Effect of lintel beam on response reduction factor of RC-infilled frames

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In this study, a three-dimensional, four-storied, reinforced concrete (RC) building is designed for seismic zone-IV and seismically evaluated for different infill configurations along with consideration of openings in infills to develop a realistic model. Four models are considered, i.e. model I (full RC-infilled frame without lintel beam), model II (bare frame without lintel beam), model III (full RC-infilled frame with lintel beam) and model IV (bare frame with lintel beam). In this study, we have evaluated the effect of lintel beams on response reduction factor of the frame structure. The nonlinear static adaptive pushover analysis has been done using Seismostruct program. In seismic design, the response reduction factor (*R*-factor) reduces from the elastic to inelastic strength. The *R*-factor is one of the design tools to show the level of inelasticity in a structure and so it has significant importance in the earthquake engineering field. The response reduction factor mainly consists of 'ductility reduction factor' and 'over strength factor', which are evaluated from static adaptive pushover analysis. Ultimately the response reduction factor is obtained for the building and compared with the value recommended by IS 1893 Part-1 (2016). The results depict that the *R*-factor values of full RC-infilled frames and bare frames with incorporation of lintel beams are higher than other frames without lintel beam. However, *R*-factor values of bare frames are lower than the corresponding values recommended in the BIS code.

Keywords: Infill walls, lintel beam, reinforced concrete frames, response reduction factor.

AT present, the most common structural system for both residential and commercial buildings consisting of multi-level framed structures is the reinforced concrete (RC)-infilled frames. So, it is important to estimate the seismic response of RC structures with masonry infill walls under seismic action. Nonlinear structural analyses and finite element methods are practised to compute the seismic reaction of RC-infilled structures. Masonry infill is one of the most popular and versatile construction materials. The use of masonry infill walls in RC structures is the current construction practice in many developing countries. Surface contact between the masonry and structural members is significantly important in earthquake-prone areas, because lateral resistance capacity of the building increases due to the stiffness of infill walls. In the present study, along with infill, the most important structural member, i.e. lintel beam has been incorporated in the frame structure. Generally, lintel beam is the horizontal member provided at the openings of walls such as doors and windows in order to carry the load of the wall, but in earthquake-prone areas, this lintel band is provided throughout the perimeter of the frames externally as well internally, because, it plays an important role in seismically active regions. Now many countries are adopting this concept to make more earthquake-resistant structures. In general, seismic design codes incorporate the non-linearity that presents in the structure by the response reduction factor (*R*-factor). The *R* factor reduces the elastic response to inelastic response of a structure. The *R*-factor is identified as response modification coefficient, behaviour factor and response reduction factor in different countries. The Bureau of Indian Standard code does not give any specific explanation regarding different factors like the effect of infill wall consideration, structural and geometrical configuration, irregularities, etc. Thus, the primary aim of the present study is to estimate the actual response reduction factor of RC frame structures with and without lintel beam and compare the same with the values recommended by the BIS code.

Alguhane *et al.*[1] performed seismic evaluation of an existing five-storey RC building with and without infill. Four models have been considered for the present study: model 1 (bare frame), model 2 (frame with infill – update from field test), model 3 (frame with infill – according to ASCE 41), model 4 (soft storey frame – according to ASCE 41). The design spectrum for Madinah area (Saudi Arabia) was studied. Finally, the response modification factor was evaluated from capacity design spectra. The authors[1] concluded that response modification factor of the bare frame did not fulfill the requirement of SBC 301 (Saudi Building Code 301). However, incorporation of infills in the frames resulted in an increase in the response modification factor and over strength factor and satisfied the code requirement. In case of open ground

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storey building, the R-factor value was less than the code requirement; so for safety purpose there is need of infills at the ground storey.

Chaulagain *et al.*[2] evaluated the response reduction factor of 12 existing irregular engineered RC buildings in Kathmandu valley, Nepal. Nonlinear static pushover analysis was used for this purpose. According to the authors[2], the Nepal code NBC-105:1994 does not provide any information regarding response reduction factor; so they followed the Indian standard code IS:1893(2002) for their study. First, they surveyed the existing buildings and collected detailed information on them (drawings, structural detailing, etc.) and modelled the existing buildings using SAP2000 software. Nonlinear static pushover analysis was used and they evaluated the seismic performance of the buildings, mainly the effect of over strength on ductility factor, beam column capacity ratio on building ductility and load path on response reduction factor. From the detailed study, they concluded that the R-factor is sensitive to both geometrical configuration and material strength. The calculated R-factor values for different cases of the buildings were less than those recommended by IS1893:2002.

Maheri and Akbari[3] evaluated the response reduction factor of RC buildings for steel X-braced and knee-braced system. The R-factor components, including ductility reduction factor and overstrength factor were evaluated from nonlinear static pushover analysis of three different frame systems, viz. unbraced RC frame, X-braced RC frame and knee-braced RC frame of different heights and configurations. They analysed the above three models for 4, 8 and 12 storey buildings using Drain 2DX software. The authors concluded that response reduction factor decreased as the height of the frame system increased. Also, response reduction factor was higher for X-braced frame and knee-braced frame compared to unbraced moment resisting frame and the knee-braced frame system was more appropriate than the X-braced frame system for behaviour factor of structures.

Shendkar and Pradeepkumar[4] evaluated the response reduction factor of two-dimensional RC frames for two different types of infill, i.e. semi-interlocked masonry and unreinforced masonry with and without opening in the infill. They used the Newmark and Hall[11] method and showed that the R-factor value effectively decreased by considering opening in the infill.

Shendkar and Pradeepkumar[5] performed a numerical simulation of RC semi-interlocked masonry (SIM) and unreinforced masonry (URM) infill for the evaluation of response reduction factor using pushover analysis and SeismoStruct software. The authors considered the distributed inelasticity in structural members to achieve more accurate results. After a detailed study, they concluded that the R-factor value was higher for RC SIM panel frame compared to RC URM panel frame, because semi-interlocked masonry infill has more inherent energy dissipation capacity due to provision of shear keys and slots to the unit bricks; also it is more useful in earthquake-prone areas.

The aim of the present study is as follows: (1) To find the realistic response reduction factor of RC-infilled frames with and without lintel beam along with the opening in the infill walls using static adaptive pushover analysis. (2) To compute the actual R-factor evaluated from the interpretation of analytical results and compare the same with the values recommended by the BIS code.

Adaptive pushover analysis

In recent years, pushover analysis is being used to examine the nonlinear response of structures. It represents a significant alternative solution for nonlinear dynamic analysis of structures. In case of multistoried structures, ignoring the effect of higher modes is one of the limitations of such approaches. Some researchers proposed to consider higher mode effects depending on adaptive pushover procedures, which include increasing variation in dynamic properties like time period, frequency, etc.[6,7]. For this, the applied load is revised at every incremental action depending on the current dynamical properties of the structure.

Antoniou and Pinho[8] used a force-based adaptive pushover analysis, in which the lateral load was continuously revised at each single step during the eigen-value analysis. SRSS method was used to combine the responses of each mode. In this advanced static analysis method, spectral amplification part is also important for updating the load vectors. According to the literature for adaptive pushover case, one can introduce the record of earthquake ground motion and define the level of damping. In the present study, for spectral amplification we considered the accelerogram time-history of the Chi-Chi earthquake in Taiwan (date: 20 September 1999) taken from the PEER database.

Response reduction factor

The R-factor is generally used to minimize elastic response to inelastic response structures. In other words, the response reduction factor is defined as the ratio of elastic strength to inelastic design strength. From the existing literature, it is seen that R-factor is mainly a function of three factors, viz. ductility factor, overstrength factor and redundancy factor. It is mathematically expressed as

$$R = R_{\mu} \times {}'\Omega \times R_R, \tag{1}$$

where R_{μ} is the ductility reduction factor, $'\Omega$ the overstrength factor and R_R the redundancy factor. Figure 1 provides an explanation of all these factors. According to

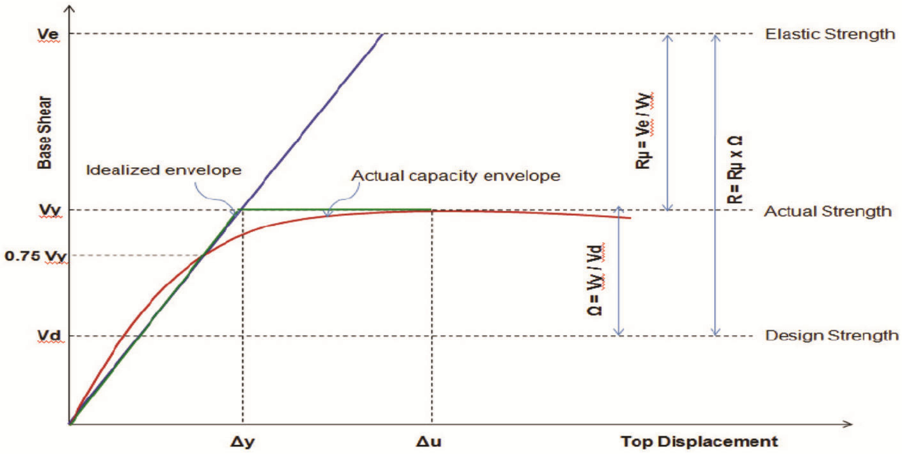

Figure 1. Interrelation between response reduction factor, over-strength and ductility reduction factor[1].

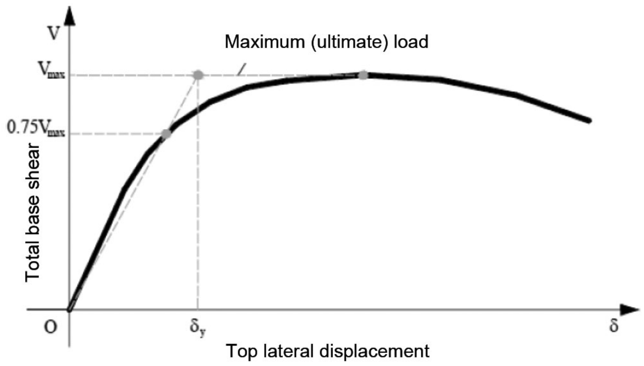

Figure 2. Reduced stiffness method[14].

Table 1. Recommended values of response reduction factor by IS: 1893 (Part-1): 2016 (ref. 13)

Frame system	R value
Ordinary moment resisting frame	3
Special moment resisting frame	5

BIS code provisions, it is mathematically represented as follows[9]

$$2R = R_{\mu} \times {}'\Omega. \quad (2)$$

According to ATC 19 (ref. 10), the product of the ductility reduction factor and overstrength factor is the response reduction factor. Table 1 provides recommended values for response reduction factor.

Ductility reduction factor (R_μ)

The ductility reduction factor provides a measure of the global nonlinear response of a structure. It mainly depends on ductility and fundamental time period of any structure. The displacement ductility μ is expressed as

$$\mu = \frac{\Delta_{\max}}{\Delta_y}, \quad (3)$$

where $\Delta_{\max}$ is the maximum displacement corresponding to peak base shear of the pushover curve and Δ_y is the yield displacement, calculated by the reduced stiffness method (Figure 2).

The R–μ–T relationships developed by Newmark and Hall were used to evaluate R_μ as follows[11]

If, time period < 0.2 sec, $R_\mu = 1$.

If, 0.2 sec < time period < 0.5 sec

$$R_\mu = \sqrt{2\mu - 1}. \quad (4)$$

If, time period > 0.5 sec, $R_\mu = \mu$.

Overstrength factor

It is a measure of the reserved strength present in a structure and may be expressed as follows

$$\Omega = \frac{V_y}{V_d}, \quad (5)$$

where V_y is the ideal yield base shear and V_d is the design base shear.

The main sources of overstrength factor are: (i) material strength, (ii) load factors and their combinations, (iii) participation of nonstructural elements like infill walls and (iv) redundancy.

Redundancy factor

Redundancy is usually defined as the gap between local yield point and global yield point of a structure. Any building should have a high degree of redundancy for

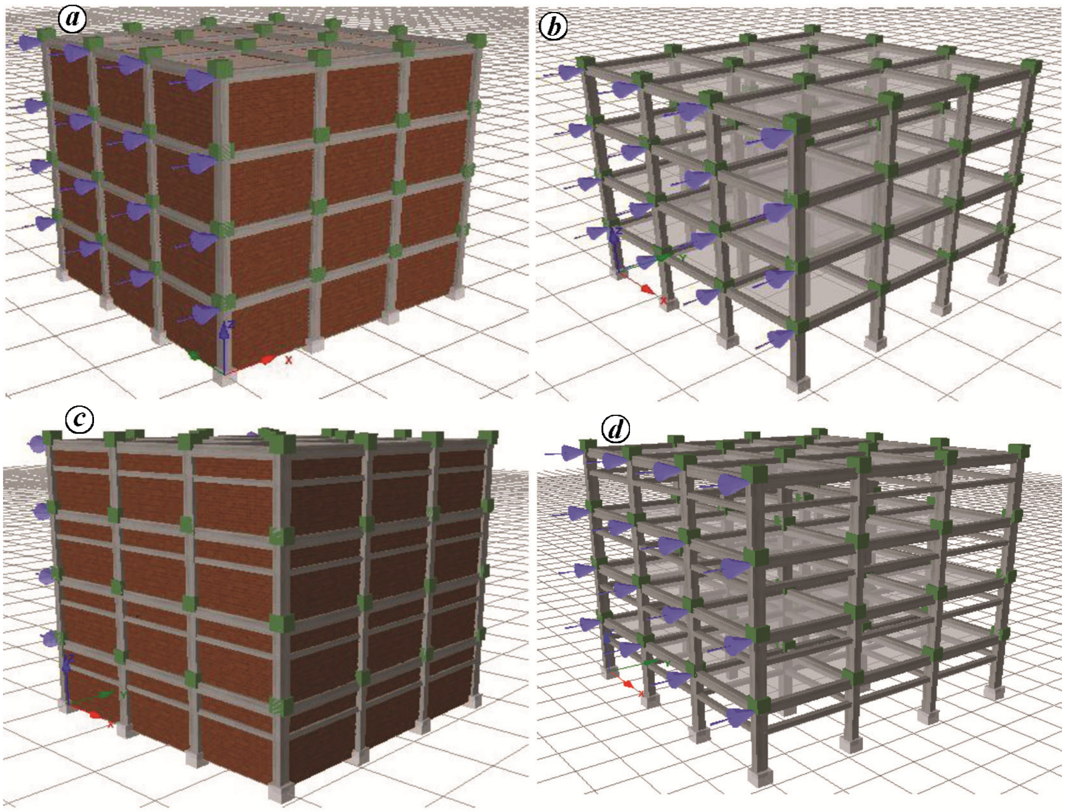

Figure 3. ***a***, Full RC-infilled frame without lintel beam. ***b***, Bare frame without lintel beam. ***c***, Full RC-infilled frame with lintel beam. ***d***, Bare frame with lintel beam.

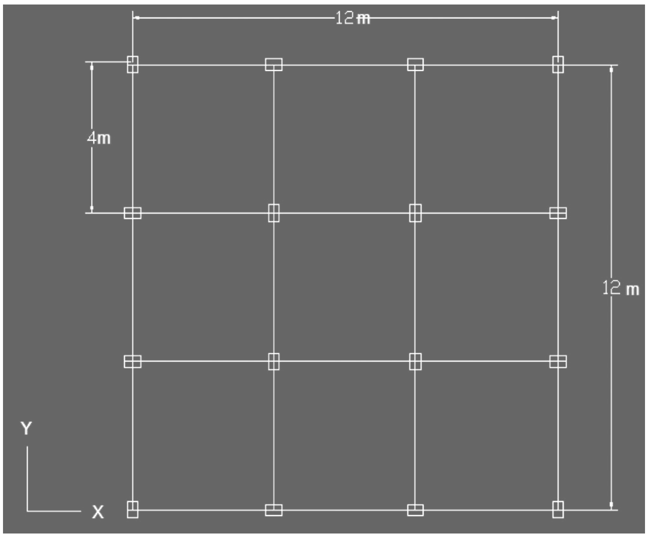

Figure 4. Arrangement of the building in planar manner.

lateral resistance. In this study, redundancy factor has been incorporated into the overstrength factor.

Model description

For this study, a four-storey three-dimensional building symmetrical on plan is considered with 3 bays in both directions, each bay span is 4 m, and storey height is 3 m. This building is situated in seismic zone IV (according to IS: 1893(Part I): 2016) and designed for lateral earthquake loads. The building is modelled using SeismoStruct software. The lintel beam is located at the height of 2 m. Models were studied for comparison of the performance of RC frame structures with and without lintel beam as follows: (i) Full RC-infilled frame without lintel beam in both directions. (ii) Bare frame without lintel beam in both directions. (iii) Full RC-infilled frame with lintel beam in both directions. (iv) Bare frame with lintel beam in both directions.

Figure 3 shows models of the building, while Figure 4 shows the building plan. Table 2 provides structural details of building. Tables 3–5 show the column, beam and lintel beam dimensions respectively.

Material parameters

(a) Concrete model (Mander model): This model is a uniaxial nonlinear constant confinement model. The transverse reinforcement plays an important role in confinement effect for the structural members.

(b) Steel model (Menegotto–Pinto steel model): This is a uniaxial steel model initially developed by Yassin[12]. It should be confined to the modelling of RC

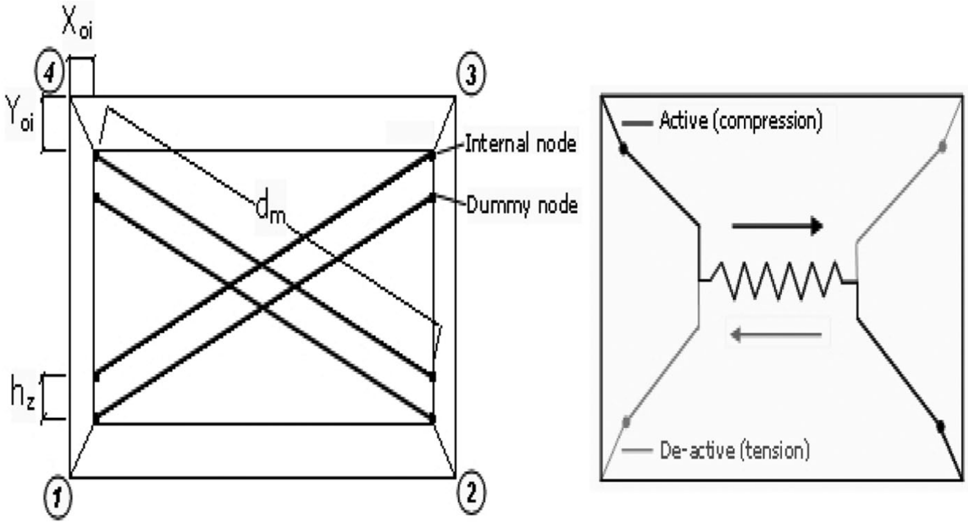

Figure 5. Inelastic infill panel element[15].

Table 2. Structural details of the building

Type of structure	Special moment resisting frames
Number of stories	4
Seismic zone	IV
Floor height	3 m
Bay length	4 m along X and Y directions
Infill wall	230 mm
Compressive strength of masonry	5 MPa
Young's modulus of masonry	2750 MPa
Width of strut with opening in infill	262 mm
Area of strut	60,260 sq. mm
Equivalent contact length (h_Z)	20.37%
Horizontal offset (X_o)	5.62%
Vertical offset (Y_o)	7.5%
Type of soil	Medium stiff soil
Column size	300 × 450 mm
Beam size	250 × 450 mm
Lintel beam size	230 × 230 mm
Slab depth	150 mm
Live load	3 kN/m^2
Material	M-25 grade concrete and Fe-415 reinforcement
Damping in structure	5%
Importance factor	1.5

structures, particularly those subjected to complex loading histories. Isotropic hardening is to be considered in this model.

(c) Infill panel element: Infill element is characterized by four axial struts and two shear springs (Figure 5). It helps define physical characteristics of infill, strut curve and shear curve parameters. Four-node panel masonry elements were developed by Crisafulli[16]. It accounts separately for shear and compressive behaviour of masonry infill and adequately represents the hysteretic response. It shows the high level of accuracy. This model is also known as 'double strut nonlinear cyclic model'. The presence of an opening in the infill will directly affect structural integrity of the structures; the effect can be incorporated by minimizing the width (diagonal strut). The stiffness reduction factor to consider opening effect(s) in the infill in numerical modelling is given as follows

$$W_{do} = (1–2.5A_r) \times W_d, \tag{6}$$

where W_{do} is the width of diagonal strut with opening in infill, W_d the width of diagonal strut and A_r is the ratio of opening area to the face area of infill. Equation (6) is valid for openings in walls greater than 5% and less than 40%. In this study, opening in infill is 1.2 m × 1.2 m and 1 m × 1 m, totaling to 2.44 sq. m, this implies approximately 20% opening area in the infill. The width of strut was calculated according to IS 1893(Part-1): 2016.

Table 2 provides all the values of material parameter.

Verification of numerical result

The work of Shendkar and Pradeepkumar[5] was verified using SeismoStruct software for two cases: (1) bare frame and (2) URM full infilled RC frame.

Table 6 describes the material and sectional properties used in the above study[5]. Table 7 describes the validation results compared with existing literature.

Results and discussion

Pushover curves

The utilization of nonlinear static analysis came into practice in the 1970s, but the potential of the method has been identified only during the last two decades. Several parameters like strength, ductility and R-factor can be

Table 3. Column dimensions and detailing

Column	Size (mm)	Main reinforcement	Shear reinforcement
All columns of the building	300 × 450	Four nos of 16 mm diameter at corners and two nos of 16 mm on the longer side.	8 mm diameter at 100 mm c/c

Table 4. Beam dimensions and detailing

Beam	Size (mm)	Main reinforcement	Shear reinforcement
All beams of the building	250 × 450	Two nos of 16 mm diameter at top as well as bottom	8 mm diameter at 100 mm c/c

Table 5. Lintel beam dimensions and detailing

Beam	Size (mm)	Main reinforcement	Shear reinforcement
All beams of the building	230 × 230	Two nos of 10 mm diameter at top as well as bottom	8 mm diameter at 200 mm c/c

Table 6. Material and sectional properties[5]

Type of structure	Ordinary moment resisting frame
No. of stories	Four storey (2D)
Infill wall	113 mm
Size of column	300 × 600 mm
Size of beam	250 × 450 mm
Material	M 20 (Mander model) and Fe 415 (Manegotto–Pinto steel model)
Compressive strength and modulus of elasticity of infill	5.5 MPa and 4000 MPa

Table 7. Validation results compared with existing literature[5]

Structural parameters from pushover curve	Bare frame		URM full infilled frame	
	Obtained results	Literature results	Obtained results	Literature results
Base shear	547	546.82	1772	1772
Ductility	3.9	3.89	1.43	1.42
Ductility reduction factor	2.61	2.6	1.36	1.35
Overstrength factor	1.252	1.25	4.06	4.05
R-factor	3.26	3.25	5.52	5.46

evaluated from adaptive pushover analysis curves. Thereby, the significance of infill and lintel beam, which play an important role in the RC frame, has been quantified. Using these pushover curves, one can estimate the capacity of the whole structure. From Figure 6, it can be inferred that RC-infilled frames have maximum capacity compared to bare frames because of the influence of infill in seismically active zones.

Base shear

Figure 7 shows that base shear is lower in bare frames compared to full RC-infilled frames. Due to symmetry of the building in both directions, i.e. X and Y, there is a small variation in base shear of different models. On an average, there is 15.83% base shear increase in bare frame with lintel beam compared to bare frame without lintel beam. Similarly, in case of full RC-infilled frame with and without lintel beam, there is a small variation in base shear.

Ductility

Using eq. (3), ductility is evaluated from Figure 1 and results are presented in Figure 8. It is higher in bare frame with lintel beam compared to all other frames. On an average, it is 9.20% more in bare frame with lintel beam compared to bare frame without lintel beam and 27.58%

more in full RC-infilled frame with lintel beam compared to full RC-infilled frame without lintel beam. This is because the lintel beam separates the infill panel and the frame allows more drift, i.e. maximum displacement corresponding to peak base shear is higher due to incorporation of lintel beam. Also in such case, lateral loads are well distributed along the building height due to presence of lintel beam.

Ductility reduction factor

Using eq. (4), ductility reduction factor is evaluated on the basis of ductility and time period. According to Figure 9, ductility reduction factor is higher for bare frame with lintel beam compared to all other frames. On an average, ductility reduction factor increases by 20.86% in full RC-infilled frame with lintel beam compared to full RC-infilled frame without lintel beam. As can be seen from Figures 8 and 9, the behaviour of ductility and ductility reduction factor is the same. In case of bare frame, the value of ductility reduction factor is the same as ductility because bare frame is under a long-period structure (if time period > 0.5 sec).

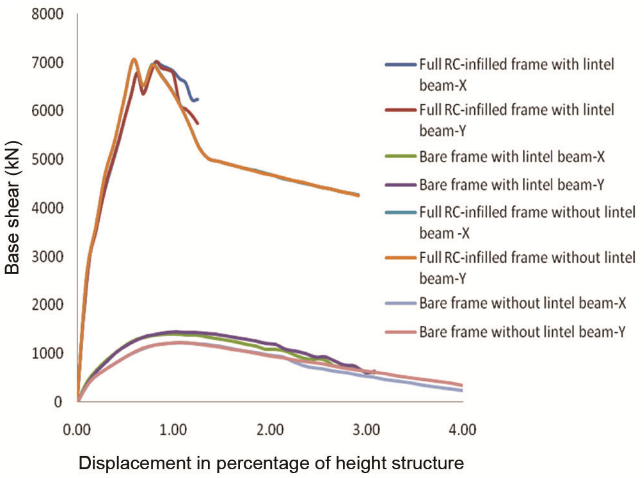

Figure 6. Comparison of pushover curves.

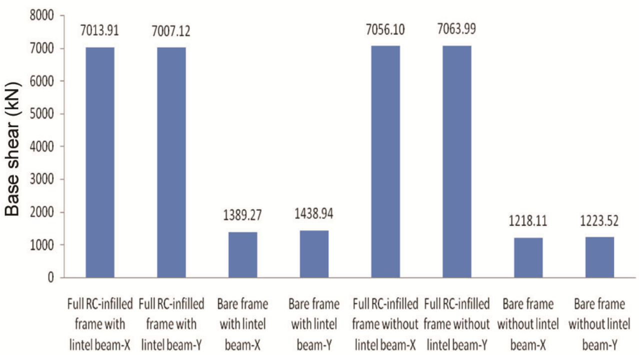

Figure 7. Comparison of base shear.

Overstrength factor

Using eq. (5), overstrength factor is evaluated based on Figure 1. According to Figure 10, the overstrength factor is higher in full RC-infilled frame without lintel beam compared to all other frames, because there is no lintel beam to separate the infill panels. In case of full RC-infilled frame with lintel beam, the infill panels are separated due to lintel beam in the frame and the main source of reserved strength is due to the masonry infill panel. In the present study, the whole infill panel is divided into two parts; hence the reserved strength of frame has been slightly reduced because, the infills are divided in two parts so the lateral resistance capacity reduces compared to single infill panel in the frame (Figure 7). The reserved strength basically depends on lateral load capacity of the frame. On an average (i.e. average value of overstrength factor in X and Y directions) there is 3.69% increase in overstrength factor in bare frame with lintel beam compared to bare frame without lintel beam. In case of full RC-infilled frame with and without lintel beam, there is about 6.03% variation of overstrength factor.

Response reduction factor

Using eq. (2), the R-factor is evaluated based on Figure 1. According to Figure 11, the response reduction factor is higher in full RC-infilled frame with lintel beam

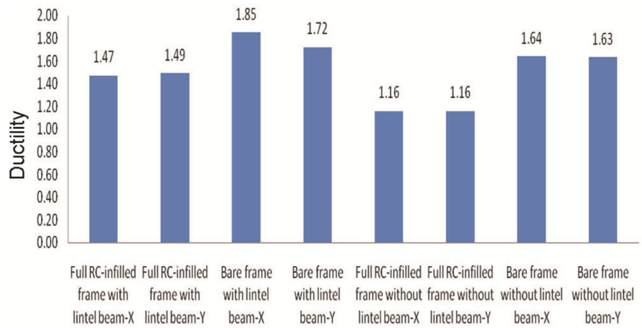

Figure 8. Comparison of ductility.

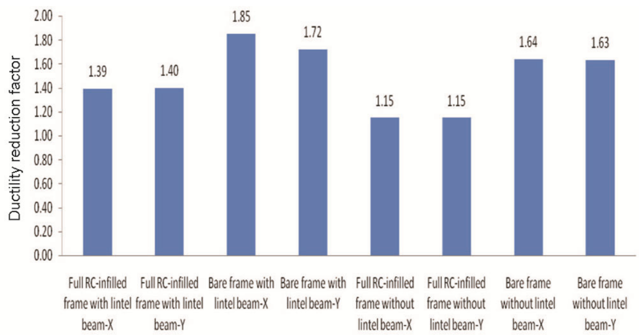

Figure 9. Comparison of ductility reduction factors.

compared to all other frames. In this study, *R*-factor depends more on ductility factor and so the behaviour of both factors for all frames is similar (Figures 8 and 11). The *R*-factor increases by 14.33% in full RC-infilled frame with lintel beam compared to full RC-infilled frame without lintel beam. Similarly, the *R*-factor increases by 13.43% in bare frame with lintel beam compared to bare frame without lintel beam. The *R*-factors evaluated of full RC-infilled frame with and without lintel beam are 34% and 17.2% more respectively, compared to BIS code values (SMRF-5). Also, in case of bare frame with and without lintel beam, the evaluated *R*-factors are 27.4% and 36% less respectively, compared to BIS code values (SMRF-5). The numerical results have been verified by Shendkar and Pradeep Kumar[4], where *R*-factor was 68% more in case of two-dimensional RC-infilled frame compared to bare frame. In this study infill plays an important role to increase the response reduction factor of the frame.

Damage of frames

To study the damage patterns of different frames, the performance criteria based on materials used in the present numerical simulation are: (i) crushing strain limit for unconfined concrete: 0.0035, (ii) crushing strain limit for confined concrete: 0.008, (iii) yield strain limit for steel: 0.0025 and (iv) fracture strain limit for steel: 0.06 (ref. 12).

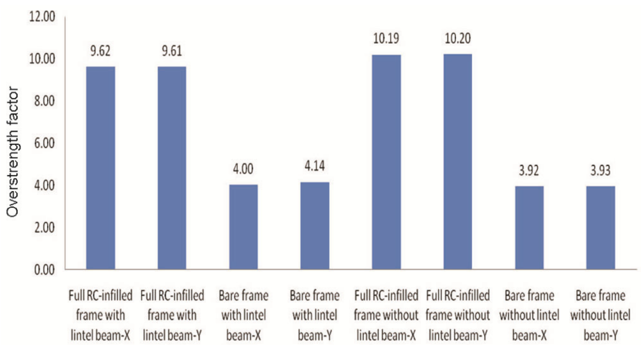

Figure 10. Comparison of overstrength factor.

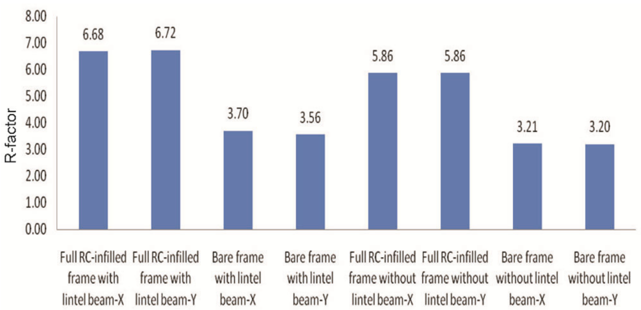

Figure 11. Comparison of response reduction factors.

According to Figure 12, in a bare frame first yielding of steel occurs at base shear of 960.82 kN and displacement 64 mm. This yield displacement is more compared to all other frames because of lower stiffness in the bare frame. First crushing of unconfined concrete, i.e. spalling of cover concrete occurs at base shear 1217.58 kN and displacement 128 mm. First crushing of confined concrete, i.e. core portion of concrete occurs at 970.66 kN and displacement 240 mm. The first fracture point is present at base shear 699.82 kN and displacement 336 mm, i.e. bare frame reaches its ultimate stage.

According to Figure 13, in the above frame first yielding of steel occurs at base shear 4688.56 kN and displacement 35 mm. This frame sustains more load compared to all other frames. First crushing of unconfined concrete, i.e. spalling of cover concrete occurs at base shear 6529.16 kN and displacement 81.67 mm. First crushing of confined concrete, i.e. core portion of concrete occurs at 5254.25 kN and displacement 151.67 mm.

According to Figure 14, in the above frame first yielding of steel occurs at base shear 4065.35 kN and displacement 30.76 mm. First crushing of unconfined concrete, i.e. spalling of cover concrete occurs at base shear 5439.54 kN and displacement 53.45 mm. First crushing of confined concrete, i.e. core portion of concrete occurs at 7013.91 kN and displacement 98.64 mm.

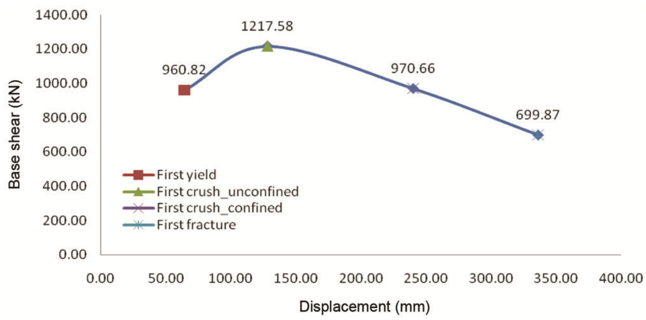

Figure 12. Damage pattern in bare frame without lintel beam.

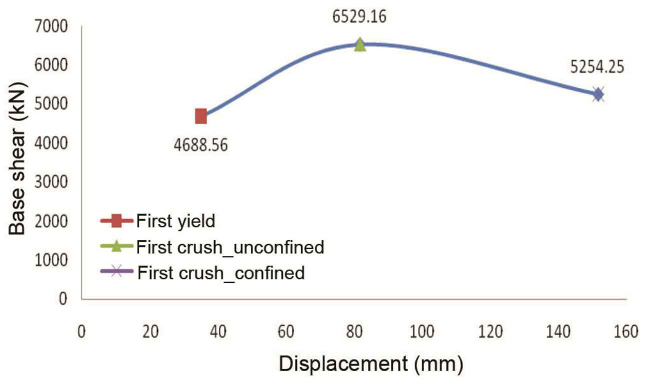

Figure 13. Damage pattern in full RC-infilled frame without lintel beam.

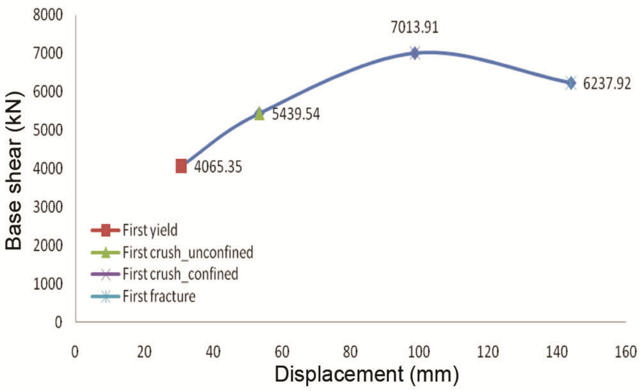

Figure 14. Damage pattern in full RC-infilled frame with lintel beam.

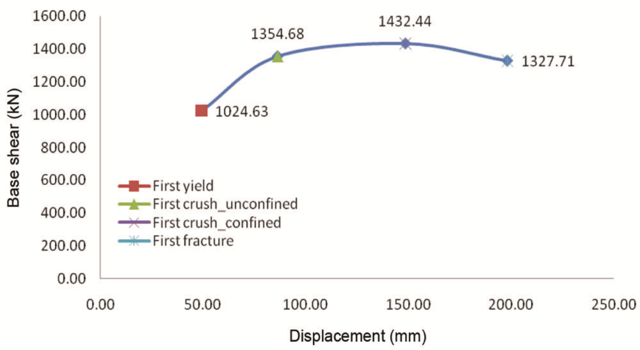

Figure 15. Damage pattern in bare frame with lintel beam.

The first fracture point is present at base shear 6237.92 kN and displacement 144 mm. According to Figures 13 and 14, the gap between yield displacement and maximum displacement is maximum in full RC-infilled frame with lintel beam compared to full RC-infilled frame without lintel beam; so ductility is maximum in full RC-infilled frame with lintel beam.

According to Figure 15, the first yielding of steel occurs at base shear 1024.63 kN and displacement 49.28 mm. First crushing of unconfined concrete, i.e. spalling of cover concrete occurs at base shear 1354.68 kN and displacement 86.41 mm. First crushing of confined concrete, i.e. the core portion of concrete occurs at 1432.44 kN and displacement 148.70 mm. The first fracture point is present at base shear 1327.71 kN and displacement 198.33 mm. According to Figures 12 and 15, the gap between yield displacement and maximum displacement is maximum in bare frame with lintel beam compared to bare frame without lintel beam; so, ductility is maximum in bare frame with lintel beam.

Conclusion

According to analytical results, the following conclusions are drawn from the present study:

(1) In case of full RC-infilled frame with and without lintel beam, there is a small variation in the base shear.

(2) Ductility and ductility reduction factor are higher in bare and full RC-infilled frame with lintel beam compared to other frames without lintel beam. This is because the lintel beam separates the infill panel and the frame allows more drift, i.e. maximum displacement corresponding to peak base shear is higher due to incorporation of lintel beam. Also in such case, lateral loads are well distributed along the building height due to presence of lintel beam.

(3) Generally overstrength factor is significantly affected by the presence of infill in the frame. However, incorporation of lintel beam in the peripheral as well as internal frames results in the separation of the infill panels from the frame. Hence, the overstrength factor of full RC-infilled frames slightly decreases because the two divided parts of infills are not capable to resist lateral load compared to single infill panel in the frame. And reserved strength basically depends on lateral load capacity of the frame.

(4) The response reduction factor is higher in case of the frames with lintel beam compared to frames without lintel beam. In this study, R-factor is considerably influenced by ductility factor.

(5) The computed values of R-factor for bare frames obtained by adaptive pushover analysis of buildings are less than those suggested in IS: 1893(Part I):2016. After incorporation of lintel beams in the frames, the computed values of R-factor for bare frames are less than those recommended by IS: 1893(Part 1):2016, because the IS code neglects factors like geometrical configurations, irregularities, incorporation of infill and lintel beam.

(6) On incorporation of lintel beams in bare frames, the R-factor values increase compared to bare frame without lintel beam. However, the computed R-factor values of these frames are less than those recommended by the BIS code.

(7) The R-factor is overestimated by 37.74% and 56.25% in the BIS code for bare frame with and without lintel beam respectively, leading to significantly lower estimate of the design base shear.

Conflict of interest: The authors declare that they have no conflict of interest.

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Received 18 September 2019; revised accepted 18 November 2019

doi: 10.18520/cs/v118/i7/1077-1086