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Seismic Evaluation of Retrofitted Reinforced Concrete Framed Buildings

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Abstract— Many existing buildings lack the seismic strength and detailing requirements of IS: 1893-2002 and IS: 13920-1993, because either they were designed for only gravity loads or built prior to the implementation of these codes. Hence it is required to assess the performance level of such buildings for safety of the structure during earthquake. In present study three buildings 8, 12 and 16 storied are considered. They are designed for only gravity loads according to IS: 456-2000 without ductile detailing. Seismic evaluation of these buildings is carried out with nonlinear static pushover analysis using SAP2000 software. Performance points and performance levels of these buildings are determined by capacity spectrum methods. All three buildings are found in life safety to collapse prevention (LS-CP) range for design basis earthquake condition. Then various retrofitting schemes viz. steel X braces, infill walls, and shear wall are employed for strengthening of these buildings, performance level requirement of operational to immediate occupancy (B-IO) under design basis earthquake is aimed at. Idealized force-displacement capacity curve is implemented to evaluate various seismic parameters from pushover curve which is based on the method recommended by FEMA 356. The results are compared based on performance point, hinge formation pattern, yield strength and lateral stiffness. The results show that there is no unique solution and several different strengthening schemes can be provided to give adequate performance. Most increase in the lateral strength and stiffness is related to using infill wall and shear wall.

Keywords— Performance point, FEMA 356, SAP2000, Lateral stiffness, steel X braces, infill walls, and shear wall.

INTRODUCTION

Evaluation of building is required at two stages (a) before retrofitting, to identify the weakness of the building to be strengthened, and (b) after retrofitting, to estimate the adequacy and effectiveness of retrofit. Evaluation is complex process, which has to take not only the design of building but also the deterioration of the material and damage caused to the building, if any. The difficulties faced in the seismic evaluation of the building are threefold. There is no reliable method to estimate the in-situ strength of the material in components of the building. Analytical method to model the behavior of the building during earthquake is either unreliable or too complex to handle with the generally available tools. The third difficulty is the unavailability of reliable estimate of earthquake parameters, to which the buildings expected to be subjected during its residual life. Hence the engineering tools needs to be sharpened for evaluating structures performance under the action of earthquake forces. The aim of the seismic evaluation is to assess the seismic capacity of earthquake vulnerable buildings or earthquake damage buildings for the future use. The evaluation may also prove helpful for degree of intervention required in seismically deficient structures [5].

Need: The Bhuj earthquake of 26 January, 2001 in Gujarat, India caused the major destruction of medium-rise and high-rise buildings. After this earthquake, many questions arose about our professional practices, building by-laws, construction materials, and education for civil engineers and architects. In addition to this current Indian codes do not address the evaluation of seismic resistance of existing building stock, which may not have been designed for earthquake forces. Seismic deficiencies should first be identified through a seismic evaluation of the structure. The selection of an appropriate intervention technique based on the structural type and its deficiencies is the most important step in retrofitting. Seismic evaluation consists of gathering as built information and obtaining the results of a structural analysis based on collected data. The prestandard and commentary for the seismic rehabilitation of buildings ATC40 and FEMA356 provides guidance for evaluating the seismic performance of existing structures and determining the necessary retrofitting methods to achieve the performance objectives. In light of these facts, it is necessary to seismically evaluate the buildings with the present knowledge to avoid the major destruction during the earthquakes in future. The buildings found to be seismically deficient should be retrofitted/ strengthened.

Scope: The scope of present study aims at evaluation of RC buildings designed as per IS: 456-2000. Total three gravity designed buildings 8, 12 and 16 storied having symmetrical plan and identical floors located in zone V are designed using SAP2000. Designed buildings are evaluated using nonlinear static pushover analysis in X and Y directions. For pushover analysis guidelines laid by

ATC40 and FEMA356 are followed. Based on performance objective operational (B) to immediate occupancy (IO) performance level is targeted at. Performance point is found out by using capacity spectrum method. Since above all three buildings failed to give desired target performance level that is operational (B) to immediate occupancy (IO), hence buildings need to be retrofitted.

Steel X braces, infill wall and shear wall are employed as the retrofitting strategies for all three buildings. Retrofitting schemes are placed at exterior bays only. Modeling of shear wall and infill wall is done by wide column analogy and single compressive strut respectively. Then from pushover curve idealized curve is drawn as per FEMA356 recommendation to extract seismic parameters.

The results of analysis are compared in terms of seismic parameters such as performance levels, hinge formation pattern, yield strength and lateral stiffness. The effectiveness of retrofitting schemes on above parameters is studied.

METHODOLOGY

In the present work 8, 12 and 16 storied gravity designed reinforced concrete buildings are considered for study. For all three buildings, the following data is used including the loadings as per relevant IS code.

1. The buildings are situated in zone V.
2. The buildings have ordinary moment resisting frame.
3. The plan area of all three buildings is 25 x 20 m.
4. It consists of 5 bays of 5 m each in X-direction and 5 bays of 4 m each in Y-direction.
5. Plinth height above GL is 0.55 m. Depth of foundation is 0.65 m below GL.
6. Height of each typical storey is 3.1 m.
7. Slab thickness is 150 mm.
8. External wall thickness is 230 mm and internal wall thickness is 150 mm. Parapet height is 1.5 m.
9. Grade of concrete is M 20.
10. Grade of steel is Fe 415.
11. Imposed load on floor is 3 kN/m^2 and imposed load on roof is 1.5 kN/m^2.
12. Floor finishes is 1 kN/m^2 and roof treatment is 1.5 kN/m^2.
13. Density of concrete is 25 kN/m^3 and density of masonry wall is 20 kN/m^3.

The plan of buildings is shown in figure 1 and 3-D view of 8, 12, and 16 storied buildings are shown in figure 2 (a), (b) and (c) respectively and Table 1 shows the geometrical properties of buildings.

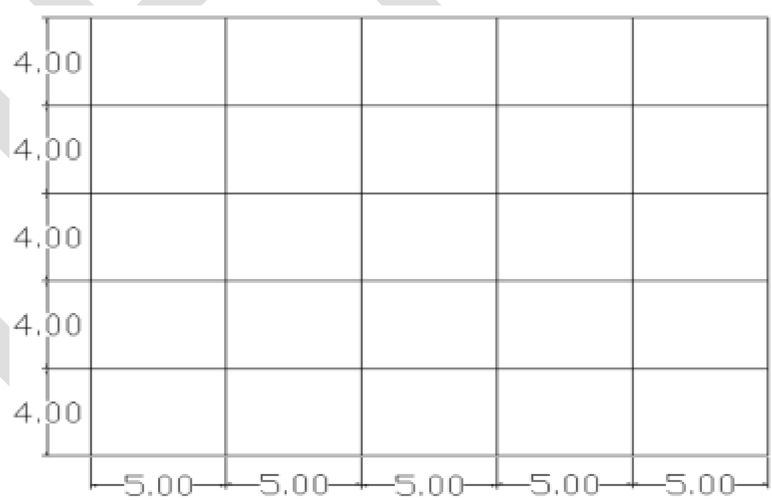


Figure 1 Plan

Note - All dimensions are in m.

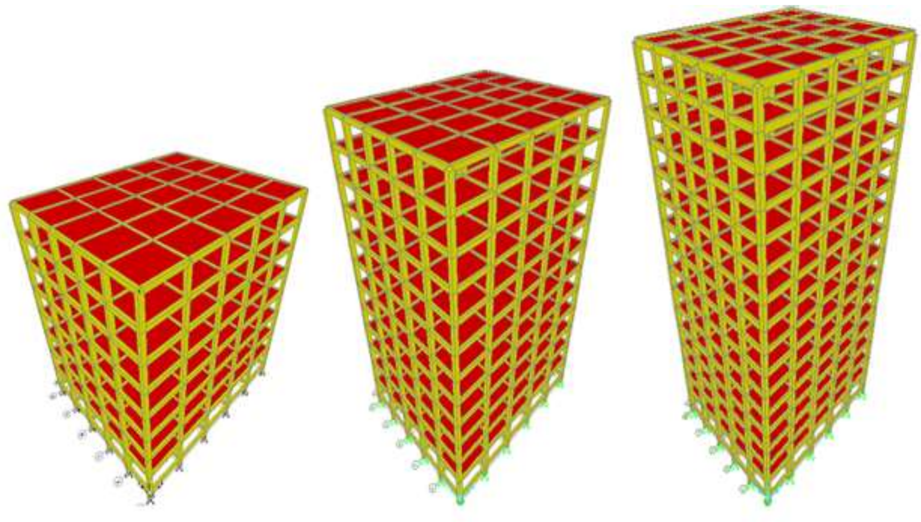


Figure 2 3D view of (a) 8 storied (b) 12 storied (c) 16 storied buildings.

Table 1 Geometrical properties of buildings

Building	Beam sizes in mm.		Column sizes in mm	
	External	Internal	External	Internal
8 storied	300x500	300x600	300x600	500x600
12 storied	300x600	300x700	500x700	700x700
16 storied	300x700	300x800	600x700	800x800

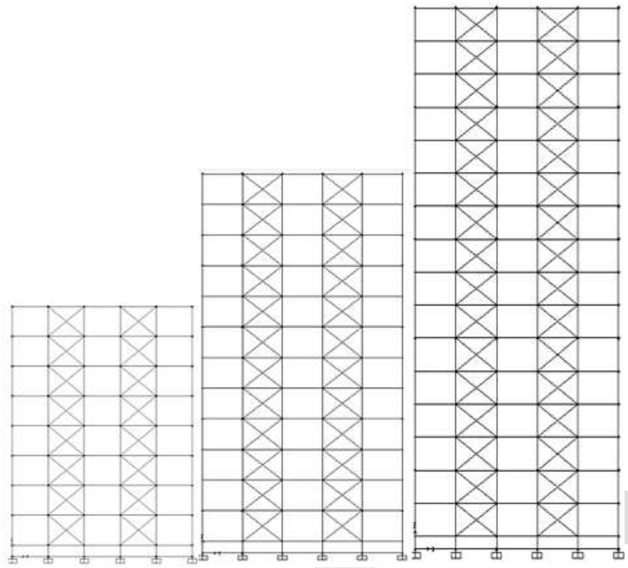
The main objective of performance based earthquake engineering of buildings is to avoid total catastrophic damage and to restrict the structural damages caused to the performance limit of the buildings. This paper deals with evaluation of the real strength of the structure and to check its performance level. For this purpose static pushover analysis is used.

RETROFITTING OF REINFORCED CONCRETE BUILDING

The most important step in the retrofitting process of a building is to create an appropriate model that will adequately represent its stiffness, mass distribution and energy dissipation so that its response to earthquake could be predicted with sufficient accuracy. After going through the extensive literature study and in order to investigate effect of steel X bracing, infill wall and shear wall as a retrofitting scheme on seismic performance of buildings it is very imperative to design and model them very precisely. This section deals with design and modeling methods adopted for above mentioned retrofitting schemes, also describes various properties considered for accurate modeling.

1 Design and modeling of steel X bracings

The steel X braces are designed to resist the base shear for DBE level earthquake according to IS: 1893 (part 1) as a first trial, and then trial and error method was adopted to bring the structural performance level within B-IO range. The braces are assigned at exterior bays only as shown in figure 3 (a), (b) and (c) for 8, 12 and 16 storied buildings respectively. Brace members are selected as round hollow section with modulus of elasticity E = 200,000 MPa and f_y = 350 MPa. Braces are modeled as truss element having pin joints at both the ends. Auto steel-axial hinges are applied at both ends of the bracings.

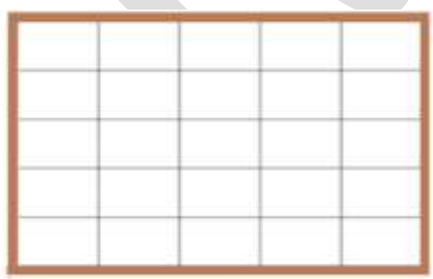


(a) (b) (c)

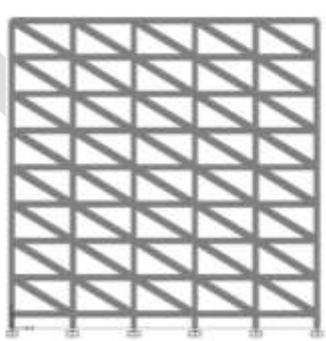
Figure 3 Arrangement of steel X braces

2 Design and modeling of infill wall

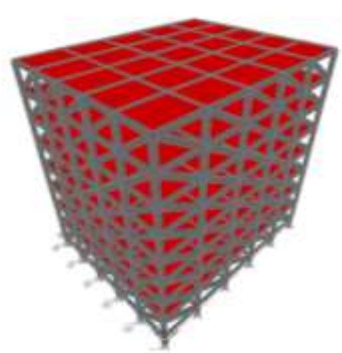
Significant experimental and analytical research is reported in the literature since last five decades, which attempts to understand the behavior of infilled frames. Different types of analytical models based on the physical understanding of the overall behavior of an infill panels were developed over the years to mimic the behavior of infilled frames. The available infill analytical models can be broadly categorized as i) macro model and ii) micro models. Thus RC frames with unreinforced masonry walls can be modeled as equivalent braced frames with infill walls replaced by equivalent diagonal strut which can be used in rigorous nonlinear pushover analysis. Arrangement of infill wall (a) plan (b) elevation (c) 3-D view as shown in figure 4.



(a)



(b)



(c)

Figure 4 Arrangement of infill wall (a) plan (b) elevation (c) 3-D view

3 Modeling of shear wall

Buildings that incorporate concrete shear wall as structural elements to resist both vertical and lateral loads are common place. The calculation of stresses and deflection in a simple shear wall requires only simple bending theory. In this project work shear wall is modeled by using equivalent frame method also referred as wide column analogy. In equivalent frame method, which is also known as wide column analogy, each shear wall is replaced by an idealized frame structure consisting of a column and rigid beams located at floor levels. The column is placed at the wall's centroidal axis and assigned to have the wall's inertia and axial area. In this method, the axial area and inertia values of rigid arms are assigned very large values compared to other frame elements. Due to its simplicity, the equivalent frame method is especially popular in design offices for the analysis of multistorey shear wall-frame structures. Modeling of shear wall by wide column analogy as shown in figure 5.

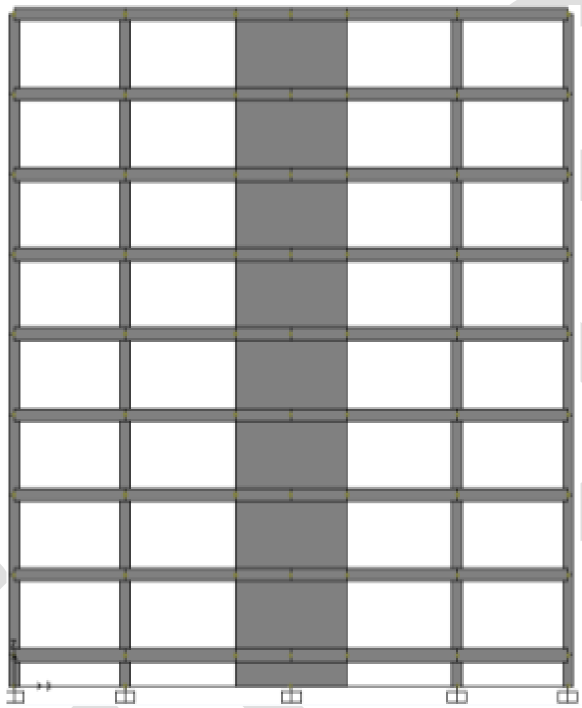


Figure 5 Modeling of shear wall by wide column analogy

PUSHOVER ANALYSIS PROCEDURE

The ATC 40 [1] provides detailed guidelines about how to perform a nonlinear static pushover analysis. The following procedure is based on the ATC 40 procedure.

• Form the analytical model of the nonlinear structure.

• Set the performance criteria, like drift at specific floor levels, limiting plastic hinge rotation at specific plastic hinge points, etc.

• Apply the gravity load and analyze for the internal forces.

• Assign the equivalent static seismic lateral load to the structure incrementally.

• Select a control point to see the displacement.

• Apply the lateral load gradually using incremental iteration procedure.

• Draw the "Base Shear vs. Controlled Displacement" curve, which is called "pushover curve".

• Convert the pushover curve to the Acceleration- Displacement Response-Spectra (ADRS) format.

• Obtain the equivalent damping based on the expected performance level. Get the design Response Spectra for different levels of damping and adjust the spectra for the nonlinearity based on the damping in the Capacity Spectrum.

• The capacity spectrum and the design response spectra can be plotted together when they are expressed in the ADRS format.

• The intersection of the capacity spectrum and the response spectra defines the performance level.

In SAP2000, a frame element is modeled as a line element having linearly elastic properties and nonlinear force-displacement characteristics of individual frame elements are modeled as hinges represented by a series of straight line segments. A generalized force-displacement characteristic of a non-degrading frame element (or hinge properties) in SAP2000 is shown in figure 6.

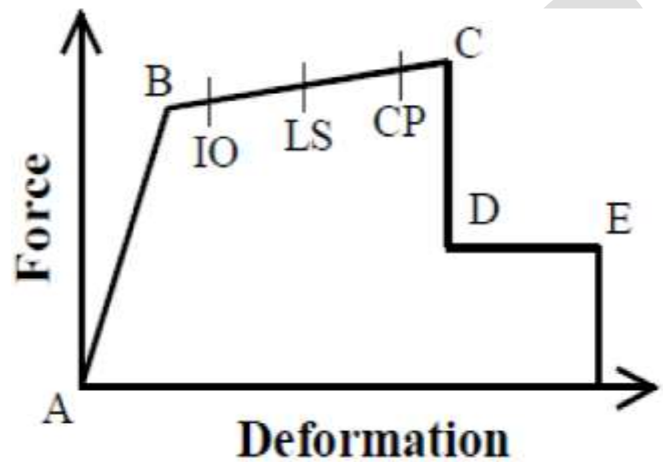


Figure 1 Generalized force-displacement characteristic [2]

Point A corresponds to unloaded condition and point B represents yielding of the element. The ordinate at C corresponds to nominal strength and abscissa at C corresponds to the deformation at which significant strength degradation begins. The drop from C to D represents the initial failure of the element and resistance to lateral loads beyond point C is usually unreliable. The residual resistance from D to E allows the frame elements to sustain gravity loads. Beyond point E, the maximum deformation capacity, gravity load can no longer be sustained. Hinges can be assigned at any number of locations (potential yielding points) along the span of the frame element as well as element ends. Uncoupled moment (M2 and M3), torsion (T), axial force (P) and shear (V2 and V3) force displacement relations can be defined. As the column axial load changes under lateral loading, there is also a coupled P-M2-M3 (PMM) hinge which yields based on the interaction of axial force and bending moments at the hinge location. Also, more than one type of hinge can be assigned at the same location of a frame element. There are three types of hinge properties in SAP2000. They are default hinge properties, user-defined hinge properties and generated hinge properties. Only default hinge properties and user-defined hinge properties can be assigned to frame elements.

RESULT AND DISSCUSSION

All three buildings 8, 12 and 16 storied gravity designed buildings attained the performance level of Life Safety (LS) - Collapse Prevention (CP) as discussed in chapter 4. The significant improvement in the seismic performance of gravity designed buildings is observed when retrofitting schemes are used as shown in table no. 2, however all strengthening schemes are able to provide the same performance level. The result of nonlinear static pushover analysis shows that building retrofitted with steel X braces, infill wall and shear wall provided targeted performance level of operational (B)-immediate occupancy (IO).

In this section, some important seismic parameters and hinge formation patterns are discussed. In addition to this comparison of performance points and capacity curves are as shown in table 2 and figure 7 to figure 12 is carried out.

Table 2 Improvement in seismic parameters

Parameters	**8 storied building**					
	X bracing		**Infill wall**		**Shear wall**	
	X	**Y**	**X**	**Y**	**X**	**Y**
Ratio of initial stiffness	2.09	1.30	3.059	1.94	3.76	2.53
Increase in yield strength	3390	2475	4300	2950	4080	3965
	12 storied building					
Ratio of initial stiffness	1.07	1.26	1.68363	1.71	1.70	1.78
Increase in yield strength	4968	3831	5145	4556	5895	6221
	16 storied building					
Ratio of initial stiffness	1.09	1.13	1.35	1.43	1.73	1.57
Increase in yield strength	4328	4938	5848	5266	7308	6578

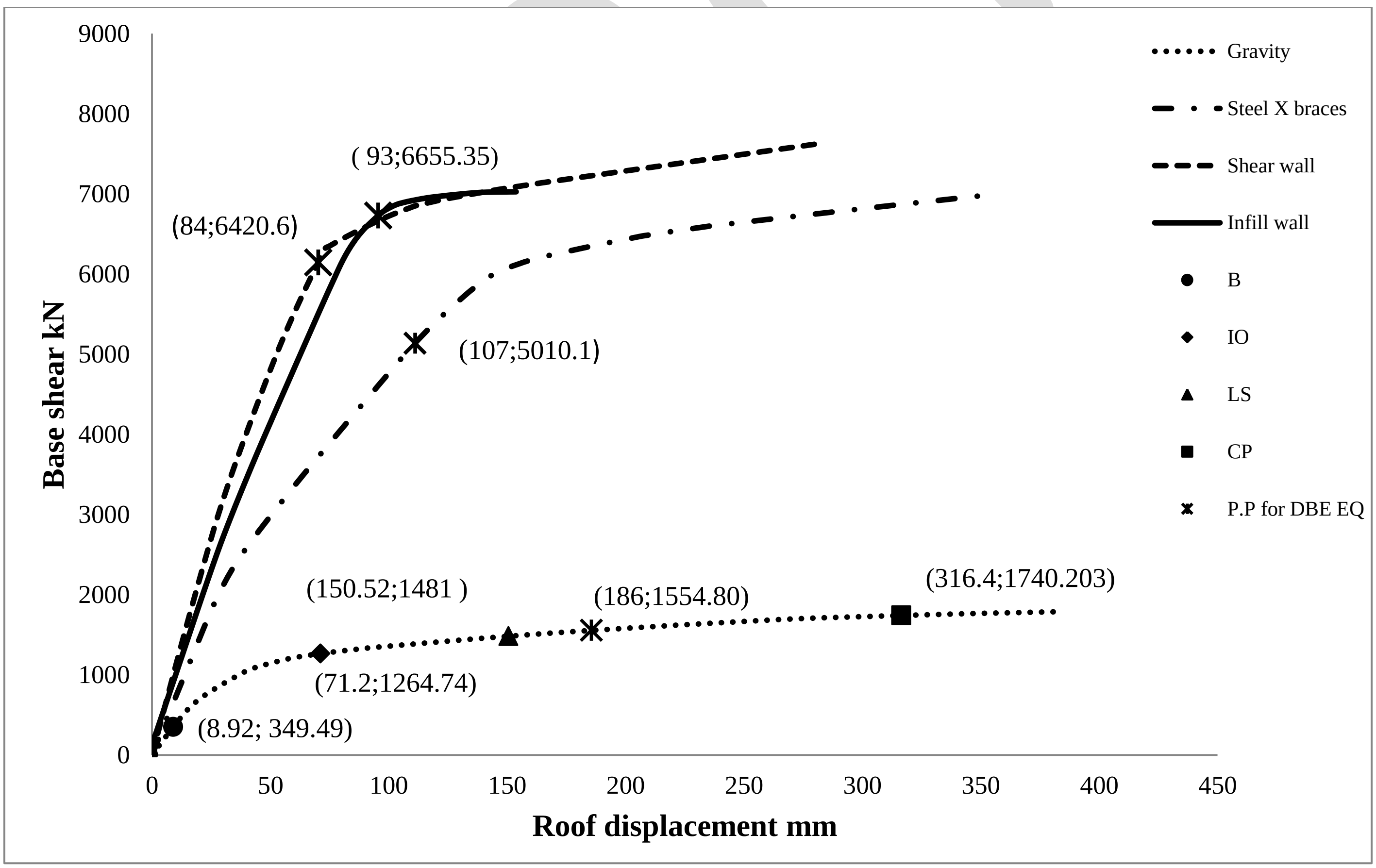


Figure 7 Comparison of various retrofitting schemes for 8 storied building in X direction

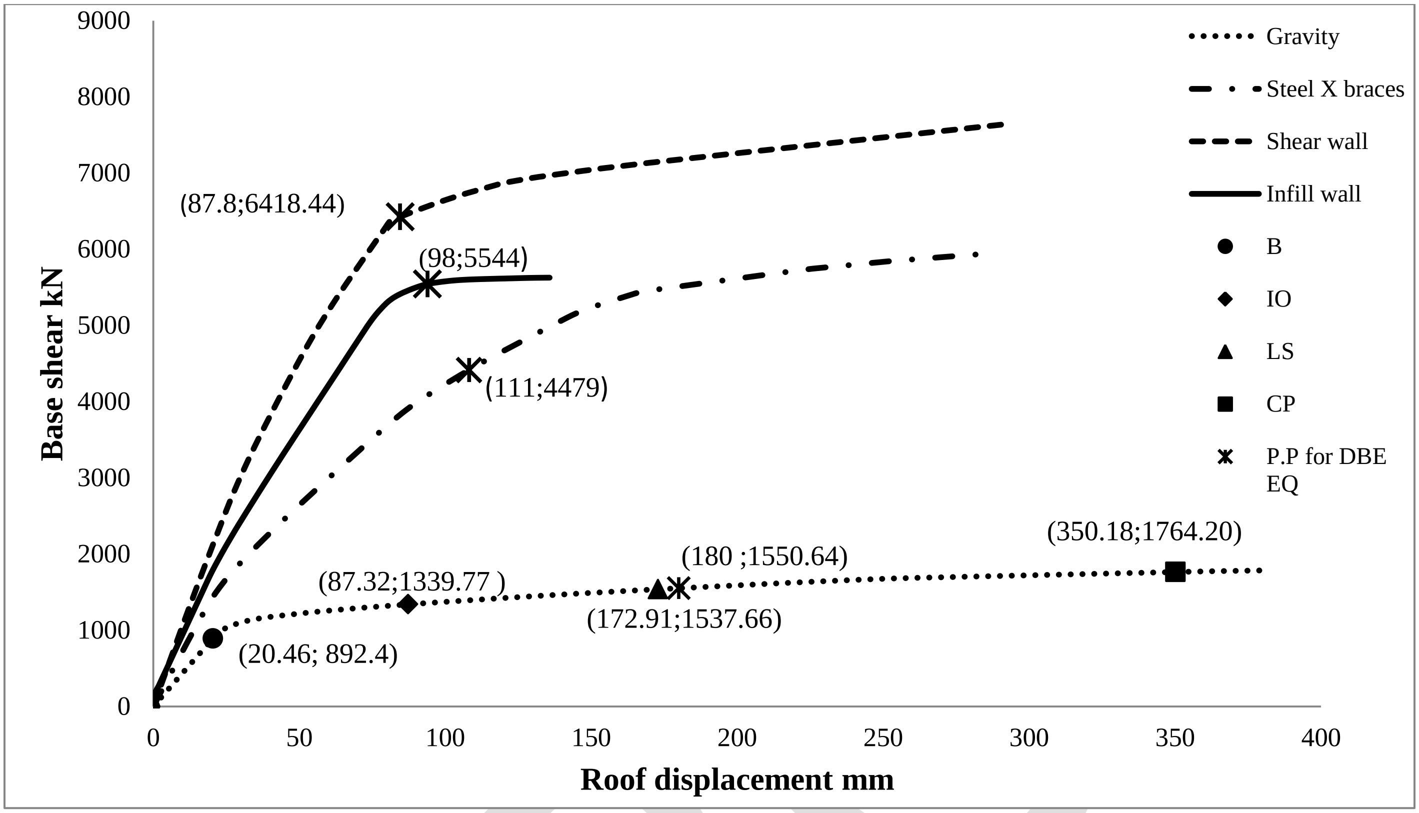


Figure 8 Comparison of various retrofitting schemes for 8 storied building in Y direction

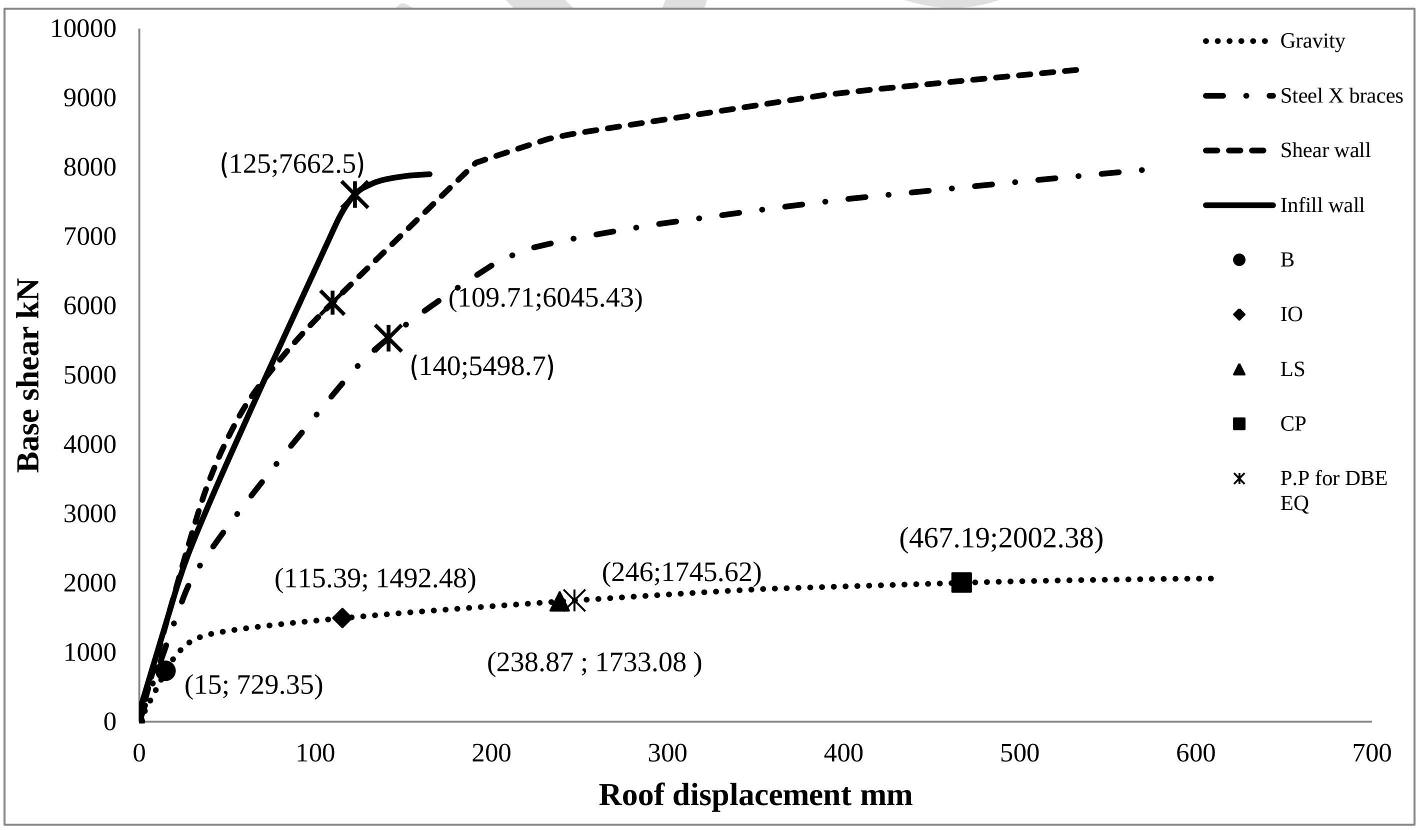


Figure 9 Comparison of various retrofitting schemes for 12 storied building in X direction

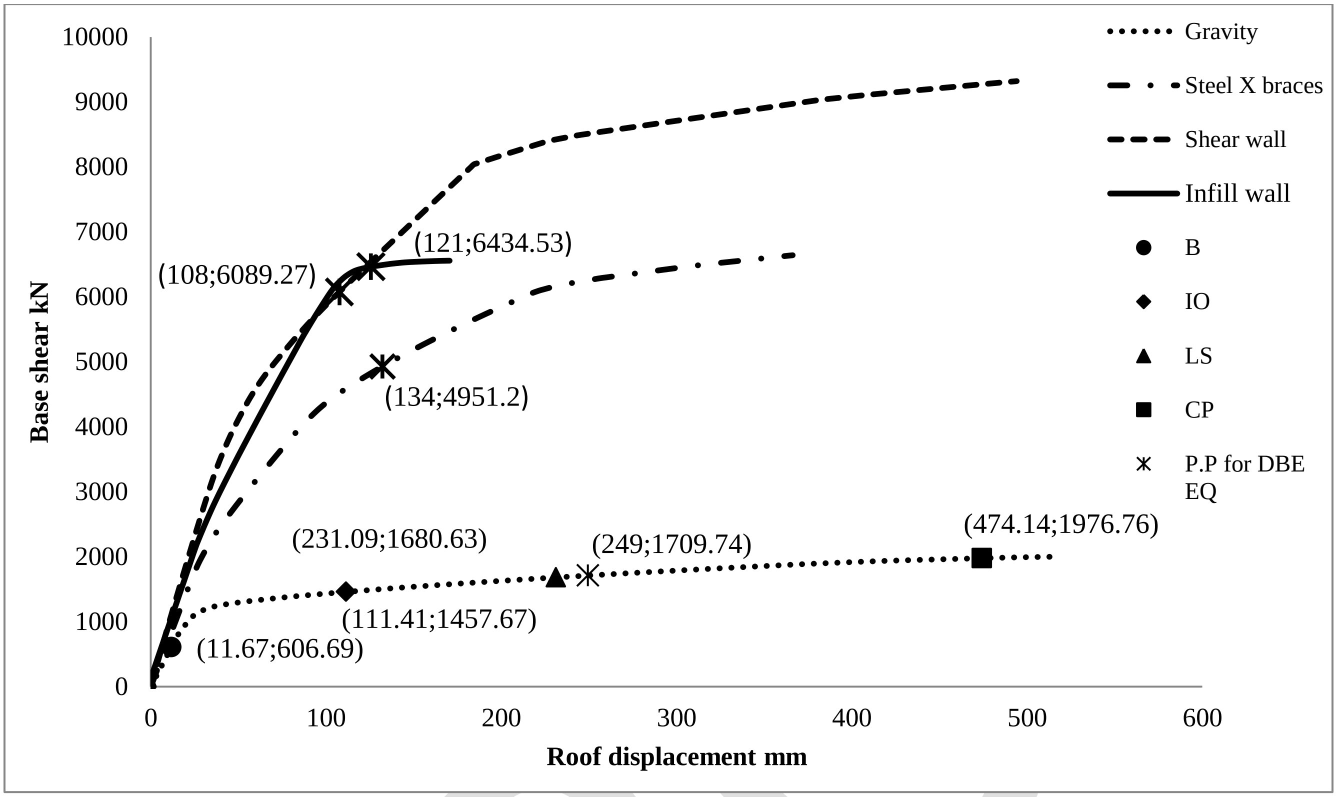


Figure 10 Comparison of various retrofitting schemes for 12 storied building in Y direction

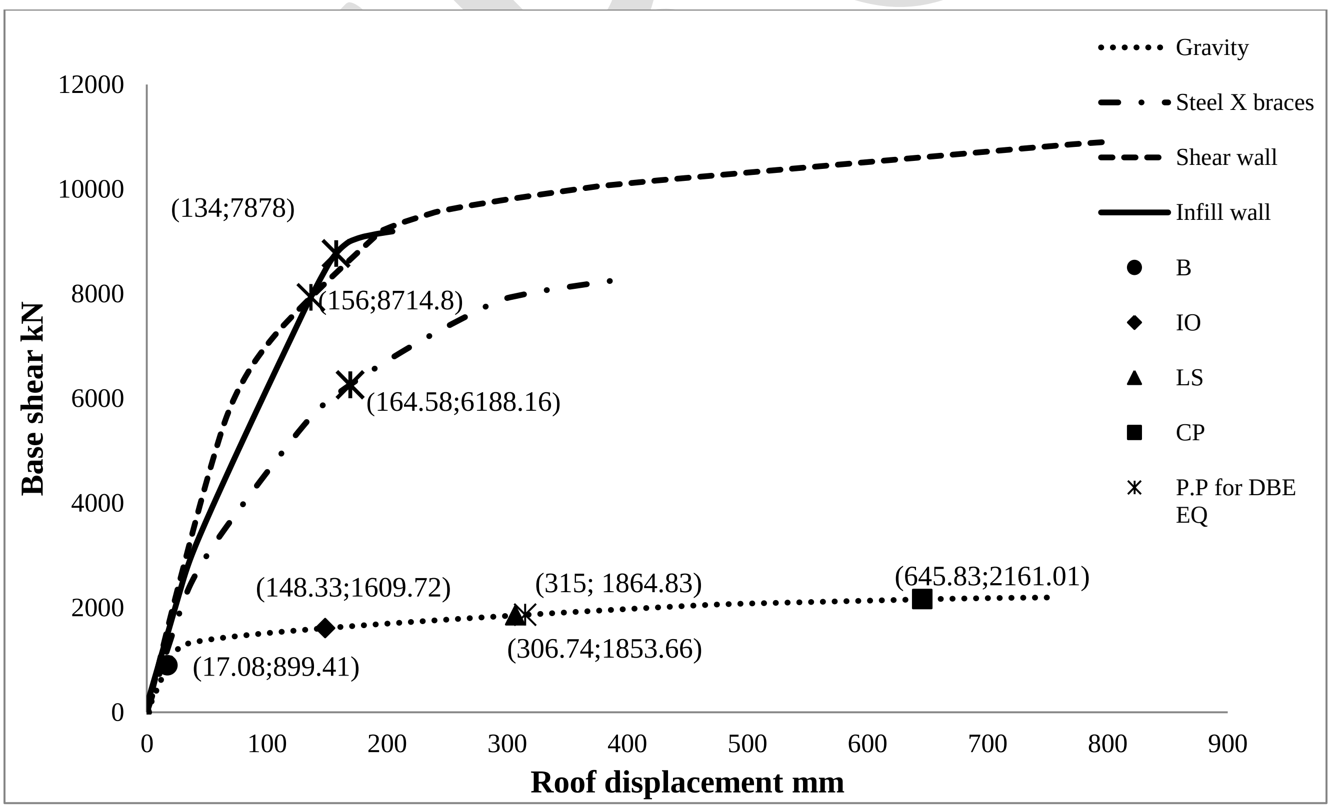


Figure 11 Comparison of various retrofitting schemes for 16 storied building in X direction

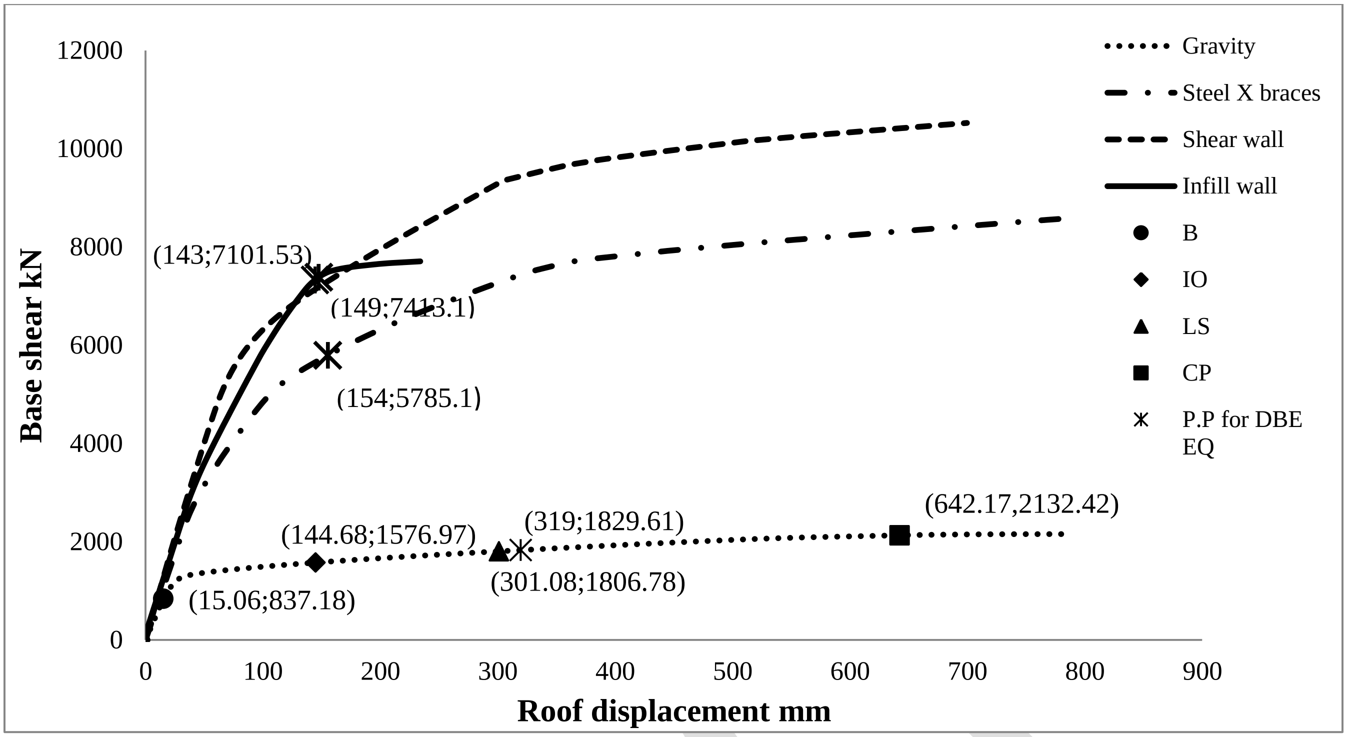


Figure 12 Comparison of various retrofitting schemes for 16 storied building in Y direction

Performance points and capacity curves for various retrofitting schemes are shown in the table no. 2 and figure 7 to figure 12 respectively. The resulting capacity curves for three retrofitting schemes shows improvement in performance levels. The buildings which were initially at LS-CP level, after retrofitting they are at O-IO level. For gravity designed buildings value of base shear and roof displacement goes on increasing as number of storeys increases. Also the base shear and roof displacement is maximum in X direction as compare to Y direction. The comparison between capacity curves shows that when the building is retrofitted with steel X bracings its roof displacement is more than any other retrofitting scheme employed. Steel X brace produces more ductility than other two retrofitting schemes. Buildings retrofitted at external bays with infills produces maximum base shear at performance point. On the other hand the building yields less roof displacement when it is retrofitted with shear walls. The base shear capacity of buildings retrofitted with shear wall is comparatively higher than other schemes.

CONCLUSION

Assessment of the performance levels of gravity designed buildings shows that these buildings are seismically deficient. As a result different strengthening schemes are used to improve performance of deficient buildings; all these different retrofitting strategies are aimed at providing B-IO performance level for DBE condition. Based on results following conclusions are drawn:

- Buildings designed as per IS: 456-2000 is seismically deficient. These buildings are unable to produce sufficient lateral load resisting capacity during an earthquake to avoid sever damages. Moreover, performance of analyzed buildings is at life safety (LS) to collapse prevention (CP) level.
- The study of hinge formation patterns shows that most of the hinges are formed in beams and very few in columns. The LS-CP hinges are formed at middle storeys only, whereas IO-LS hinges are formed at upper and lower storeys.
- It is observed that as building height increases value of base shear and roof displacement also increases. The value of base shear at performance point is maximum for 16 storied building and it is 1.19 times and 1.06 times more than 8 and 12 storied building in X direction. Whereas in Y direction it is 1.80 times and 1.07 times more than 8 and 12 storied buildings base shear values at performance point.

Assessment of the performance levels of gravity designed buildings shows that these buildings are seismically deficient. As a result different strengthening schemes are used to improve performance of deficient buildings; all these different retrofitting strategies are aimed at providing B-IO performance level for DBE condition. Based on results following conclusions are drawn:

- Comparison between three strengthening strategies shows that most increase in effective lateral stiffness at yield point is maximum when building is retrofitted with shear wall.
- For 8 storied building lateral stiffness is increased by 3.48 times, 1.79 times and 1.22 times in X direction whereas in Y direction it is increased by 2.37 times, 1.94 times and 1.32 times when retrofitted with shear wall over gravity building, steel X braced building and infill building respectively.
- For 12 storied building lateral stiffness is increased by 1.70 times, 1.58 time and 1.01 times in X direction whereas in Y direction it is increased by 1.78 times, 1.40 times and 1.04 times when retrofitted with shear wall over gravity building, steel X braced building and infill building respectively.
- For 16 storied building lateral stiffness is increased by 1.73 times, 1.59 time and 1.27 times in X direction whereas in Y direction it is increased by 1.57 times, 1.39 times and 1.09 times when retrofitted with shear wall over gravity building, steel X braced building and infill building respectively.
- Maximum base shear carrying capacity is noted in case of infill wall at performance point. It is because of infill wall increase stiffness of the building more than other two retrofitting schemes and hence attracts more lateral loads.
- At performance point maximum roof displacement is observed in case of steel X braces. This is because steel itself more ductile material than concrete also steel braces contributes negligible mass and stiffness to the original mass and stiffness of the structure.

A number of different strengthening systems can be adopted to improve the seismic performance of deficient buildings. The performance of particular retrofitting strategies depends upon the structural properties of original deficient building. In this case shear wall placed in outer bay improved the performance to desired level.

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