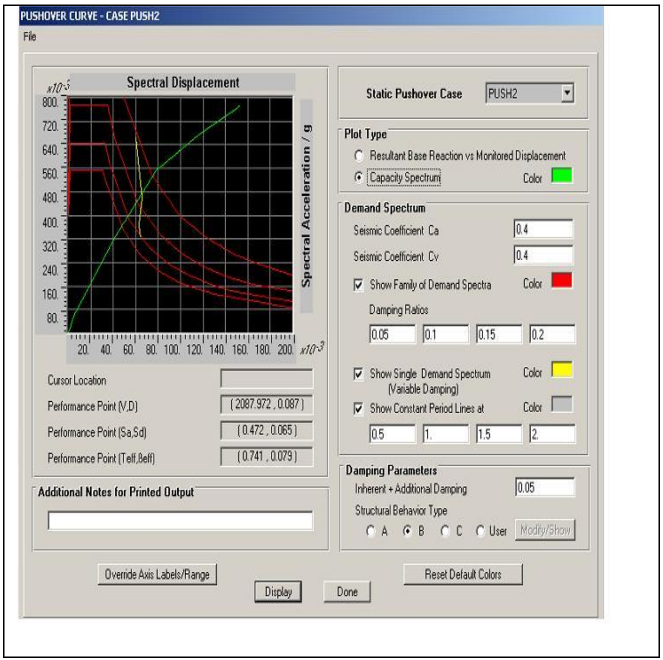
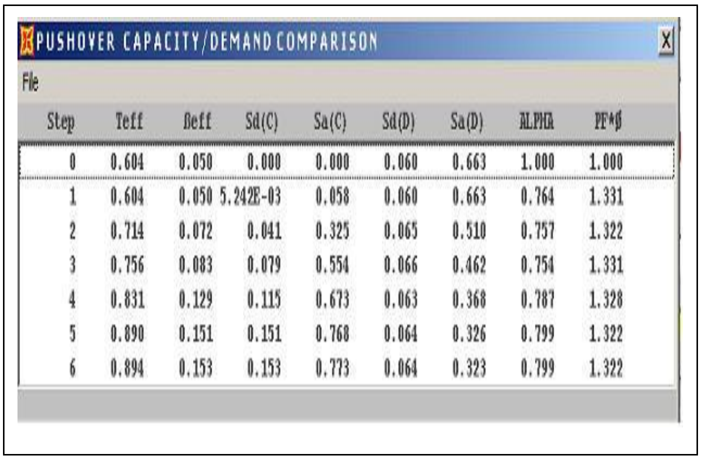


Fig. 12. Capacity Spectrum Curve



PUSHOVER CAPACITY/DEMAND COMPARISON

File

Step	Teff	Beff	Sd(C)	Sa(C)	Sd(D)	Sa(D)	ALPHA	PF*Ø
0	0.604	0.050	0.000	0.000	0.060	0.663	1.000	1.000
1	0.604	0.050	5.242E-03	0.058	0.060	0.663	0.764	1.331
2	0.714	0.072	0.041	0.325	0.065	0.510	0.757	1.322
3	0.756	0.083	0.079	0.554	0.066	0.462	0.754	1.331
4	0.831	0.129	0.115	0.673	0.063	0.368	0.787	1.328
5	0.890	0.151	0.151	0.768	0.064	0.326	0.799	1.322
6	0.894	0.153	0.153	0.773	0.064	0.323	0.799	1.322

Fig. 13. Tabular Data For Capacity Spectrum Curve

9. The pushover displaced shape and sequence of hinge information on a step-by-step basis was obtained.
10. Output for the pushover analysis can be printed in a tabular form for the entire model or for selected elements of the model. The types of output available in this form include joint displacements at each step of the pushover, frame member forces at each step of the pushover, and hinge force, displacement and state at each step of the pushover [5].

V. RESULTS AND DISCUSSIONS

A. *Base Force*

The base force for the six-storey building with different combination of element retrofitting at various floor levels is presented in Table 2. The variation of base force for various cases of retrofitting of building is shown in Figure 2.

It is observed that with retrofitting of beams only, there is a very minimal percentage increase in the base force varying from 11.9% to 26.93%, which the structure can carry. However, with the retrofitting of storey columns, there is quite an appreciable gain in the base force carrying capacity of the structure. The percentage change varies from 15.64% to 98.25%. Further it is observed that, retrofitting of columns at 2nd storey there is a decline in the base force capacity, but after 2nd storey, there is predominant increase in base force due to retrofitting of columns only. The combination of retrofitting of beams and columns both, show a consistent increase in base force capacity but it becomes more predominant from 3rd Storey onwards.

TABLE II. COMPARISON OF BASE SHEAR

RETROFITTING LEVEL	CASES	INCREASE IN NO. OF ITERATIONS	BASE SHEAR (KN)	PERCENTAGE INCREASE
Original structure		4	3049.4314	
RETROFITTING UPTO 1st STOREY	CASE 1	5	3415.1372	11.9
	CASE 2	6	3722.8994	22.08
	CASE 3	5	3763.8350	23.42
RETROFITTING UPTO 2nd STOREY	CASE 4	7	3800.3967	24.62
	CASE 5	4	3526.5369	15.64
	CASE 6	6	3543.8384	16.21
RETROFITTING UPTO 3rd STOREY	CASE 7	5	3588.6655	17.68
	CASE 8	4	3689.0637	20.97
	CASE 9	4	3679.8408	20.67
RETROFITTING UPTO 4th STOREY	CASE 10	5	3646.4312	19.57
	CASE 11	8	3848.0723	26.18
	CASE 12	8	5204.1719	70.66
RETROFITTING UPTO 5th STOREY	CASE 13	6	3870.7119	26.93
	CASE 14	6	5983.6665	96.22
	CASE 15	8	6493.8042	112.95
RETROFITTING UPTO 6th STOREY	CASE 16	6	3835.5139	25.77
	CASE 17	6	6045.7153	98.25
	CASE 18	8	6533.5293	114.25

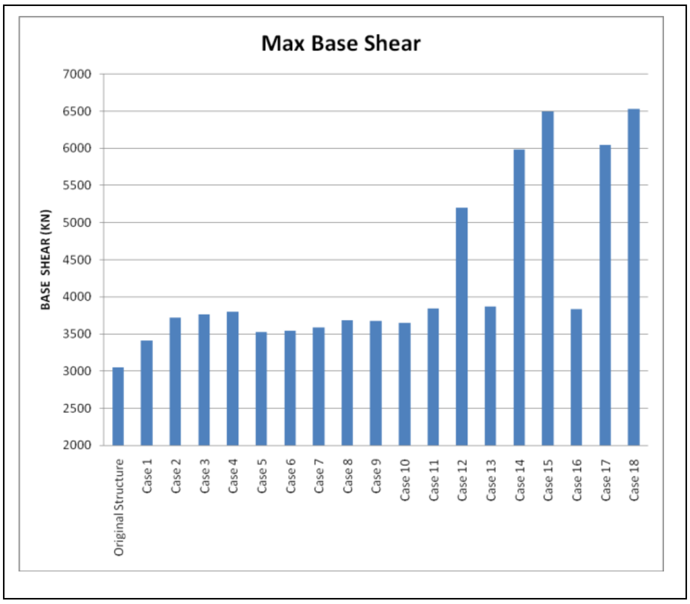


Fig. 14. Variation of Base Shear

B. Roof Displacement

The Roof displacement for the six-storey building with different combination of element retrofitting at various floor levels is presented in Table 3. The variation of Roof displacement for various cases of retrofitting of building is shown in Figure 3.

It is observed that with retrofitting of beams only, there is a decrease in the roof displacement upto 4th storey and after 4th storey it got little increased upto5th storey (31.16% to 8.05%) and after 5storey it again decreases to (14.23%). This percentage varies from 31.16% to 8.05%. However, the trends shown by retrofitting of columns only is there is a decrease in the roof displacement upto 2nd storey and after 2nd storey it predominantly increases upto 5th storey and again decreases slightly at 6th storey. The percentage change varies from -8.59% to 102.61%. The combination of retrofitting of beams and columns both, show a consistent decrease in the roof displacement upto 3rd storey and after 3rd storey it predominantly increases upto 5th storey and again decreases slightly at 6th storey.

TABLE III. COMPARISON OF ROOF DISPLACEMENT

RETROFITTING LEVEL	*CASES*	*INCREASE IN NO. OF ITERATIONS*	*ROOF DISPLACEMENT S (mm)*	*PERCENTAGE INCREASE*
Original structure		4	148.9	
RETROFITTING UPTO 1st STOREY	CASE 1	5	169.6	13.90
	CASE 2	6	168.0	12.82
	CASE 3	5	169.6	13.90
RETROFITTING UPTO 2nd STOREY	CASE 4	7	195.3	31.16
	CASE 5	4	136.1	-8.59
	CASE 6	6	124.4	-16.45
RETROFITTING UPTO 3rd STOREY	CASE 7	5	163.3	9.67
	CASE 8	4	143.9	-3.35
	CASE 9	4	115.9	-22.16
RETROFITTING UPTO 4th STOREY	CASE 10	5	160.9	8.05
	CASE 11	8	153.3	2.95
	CASE 12	8	220.1	47.81
RETROFITTING UPTO 5th STOREY	CASE 13	6	177.7	19.34
	CASE 14	6	301.7	102.61
	CASE 15	8	292.1	96.17
RETROFITTING UPTO 6th STOREY	CASE 16	6	170.1	14.23
	CASE 17	6	286.7	92.54
	CASE 18	8	274.3	84.21

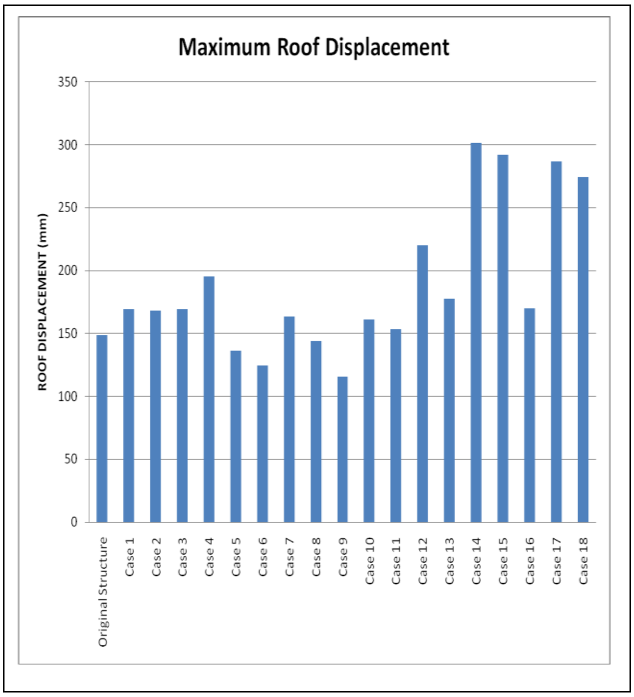


Fig. 15. Variation of Roof Displacement

VI. CONCLUSIONS

Based on the present study, the following conclusions can be drawn:

1. There is a minimal increase in the base shear due to retrofitting of beams only. An increase of only 11.9% to 26.93% is observed when the beams are retrofitted.
2. The retrofitting of columns results into an appreciable gain in base shear. This increase varies from 15.64% to 98.25%. The maximum increase is for the case when all the columns are retrofitted upto 6^{th} storey only.
3. The retrofitting of both beams and columns gives an appreciable increase in the base shear of the structure. This range varies from 16.21% to 114.25%. The maximum value of 114.25% increase is obtained when all the beams as well as columns are retrofitted upto the 6^{th} storey.

4. The retrofitting of beams results into a decrease in the roof displacement upto 4th storey and again got increased at 5th storey and again further decreases at 6th storey of the structure. This decrease varies from 31.16% to 8.05%.
5. The retrofitting of columns results into an appreciable decrease in the maximum roof displacement upto 2th storey and suddenly appreciable increase is seen at 5th storey and again further slightly decreases at 6th storey which the structure can carry without failure. This decrease varies from 102.61% to -8.59%. The maximum roof displacement is observed for the case, when all the columns have been retrofitted upto 5th storey.
6. The retrofitting of both beams and columns in different combinations cause a decrease of 13.90% to -22.16% in roof displacement upto 3rd storey and further increases upto 5th storey from -22.16% to 96.17% in roof displacement and again slightly decreases at 6th storey.

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