

Original Article

# Performance-Based Seismic Assessment of Response Reduction Factor for C-Shaped RCC Buildings

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**Abstract** - With the growing demand for infrastructure and habitations, it is seldom possible to go with regular configurations. Therefore, the layout of buildings unavoidably involves various types of irregularities. This study focuses on one such irregularity that arises in plan, i.e., the re-entrant corner irregularity in C-shaped plan buildings. The buildings are designed using relevant Indian codes. Nonlinear static pushover analysis is carried out to obtain the buildings' inelastic response. Three-dimensional models of the buildings are subjected to non-linear pushover analysis, and the seismic performance is studied in the inelastic range wherein the Response Reduction Factor (R) is obtained for various storey configurations with different irregularity indices. The Special Moment Resisting Frame (SMRF) system is used as the structures are designed for seismic zone IV. While the design codes provide a single value for the response reduction factor for a structural system irrespective of any irregularity, it is seen from this study that the complex nature of irregularity creates variations in R values, leading to lower values in some cases, thereby affecting the safety of the structure under a seismic event.

**Keywords** - C-Shaped Buildings, Plan Irregularity, Pushover Analysis, Seismic Performance.

## 1. Introduction

RCC framed structures are one of the most widely adopted structural forms of building construction. Gravity loads, i.e., loads generated due to self-weight of structural elements, occupancy, etc., as well as lateral loads like earthquake loads, etc, need to be considered during the design of these buildings to ensure that the structure remains safe under the action of all expected loads. The construction of these buildings is seldom possible in a perfectly regular configuration. Usually, certain irregularities always occur in a structure due to architectural considerations, construction limitations, etc.

The estimation of seismic forces on the buildings is crucial for a safe and economic design. Such types of buildings experience variations in their seismic response as compared to regular buildings, as the load paths differ and the distribution of forces changes. During a seismic event, the structures may undergo a non-linear response due to the massive displacements and rotations experienced. The Response Reduction Factor (R) is very important in determining the design of seismic force as per IS 1893:2016 –Part 1 [1] and various other international codes related to seismic design of buildings. It represents the ratio of the elastic base shear demand to the inelastic base shear demand that accounts for ductile behaviour, overstrength, and redundancy. The usual design process for Indian buildings

involves designing the buildings for a seismic force obtained from the response spectrum method. By consideration of the R factor, the buildings are designed for lower seismic forces than the expected ones by taking advantage of the ductility in the system, which will lead to energy dissipation. It is, however, seen that the IS 1893-2016 code provides a single value of response reduction factor for regular as well as irregular buildings for the same lateral load resisting system.

Various studies have highlighted the importance of considering variations in the R factor for a safe and economic design of RCC structures. It is expected that the R factor may be less than what is prescribed in the IS code, and various factors like irregularities may reduce the R factor further [2]. A slight increase in the initial cost of the structure for ductile detailing helps achieve a better ductile response and saves on the repair costs of the structure [3]. A study on vertical irregularities generated from setback in structures indicated that the capacity of inelastic deformation significantly reduced as the degree of irregularity increased [4]. Even for 2D frames without any irregularity, it was observed that the Response reduction factor values obtained at different performance levels are less than those given in the IS code. IS 1893 overestimates the R value, which may lead to underestimation of base shear for some cases [5]. Studies on RCC buildings with T-shaped building plans, different heights of buildings, and designs for different values of R



factor have demonstrated the effect of R factor and building height on seismic vulnerability [6]. While considerable research is available on various irregularities, there is limited research available for buildings with irregular plans [7]. It has been observed that minimal research has been done on inelastic response using 3D analysis, as well as for irregular buildings [8].

This study aims to evaluate the performance of C-shaped plan buildings in terms of the R factor achieved. As per IS 1893, such plans are classified under plan irregularity with re-entrant corners when the ratio of the re-entrant dimension to the total length of the structure in any plan direction exceeds 0.15. The flow of work carried out in this study for the performance-based evaluation has been depicted in Figure 1. While most of the studies focus on pushover analysis for individual frames by plane frame analysis, considering the complex nature of re-entrant corner buildings, the Pushover Analysis (POA) has been done for 3-dimensional finite element models of all buildings.

The objective of this study is therefore to create 3D simulation models of the buildings in ETABS software with varying ratios of re-entrant corner dimensions in X and Y directions, with a C shape plan configuration. Subsequently, pushover analysis is carried out for the 3D models in X and Y direction and thereby obtain the R factor for these buildings.

The novelty of this study is that analysing the buildings using three-dimensional models gives a much better idea about the participation of all the framing elements of the building, which cannot be accurately captured in plane frame analysis. The buildings considered have the same total outer dimension and varying dimensions of re-entrant ratios. This gives a better idea about the variation of the R factor with the changing values of re-entrant corner dimensions. Also, three different heights of buildings have been considered, i.e., 4 storey, 8 storey, and 12 storey to capture the effect of variation in height on the obtained values of R factor.

## 2. Modelling and Structural Parameters of the Buildings

The various parameters considered in this study can be divided into two significant parts, viz., geometric and loading parameters, and parameters for modelling non-linearity.

### 2.1. Geometric and Loading Parameters

For the present study, RCC moment resisting frame buildings are considered with 5m c/c bay spacing and 3m storey height. The axis along the line of symmetry in the plane is considered the X axis, and the normal to it is considered the Y axis. The plan configurations are shown in Figures 2, 3, and 4. The buildings fall under re-entrant corner irregularity with varying re-entrant dimension ratios, such that the re-entrant dimension along the X axis, i.e.,  $A_x$ , is varied for all models and the re-entrant dimension along the Y axis, i.e.,  $A_y$ , is kept the same. The details of the models considered are as per Table 1.

The floor finish load and live load are considered as  $1.5\text{kN/m}^2$  and  $3\text{kN/m}^2$  respectively. Loads due to walls have been considered as  $4.5\text{kN/m}$ . The slabs are taken as 150mm thick, and the self-weight has been calculated by taking the density of concrete as  $25\text{kN/m}^3$ . The zone factor is taken as 0.24 for a building in seismic zone IV. The importance factor is 1.2. Response Reduction Factor (R) is considered to be 5 for the design. The building is taken to be resting on hard soil and has been provided with fixed supports. As per IS 1893-2016, the frame elements have been modelled as having cracked section stiffness, i.e., beams having 35% and columns having 70% of gross section stiffness. For the design of buildings, the base shear has been calculated on the basis of the empirical time period for all models, as per IS 1893. M35 grade concrete and Fe500 grade steel are used for design, and the building is designed as per IS 456-2000 [9] and detailed as special moment resisting frames as per IS 13920-2016 [10].

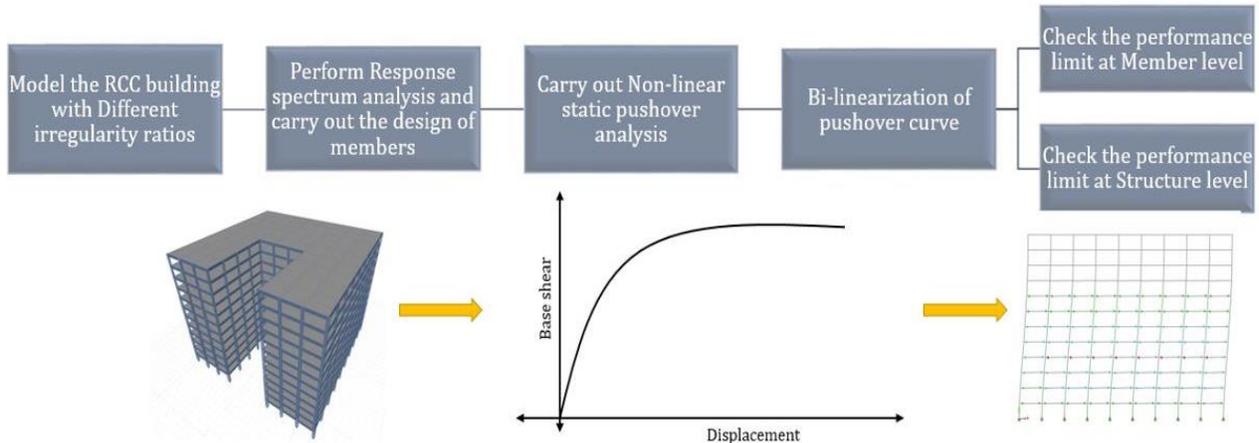


Fig. 1 Methodology adopted in this study for performance based evaluation of R factor

The member sizes are proportioned such that the first two modes of vibration predominantly govern translational directions X and Y. It has been ensured that the buildings do not have torsional irregularity due to the first two modes of vibration. For 4-storey models, the column sizes are 350x500 mm throughout the height of the building, and beam sizes have been kept as 300x500 mm on all storeys. For 8-storey models, the sizes of columns have been kept as 500x750 mm, 500x700 mm, 450x600 mm, and 400x600 mm for the ground storey, 1<sup>st</sup> to 3<sup>rd</sup> storey, 4<sup>th</sup> to 5<sup>th</sup> storey, and 6<sup>th</sup> to top storey, respectively, and beam sizes are kept as 300x500 mm on all storeys. For 12-storey models, the sizes of columns have been kept as 650x800 mm, 500x700 mm, and 400x600 mm for ground storey to 3<sup>rd</sup> storey, 4<sup>th</sup> to 7<sup>th</sup> storey, and 8<sup>th</sup> to top storey respectively, and beam sizes are kept as 300x600 mm on all storeys.

**2.2. Modelling to Simulate Non-Linear Behaviour**

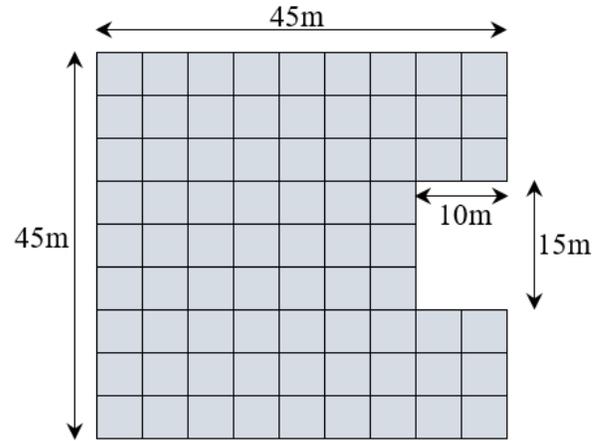
The Pushover Analysis (POA) method helps to get an idea of the nonlinear behaviour of the building, which is essential to obtain the R factor. For nonlinear pushover analysis, the hinges in beams have been modelled as lumped plasticity hinges with a degree of freedom in the direction of M3 (central axis moment) as per FEMA 356 [11]. Lumped fiber hinges with P-M2-M3 (axial load and biaxial moments) degree of freedom have been modelled in columns. Pushover analysis is carried out in X and Y directions according to respective mode patterns, i.e., 1<sup>st</sup> and 2<sup>nd</sup> modes, and the displacement is monitored at the roof level.

Two performance levels have been considered, one at the member level and another at the structure level. The structure must remain safe and stable at the member level (PL-M) as well as the global structural level (PL-D). The member level criteria is considered based on the plastic rotation limits as per FEMA 356, i.e, 0.025 at the collapse prevention level for main beams. For structure-level performance limits, inter-storey drift is considered as the limiting condition, and the limiting values have been taken as per ATC-40 [12] as  $0.33V_i/P_i$ , where  $V_i$  is the shear acting on a floor and  $P_i$  is the vertical load on that floor. This value works out to be 0.0237.

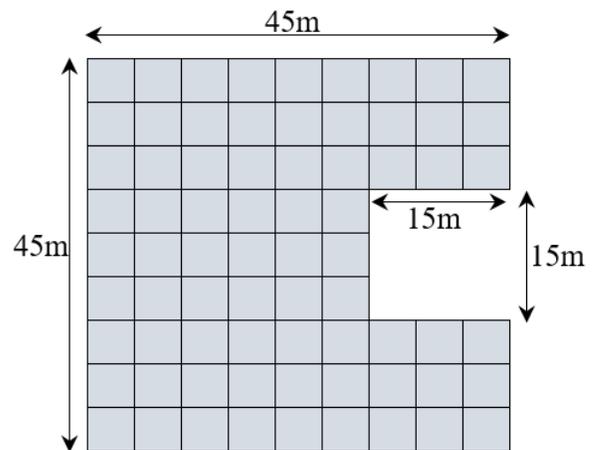
**Table 1. Details of building models considered**

Model	Storeys	Re-entrant ratio ( $A_x/L$ )	Re-entrant ratio ( $A_y/L$ )
M1	4	0.22	0.33
M2	4	0.33	0.33
M3	4	0.44	0.33
M4	8	0.22	0.33
M5	8	0.33	0.33
M6	8	0.44	0.33
M7	12	0.22	0.33

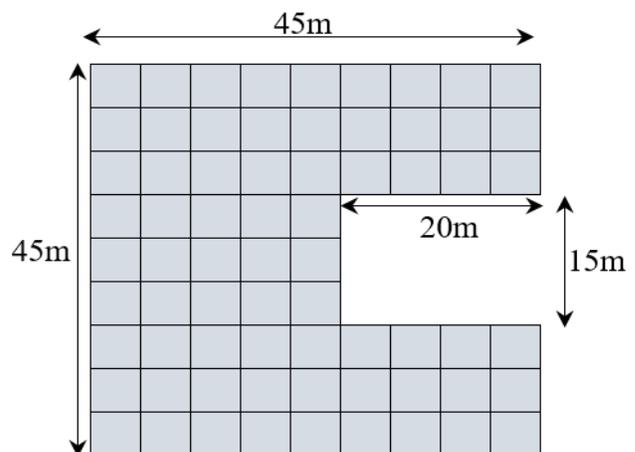
M8	12	0.33	0.33
M9	12	0.44	0.33



**Fig. 2 Plan for models M1, M4, and M7**



**Fig. 3 Plan for models M2, M5, and M8**



**Fig. 4 Plan for models M3, M6, and M9**

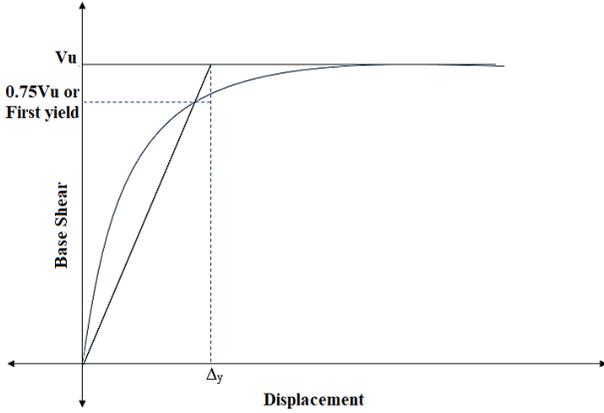


Fig. 5 Bilinear Idealization of the POA curve

**2.3. Calculation of Response Reduction Factor (R)**

The R factor is calculated as the product of the ductility factor and the overstrength factor. The overstrength factor has been taken as the ratio of ultimate base shear to design base shear [13]. While other factors, like the damping reduction factor, may also contribute in some cases, since there are no supplemental energy dissipating devices considered in this study, the damping reduction factor is not considered. The expressions for the calculation of the ductility factor have been taken as per Newmark [14].

The yield displacement was obtained using the reduced stiffness method, wherein the initial stiffness is taken at a

point passing through 0.75Vu or first hinge formation (whichever is earlier) [15] as shown in Figure 5.

**3. Results and Discussion**

The capacity curves for all nine models considered have been obtained from pushover analyses in the X direction and are represented in Figures 6, 7, and 8. Similarly, the capacity curves for Y-direction pushover analyses are represented in Figures 9, 10, and 11. It can be seen that for most of the cases considered, the drift level performance (PL-D) is achieved before the performance level for member level (PL-M) collapse hinge formation. This is consistent with the observations in previous studies, also [2]. As the number of storeys increases, the failure points are achieved at higher displacements. As represented in the figures, the difference between drift level performance point displacement and member level performance point displacement continues to increase as the number of stories increases. This indicates that drift criteria should be an important consideration for the seismic performance of buildings with a larger number of storeys.

Variation can be seen in the performance of the same structure under X-direction and Y-direction pushover cases. For pushover along the X axis, the PL-D and PL-M points are much more apart, i.e, drift level and member level performance is achieved almost at the same base shear and displacement.

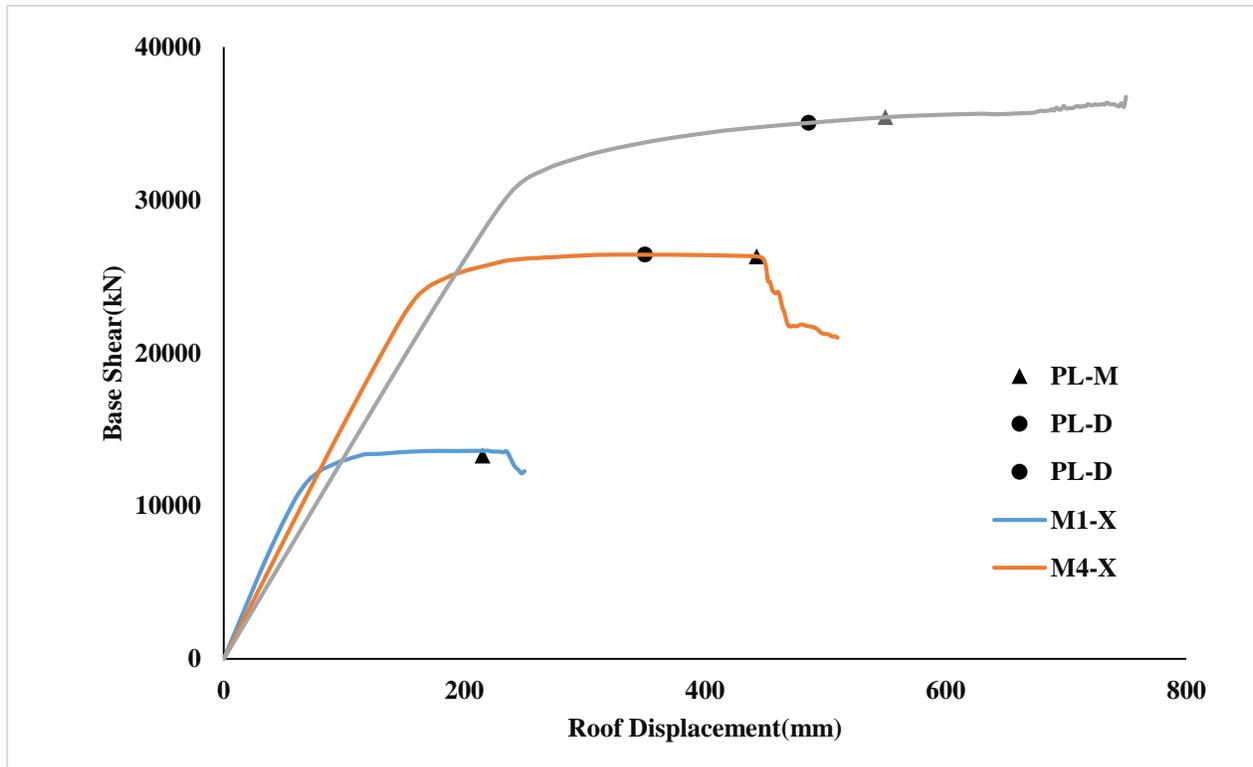


Fig. 6 POA curves for M1 model, M4 model and M7 model for X direction

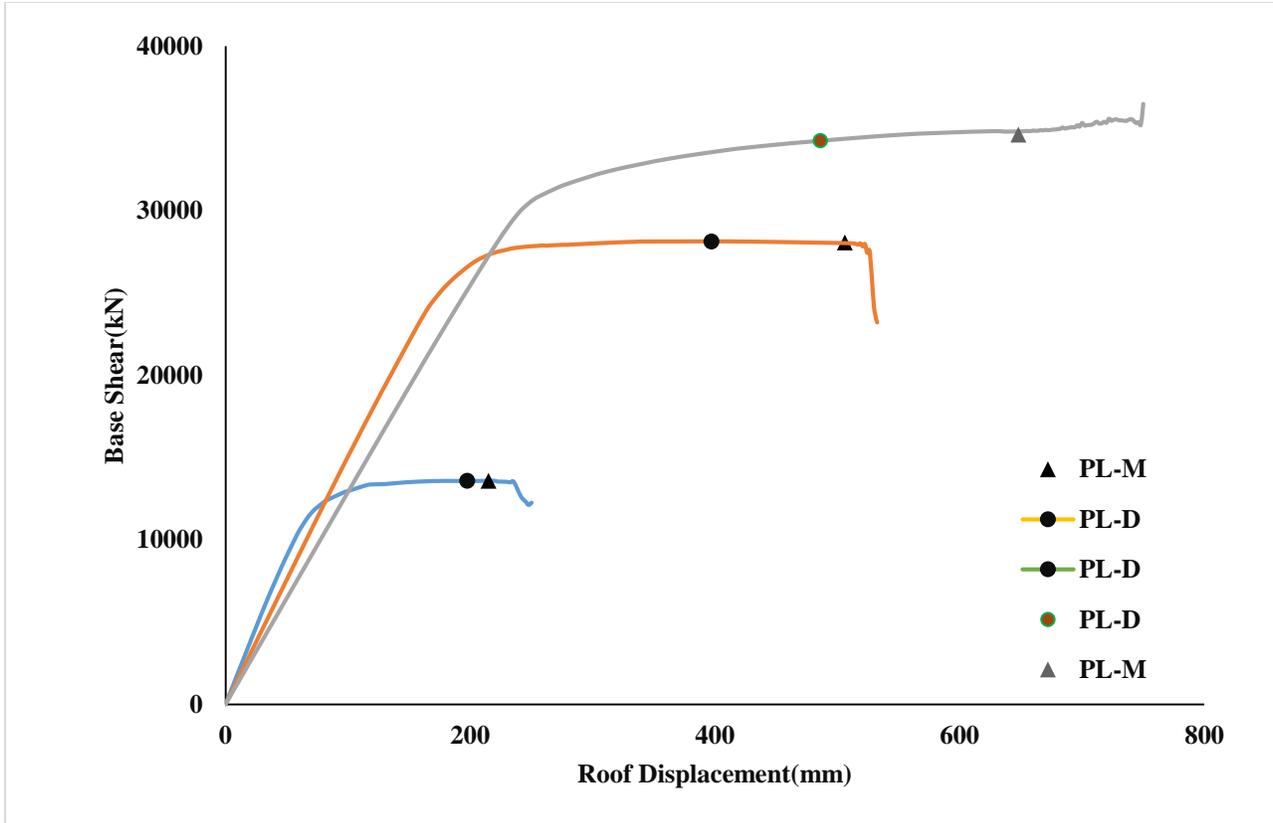


Fig. 7 POA curves for M2 model, M5 model and M8 model for X direction

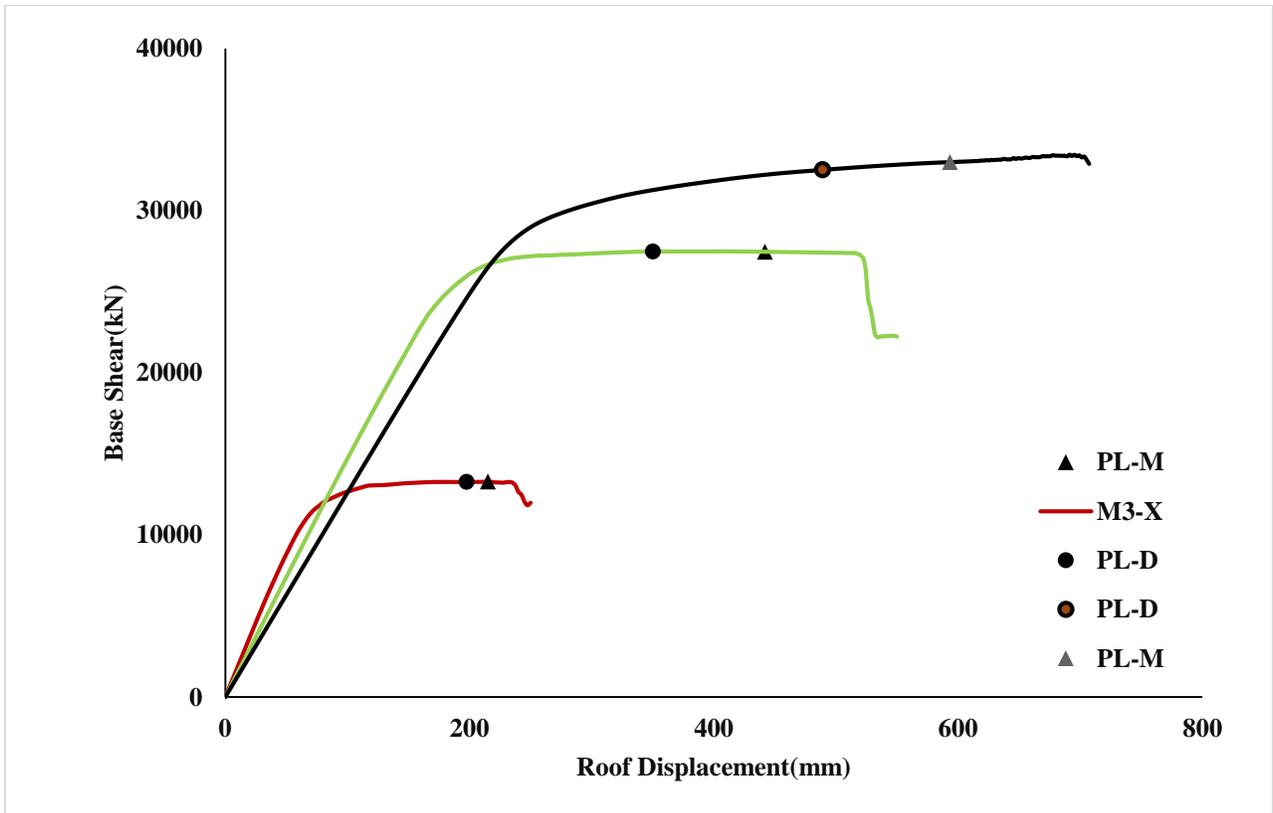


Fig. 8 POA curves for M3 model, M6 model and M9 model for X direction

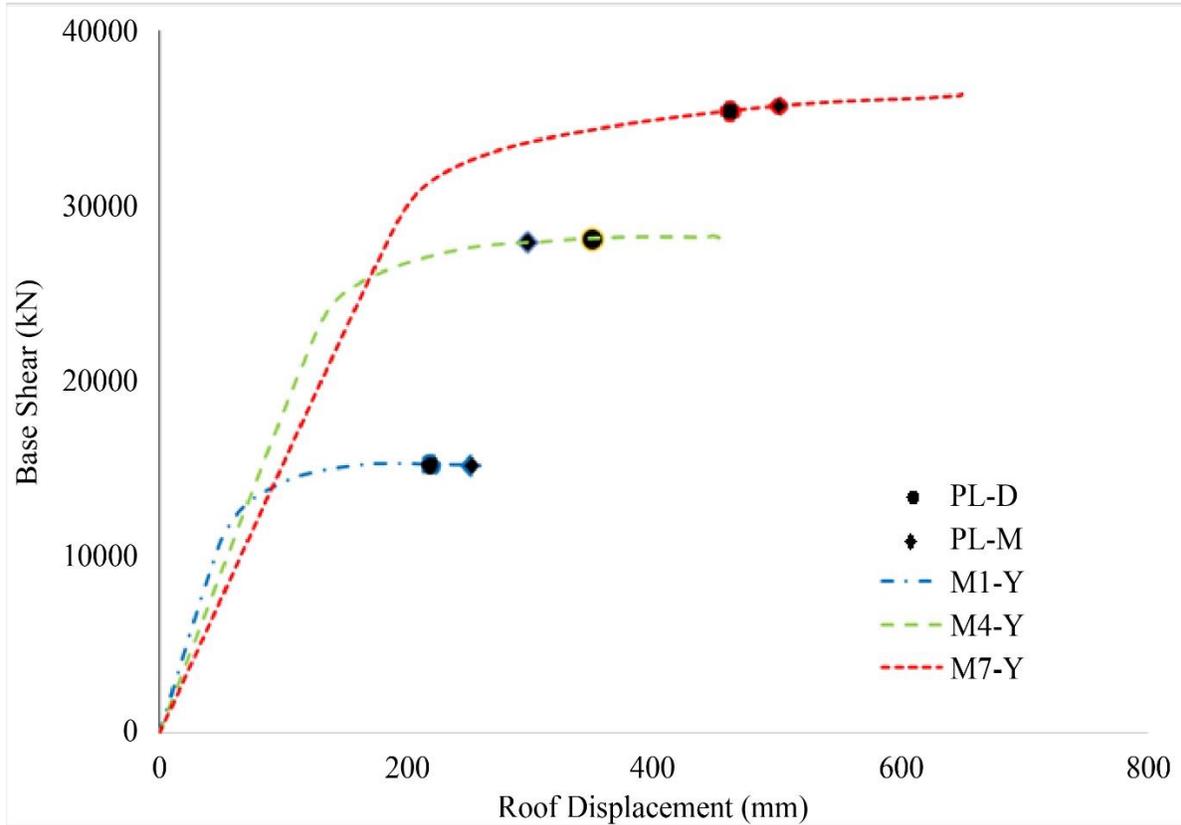


Fig. 9 POA curves for M1 model, M4 model and M7 model for Y direction

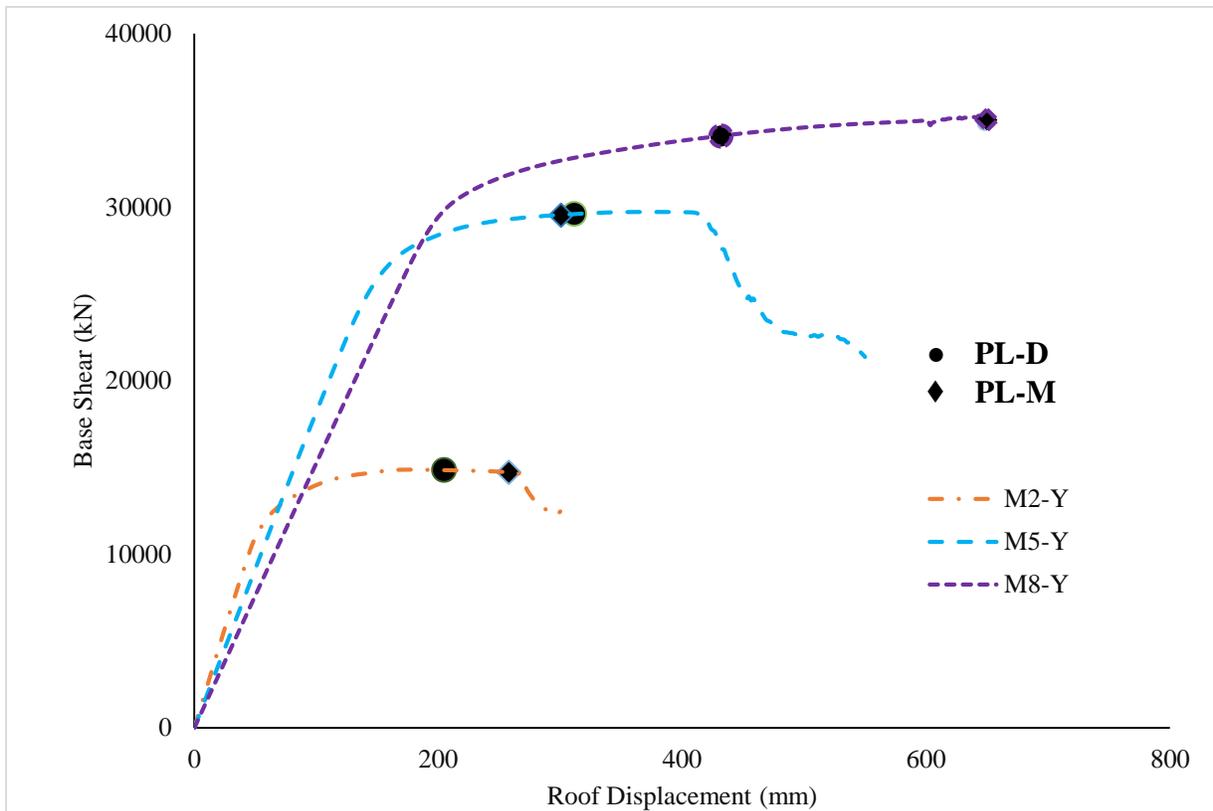


Fig. 10 POA curves for M2 model, M5 model and M8 model for Y direction

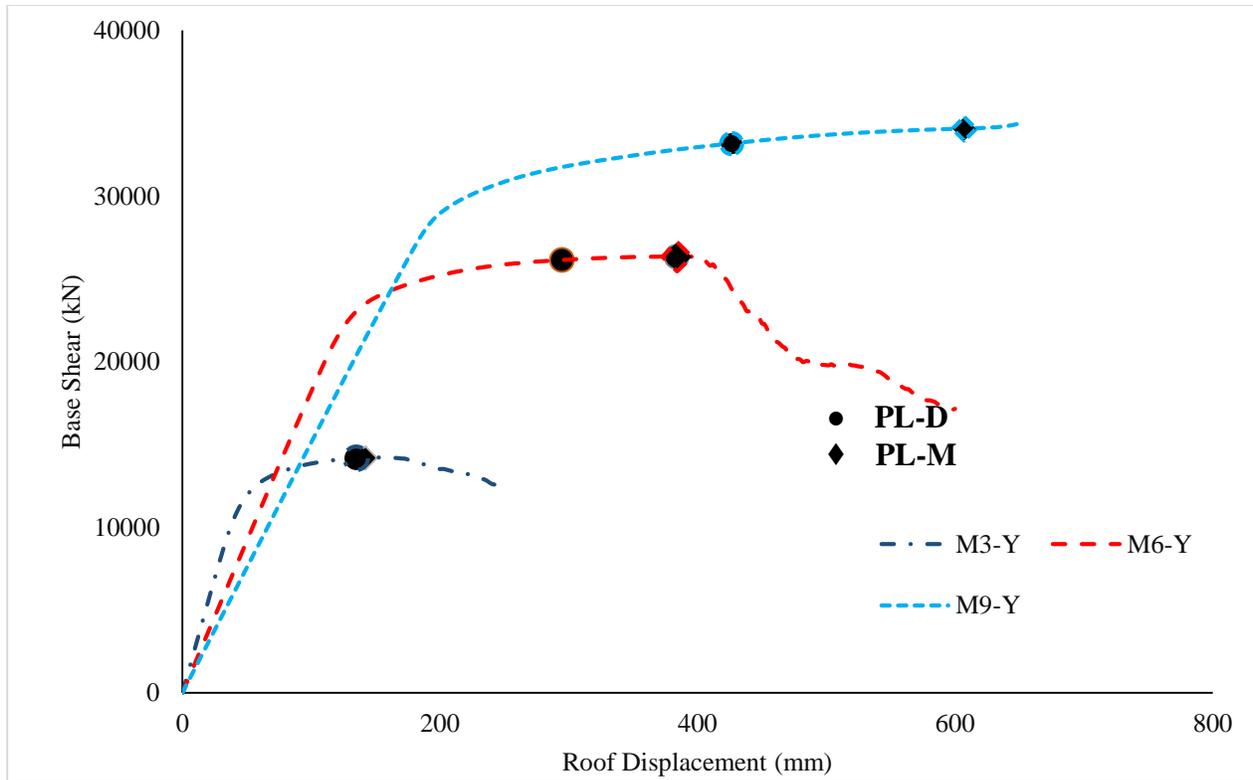


Fig. 11 POA curves for M3 model, M6 model and M9 model for Y direction

The bilinear Idealization of the pushover curves was carried out, and response reduction factors were calculated. The values of response reduction factors obtained from analysis in the X direction and Y direction are represented in Tables 2 and 3, respectively.

It can be seen from the pushover curves that as the storeys increase, the ultimate base shear also increases. The displacements corresponding to the respective performance limits are also greater for a higher number of stories.

Table 2. Response Reduction Factor from the Pushover analysis in the direction

Model	Drift criteria	Member collapse criteria
M1	6.2	6.6
M2	6.3	6.9
M3	6.5	7.1
M4	4.5	5.7
M5	5.1	6.6
M6	4.6	5.8
M7	4.2	4.7
M8	4.2	5.6
M9	4.3	5.2

Table 3. Response Reduction Factor from Pushover analysis in the Y-direction

Model	Drift criteria	Member collapse criteria
M1	8.3	9.6
M2	8.1	10.2
M3	6.8	7.0
M4	5.2	4.4
M5	4.9	4.8
M6	4.9	6.3
M7	4.7	5.0
M8	4.5	5.9
M9	4.5	6.5

It can be observed that for almost all models, the drift criteria performance gives a lower value of the Response Reduction Factor (R) than that of the member collapse criteria. This implies that the structure exceeds its drift level performance limit much earlier than forming plastic hinges in the members at the specified limits. Thereby, the values of the R factor are governed mainly by drift criteria in this study, while R factor values from member collapse criteria are on the higher side.

While IS 1893-2016 provides a single value of R=5 for all these buildings, a significant variation is seen in the

obtained response reduction factor values from the analyses carried out. The maximum and minimum R factor value from the level collapse criteria are 10.2 and 4.4, respectively. The maximum and minimum R factor value from the drift limit criteria are 8.3 and 4.2, respectively. Therefore, while the IS code is conservative for the values obtained above 5, it underestimates the forces acting on the buildings, which is considered up to 16%, mainly due to the drift criteria. This implies that the design seismic forces obtained as per the IS code lead to a safe design if only the member collapse criteria is considered to be the performance limit. However, the designs should be more stringent when the drift performance criteria are also to be met. It will also affect the economy of the design as higher forces will lead to higher sections of size, and a greater amount of reinforcement will be required to resist the axial forces, shear forces, and bending moments generated.

#### 4. Conclusion

It can be seen that only one value of the R factor, as given in code for the SMRF system, does not apply to all the buildings. As the irregularity changes, the R factor changes. This implies that keeping only one value of R factor based only on the structural system, as provided currently in the IS code, may not be sufficient. A considerable effect is seen on the values of the R factor obtained with respect to height. i.e., as height increases, the R values reduce. In most cases, the

roof displacement corresponding to the drift criteria is less than the member collapse criteria. It thereby implies that the performance limit of the drift criteria is much more stringent in many cases than the performance limit of the member collapse level. It becomes highly imperative that the buildings with a greater number of storeys be designed with a lesser value of R, leading to greater forces on the building and an increase in forces and moments in the structural elements. This will lead to larger section sizes and increased requirements of design reinforcement in structural elements, thereby affecting the economy of structural design, but it will lead to safer designs.

While the range of R factors is widespread around the code-specified value of 5, it is important to note that many buildings obtained R factors around 4 based on the drift limitation performance. This study, undertaken for three-dimensional models of RCC buildings, also highlights the differences in responses obtained under pushover cases for both axes. It should be taken into account that detailed studies are required to obtain a correlation between the degree of irregularity for different plan shapes, height of structure, and response reduction factor. Overestimation of R may lead to an under-designed structure, while underestimation of R may lead to uneconomical structures.

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