Effect of Revised Seismic Design Provisions on Seismic Performance of RC Frame Buildings with and Without Infills

P. L. Kurmi and P. Haldar

Abstract Indian Standard for seismic design of Reinforced Concrete (RC) frame buildings with Un-Reinforced Masonry (URM) Infills have undergone significant revisions in 2016 compared to its older version in 2002 and 1993, respectively. Two of the major revisions of BIS 13920-2016 are the inclusion of capacity design criteria to ensure strong-column weak-beam and selection of column dimension based on largest longitudinal beam rebar. The revised seismic design standard also recommends modeling guidelines for Un-Reinforced Masonry (URM) infill using the equivalent diagonal strut to take into account the complex infill-frame interaction. Under lateral loading, infills contribution to global strength and stiffness is often ignored for being treated as non-structural elements in general design practice. The present study attempts to evaluate the comparative seismic response of Special Moment Resisting Frame (SMRF) RC buildings with and without infills, designed with revised and older versions of Indian seismic standards. Capacity curves have been developed through nonlinear static pushover analysis. It has been observed that revised code provisions improve the structural performance in terms of stiffness, strength, inelastic displacement capacity, and eventually results in the desired ductile failure mechanism of the RC frames. However, considering the effect of infills as per the revised Indian standard has led to reduced inter-storey drift and ultimate inelastic deformation compared to the bare frame and the general design practice. It has been observed that the infill-frame interaction plays a key role in the overall performance as well as govern the failure mechanism of the structure as a whole.

Keywords Infilled RC frame buildings · Nonlinear analysis · Seismic design code · Seismic performance

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C. Ha-Minh et al., (eds.), *CIGOS 2021, Emerging Technologies and Applications for Green Infrastructure*, Lecture Notes in Civil Engineering 203,
https://doi.org/10.1007/978-981-16-7160-9_13

1 Introduction

The traditional approach for seismic design of RC frame buildings has been force-based which has been adapted by Indian seismic design standards [1, 2], like many other national codes. In force-based design, base shear is computed based on expected seismic hazard level, importance of the building, and probable reduction in seismic demand to considering the ductility of the structure. The inelastic effects are indirectly considered for controlling seismic demand, using the effective Response Reduction Factor (*I*/*R*), where *I* represents the Importance Factor, and *R* represents the reduction factor for ductility and overstrength [3]. Several important aspects of controlling parameters related to seismic hazard, design, and detailing have been modified, removed or introduced in the latest revision of Indian seismic design standards [1, 4], which are summarized in Table 1. An important revision can be observed in the design response spectra of the revised seismic design standard [1]. The design response spectra have been merged with the flat plateau of acceleration-controlled zone, which eventually increases the seismic hazard in case of approximate linear analysis method. The fundamental natural time period of design response spectra is also extended from 4 to 6 s. Figure 1 shows the comparison of design response spectra for approximate linear elastic analysis of older [2] and revised Indian seismic design standard [1]. However, the design spectra for linear dynamic analysis remains same. The definition of irregular buildings in plan and elevation has undergone some key changes in the revised standard [1] as compared to irregular building definition of older standard [2], which is not reported here due to brevity.

It is widely understood from the past earthquakes that the presence of infills significantly alters the seismic response of RC buildings leading to undesirable failure of frames and infills, and thus complex interaction between frame and infill can never be ignored under seismic loading. Hence, realistic estimation of seismic response of infilled RC frame requires incorporation of infills in the structural analysis and design stages. To simulate the infills, the modeling approaches are classified into two major categories, namely micro-models and macro-models. The micro models [5] are based on the complicated nonlinear Finite Element (FE) analysis involving

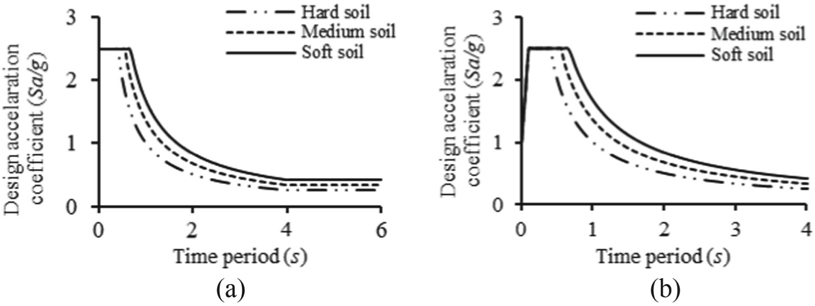

Fig. 1 Design response spectra for approximate linear analysis. **a** BIS 1893-2016. **b** BIS 1893-2002

intensive computational efforts, whereas the macro models [6] utilize to represent the infill using an equivalent diagonal strut analogy that can capture the global response of infilled RC frames with reasonable accuracy. The revised Indian seismic design standard, recommends modeling of infills using a single equivalent diagonal strut, and suggests an empirical relationship to estimate the width of the strut. Moreover, the revised standard does not offer any reduction factor to equivalent diagonal strut to account for opening in infills. The revised standard also remains silent on the estimation of governing strength of infill under lateral load, which is essential for nonlinear analysis. Among the various failure modes and strength of infills available in the literature [6], Haldar et al. [7, 8] highlighted that the strength of infills is usually minimum in shear, and thereby the sliding shear failure of the infill panel along the bed joint governs the failure modes of infill. Along with the revised seismic design Indian standards BIS 1893-2016 [1], Indian ductile design and detailing standard BIS 13920-2016 [4] has also been revised in 2016, and two major provisions have been incorporated: (1) selection of column dimension based on the largest beam longitudinal bar, and (2) capacity design. The capacity design for moment resisting frames enforcing Strong-Column Weak-Beam (SCWB) concept using an SCWB ratio (i.e., the ratio of the sum of nominal moment capacities of all columns to the sum of nominal flexural strengths of beams, framing into the same joint, in the direction under consideration). National standards of several other countries like EC 8-2004 [9], NZS 3101-2006 [10], and ACI 318-14 [11] recommend an SCWB ratio to ensure capacity design which was missing in the older version of Indian ductile and design and detailing standard [12]. In the latest revision of the Indian ductile design and detailing standard [4], an SCWB ratio of 1.4 has been recommended for SMRF buildings in moderate to high seismicity areas like seismic zones III, IV, and V, and kept optional for lower seismicity area like seismic zone II. The seismic performance of a building, designed according to the code practices, depends on the overall effect of the controlling parameters and other provisions for design and detailing. However, due to lack of awareness of impact on the overall performance of the building and difficulty in incorporating these revised provisons in the analytical model, in practice, the designers end up making flexible buildings in many cases. The present study attempts to evaluate the comparative seismic performance of Special Moment Resisting Frame (SMRF) mid-rise (4-storey) RC buildings with and without infills, designed with revised and older versions of Indian seismic standards through nonlinear static pushover analysis to bring out the enormous effect of two of the major revisions of BIS 13920-2016, which are capacity design and selection of column dimension with and without modeling of URM infill on the over all performance of the buildings.

Table 1 Comparison of controlling parameters related to seismic hazard, design and detailing

Parameters	Structure type	BIS 1893-2002 /BIS 13920-1993	BIS 1893-2016/BIS 13920-2016
Fundamental period (T_a in sec)	RC steel composite MRF building	NIL	$T_a = 0.080\text{h}^{0.75}$
	RC building with structural wall	NIL	$T_a = \frac{0.075\text{h}^{0.75}}{\sqrt{A_w}} \geq \frac{0.09\text{h}}{\sqrt{a}}$ $A_w = \sum_{i=1}^{NW}\left[A_{wi}\left\{0.2+\left(\frac{L_{wi}}{h}\right)\right\}^2\right.$
Response reduction factor (R)	Flat slab-structural wall system	NIL	3.0
Importance factor (I)	Occupancy > 200 persons	NIL	1.2
Damping factor	RC and steel	3.2 to 0.5	NIL
Cracked stiffness properties (I_{eff})	RC and masonry	NIL	70% $I_{gross\ column}$ 35% $I_{gross\ beam}$
	Steel	NIL	$I_{gross\ column}$
Modelling of infill	Unreinforced masonry	NIL	$w_{ds} = 0.175\alpha_h^{-0.4} L_{ds}$ $\alpha_h = h\left[\sqrt[4]{\frac{E_m t \sin 2\theta}{4E_f I_c h}}\right]$
Minimum design lateral force	RC and Steel	NIL	Zone II–0.7, III– 1.1, IV–1.6, V–2.4%
Selection of column dimension	RC	NIL	20 times the diameter of largest beam rebar
Strong-column weak-beam	RC	NIL	SCWB ratio ≥ 1.4
Beam-column joint shear strength	RC	NIL	$\tau_{jc} = 1.5A_{ej}\sqrt{F_{ck}}$ $\tau_{jc} = 1.2A_{ej}\sqrt{F_{ck}}$ $\tau_{jc} = 1.0A_{ej}\sqrt{F_{ck}}$

2 Analysis and Design of RC Frame Buildings with and Without Infills

The buildings considered in the present study have a generic plan, as shown in Fig. 2. The plan is symmetric with significantly different redundancy in the two directions. The storey height is considered as 3.3 m. The buildings have been assumed to be situated on medium (Type II) soil as per BIS 1893-2016 [1]. For design, M25 grade concrete and Fe500 grade steel have been used. The revised ductile design and detailing standard [4] recommends, the minimum dimension of the column shall not be less than 20 times the diameter of the largest beam longitudinal bar or 300 mm,

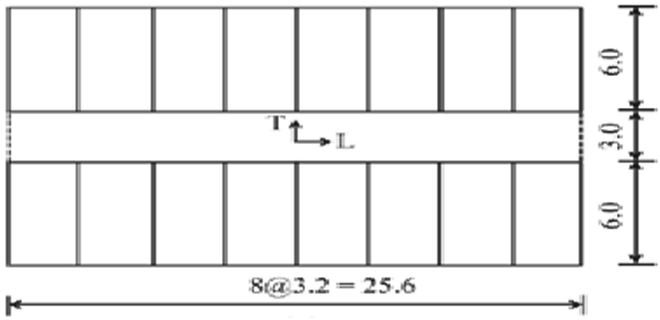

Fig. 2 Plan of the considered building (All dimensions are in metre)

whichever is greater. Hence, the selection of the column dimension is directly related to the selection of the largest beam longitudinal rebar. The beam longitudinal bar diameter is selected as per BIS 456:2000 [13], to keep sufficient space between the adjacent bars so that the needle vibrator can be immersed during concrete casting. The present study assumes to have at least 50 mm clear space between the adjacent bars to select the appropriate diameter of the longitudinal beam bar. Hence, the estimated column sizes as per the revised ductile design and detailing standard BIS 13920-2016 were 500X500 *mm*. The column dimensions for buildings designed as per older seismic design standard BIS 1893-2002 [2] have been proportioned to have 2–4% demand steel, and estimated column sizes were 375 × 375 mm. The beam sections have been proportioned to have a maximum of 1% demand steel on each face. The beam sections were sufficient for both the buildings designed as per older and revised seismic standards and therefore kept same in both the building models. The estimated beam sizes were 250 × 400 mm and 350 × 500 mm along the longitudinal and transverse direction, respectively. The dead load (DL) and live load (LL) are calculated using the Indian standard IS 875, Part 1 [14] and Part 2 [15], respectively. The slab thickness is assumed to be 150 mm and found safe against the limit state design criteria [13]. External unreinforced brick masonry wall thickness is considered to be 230 mm, and the internal walls as 110 mm as per the prevailing practices in India. Also, a 230 mm thick parapet wall of 1 m height is considered along the roof periphery. Three-dimensional 4-storey space frame with slab as rigid diaphragm has been designed as per revised and older Indian seismic standards [1, 2, 4, 16]. Considering the fair quality of masonry, the compressive strength of infill panels is considered 4.1 MPa, consistent with the typical compressive strength of masonry in Northern India [17]. For nonlinear analysis, ASCE 41-17 [18] flexural (M) concentrated hinges are assigned at both ends of the beams, and axial force-moment interaction (P-M-M) concentrated hinges are assigned to both ends of columns considering conforming transverse reinforcement. The effective stiffness values, as suggested in BIS 1893:2016 [1] have been used for concrete frames. The sliding shear strength for infill panel is estimated using ASCE 41-17 [18]. P-delta analysis is included in both linear and nonlinear analysis. The analysis and design have been performed in the structural analysis program SAP2000 V 22.2.0 [12].

3 Comparison of Seismic Performance of RC Frame Buildings with and Without Infills

Figure 3 represents capacity curves of the considered RC frame buildings with and without infills along the longitudinal and transverse directions, respectively. The seismic performance parameters derived from capacity curves in terms of peak strength, effective stiffness, and inelastic displacement are further summarized in Table 2. It can be observed from Fig. 3 as well as comprehend from Table 2 that the buildings designed with the revised seismic design provisions improve the overall seismic performance as compared to its older counterpart. In case of bare frame buildings designed with revised seismic standard, the peak strength is found to be increased by 26% and 27.8%, effective stiffness is found to be increased by 41.5% and 38.4%, and inelastic displacement is found to be increased by 15.7% and 12.1% along the longitudinal and transverse directions respectively, as compared to its older counterpart. In case of uniformly infilled frame buildings designed as per revised seismic design standards, the peak strength is found to be increased by 20.1% and

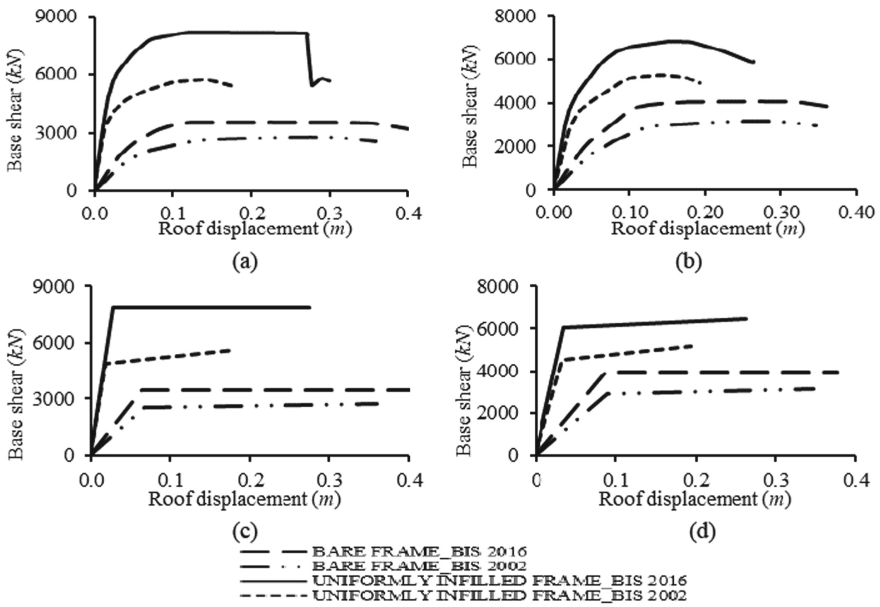

Fig. 3 Capacity curves of considered RC frame buildings. **a** Longitudinal direction. **b** Transverse direction. **c** Bilinear representation of capacity curves along longitudinal direction. **d** Bilinear representation of capacity curves along transverse direction

Table 2 Comparison of seismic performance parameters of the considered buildings

Model	Peak strength (kN)		Increase in peak strength (%)		Effective stiffness (kN/m)		Increase in effective stiffness (%)		Inelastic displacement (m)	
	Long	Trans	Long	Trans	Long	Trans	Long	Trans	Long	Trans
Bare frame_BIS 2016	3522	4070	26	27.8	53720	44969	41.5	38.4	0.338	0.288
Bare frame_BIS 2002	2795	3185			37952	32486			0.292	0.257
UI frame_BIS 2016	8157	5729	20.1	8.3	275262	175435	7.8	30.1	0.247	0.228
UI frame_BIS 2002	6793	5288			255251	134764			0.16	0.159

8.3%, effective stiffness is found to be increased by 7.8% and 30.1%, and inelastic displacement is found to be increased by 54.3% and 43.4% along the longitudinal and transverse direction of the building respectively, as compared to its older counterpart. These improvements over the seismic performance can be attributed to the combined effect of two major provisions, which are capacity design and selection of column dimension based on the largest beam longitudinal rebar as it led to higher column sections to satisfy the design requirements of the revised seismic design and detailing standard [4]. Considering the effect of infills as per the revised seismic design standard, it is observed that the simulation of infills in the structural analysis of RC frame building significantly increases the lateral strength and stiffness of the global structure and reduces the deformation capacity as compared to its bare frame counterpart and general design practice of ignoring infills in analysis and design stages. The beneficial contribution of infills to the lateral resistance and stiffness of the structure can never be ignored. However, it reduces the plastic deformation and causes yielding of RC frames at lower displacement level.

4 Comparison of Collapse Mechanism of RC Frame Buildings with and Without Infills

The comparison of collapse mechanism of the buildings designed with revised and older seismic standards is shown in Fig. 4. It is observed that in case of bare frame building designed as per revised seismic design standards, the collapse of ground floor level columns occured after the complete failure of all most 80% beams. In case of bare frame designed as per older seismic design standards, columns at ground and

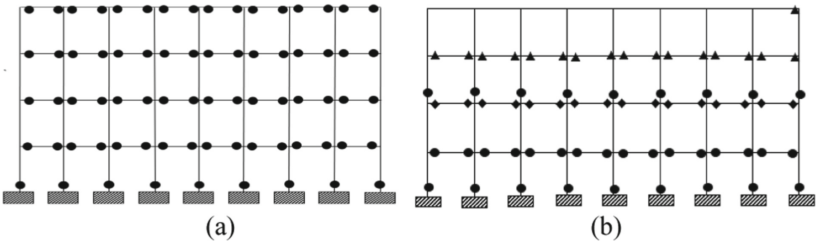

Fig. 4 Comparison of typical collapse mechanism of considered buildings. **a** and **b** Bare frame buildings designed with revised and older seismic standards, respectively. ◆ IO, ⊙LS, ▲CP, and • Beyond CP

second-floor level collapsed after the complete failure of 10 to 20% beams. Therefore, it can be concluded that capacity design ensures the complete failure of beams before columns, resulting the of overall failure of RC frames in a more ductile manner. In case of uniformly infilled frame buildings designed with revised and older seismic standards, the infills being weaker as compared to frames dominate the overall failure mechanism. The infills at ground and first-floor level undergo complete failure, and the ultimate failure of buildings occurred due to formation of plastic mechanism at the bottom of ground floor level columns. The collapse mechanism of RC frame building with infills is not shown here due to brevity.

5 Conclusions

In the present study, an attempt has been made to study the seismic performance of a generic mid-rise (4-storey) SMRF RC frame building with and without simulation of infill walls, designed as per revised and older versions of Indian seismic design standards. The two major design provisions introduced in the revised seismic design and detailing standard are capacity design, and selection of column dimension based on the largest longitudinal beam rebar. The combined effect of these two provisions leads to significant improvement of seismic performance in terms of peak lateral strength, effective lateral stiffness, inelastic displacement capacity, and improving the failure mechanism in a more ductile manner. It is also observed that the presence of infills significantly increases the global strength and stiffness of the RC building, but reduces the deformation capacity and dominates the overall structural failure mechanism.

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