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Evaluation of Response Reduction Factor of Regular and Irregular Steel Moment Building Frames

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Abstract

One of the most important parameter for the earthquake resistant design of structures is response reduction factor which is used for reducing the design force caused by earthquakes. Seismic code books incorporate the nonlinear response of a structure by including a factor called Response reduction factor 'R' so that approach based on a linear elastic force can be used for design. The response reduction factor depends on ductility, strength, structural redundancy and damping which must be taken into consideration while determining the response modification. For this study a regular building model, a re-entrant plan irregular model and vertical geometric irregular model of 6 and 9 storeys have been modelled and analysed. The evaluation of response reduction factor is done using nonlinear pushover analysis. It was observed that the response reduction factor decreases when the height of the models increases and considering the effect of irregularity in the frame the response reduction factor increases. All the models buildings are analysed and compared for the outcomes such as maximum storey drifts, storey displacements, time periods and modes of frequencies and the conclusions are presented at the end of the paper.

Keywords: Irregular Building, Pushover Analysis, Response Modification Factor, Response Reduction Factor, Steel Moment Frames

INTRODUCTION

In general, any civil engineering structure is to be designed to withstand potential earthquake and wind forces. We find that actual structures are often irregular because total regularity is an idealization that occurs rarely in practice in reality. As per the IS 1893 definition, R factor which is used to reduce actual base shear forces to design lateral forces, because at design basis earthquake (DBE) shaking structure should remain in elastic response. The response of the structure will be linear until yielding takes place, but as soon as yielding occurs at any section the behavior of structure is inelastic. Designing a structure based on the elastic spectrum would be too costly. To reduce the seismic design loads, IS code book introduced response reduction factor. The reduction in the seismic loads can be achieved only if adequate ductility is built by proper design and proper detailing of the elements is done. Reduction factor reflects the capability of the structure to dissipate energy through inelastic behavior. i.e. Response reduction factor (R) is used to reduce the structure's elastic response. It is used to reduce the design forces in earthquake resisting design and account for over-strength and ductility of the structure. The value of response reduction factor depends on ductility factor, strength factor, structural redundancy factor and damping factor. The analysis revealed that three major factors affects the actual value of response modification factor, called reserved strength factor, ductility factor and redundancy factor and therefore, the appropriate response reduction factor to be used during the seismic design process must be taken into account. Over-strength is developed because the structure's maximum lateral strength is always greater than its structural design strength. Once it enters the inelastic phase, it is capable of resisting and absorbing the large amount of seismic energy. Hence, seismic codes introduce a reduction in design loads, taking benefit of fact that structure possess over-strength and ductility.

The Applied Technology Council first proposed the response reduction factor in 1978. The base shear vs roof displacement relationship was developed in 1986 by Uang and Bertero with concentrated braced frame and in 1987 byWhittaker with eccentric braced frame. Using this data, Berkeley researchers proposed to divide R into three different factors, making the following contribution from reserved strength ductility and viscous damping, as follows, $R = R_s \times R_\mu \times R_\xi$ where R_s is the strength factor taken as the ratio of design base shear to that of the base shear at yielding, $R_\mu$is the ductility factor taken as the ratio of the maximum base shear considering the elastic behaviour of the structure to that of the maximum base shear corresponding to the collapse mechanism and $R_\xi$is the damping reduction factor. Much research (ATC,1982; Freeman,1990; ATC,1995) has been completed since first formulation for R is proposed, and give new formulation of R as follows, $R = R_s \times R_\mu \times R_R$. Here, R_R is the redundancy factor. This formulation with the exception of the redundancy factor is similar to those proposed by the Berkley researchers. A fourth factor, the viscous damping factor was included in the new formulation primarily to account for response reduction provided by supplemental viscous damping devices.

LITERATURE REVIEW

Abdollahzadeh et al. (2013, 2015, 2018), in his study presented R factor for dual moment resistant frame with buckling-restrained brace (BRB) and also for suspended zipper braced frames. He concluded that the ductility, over-strength and response modification factors for all the models analysed decreased when the height of the building was increased and that the average of final response modification factor of the structure when there is a repetition of the earthquake is less than that which is subjected to a single earthquake. Devrim Siahpolo et al. (2016) the R factor of the moment steel frame was calculated by applying the adaptive pushover methods, and then the study concluded in which the R factor and the over strength factor were reduced for all pushover methods with increasing heights. The ductility-based design is studied by Bansal and Gagandeep (2014) which takes into account vertical irregular structure using Response Spectrum Analysis and Time history Analysis. Mass irregularity, stiffness irregularity and vertical geometry irregularity was considered. It was found that compared to similar regular building frames the mass irregular building frames experience larger base shear & stiffness irregular building experienced lesser base shear and has larger inter storey drifts. Whittaker et al. (1999) presented a draft formulation of the response modification factor as the product of related to reserve strength, ductility, and redundancy.

The main objectives of this paper is the to evaluate the response reduction factor R of regular and irregular steel moment building frame and to compare the computed response reduction factor with the response reduction factor specified in IS 1893. The ductility reduction factor is equal to $R\mu = Ve/Vm$, here Ve is the maximum base shear considering elastic behavior of the structure and Vm is the maximum base shear corresponding to the formation of a collapse mechanism. The relation between the actual reserved strength of the structure (Vm) and the formation of the first plastic joint (Vs) with the over-strength factor (Rs) is given in the equation $Rs = Vm/Vs$. Redundancy factor 'RR' depends on number of vertical framings participating in the seismic resistance and taken as one in present study. In the end, the overall behavior factor of the structure is equal to $R = R\mu \times Rs$.

METHODOLOGY

Six analytical models of steel framed structure of different stories namely 6 & 9 story with horizontal and vertical irregularity were used in this study. For analysis purpose, regular and irregular building models with plan & vertical irregularities with certain percentage of irregularities have been used with constant heights of 6 & 9 Stories. The six models are labelled as M1, M2, M3, M4, M5 and M6. The models M1 and M4 with plan dimensions of 22m x 22m, as shown in Figure 1, are regular buildings of 6 and 9 stories respectively. The models M2 and M5 are re-entrant corner plan irregular buildings of 6 and 9 stories respectively, as seen in Figure 2. Figure 3 depicts plan view of 4th to 6th floor of vertical geometry irregular model M3 and for base to 3rd floor of vertical geometric irregular building the plan view as same as figure 1. The models M3 and M6 are vertical geometric irregular buildings of 6 and 9 story respectively. 3D view of the building models can be seen in Figures 4-6. The geometric details and loading details of the building models are as shown in Tables 1 and 2.

According to IS 1893:2002, for Re-entrant plan irregularity A/L > (0.15-0.20). From model M2 and M5, A=17m and L=22m. The ratio A/L = 0.77 > 0.2. According to IS 1893:2002, for vertical geometric irregularity L2 > 1.5L1. From model M3 and M6, L1=13m and L2=22m. The ratio L2/L1 = 1.69 > 1.5.

The buildings are modelled using finite element software ETABS and equivalent static analysis & pushover analysis is performed. The section properties of the structural members were chosen such that the structure fulfilled the safety and serviceability requirements specified in the design codes IS 800:2007, IS 1893:2002 & AISC 360 (2016). The building frame used in this study is assumed to be located in Indian seismic zone V. Seismic parameters as shown in Table 3. Seismic loads are estimated in accordance with IS 1893:2002, and steel building frame design is carried in accordance with IS 800:2007 standards. The horizontal seismic coefficient (Ah) is calculated according to IS 1893:2002.

Table 1: Geometric Details of the building models

Parameter		Value/Section
Storey Height		3 m
Slab: Deck (Filled Type)	Slab depth	115 mm
	Rib depth	75 mm
	Rib Width (Top & Bottom)	175 mm & 150 mm
	Rib spacing	300 mm
	Shear Stud Dia.	19 mm
	Shear Stud Height	150 mm
Beams	Primary Beams	ISLB300
	Secondary Beams	ISLB150, ISLB175, ISLB200
Columns	Steel Tube: Square Type	200 mm X 16 mm, 200 mm X 10 mm, 250 mm X 16 mm, 250 mm X 10 mm, 300 mm X 16 mm, 300 mm X 10 mm
Grade Of Steel		Fe345
Grade Of Concrete		M25

Table 2: Details of the loading applied on models

Parameter	Value
Floor Finish Load	1.5 kN/m^2
Live Load	2 kN/m^2

Table 3: Seismic parameters

Parameter	Value
Seismic Zone	V
Zone Factor	0.36
Importance Factor	1
Response Reduction Factor	4

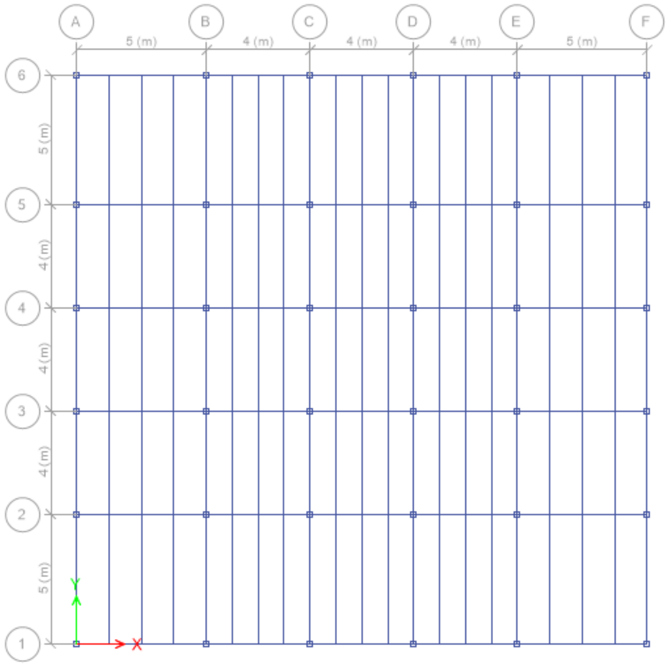


Figure 1: Top View (Plan) for model M1 and M4

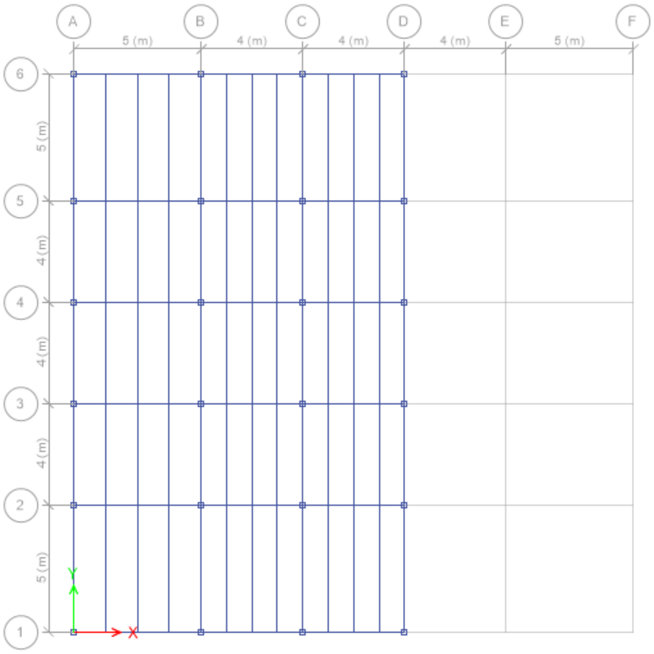


Figure 3: Top View (Plan) for model M3 and M6

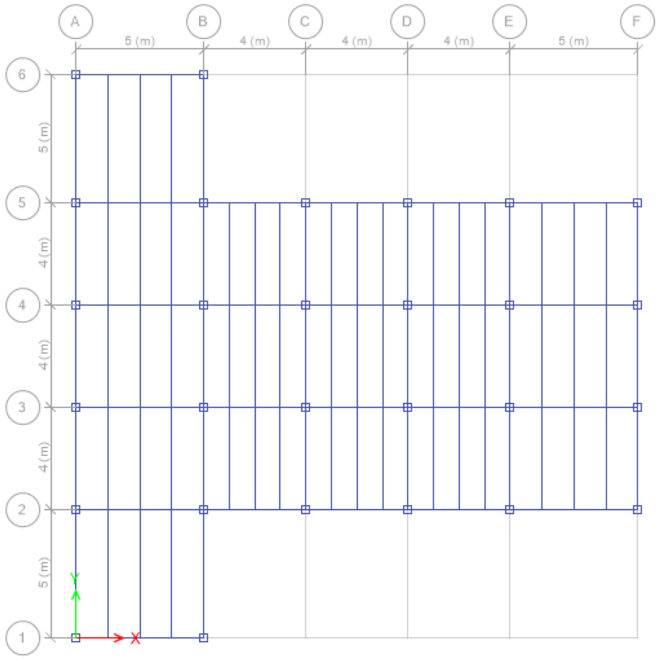


Figure 2: Top View (Plan) for model M2 and M5

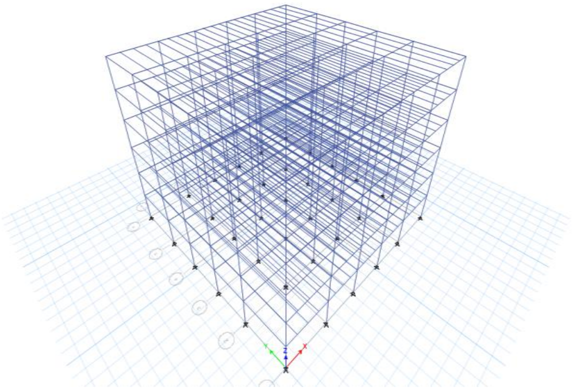


Figure 4: 3-D View for model M1

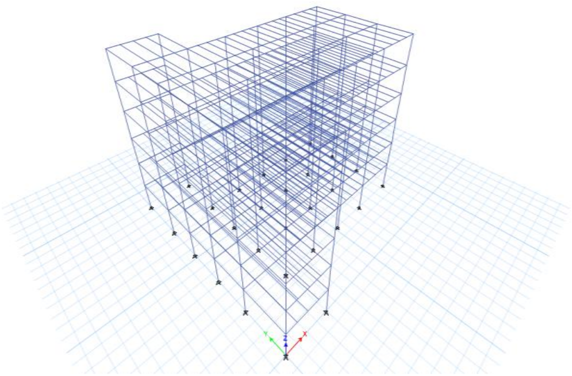


Figure 5: 3-D View for model M2

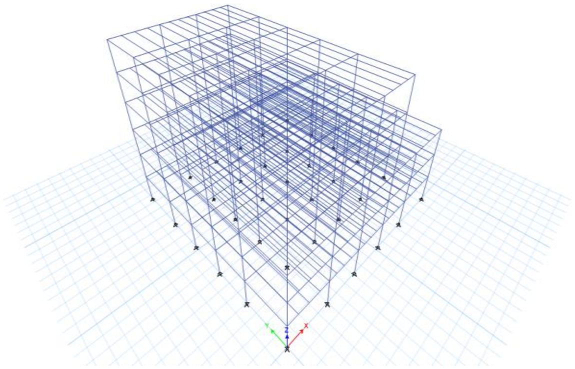


Figure 6: 3-D View for model M3

RESULTS AND DISCUSSIONS

Base Shear Vs Target Displacement

Nonlinear static analysis is performed on the building models and a curve is plotted between base shear and displacement, known as pushover curve, for both x & y directions and then capacity of the building is determined by the pushover curve. The figure 7 shows the pushover curve for model M1, the performance point of the steel moment frame is found at the base resistance of 5298.16kN with the displacement of 0.46 m in x-direction and 4940.45kN with the displacement of 0.47 m in y-direction. The shear values corresponding to the formation of the first plastic joint are 836.45 kN and 808.35 kN in x & y directions respectively. The Figure 8 shows the pushover curve for the model Me and the final base shear of the steel moment frame which is found at the base resistance of 4843.53 kN with the displacement of 0.53 m in x-direction and 4582.86 kN with the displacement of 0.50 m in y-direction. The shear values corresponding to the formation of the first plastic joint are 678.84 kN and 668.45 kN in x & y direction respectively. The figure 9 shows the pushover curve for the model M3, with the base resistance of 4911.51 kN at the displacement of 0.46 m in x-direction and 4602.25 kN at the displacement of 0.48 m in y-direction. The shear values corresponding to the formation of the first plastic joint is 731.56 kN and 684.83 kN in x & y directions respectively. Similarly, the figures 10 – 12 show the pushover curve for the 9 story models M4, M5 M6 in both x & y directions. The base resistance of model M4 is 5280.70 kN at the displacement of 0.53 m in x-direction and 5692.24 kN at the displacement of 0.60 m in y-direction. The shear values corresponding to the formation of the first plastic joint is 915.48 kN and 941.26 kN in x & y directions respectively. The base resistance of model M5 is found to be 3724.71 kN at the displacement of 0.59 m in x-direction and 3860.15 kN at the displacement of 0.59 m in y-direction. The shear values corresponding to the formation of the first plastic joint is 629.22 kN and 646.59 kN in x & y directions respectively. The base resistance of model M6 is 5182.80 kN at the displacement of 0.57 m in x-direction and 5444.79 kN at the displacement of 0.62 m in y-direction. The shear values corresponding to the formation of the first plastic joint is 835.33 kN and 828.33 kN in x & y directions respectively.

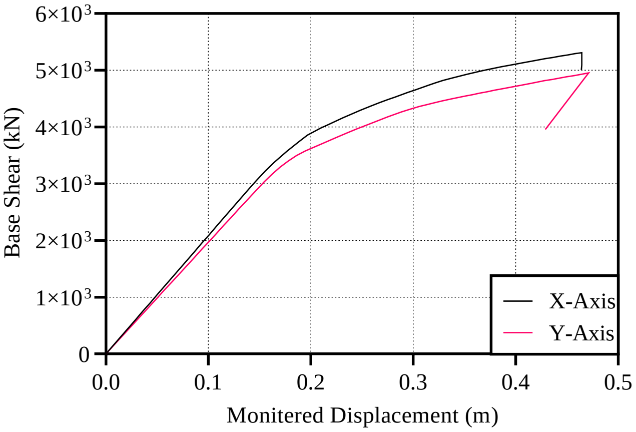


Figure 7: Pushover Curve for model M1

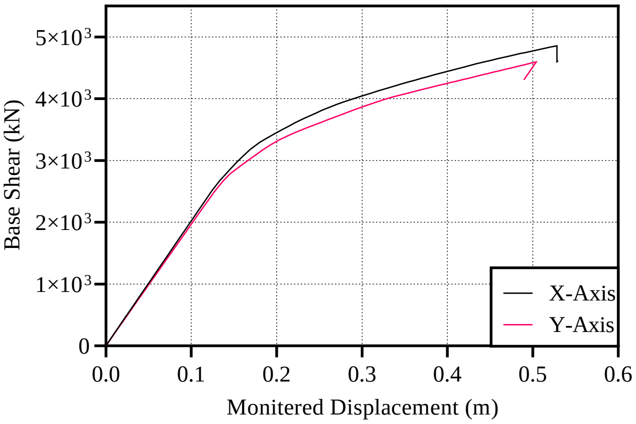


Figure 8: Pushover Curve for model M2

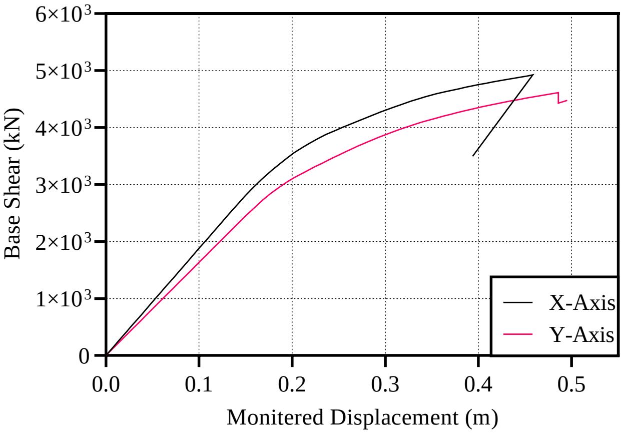


Figure 9: Pushover Curve for model M3

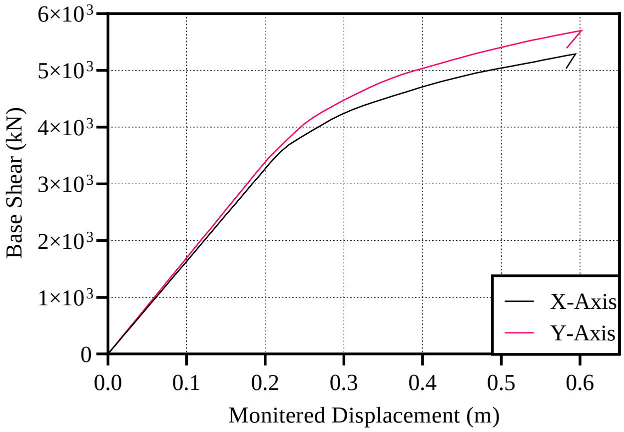


Figure 10: Pushover Curve for model M4

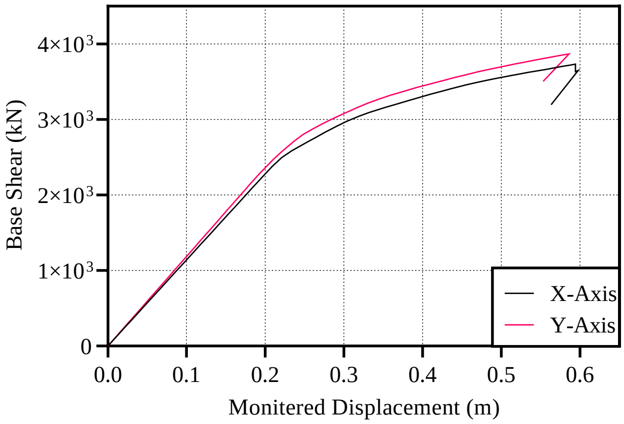


Figure 11: Pushover Curve for model M5

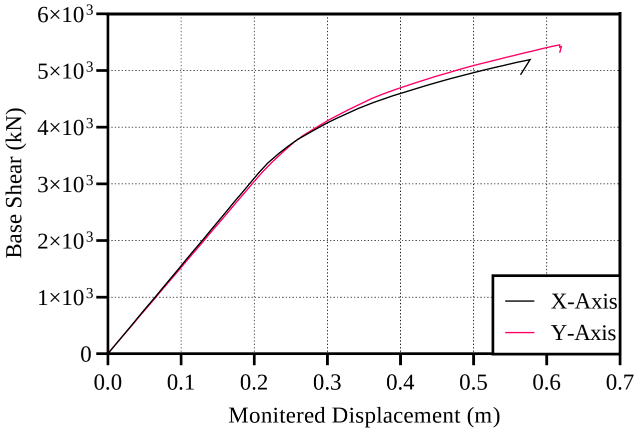


Figure 12: Pushover Curve for model M6

Response Reduction Factor

The Tables 4 and 5 show the base shear values corresponding to the formation of first plastic jointV_S, final base force V_e (ultimate force) corresponding to elastic behaviour and maximum base shearV_m corresponding to formation of collapse mechanism resulting from the static pushover analysis.The Table 6 and 7 represent the values of the ductility reduction factorR_μ, over-strength reduction factor R_S and final response reduction factor R for the building models. The parameters are calculates using the formulae below:

$R_\mu = V_e/V_m$
$R_s = V_m/V_s$
$R = R_\mu.R_s$

Table 4: Base Shear Values for 6 story models

Base Shear (kN)	M1		M2		M3	
Dir	X	Y	X	Y	X	Y
V_s	836	808	679	668	732	685
V_e	5298	4940	4843	4583	4911	4602
V_m	5045	4884	4170	4052	4620	4129

Table 5: Base Shear Values for 9 story models

Base Shear (kN)	M4		M5		M6	
Dir.	X	Y	X	Y	X	Y
V_s	915	941	629	647	835	828
V_e	5281	5692	3725	3860	5183	5445
V_m	4569	4892	3201	3309	4392	4582

Table 6: Reduction Factor Values for 6 story models

R	M1		M2		M3	
Dir.	X	Y	X	Y	X	Y
R_μ	1.051	1.012	1.162	1.131	1.064	1.115
R_S	6.032	6.042	6.144	6.063	6.316	6.03
R	6.34	6.115	7.14	6.858	6.721	6.724

Table 7: Reduction Factor Values for 9 story models

R	M4		M5		M6	
Dir.	X	Y	X	Y	X	Y
R_μ	1.156	1.164	1.164	1.167	1.181	1.189
R_S	4.992	5.197	5.087	5.118	5.258	5.532
R	5.771	6.05	5.922	5.973	6.21	6.578

The Figures 13 and 14 show the comparison of ductility reduction factor, over strength reduction factor and final response reduction factor. While observing the obtained results, it can be concluded that the ductility response reduction factor increases and strength reduction factor decreases with an increase in height of the buildings. While considering the irregularity in the model, the ductility factor increases in irregular model and also the strength factor also increases while compared to the regular models. Overall response reduction factor decreases with an increase in the height of the building model. All the obtained values for R are greater than the code prescribed value of 4 for steel frame structures.

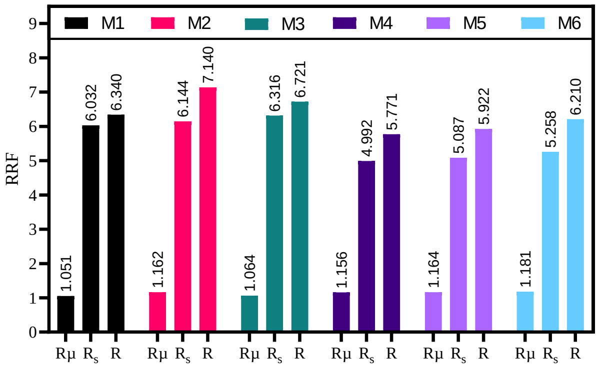


Figure 13: Reduction Factor in X-direction

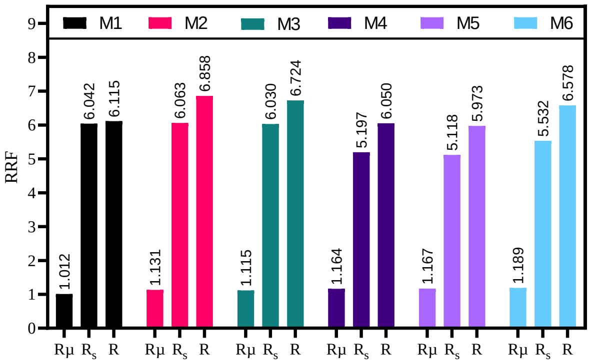


Figure 14: Reduction Factor in Y-direction

After calculating the response reduction factor the models used in this study are reanalysed with the calculated response reduction factor and the results are compared with the results of same models calculated by taking the response reduction factor (R = 4) given in IS1893:2002. The parameters calculated using the code specified value of R = 4 and the values given in Tables 6 and 7 are labelled as M1a, M2a, M3a, M4a, M5a, M6a and M1b, M2b, M3b, M4b, M5b, M6b respectively.

Displacements

The Figures 15 and 16 show the top storey displacement of the building models in X and Y directions respectively. It can be seen that the displacement is 58.5% more in M1a with a value of about 55.7 mmwhen compared to 35.2mm in M1b. Displacement of the model M2a is 44.9mm which 78.5% more than M2b with 25.25 mm. Similarly, for the models M3, M4, M5 and M6 the difference is 68%, 44%, 48% and 55% in X direction. Similar results are obtained in the other direction. The maximum displacement calculated using the values of R given in Tables 6 and 7 are less when compared to the values calculated using R = 4 as given in IS 1893:2002. It can also be noted that the maximum displacement calculated by taking R = 4 is greater than the code specified limit of H/500.

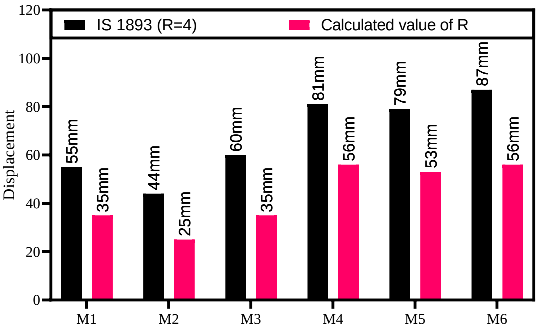


Figure 15: Maximum displacements in X-direction

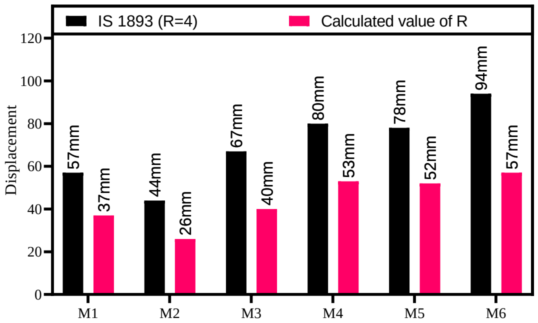
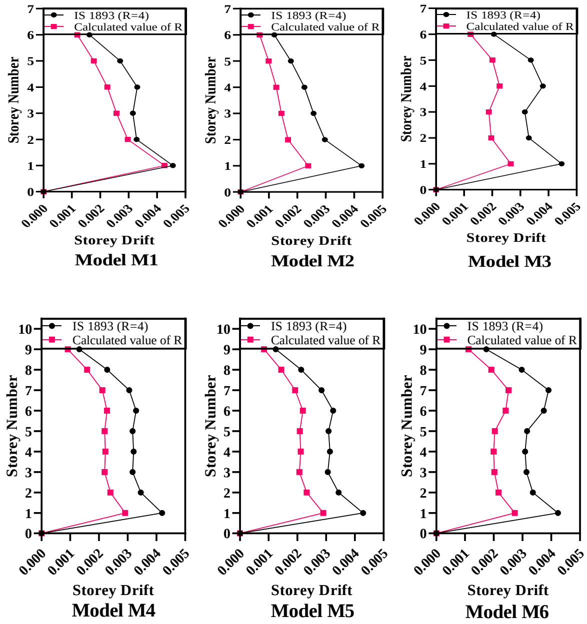


Figure 16: Maximum displacements in Y-direction

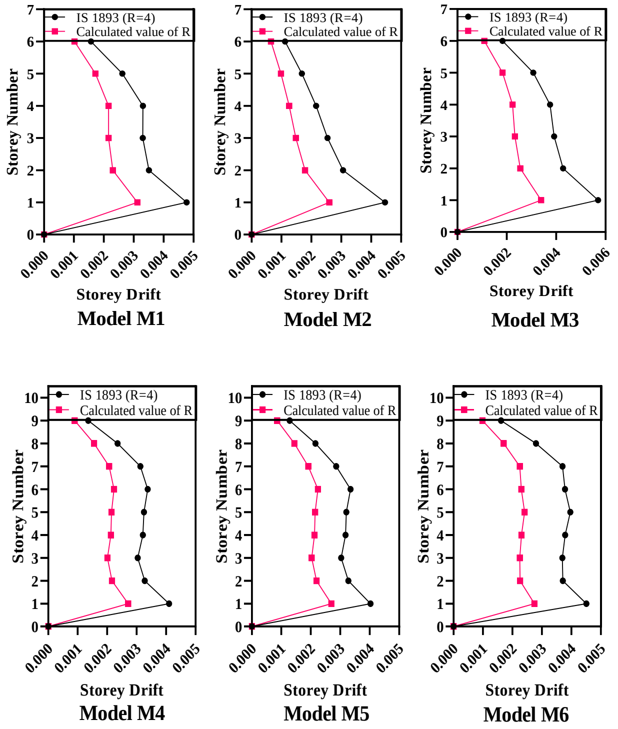
Drifts

The Figures 17 and 18 present the graphical representation of story drift for the building frames in X and Y directions respectively. Story Drift is greater than specified value 0.004 for the models M1a, M2a, M3a, M4a, M5a and M6a. IS code specified the story drift shouldn't be greater than the 0.004. After reanalysing with models with calculated response reduction factor (Tables 6 and 7) it is observed that the story drift decreased and found to be within specified limit.



Model M1
Model M2
Model M3
Model M4
Model M5
Model M6

Figure 17: Storey drifts in X-direction



Model M1 Model M2 Model M3

Model M4 Model M5 Model M6

Figure 18: Storey drifts in Y-direction

Base Shear

After reanalysing with calculated response reduction factor (Table 6 and 7) the story shear decreases. The story shear for model M1a is 808.35kN whereas for M1b it is reduced to 527.73kN which is 34.5% less in both X and Y directions. Similarly, for other two models M2 and M3 the values are reduced approximately by 41.68% and 40.5% respectively.The story shear for model M4a is 915.48kN and for M4b it is 634.54kN which is 30.69% less in both x and y direction. Similarly, for other two models M5 and M6 the values are reduced approximately by 32.46% and 35.59% respectively.

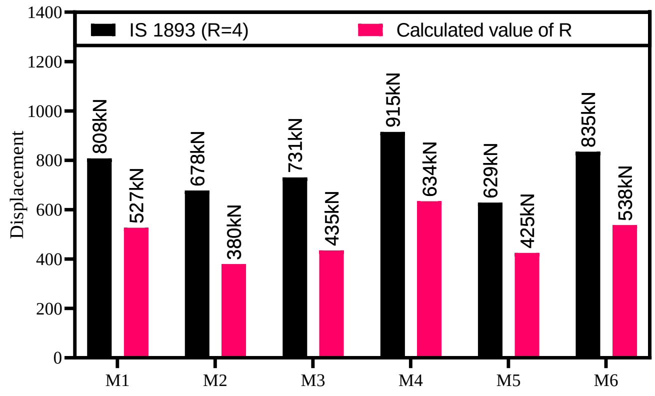


Figure 21: Base shear in X-direction

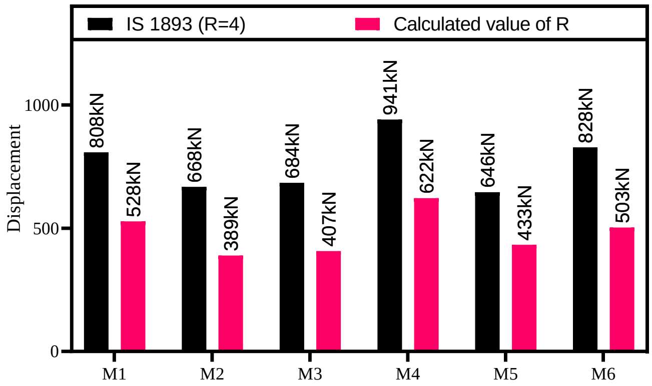


Figure 22: Base shear in Y-direction

CONCLUSIONS

After interpretation of the results from the analyses done in this study, it can be concluded that:

- The calculated response reduction factor for the model M1 increases by 55%, for the models M2, M3, M4, M5 and M6 the difference is around 74%, 68%, 47% 48% and 59% when compared to the value of '4' given in IS 1893:2002.
- The calculated value of R for the re-entrant plan models (M2 and M5) and vertical geometric irregular models (M3 and M6) is expected to be even higher due to irregularity in the structure and when the height of the structure increases the R value decreases.
- The value of R given in IS 1893:2002 is based on the assumption of uniformly reducing the seismic demand of the whole structure without taking into account the individual member capacity which can be considerably higher than the demand at the member level.

Hence, due to the increased values of R the response parameters like displacement, drift and shear for the buildings considered in this study are less compared to the codal response values.

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