Studies on Seismic Performance of RC Framed Buildings Using Pseudo-optimization Method

G. Priyusha, C. Shreyasvi, and K. Venkataramana

Abstract Most of the RC framed buildings which are designed for seismic prone regions have to follow the ductile detailing procedure outlined in earthquake resistant design code IS 13920(2016) while the infill wall in the RC frames must follow the procedure outlined in IS 1893 (Part 1): 2016. Earthquake resistant design aims to completely utilize the ductile behaviour of the members and it's constituent materials. Nonlinear analysis is frequently used to explore the ductile behaviour of the structure which is visible only beyond the yield limit/the linear range of the material behaviour. However, nonlinear dynamic analysis can be time consuming and resource intensive. Therefore, the goal of the present study is to utilise the material strength to full potential while keeping the analysis simple and robust. Hence, a pseudo optimization technique was adopted to improve the existing analysis and seismic design methods. The adopted method employs linear models of a structure whose seismic design has been enhanced and optimised based on modal energy. The pseudo-optimized design is a three-step process. The first step is to perform Pushover analysis to evaluate the seismic capacity of the existing building. In the next step, the variation of storey stiffness, storey strength and modal energy shall be examined along the height of the building considering the in-plane stiffness and strength of unreinforced masonry (URM) infill walls. As a last step, based on the modal energies observed in various structural members, the design is optimised. This method is practitioner friendly and has potential for industry level applications.

Keywords Pseudo-optimization method · Pushover analysis · Equivalent diagonal strut · RC frame building · Modal energy

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1 Introduction

Buildings with reinforced concrete frames (RCFs) are widely used all over the world because they are an economical construction technology with the use of easily accessible materials. RCF has previously shown itself to be a reliable seismic performer. In order to analyse a RCF, majority of structural designers today use finite element based software. This involves employing elastic models and analysing them for lateral force in additional to the existing vertical loads. Due to competitive pricing and other financial aspects involved in execution of a seismic design, engineers tend to keep the design of RC structures as close to the minimum code requirements as is practical. This study outlines a design method that practitioners can use to enhance their designs of bare and infilled RCF, with these benefits: (a) The data is used from the elastic models that are typically created in design practises and, therefore, requires no additional time in building modelling; (b) When compared to a traditional design, the building's construction costs are just slightly more and (c) The suggested design procedure needs little extra effort. Without substantially altering the way design offices now operate, the suggested design technique attempts to encourage safer structures.

1.1 Literature Review

Researchers have suggested a number of design techniques to create cost-effective seismic designs that meet or exceed code minimum performance due to the emergence of RCF. The efforts on the optimal configuration under various constraints are shown in [1–3]. These approaches were put out by many scholars, considerably streamlining the analysis [4–6]. Another popular approach is performance-based design (PBD) [7], which is based on FEMA P-58. The main goal of this study is to apply the pseudo-optimization technique [8] to an infilled RC frame design for residential applications using linear elastic models. The lateral stiffness and strength of the frame element are increased by the presence of infills [9, 10]. For bare RC frame and infilled RC frame buildings, a 3D model has been generated using structural analysis software, and analysis has been done in accordance with Indian norms.

2 Methodology

Proposed Design Method

This method imposes two restrictions on the system. In the first place, the method must use a linear elastic model, as is customary for the design process, to avoid increasing the amount of modelling effort that is required. Second, the design method must be easy to implement with the help of the software tools that are readily available in design offices (such as software for structural design and analysis and spreadsheets).

After the conventional process of designing a building, you will need to complete the following three steps to follow the proposed method:

Step 1. In each independent (lateral) direction, apply seismic load patterns proportional to the prevailing mode of vibration to the building's linear elastic model. The modal energy is evaluated directly from the existing design software ETABS or SAP2000.

Step 2. Based on the visual examination of higher normalized modal energy (NME) values, dimensions of structural elements have been modified.

a. For Columns, the area of cross-sections shall be increased for the top 25% of the NMEs list. Similarly, the bottom 25% of NMEs shall be reduced in cross-sections.
b. For Beams, increase the depth of the section with higher NME values and it is performed floor-wise for ease of construction.
c. As per practice in the Indian region, the higher dimensions are chosen as per the standard available sizes onsite.

Step 3. A similar increase in reinforcement is made based on the model's original RC design's safe evaluation.

3 Modeling and Analysis in ETABS Software

A five-story RC residential structure in seismic zone III is taken into consideration for the current analysis. Below is a picture of the building's plan and elevation (Fig. 1a, b). The soil type is medium stiff, and the plan comprises four orthogonal bays of 3 m each. 3 and 2 kN/m^2 are the superimposed dead load and live load. It has been designed in accordance with the IS 1893 (Part 1):2016 and IS 13920:2016 standards, respectively.

Four models are considered in this study, the first two models (model 1, 2) are of traditional design and remaining two models (model 3, 4) are of proposed design. To know the effectiveness of proposed design, model 1(bare frame) and model 2(infilled frame) are designed by conventional method later proposed methodology is applied on them and the results are obtained in models 3 and 4 respectively.

Model 1: Traditional Design of Bare RC Frame (TD Bare)

Beams are 230 × 300 mm^2 having a top and bottom reinforcement of 250 mm^2 at the joints. Columns are of 300 × 300 mm^2 with uniform reinforcement on all sides ($p_t = 1.0\%$) are assigned to model 1 and 2.

The Normalized Modal Energy of the beam in frame A for storeys 1 and 2 is higher than that of the remaining storeys, as can be seen in Fig. 2a, hence these floors are given the B1 230 × 350 dimension. Storeys 3 and 4 have been allocated for the B2 230 × 300 beams. Due to its lower NME values, the top floor B3 has 230 × 230

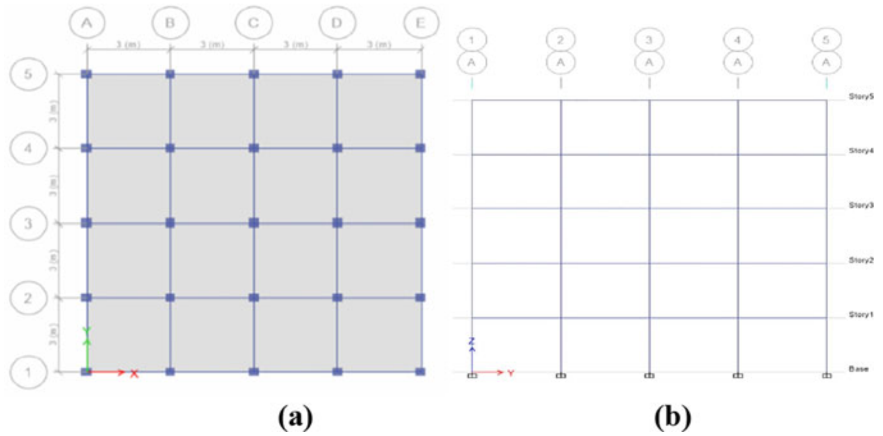

Fig. 1 **a** Plan and **b** elevation of proposed building

beams assigned to it. Figure 2b shows that, in the case of columns, higher NME is observed in the ground and first floor and lower NME for the roof level. As a result, the columns on the ground and first floors are given the C1 350 × 350 dimension, and the remaining levels 3, 4, and 5 are given C2 300 × 300 columns. It is noted that the NME of the top storey is lower than intermediate stories and the dimension could be further reduced. Since the IS 13920:2016 [11] code specifies the minimum dimension of the column to be 300 mm we have adopted the same.

As mentioned above the updated dimensions are used in models 3 and 4, refer to Table 1.

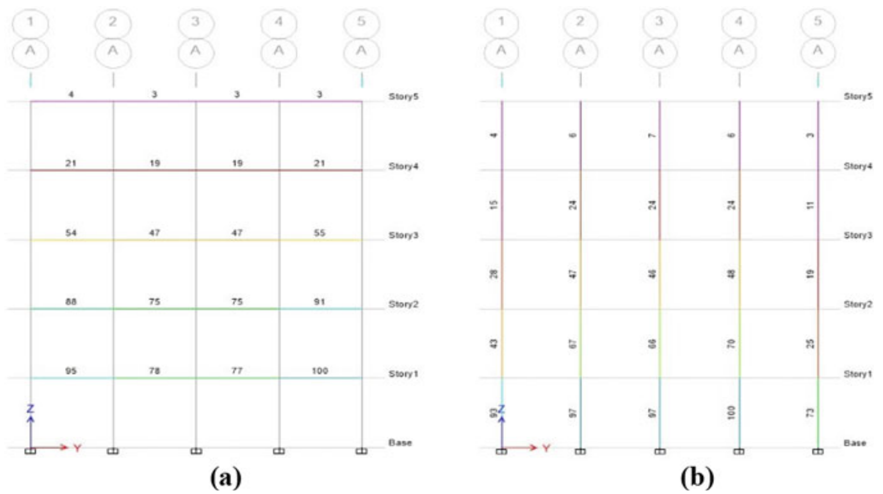

Fig. 2 Normalized modal energies (NME) of **a** beams **b** columns

Table 1 Proposed model's structural details for columns and beams

Column dimension (mm)	Reinforcement (mm^2)	Beam dimension (mm)	Top and bottom reinforcement (mm^2)
C1 350 × 350	1020 ($p_t = 0.83\%$)	**B1** 230 × 350	300
C2 300 × 300	804 ($p_t = 0.89\%$)	**B2** 230 × 300	230
		B3 230 × 230	230

Model 2: Traditional Design Infilled RC Frame (TD Infilled)

The uniformly distributed load applied on peripheral beams of the floors and roof is 13.8 and 4.8 kN/m. The NME for the beams and columns is shown in Fig. 3a, b, for bracings it is shown in Fig. 3c.

Properties of Equivalent Diagonal Strut

Compressive strength of brick (f_b) = 10.3 MPa (First class brick as per IS:3495 (Part 1)-1992).

Compressive strength of mortar (f_{mo}) = 7.5 MPa (H2 grade as per IS:1905-1987).

The modulus of elasticity E_m (in MPa) of masonry infill shall be taken as

$$E_m = 550 f_m \tag{1}$$

where f_m is the compressive strength of masonry prism (in MPa) obtained as per IS 1905 or given by the expression:

$$\begin{aligned} f_m &= 0.433 f_b^{0.64} f_{mo}^{0.36} \\ &= 3.98\,\text{MPa} \end{aligned} \tag{2}$$

Substituting the value of Eq. (2) in Eq. (1), we get $E_m = 2188$ MPa.

The width of the diagonal strut of unreinforced masonry (URM) without openings as shown in Fig. 4. shall be taken as:

$$\begin{aligned} w_{ds} &= 0.175\,\alpha_h^{-0.4} L_{ds} \\ &= 409.46 \sim 410\,\text{mm} \end{aligned} \tag{3}$$

where,

$\alpha_h = h \sqrt[4]{\frac{E_m t \sin 2\theta}{4 E_f I_c h}} = 3.4.$

$L_{ds} = 3818$ mm and t = 230 mm.

E_m and E_f are the moduli of elasticity of the materials of the URM infill and RC frame.

I_t is the moment of inertia of the adjoining column, t is the thickness of the infill wall and Θ is the angle of the diagonal strut with the horizontal.

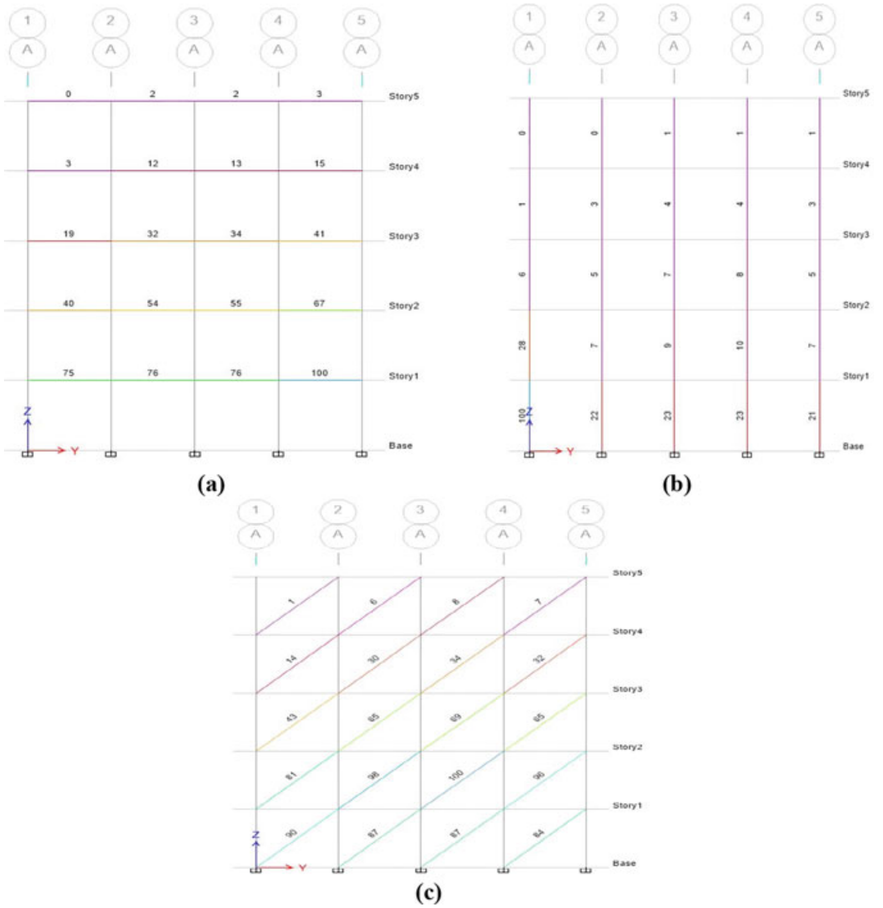

Fig. 3 Normalized modal energies (NME) for infilled RC frame of **a** beams **b** columns **c** bracings/strut

Model 3: Proposed Design Bare RC Frame (PD Bare)

The results from the normalized NME of Fig. 5a, b for the beams and columns of the redesigned building show that the work undertaken by structural members is on average higher compared to model 1 due to the application of the proposed methodology in the Pseudo-optimization case (PSO case).

Model 4: Proposed Building Infilled RC Frame (PB Infilled)

In this model, the infilled walls have been modeled as the diagonal strut element which helps in resisting the lateral load. The proposed methodology is applied for this building and the NME is shown in Fig. 6a, b.

The NME values of the beams and columns for the infilled case have been decreased due to the fact that the lateral load is being shared by the strut elements

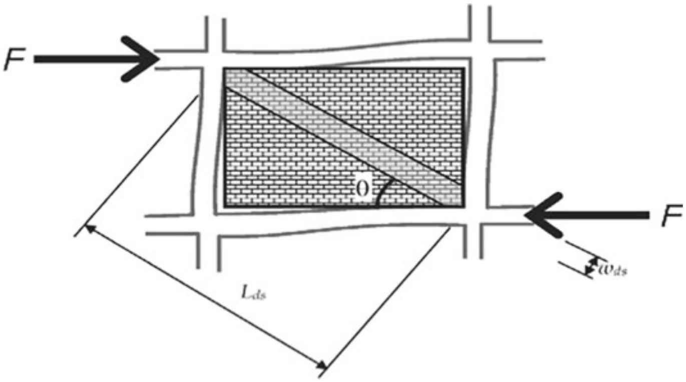

Fig. 4 Equivalent diagonal strut of URM infill wall [12]

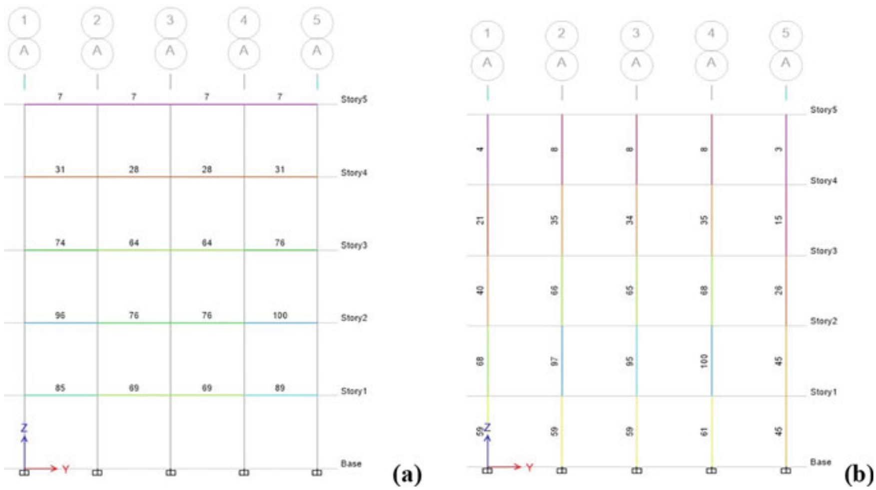

Fig. 5 PSO case NME **a** beams **b** columns

as shown in Fig. 6c, hence the work undertaken by structural elements has been reduced. The pattern of the optimization remains the same as it is been followed in model 3.

4 Results and Discussions

The results obtained by the seismic responses are plotted below for the various models considered for the study. The lateral load carrying capacity for model 4 is increased after applying the proposed method as shown in Fig. 7. It can be noted that

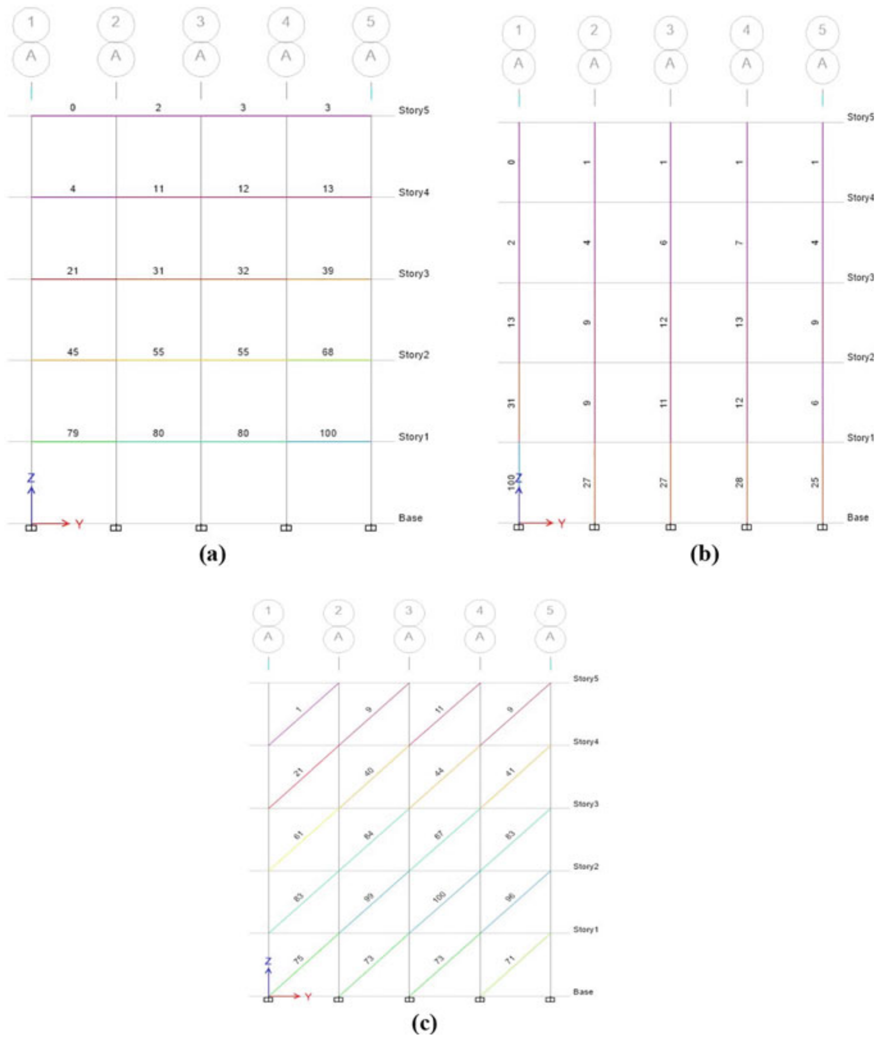

Fig. 6 PSO case NME for **a** beams **b** columns **c** bracings/strut

the load-carrying capacity for the proposed building (M3, M4) has been increased compared to traditional buildings (M1, M2). It can be concluded the proposed method of optimization has shown better load carrying capacity under seismic loads.

The maximum storey displacement for model 4 is less compared to the remaining models and it is shown in Fig. 8. The displacement values for models 1 and 3 for bare frames and models 2 and 4 for infilled frames where the storey displacement has been reduced to some extent after the application of the proposed method which can be regarded as advantageous. Storey displacement is the absolute value of displacement of the storey under the action of lateral load.

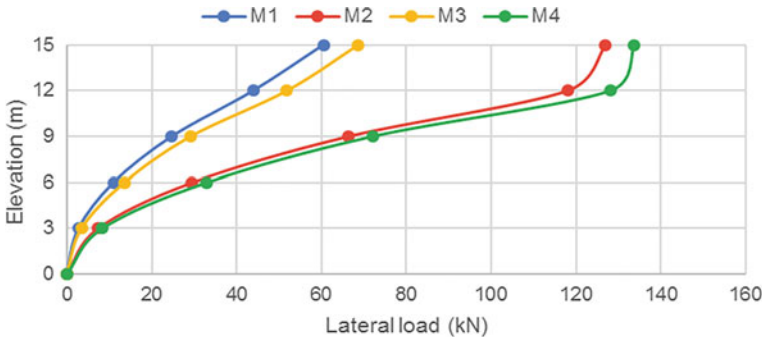

Fig. 7 Lateral load distribution along with storey height

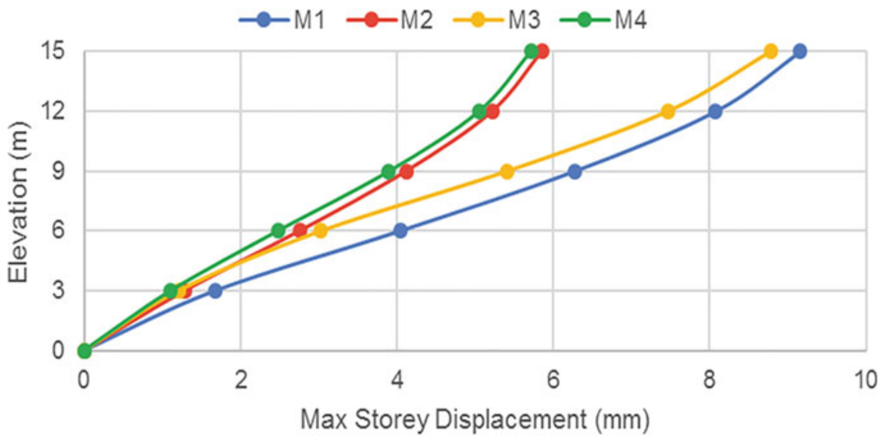

Fig. 8 Maximum storey displacement for various models

The storey drift plotted for various models is shown in Fig. 9, it is observed that after applying the proposed method there is a shift in the drift from storey 2 to storey 3 as seen for model 3 and model 4. As per IS 1893, storey drift in any storey shall not exceed 0.004 times the storey height and the values observed are within the limits specified in the standard.

The storey stiffness is highly affected by the influence of infills (M2 and M4), also it is evident from Fig. 10 that there is a further increase in stiffness values after applying the proposed method (M3 and M4). It can be observed that the lateral stiffness of infilled frame (M2, M4) is approximately increased by three to four times that of bare frame (M1, M3) indicating the role played by masonry infills contributing to the overall stiffness of the building.

Table 2 summarizes the results obtained after the earthquake analysis and pushover analysis.

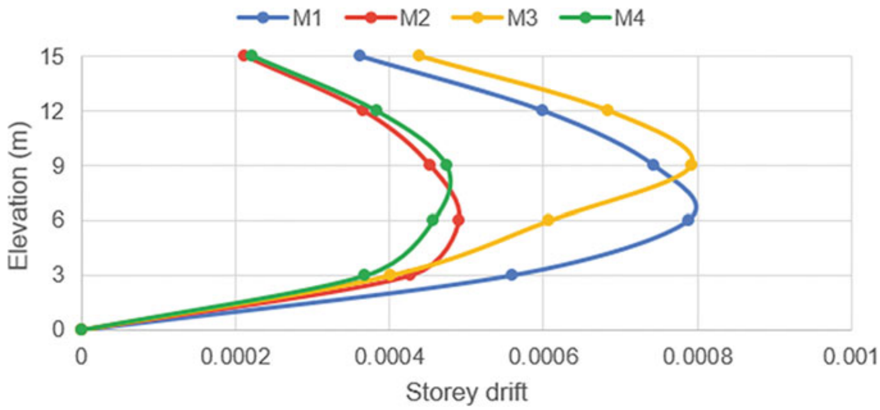

Fig. 9 Maximum storey drift for various models

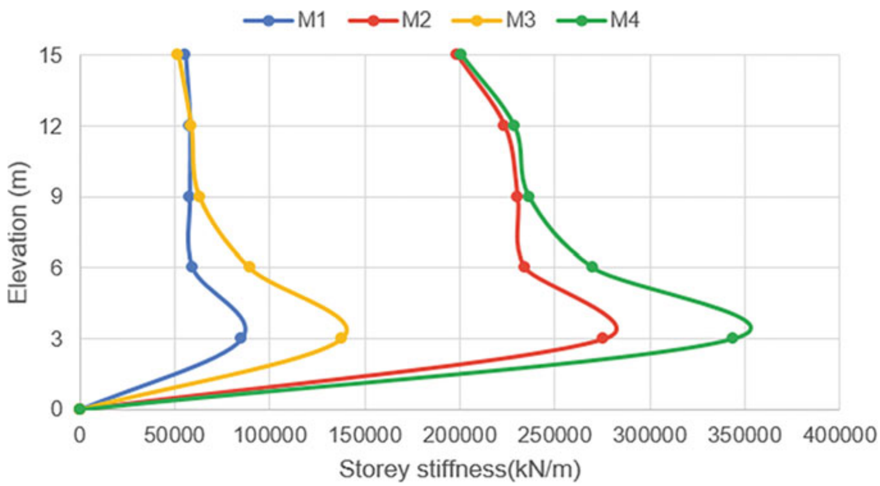

Fig. 10 Storey stiffness for various models

The maximum storey displacement is reduced significantly from model 3 to model 4 due to the additional lateral stiffness of masonry elements. Also, this accounted for the reduction in maximum storey drift by an amount of 40% from model 3 to model 4 after the application of the proposed method. The storey stiffness for infilled RC frame building is higher due to the additional lateral stiffness of the masonry. The overstrength factor and displacement ductility ratio are calculated from the results of the pushover analysis.

Table 2 Dynamic response parameters obtained from the earthquake analysis

Parameters	Model 1 (TD bare)	Model 2 (TD infilled)	Model 3 (PD bare)	Model 4 (PD infilled)
Time period (s)	0.983	0.618	0.894	0.581
Max story displacement (mm)	9.16	5.86	8.78	5.71
Max story drift	0.000788	0.000491	0.000792	0.000474
Story stiffness (kN/m)	85,295	275,680	138,108	343,700
Design base shear (kN)	141.44	348.00	156.66	374.07
Overstrength factor (Ω)	1.18	4.02	1.13	3.20
Displacement ductility ratio (μ)	1.62	4.13	1.29	3.24

Table 3 Concrete volume of structural elements

Model	Column (kN)	Beam (kN)	Total weight (kN)	Volume (m^3)
Model 1 and 2	843.50	931.22	1774.72	70.98
Model 3 and 4	965.33	941.80	1907.14	76.28

Material Quantity

- The increase in the material quantity of M30 grade concrete from model 1 to model 3 is 7.46% as shown in Table 3.
- The approximate increase in steel is 5.75% from model 1 to model 3 (9130–9655 kg).

5 Conclusions

The proposed design procedure aims to provide safer structures with the least amount of interference to the current operations of the design office. A term called overstrength is used to measure the discrepancy between a material, component, or structural system's required and actual strength. The overstrength ratio is, in other words, extra or reserve strength above the design strength. The ratio of peak elastic (yield) displacement to peak inelastic (target) displacement is known as the displacement ductility ratio. It provides a more accurate assessment of the structure's ductile capacity. For the pushover analysis, 4% of the building height, or 600 mm for all models, is used as the monitored displacement.

- The maximum story drift for infilled RC frame building is reduced by 40% compared to the bare RC frame building which is designed by the proposed methodology (models 3 and 4).
- The base shear is increased from 157 to 374 kN indicating the load resisting capacity to be increased from model 3 to model 4.
- The storey stiffness for the bare and infilled frame as per the proposed method are 138,108 and 343,700 kN/m which indicates that the masonry infills played a major role in increasing the lateral stiffness of the building. Hence, the effect of infills has a major impact on increased stiffness.
- The overstrength factors for the bare and infilled RC frames in the proposed designs are 1.13 and 3.20, respectively, highlighting the significance of the suggested method in utilising the building's reserve strength.
- The displacement ductility ratio for the proposed designs for the bare and infilled RC frame are 1.29 and 3.24 respectively. This implies that the ductility of the building is increased upon applying the proposed methodology.
- Brick infill walls present in RC frame buildings reduce the structural drift by 40% but increase the strength and stiffness by 138 and 148% respectively from models 3–4. The time period for the infilled RC frame building is lower than the bare RC frame building.
- The increase in material quantities between the traditional and proposed designs is approximately 7% for M30 grade concrete and 5% for Fe415 grade steel. As the optimization was primarily performed on columns and beams, the aforementioned variations only apply to them.

References

1. Arroyo O, Gutiérrez S (2017) A seismic optimization procedure for reinforced concrete framed buildings based on eigenfrequency optimization. Eng Optim 49(7):1166–1182. https://doi.org/10.1080/0305215X.2016.1241779
2. Arroyo O, Liel A, Gutiérrez S (2018) A performance-based evaluation of a seismic design method for reinforced concrete frames. J Earthq Eng 22(10):1900–1917. https://doi.org/10.1080/13632469.2017.1309605
3. Fragiadakis M, Lagaros ND (2011) An overview to structural seismic design optimisation frameworks. Comput Struct 89(11–12):1155–1165. https://doi.org/10.1016/j.compstruc.2010.10.021
4. Naeim F, Performance based seismic engineering (Chapter 15)
5. Papavasileiou GS, Charmpis DC (2016) Seismic design optimization of multi-storey steel-concrete composite buildings. Comput Struct 170:49–61. https://doi.org/10.1016/j.compstruc.2016.03.010
6. Zou XK, Chan CM, Li G, Wang Q (2007) Multiobjective optimization for performance-based design of reinforced concrete frames. J Struct Eng 133(10):1462–1474. https://doi.org/10.1061/(asce)0733-9445(2007)133:10(1462)
7. Kappos AJ, Ellul F (2000) Seismic design and performance assessment of masonry infilled R/C frames. In: Proceedings of 12th world conference on earthquake engineering, Auckland, New Zealand, pp 1–8 [Online]. Available: http://www.iitk.ac.in/nicee/wcee/article/0989.pdf

8. Arroyo O, Liel A, Gutiérrez S (2021) Practitioner-friendly design method to improve the seismic performance of RC frame buildings. Earthq Spectra 37(3):2247–2266
9. Sukrawa M (2015) Earthquake response of RC infilled frame with wall openings in low-rise hotel buildings. Proc Eng 125:933–939. https://doi.org/10.1016/j.proeng.2015.11.118
10. Priyusha G, Shreyasvi C, Venkataramana K (2022) Seismic performance of infilled RC frames by pseudo-optimization method. In: Marano GC et al (eds) Lecture notes in civil engineering, vol 284. Springer, Cham, pp 127–136. https://doi.org/10.1007/978-3-031-12011-4_11
11. IS 13920:2016 (2016) Indian standard ductile design and detailing of reinforced concrete structures subjected to seismic forces-code of practice, first rev. Bureau of Indian Standards, New Delhi, 2016. www.standardsbis.in
12. IS 1893 (Part 1):2016 (2016) Indian standard criteria for earthquake resistant design of structures, part 1 general provisions and buildings, sixth rev. Bureau of Indian Standards, New Delhi. www.standardsbis.in