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Evaluation of Response Reduction Factor and Ductility Factor of RC Braced Frame

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ABSTRACT

Response reduction factor is the factor by which the actual base shear force should be reduced, to obtain the design lateral force during design basic earthquake (DBE) shaking. The response reduction factor (R) is basically depends on Over strength (R_s), Ductility (R_μ), Redundancy (R_R). So there is a need to come up with realistic R factors for different structural systems used in various countries. In the present study efforts are made to evaluate the response reduction factor and ductility of RC braced frame using nonlinear static pushover analysis. The types of the frame considered in this study are RC frame with X bracing at centre bay, RC frame with X bracing at alternate bays, shear wall at center and alternate bays. The result of this study shows that R factor and lateral strength of RC frames are considerably affected by the types and arrangement of the bracing system.

1 Introduction

The earthquake is a phenomenon that releases high amount of energy in a short time through the earth. Structures designed to resist moderate and frequently occurring earthquakes must have sufficient stiffness and strength to control deflection and prevent any possible collapse. In other words, a structure not only should dissipate a considerable amount of imported energy by ductile behaviour, but also it should be able to control the deformations and transfer the force to foundation through enough lateral stiffness in ground motions. Braced frame systems offer an attractive solution to satisfy multiple design objectives. Their elastic properties provide the stiffness and strength needed to achieve operational performance objectives, which are primarily defined by the performance of non-structural elements. Current force-based design procedure adopted by most seismic design codes allows the seismic design of building structures to be based on static or dynamic analyses of elastic models of the structure using elastic design spectra. The codes anticipate that structures will undergo inelastic deformations under strong seismic events; therefore, such inelastic behaviour is usually incorporated into the design by dividing the elastic spectra by a factor R which reduces the spectrum from its original

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elastic demand level to a design level. The most important factors determining response reduction factors are the structural ductility and over strength capacity.

Riddell et al. [1] evaluated response modification factors and ductility factors of short period buildings, where the reduction of linear elastic response spectra is smaller than the values for intermediate and long period structures for various sets of earthquake records. An idealized and simple variation of the response modification factor as a function of the period of vibration suitable for seismic codes formulation is also presented. Miranda [2] presented the different components of so called R factors and discusses how these can be incorporated into a performance-based earthquake resistant design. He also describes how strength reduction factors derived from single-degree-of-freedom systems need to be modified in order to be used in the design of multi -degree-of-freedom systems. Elanashai and Mwafy [3] addressed the issue of horizontal over strength in modern code/standard for design of reinforced-concrete (RC) buildings. The relationship between the lateral capacity, the design force reduction factor, the ductility level and the over strength factor are also investigated. Maheri and Akbari [4] evaluated the seismic behaviour factor for steel X-braced and knee-braced RC buildings using nonlinear pushover analyses of brace-frame systems having different heights and configurations. Authors concluded that Types of bracing had more localizes effects on the 'R' factor. Mahmoudi and Zaree [5] evaluated the response modification factors of conventional concentric braced frames as well as buckling restrained braced frames. Authors concluded that the number of bracing bays and height of buildings have greater effect on the response modification factor. Kadid and Yahiaoui [6] investigated the seismic behaviour of RC buildings strengthened with different types of steel braces like X-bracing, inverted V bracing, ZX bracing and Zipper bracing.

The R factors in many developing countries are often adopted from the well developed seismic design codes used in the United States or Europe. These R factors provide false representation for the structural practices applied in developing countries and thus considered unrealistic. Here in present study 4-storey RC building frame analyzed using static nonlinear pushover analysis and efforts are made to evaluate lateral strength, response reduction factor and ductility factor of RC braced frame.

2 Concept of Response Reduction Factor

The code provision allows the structure to be damaged in the case of sever shaking. Hence, the structure is designed for seismic force much lesser than that expected under strong earthquakes, if the structure were to remain linearly elastic. Thus, the Indian seismic standard IS 1893 [7] provides a realistic force for an elastic structure and then divides that force by $2R$. In other words, the term R gives an indication of the level of over strength and ductility that a structure is expected to have. Thus, the structure can be designed for much lower force than is implied by the strong shaking by considering the following factors, over strength factor (R_S), redundancy factor (R_R), ductility factor (R_{μ}) which will prevent the collapse of the structure.

Over strength factor accounts for the yielding of a structure at load higher than the design load due to various Partial safety factors, strain hardening, oversized members, confinement of concrete. Non-structural elements also contribute to the over strength. According to ATC-19 [8], over strength R_S is defined as the ratio of base shear at the roof displacement corresponding to the limiting state of response (V_o) to design seismic base shear (V_d) as per IS: 1893 (Part 1) 2002 [7].

Redundancy factor depends on the number of vertical framing participate in seismic resistance. Yielding at one location in the structure does not imply yielding of the structure as a whole. Hence the load distribution, due to redundancy of the structure, provides additional safety margin. The values of redundancy factor as suggested by ATC-19 [8] are shown in Table 1.

Table 1 - Value of Redundancy Factor

Lines of vertical seismic framing	Draft redundancy factor
2	0.71
3	0.86
4	1.00

Ductility is the capacity of material/structure to absorb energy by deforming into the inelastic range. Ductility factor is a ratio of ultimate or code specified displacement to the yield displacement. In present study equation suggested by Miranda and Bertero [9] is used to evaluate the ductility factor R_μ ,

$$R_\mu = (\mu - 1/\Phi) + 1 \tag{1}$$

Where,

For rock site:

$$\Phi = 1 + (1 / (10T - \mu T) - (1e^{-1.5(\ln T - 0.6)^2} / 2T)) \tag{2}$$

For alluvium site:2

$$\Phi = 1 + (1 / (12T - \mu T) - (2e^{-2(\ln T - 0.2)^2} / 5T)) \tag{3}$$

For soft soil site:

$$\Phi = 1 + (T_g / 3T) - (3T_g e^{-3(\ln(T/T_g) - 0.25)^2} / 4T) \tag{4}$$

T_g is the predominant period of the ground motion.

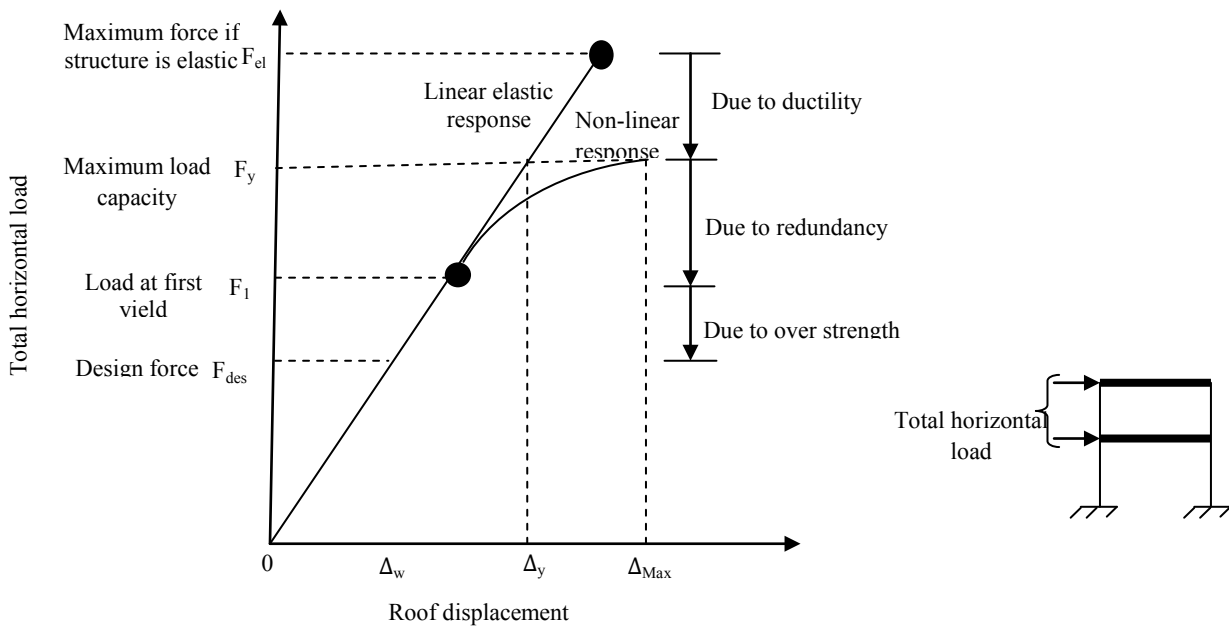


Fig. 1 - Concept of response reduction factor

3 Frame Considered In This Study

In the present study a typical 4-story RC frame has been taken for the analysis. The floor plan and elevation of the building is shown in figure 2. The building parameters are defined as, building plan dimension 18m x 9m, Concrete Grade M25, Steel Grade – F_y 415 MPa, Slab Thickness – 110mm, height of each storey – 3.2m and height of ground storey is 4.2m. Live load is taken as 2 kN/m² at floor level and 0.75 kN/m² at roof level. It is assumed that the building is located in zone-IV and soil type is medium.

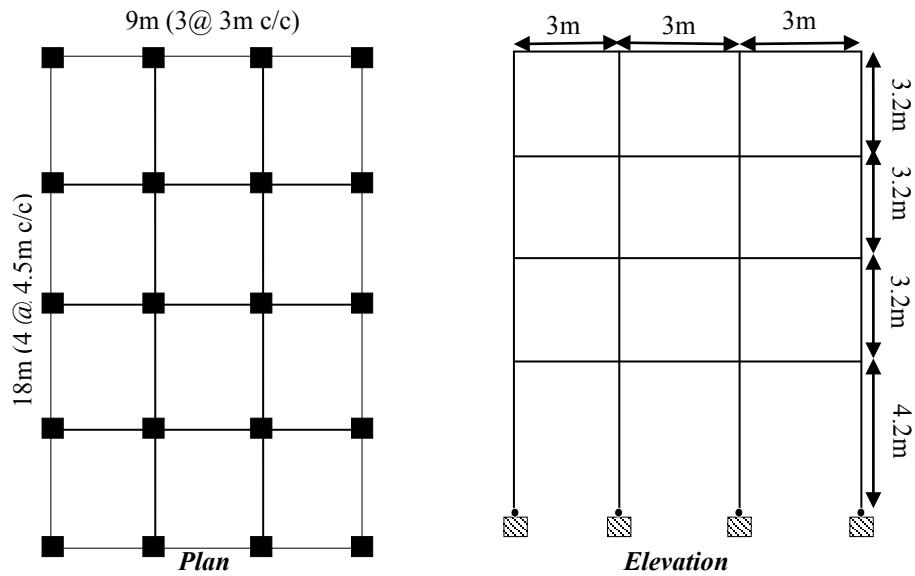


Fig. 2 - Plan and elevation of 4 storey building

RC frame was designed using the most critical load combination of IS 456:2000 [10] and IS1893:2002[7]. Size and reinforcement details of designed beams and columns are shown in Tables 2 and 3 respectively.

Table 2 - Beam size and reinforcement details

Beam	Beam size	Top reinforcement	Bottom reinforcement
Ground/1 st story	300x450	3 bars of 20mm dia.	3 bars of 20mm dia.
2 nd story	300x450	3 bars of 18mm dia.	3 bars of 18mm dia.
3 rd story	300x450	3 bars of 16mm dia.	3 bars of 16mm dia.
4 th story	300x450	3 bars of 12mm dia.	3 bars of 12mm dia.

Table 3 - Column size and reinforcement details

Column	Column size	Top reinforcement	Bottom reinforcement
Ground/1 st story	300x450	4 bars of 20mm dia.	4 bars of 20mm dia.
2 nd story	300x450	3 bars of 20mm dia.	3 bars of 20mm dia.
3 rd story	300x450	2 bars of 20mm dia.	2 bars of 20mm dia.
4 th story	300x450	2 bars of 20mm dia.	2 bars of 20mm dia.

In this study mid frame as shown in figure 2 is considered for the analysis. The calculated design seismic base shear (V_B) and corresponding lateral forces (Q_i) on the mid-frame as per IS: 1893, are shown in Table 4.

Design seismic base shear,

$$V_b = A_h \cdot W \tag{5}$$

Where $A_h = (Z/2) \times (I/R) \times (S_a/g)$ (design horizontal seismic coefficient for the structure)

W = Seismic weight of frame

Z= Zone Factor = 0.24 (from Table 2 of IS 1893 (Part 1):2002)

I= Importance Factor = 1 (from Table 6 of IS 1893 (Part 1):2002)

R= Response Reduction Factor = 5 (from Table 7 of IS 1893 (Part 1):2002)

S_a/g = average Response acceleration coefficient for medium soil = 2.5 (from Figure IS1893 (Part1):2002)

lateral forces at each storey level,

$$Q_i = (V_B W_i h_i^2 / (\sum W_i h_i^2))^2 \quad (6)$$

Table 4 - Storey forces for 4 – storey building

Floor level	W_i (kN)	h_i (m)	$W_i h_i^2$	Q_i (kN)
Roof	269.418	13.8	51307.96	36.83
3 rd floor	399.726	10.6	44913.21	32.24
2 nd floor	399.726	7.4	21888.99	15.71
Ground/1 st floor	436.491	4.2	7699.70	5.52
Σ	1505.361	$\Sigma W_i h_i^2$	125809.8	$V_b = 90.32$

Different RC frame configurations considered in the present study are:

- Bare frame
- RC frame with X-bracing in center bay
- RC frame with X-bracing in alternate bay
- RC frame with Shear wall in center bay
- RC frame with Shear wall in alternate bay

4 Analytical Modeling of Reinforced Concrete Members

Plasticity in RC members was assumed to be lumped at probable locations. The program defined plastic hinge properties of SAP2000 Program as per FEMA356 provisions were used to take into account the material nonlinearity. Flexural hinge properties involve axial force, bending moment as per FEMA356 provisions were used to take into account the material nonlinearity. Plastic hinges that generally develop are those corresponding to flexure and shear. Plastic hinges that generally interaction (P-M) as the failure envelop and bending moment rotation (M- θ) as the corresponding load deformation relation; shear hinge properties involve shear force-shear deformation relation (V- Δ). The different inelastic stages are suggested on pushover curves to facilitate the description of behaviour of different members of the RC frame building at various stages: (1) P_{C1} : formation of plastic hinge in the first/ground-storey columns; (2) P_{B1} : formation of plastic hinges in first/ground-storey beams; (3) P_{C2} : formation of plastic hinge in the second-storey columns; (4) P_{B2} : formation of plastic hinges in second storey beams; (5) P_{C3} : formation of plastic hinge in the third-storey columns; (6) P_{B3} : formation of plastic hinges in third-storey beams; (7) P_{C4} : formation of plastic hinge in the roof-storey columns; (8) P_{B4} : formation of plastic hinges in roof-storey beams.

5 Bare RC Frame (RC-1)

Bare frame represents the currently used common practice of not including the strength and stiffness of masonry in analysis and design procedure. The capacity curve obtained from the nonlinear pushover analysis of the bare RC frame building is shown in Figure 3. Linear behavior was observed in different member of RC frame upto a base shear of 15% of seismic weight and upto a roof displacement corresponding to 0.5% drifts. Non-linearity was observed to be well distributed along the height of the frame. Failure of the frame was found to take place due to flexure failure of open ground storey columns at the ultimate lateral load corresponding to 17% of seismic weight and lateral drift of 2.4%.

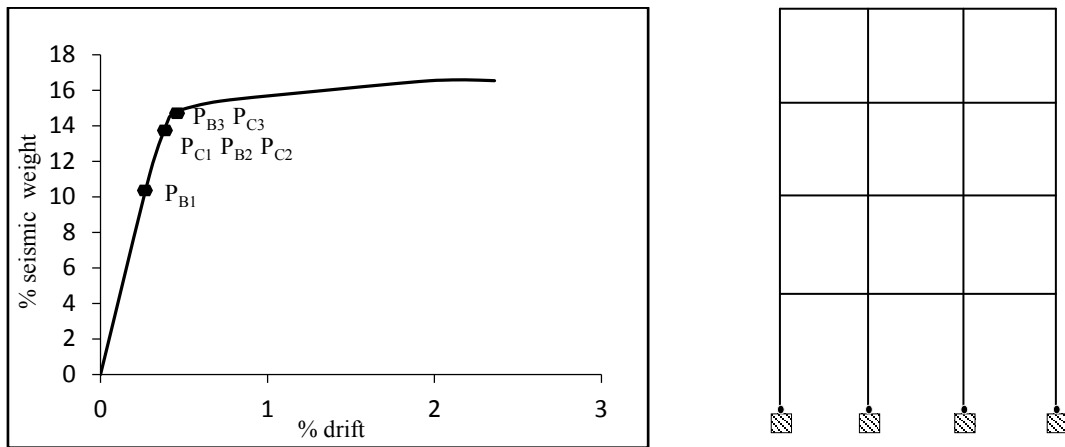


Fig. 3 - Pushover curve for bare frame

6 RC Frame With X-Bracing

Bracings as lateral load-resistant system are one of the most commonly used methods to resist lateral loads such as earthquake. The braced frame response to earthquake loading depends mainly on the asymmetric axial resistance of the bracing members. Conventional steel bracings dissipate considerable energy yielding under tension. Lateral load performance of the RC frame with X-bracing is studied for the following two cases: (1) Providing diagonal bracings in centre bay, and (2) Providing diagonal bracings in alternate bays. These diagonal braces were not designed formally because strength of such braces is usually very high. The size and reinforcement of bracing were kept identical to that of existing ground storey column of considered frame [Table 3].

6.1 RC frame with X-bracing 9 (RC - B1)

First inelastic activity was observed at lateral load corresponding to 33% of seismic weight and 0.15% drift [figure 4]. The ultimate strength of frame was found to be that corresponding to 48.76% of seismic weight and 0.34% of lateral drift. Plastic hinges were found to develop in the ground as well as upper storey members. However failure of plastic hinges was found to be concentrated in upper storey members. The value of response reduction factor and ductility factor was found to be 5.97 and 1.31 respectively.

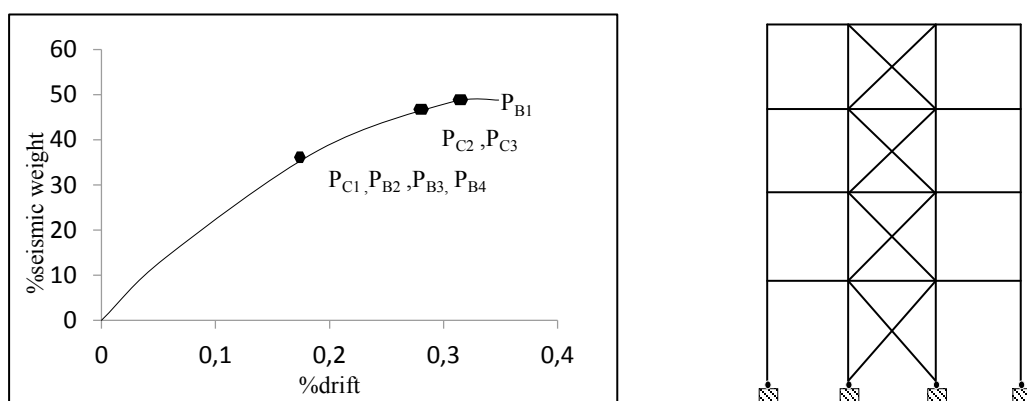


Fig. 4 - Pushover curve for RC bracing in center bay

6.2 RC frame with X-bracing in alternate bays (RC - B2)

From capacity curve shown in Figure 5, it was observed that first inelastic activity was observed at lateral load corresponding to 40% of seismic weight and 0.19 % drift. The ultimate strength of frame was found to be that corresponding to 67.4% of seismic weight and 0.30% of lateral drift. Plastic hinges were found to develop in all the ground

as well as upper storey members. The value of response reduction factor and ductility factor was found to be 10.7 and 2.04 respectively.

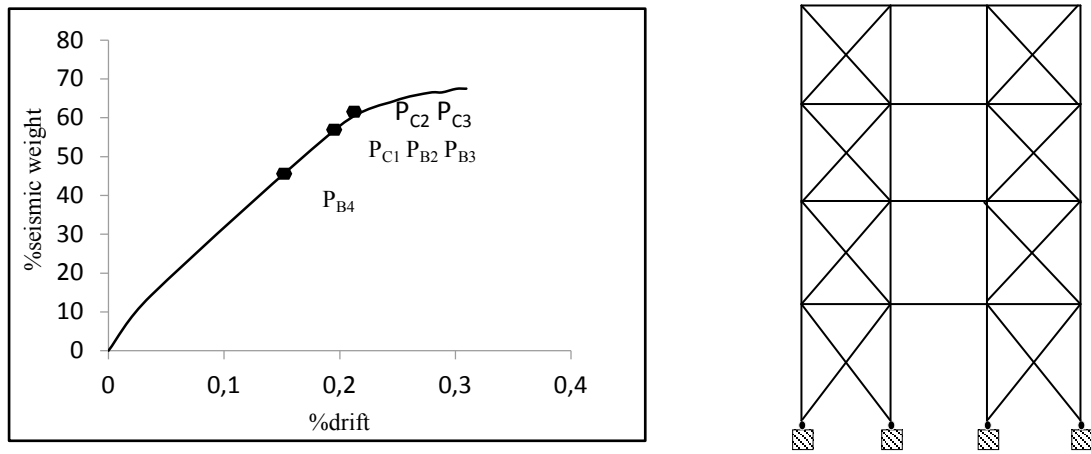


Fig.5 - Pushover curve for RC bracing in alternate bay

7 RC Frame With Shear Wall

Another most commonly used lateral load-resistant system to resist lateral loads such as earthquake is the RC frame with shear wall. Lateral load performance of the RC frame with shear wall is studied for the following two cases: (1) Providing shear wall in centre bay, and (2) Providing shear wall in alternate bays. RC shear walls having a thickness of 190 mm are modelled using 4-noded nonlinear layered shell elements. The vertical and horizontal reinforcement ratio of 0.25% was used in shear wall.

7.1 RC frame with shear wall in center bay (RC - S1)

In this case the frame was strengthened by providing RC shear wall in only center bay of all stories. The remaining two bays of all stories were left open. First inelastic activity was observed at lateral load corresponding to 49% of seismic weight and 0.23% drift (Figure 6). The ultimate strength of frame was found to be that corresponding to 65% of seismic weight and 1.6% of lateral drift. The value of response reduction factor and ductility factor was found to be 5.09 and 0.53 respectively.

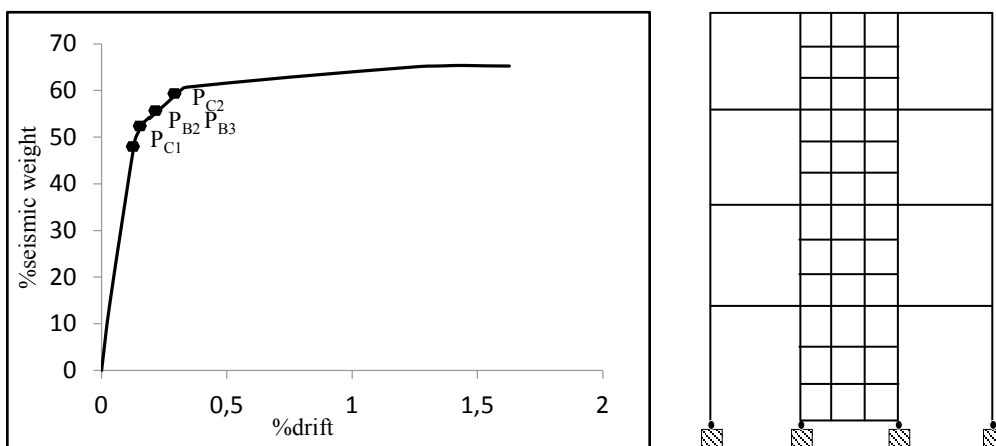


Fig. 6 - Pushover curve for shear wall in center bay

7.2 RC frame with shear wall in alternate bays (RC - S2)

In this case the frame was strengthened by providing RC shear wall in alternate bays of all stories. The centre bay of all stories was left open. First inelastic activity was observed at lateral load corresponding to 80% of seismic weight and 0.27% drift (Figure 7). The ultimate strength of frame was found to be that corresponding to 106% of seismic weight and 1.58% of lateral drift. The value of response reduction factor and ductility factor was found to be 10.15 and 0.63 respectively for this type of frame.

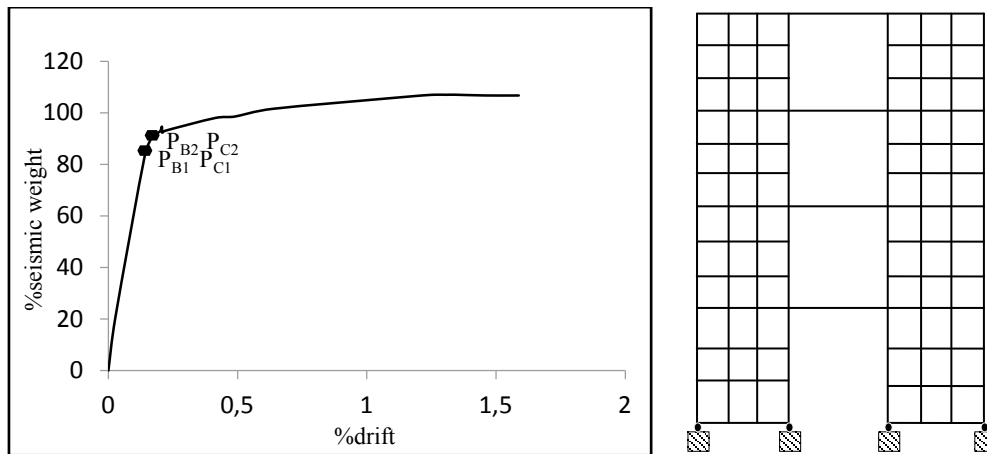


Fig. 7 - Pushover curve for shear wall in alternate bay

8 Evaluation of Responses Reduction Factor and Ductility factor

The calculation for evaluation of response reduction factor as per ATC-19 for bare RC frame in seismic zone-IV is shown below. The calculations of ‘R’ factor for other frames are not shown here due to paucity of space.

Estimation of strength factor:

Maximum Base Shear (from pushover curve)

$$V_o = 224 \text{ kN}$$

Design Base shear (as per EQ calculation)

$$V_d = 90.32 \text{ kN}$$

Strength factor according to ATC – 19

$$R_s = V_o / V_d = 224 / 90.32 = 2.48$$

Estimation of ductility factor:

Maximum drift capacity (0.004 x H), $\Delta m = 55.2 \text{ m}$

Yield drift (from pushover curve), $\Delta y = 50 \text{ mm}$

Displacement ductility ratio according to ATC – 19

$$\mu = \Delta m / \Delta y = 55.2 / 50 = 1.10$$

Equation for ductility factor, derived by Miranda and Bertero [7]

$$R \mu = \{(\mu - 1 / \Phi) + 1\} \tag{7}$$

Φ for medium soil:

$$\Phi = 1 + \{1 / (12T - \mu T)\} - \{(2 / 5T) * e^{-2(\ln(T) - 0.2)^2}\} \tag{8}$$

T = 0.38 seconds (From analysis)

$$\Phi = 1.17$$

$$R_{\mu} = 1.08$$

Estimation of redundancy factor:

The value of redundancy factor as suggested in ATC-19 is summaries in Table-1.

Estimation of response reduction factor R:

$$R = R_S \times R_{\mu} \times R_R \quad (9)$$

$$R = 2.48 \times 1.08 \times 1$$

$$R = 2.70$$

Provision of bracing and shear wall in RC frame significantly increases its global strength as compared to bare frame. Table 5 shows the value of R-factor and its key component of considered RC frame in this study. The values of the response reduction factor are considerably affected by the types and arrangements of the bracing systems. Figure 8 shows the comparative values of response reduction factor for different types of RC frame considered in this study. Provision of bracing in alternate bays increases the values of responses reduction factor nearly 3.91 and 1.8 times respectively as compared to the RC frame with bracing at center bay and bare RC frame respectively. Provision of shear wall in alternate bays increases the values of responses reduction factor nearly 1.99 and 3.75 times respectively as compared to the RC frame with shear wall at center bay and bare RC frame respectively.

Table 5 - Response reduction factor and its key component of RC frame

Types of Frame	R_S	R_R	R_{μ}	R	μ
Bare frame (RC-1)	2.48	1	1.08	2.70	1.10
RC bracing central bay (RC-B1)	5.03	1	1.19	5.97	1.31
RC bracing alternate bay (RC-B2)	9.66	1	1.09	10.57	2.04
Shear wall center bay (RC-S1)	10.47	1	0.48	5.09	0.535
Shear wall alternate bay (RC-S2)	16.91	1	0.60	10.15	0.63

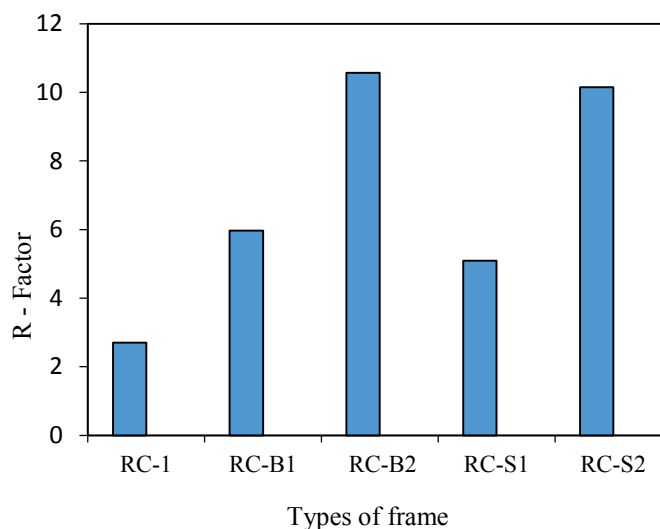


Fig. 8 - Response reduction factor of RC frame

9 Conclusion

In this study the lateral strength, ductility factor and response reduction factor (R) of 4-storey RC braced frame are evaluated using nonlinear static pushover analysis. The significant outcomes of the present study are summarized as follows:

- Large increase in lateral strength and stiffness of RC braced frame was observed as compared to bare RC frame. Yield lateral force for the RC frame with X-bracing at alternate bays was found to be 40% of seismic weight, and it was about 1.21 and 2.7 times more than that observed in the case of the RC frame with X-bracing at center bay and bare RC frame respectively.
- Ultimate lateral force for the RC frame with X-bracing at alternate bays was found to be 67.4% of seismic weight, and it was about 1.38 and 3.96 times more than that observed in the case of the RC frame with X-bracing at center bay and bare RC frame respectively.
- Yield lateral force for the RC frame with shear wall at alternate bays was found to be 1.6 and 5.3 times more than that observed in the case of the RC frame with shear wall at center bay and bare RC frame respectively.
- Ultimate lateral force for the RC frame with shear wall at alternate bays was found to be 1.6 and 6.2 times more than that observed in the case of the RC frame with shear wall at center bay and bare RC frame respectively.
- The response reduction factor of RC frame is considerably affected by the types and arrangements of the bracing systems. Provision of bracing/shear wall in alternate bays increases the values of responses reduction factor nearly 1.88 to 2.2 and 3.75 to 3.9 times respectively as compared to the RC frame with bracing/shear wall at center bay and bare RC frame respectively.

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