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Comparative study of Reinforced Concrete Structure by Non-Linear Static Pushover Analysis considering Behaviour of Fixed-Base and LRB Base Isolator

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Abstract

The present study focuses on the seismic performances of mid-rise Reinforced Cement Concrete (RCC) frame buildings using Non-linear Static Pushover Analysis. All frame buildings were modeled, analyzed, and assessed for seismic loading using ETABS software. The building models were evaluated while considering changes in three building characteristics: Aspect ratio, Storey height, and Base support. ASCE-41 code provided auto-generated hinges for the structural members and was also used to project displacement monitored base shear curve for target displacement of 250mm. Moreover, Uniform Building Code (UBC) was used to model and design the Lead Rubber Bearing (LRB) system for buildings with base-isolation system. The resulting base shears, plastic hinges, and performance points of the analysed building provided the data for evaluating the building's seismic performance.

Keywords

Base Shear,Lead Rubber Bearing, Plastic hinge, Pushover, Target Displacement

1. Introduction

Earthquakes are an undesirable phenomenon-resulting from the sudden release of stored energy in the earth's crust- which can severely affect the buildings. During the earthquake, the building's inertia responds to the acceleration transmitted from the ground with the development of stress in the structural members. These earthquake-induced stresses can result in building damage or failure and have been a point of interest in structural engineering. One of the ways to mitigate these adverse stresses would be understanding the influence of the geometrical configuration of the structure on seismic forces and manipulating them. Building structural configuration determines the eccentricity- produced due to discrepancy in the center of mass, stiffness and storey height can accentuate the moment, base shear, and storey drift, thus exacerbating the seismic effect. So, the optimization of structural composition can help optimize the building's seismic performance. Moreover, in the past few decades, isolation systems in buildings have become prevalent in dwindling seismic energy from the ground, concomitantly improving their seismic performance.

Numerous studies have presented similar ideas asserting the importance of the aspect ratio, storey height and sub structural design of the buildings in determining the resultant stress and moment developed in the buildings. Researchers like Anwaruddin et al. provided a comparative structural strength and deformation demand in buildings with changes in building irregularity, where the buildings with irregularities performed poorly[1]. Alashker et al. studied the effect of building configuration on the seismic performance of RCC buildings and concluded that base shear significantly increased with the building aspect ratio[2]. Likewise, Haque et al. contributed to the study with their paper extending to the multi-storied buildings and affirmed that buildings with regular plans had improved seismic performance[3].Moreover, Ghasmi et al. studied the effect of seismic base isolation in the seismic requirement for RCC building, and found that building with base isolation performed far better during earthquake. [4]

These papers provide deep insights into the influence of particular building characteristics on seismic performance. However, neither of them gives a comprehensive outlook on the improvement of building seismic performance.

The paper's objective is to provide a comprehensive study of the seismic performance of mid-rise buildings with change in aspect ratio and storey height using non-linear static pushover analysis while considering the analytical parameters such as base shear, plastic hinges, and performance points. This study would help better understand the interdependence between the building configuration and stress produced during the earthquake. Moreover, the buildings were also analyzed with a base isolation system to evaluate the corresponding change in the seismic forces and building performances.

1.1 Pushover Analysis

Pushover Analysis is a static procedure that uses a simplified non-linear technique to evaluate the expected performance of a structural system in design earthquakes while estimating the structural strength and deformation demand compared to the available capacities at the performance level of interest. The pushover analysis provides a method to predict seismic force and deformation demand while accounting for the redistribution of internal forces subjected to the structure when inertia forces exceed the elastic range of structural behavior [5].

During the earthquake, structures redesign themselves intermediately; when an individual component of a structure yields or fails, the dynamic forces on buildings relocate towards other components. Pushover Analysis simulates this phenomenon by applying load until the weak link gets ascribed, then the model revises the analysis with the changed force distribution to identify another weak link. This process continues until a yield pattern for the whole structure under seismic load is recognized. The analysis provides response characteristics that assist the structural designers in predicting the critical region and optimizing the design through detailing [5, 6]. In pushover analysis, the building is subjected to gravity load and monotonic lateral load pattern with constant increment until the target displacement is achieved. The analysis can be executed with Force-controlled and Displacement controlled methods. Federal Emergency Management Agency (FEMA) and Applied Technical Council (ATC) provide a detailed account of the design and evaluation for the non-static analysis. The evaluation depends on assessing performance parameters such as inelastic element deformations, element deformation, element-connection forces, global drift, and inter-storey drift [5].

Hinges are formed on a structure where cracking and yielding occur in relatively higher intensity, resulting in high flexural or shear displacement, as these members approach their ultimate strength under cyclic loading. In actual buildings, hinges can be seen as cross diagonal cracks at either end of the structural member. Consequently, they are modelled at either end of column and beam in pushover analysis. The hinge in the structure represents the localized force-displacement relation of a member through its elastic and inelastic phases under the seismic load. Figure 1 provides the typical force-deformation diagram, where A, B, C, D, and E in the diagram denotes the force-deflection behaviour of the hinge. The force-deflection curve between A-B denotes the elastic state, B-C denotes the plastic state, and E denotes the collapse. The figure also shows the non-linear states defined as ‘Immediate Occupancy (IO), ‘Life Safety (LS), and ‘Collapse Prevention (CP) within its plastic range of the curve [6] [7].

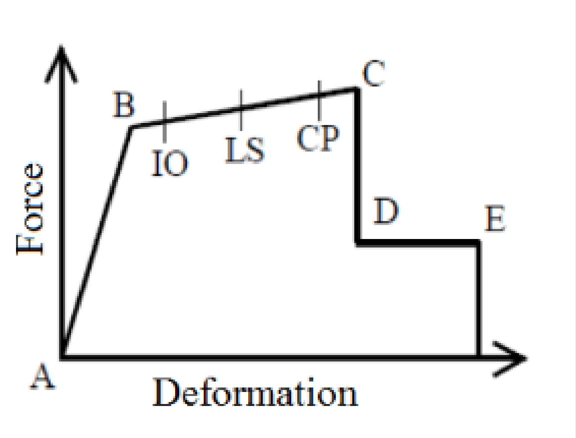

Figure 1: Perfrormance Level for pushover

1.2 Lead Base Isolator

Earthquake load on a structure is due to the inertial property of the structure. During the earthquake, the lower part of the structure is forced to move along the ground motion, while the upper part by virtue of inertia attempts to maintain the original state of rest; two deformation behaviour between the lower and upper parts within the structure induce the inertia force. This inertial force produced is proportional to the product of the structural mass and the ground accelerations, ensuring greater seismic effect for larger structures and acceleration. For the conventional earthquake-resistant design, high-rise buildings and heavy structures would be attributed to the larger structural members; not only will this result in uneconomical but also unsophisticated design. Likewise, when a building is subjected to an earthquake even though the collapse is avoided, the drift can adversely affect the functional and utility aspect of the structure. For these major reasons, base isolation is provided.

Base isolation is a passive vibration system that decouples the structure from damaging earthquake energy. The system requires no external power source but instead uses the motion of the structure to develop the control force. In this method, the entire superstructure is supported on a discreet isolator separated from the ground, which increases the flexibility of the structure while reducing the effect of an earthquake.

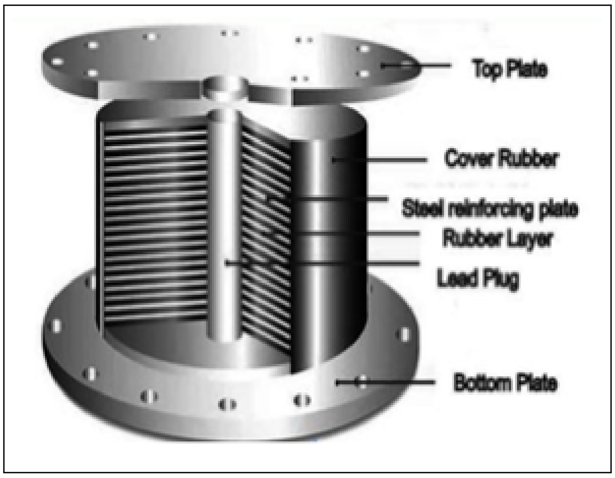

Figure 2: LRB isolator [8]

Lead rubber bearing (LRB) isolator is one of the most common and widely used base isolation techniques. LRB isolators are a single compact unit that provides vertical load support, horizontal flexibility, supplemented damping and centring force to the structure. It contains a cylindrical lead core on the centre surrounded by alternate layers of laminated rubber and vulcanized steel shim plates. These reinforcement steel plates are fully embedded in the elastomeric material with steel plates provided at both ends of the isolator. The yielding of the lead core provides energy dissipation and damping to the isolator, which is equivalent to a viscous damping coefficient of up to 30. Likewise, the rubber provides flexibility to the building and the steel shim plates act as a reinforcement in the load-carrying capacity of the isolator, providing the structure with flexibility in both orthogonal horizontal directions, while still stiff enough to withstand the vertical loads of the structure [8].

2. Modeling

The study provides a parametric analysis of RCC Building using pushover analysis in ETABS 2018, as per ASCE-41 code [9]. Within the provided category, the building is analyzed with changes in three building characteristics:

- Aspect Ratio
- Storey Height
- Provision for Base Isolation

Two bay two-dimensional frame with each bay equal to 4m, except for building with aspect ratio 1.5 where the combination of 4m and 5m, was used. For the change in aspect ratio, the corresponding increase or decrease in bays was done in the global x-direction. Mid-rise buildings from 4 to 6 stories were modeled with the ground and the typical height of the floor equal to 3m. The structural members' sectional properties are given in Table (1). Moreover, the building was further evaluated with a change in the support assigned between structure and ground.

Initially, a Fixed base (F.B) was provided as support for analysis and then replaced with an LRB base isolator. The base isolation system was designed using UBC-97 code[10].

2.1 Structural Member Properties

For modeling of structure columns of size 500x500mm and beams of 350x 550 are used in all models. For the material properties in concrete and rebar, IS 456: 2000 [11] is used. The material properties used in the models are shown in Table 1.

Table 1: Material Properties

Parameters	Values
Modulus of elasticity of concrete Ec	25000 MPa
Characteristic strength of concrete,fck	25 MPa
Yield stress for rebar,fy	415 MPa

2.2 Loading and Seismic Properties:

The modelled structures are initially checked for earthquake loading using the Equivalent Static Method. For this, the load pattern and load cases along with model cases and mass source are defined. The load combinations are considered as per IS 1893:2016. Likewise, in the mass source, the earthquake force was calculated for the full dead load and 25 percent of the live load. Moreover, the structures are analyzed for Seismic Zone V, with Importance Factor 1 and medium type soil. The applied load and seismic data on the structures are presented in Table 2 and Table 3 respectively. The designed structures are then further proceeded for pushover analysis.

Table 2: Load Applied

Load	Value(KN/sq.m)
Dead	Self-Weight as per IS 875-Part 1
Live	3
Floor Finish	1.5
Partition Load (on Slab)	3

Table 3: Seismic Data

Component	Value
Zone factor(Z)	0.36
Importance Factor	1
Response Reduction Factor(R)	5
Soil Type	Medium
Eccentricity Ratio	0.05

2.3 LRB Modeling

Uniform Building Code (UBC) provides the modelling, design criteria, and seismic analysis for the base isolation system [10]. Naeim et al. and Venkatesh et al. have previously presented a systematic procedure for the design of an LRB system based on UBC; this paper considers the provided outline for the design of isolators [12, 13]. These isolators were designed conforming to the change in the type of structure and number of storey. For every instance, each column in the building was provided with an identical isolator. The Target Period (TD) was considered 3 times the time period of the fixed-based frame.The details of selected parameters and preliminary design are presented in Table 4 and Table 5.

Table 4: Parameters

Component	Value
Seismic Zone factor	Zone 3, Z = 0.30
Seismic source type	B type
Soil profile type	Stiff Soil
Near Source Factor	$\Delta > 15$km, $N_a = 1$ and $N_v = 1$
Maximum capable earthquake response coefficient (M_m)	1.25
Effective damping of the isolation system	0.05
Yield Strength of Lead	10 Mpa
Maximum Shear Strain of Rubber(γ)	1

Table 5: Isolator Properties

R.C.C Strucutre(Aspect Ratio: 1)		
Isolator Properties	Storey 4	Storey 6
Bearing Height(mm)	270	353
Characteristics Strength(KN)	27.88	29.42
Yield Strength (KN)	30.98	32.69
Effective Stiffness(KN/m)	1679.79	1307.6
Post-Yield Stiffness(KN/m)	16811.63	13086.70
Vertical Stiffness(KN/m)	597842.55	465379.45
Bearing Diameter(mm)	770	790
Lead core diameter(mm)	60	60

3. Building Analysis

Finite element modeling software, ETABS 2018, was used for analyses. All structures with different aspect ratios, storey height, and support conditions were designed and then evaluated using pushover analysis. Nonlinear hinges were assigned to column and beam at both ends at a relative distance of 0.1 and 0.9 from the individual member connection. For this, the table of ASCE 41-17 properties of hinges was assigned to these frame elements ie. P-M2-M3 for column and M3 hinge for beam [8]. The analyses were performed in a displacement-controlled method with the roof level displaced up to 250 mm. Finally, the seismic response of the building for push along global x-direction in different scenarios was observed and compared.

4. Result and Discussion

The results obtained from the analysis of all the building models are discussed and compared in the following sections.

4.1 Base Shear and Displacement

For all building models, a resultant base shear vs monitored displacement graph was plotted using ASCE 41-13 NSP as plot type. In addition, the demand spectrum was modified with acceleration (Ss) and acceleration (S1) as 1.83 and 0.85 respectively.

First of all, the change in the pushover curve with the corresponding change in aspect ratios was compared. For this, a four-storey RCC building was analyzed with the change in its aspect ratio. The changes were made with the addition of structural and nonstructural members of identical shape, size and loading in the global x- direction.

Figure 3 represents the resulting pushover curves for x-direction considering five changes in aspect ratio. Base shear increased with the increase in roof displacement. Likewise, for this analysis, the increase in base shear was found to have a positive correlation with aspect ratio. Considering the curves for buildings with aspect ratios from 1 to 1.5, it can be seen that there was a marginal increase in base shear with the increase in the aspect ratio. However, there was a drastic increase in shear force for building with aspect ratios of 1.66 and 2 compared to buildings with smaller aspect ratios.

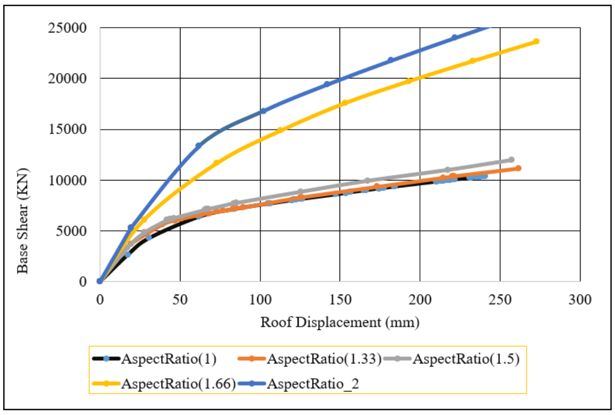

Figure 3: Pushover curves for fixed base RCC Structure of 4 storey with different aspect ratios

Secondly, the change in the pushover curve with the corresponding change in storey height was compared. For this, we used the sample 4 storey RCC buildings and added a replicated floor on top for 5 storey and 6 storey. From Figures 4 it is found that for target displacement of 250mm, base shear decreases with the increase in storey height.

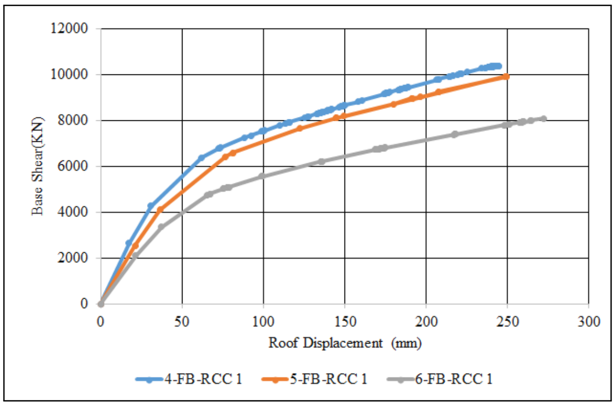

Figure 4: Pushover curves for fixed base RCC Structure of aspect ratio 1 with different storey level

Finally, the buildings were studied with the change in base support. The fixed-based support for all columns were replaced with spring support i.e. Lead Rubber Bearing. 4 storey and 6 storey buildings were compared for the assessment and evaluation of change in seismic perfomance with the change in base support.

Comparing the base shear vs roof displacements curves, it can be clearly seen that there was a significant decrease in the base shear. In 4 storey building, the installment of the isolation system has resulted in a 60 percent decrease in base shear whereas for 6 storey the decrease is 48 percent.

Likewise, for this case also the decrease in base shear for an increase in storey height holds true.

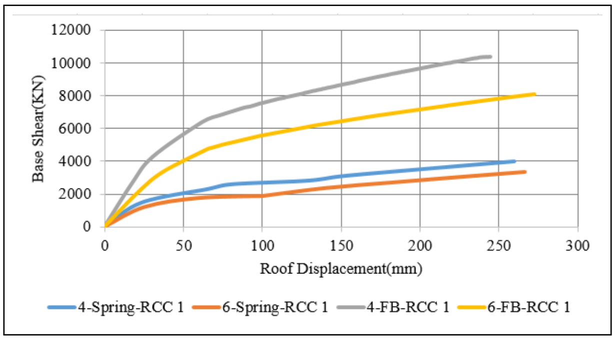

Figure 5: Pushover curves for fixed base and Base Isolated(spring) RCC Structure of aspect ratio 1 with different storey level

4.2 Performance Level and Hinges

With the change in base support for the buildings, the performance point also shifted toward right direction. So, the base isolated buildings were analyzed for a target displacement of 400mm.So, in this section building performance and their corresponding base shear are compared.

From Table:6, it can be seen that the performance point increased for base isolated buildings compared to their fixed base counterpart.However, the analysis also presented a decrease in shear force. For 4 storey building after base isolation target displacement increased by 90% and base shear decreased by 43%. Whereas, for 6 storey building displacement increased by 60% and base shear decreased by 46%.

Table 6: Building Performance Point

storey	Footing types	Performance point.(mm)	Base Shear(KN)
4	F.B	96.59	7336
6	F.B	226	7508
4	Spring	282.6	4185.5
6	Spring	366.172	4098.95

Finally, the formation of plastic hinges in the structure were evaluated. For this, 4 storey buildings with different aspect ratios and their corresponding hinges in four different groups according to their non-linear state were compared. The state are shown in detail in Figure 1. The number of hinges formed were converted into percent of the total number of hinges.

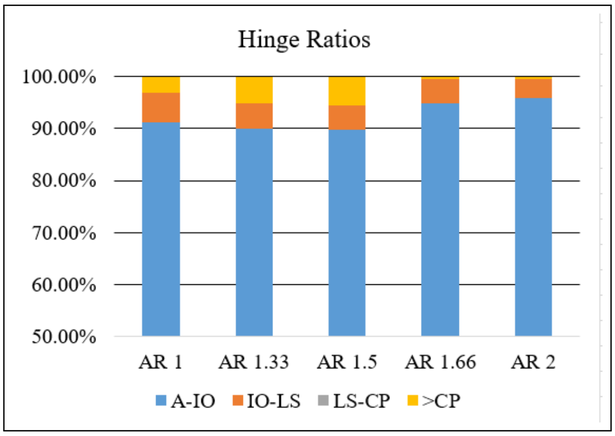

Figure 6: Percentage of hinges formed at different performance level for 100mm target displacement

Fig:6 shows the percent of hinges in different states for the individual building for a roof displacement of 100mm. It can be seen that buildings with higher aspect ratios had comparatively fewer hinges exceeding the Immediate Occupancy(IO) state and Collapse Prevention (CP) state. From the figure, we can infer that at this displacement buildings with higher aspect ratios performed better than the lower aspect ratios.

Fig:7 shows the percent of hinges in different states for the individual building for a roof displacement of 250mm. It can be seen that buildings with higher aspect ratios had a comparatively higher number of hinges exceeding the IO state but a lower number of hinges exceeding the CO state. From both the above performance point figures it is clear that there is a distinction in seismic performance for building with aspect ratios 1, 1.33, 1.5 and buildings with aspect ratios 1.66 and 2.

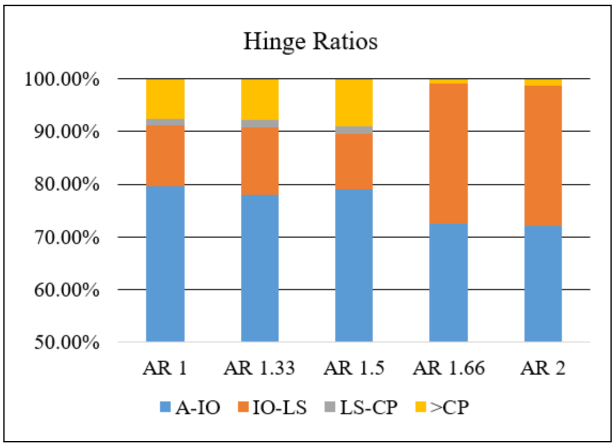

Figure 7: Percentage of hinges formed at different performance level for 250mm target displacement

5. Conclusion

This method of analysis promises to be a useful and effective tool for performance based design of structure. Buildings with different plan aspect ratio and number of storey have been analyzed by this method and results have been compared in terms of base shear, displacement and, plastic hinge pattern. From the study, the following conclusions were drawn.

- The plan dimensions significantly influenced the seismic behavior of the buildings, where it was found that base shear increase gradually with an increase in aspect ratio up to buildings with aspect ratio equal or less than 1.5. However, the base shear increase drastically with additional increase in aspect ratio.
- For the target displacement of 250mm in the given study, the base shear decreased with an increase in the aspect ratio.

- For the target displacement of 250mm, the buildings with higher aspect ratio performed better than the lower counterpart. The number of collapse hinge formed in the building with lower aspect ratio was higher than the higher aspect ratio.

- With the introduction of base isolation system, target displacement be significantly increased in the buildings. This showed that the isolated buildings performed better during earthquakes than the fixed base buildings.

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