Case Study

Seismic assessment of existing gravity load-designed RC framed building: a case study from Warangal, India

Praveen Oggu[1] · K. Gopikrishna[1] · Shubham Sewaiwar[1]

Abstract

Most of the existing reinforced concrete (RC) buildings in India are either designed before the existence of seismic design codes or without proper provisions to resist lateral loads. These structures generally possess low strength and limited ductility, thereby always prone to global failure and are a primary reason for causalities during an earthquake. Hence, seismic evaluation of these structures and strengthening, if necessary, is essential to prevent a disaster during its serviceable lifetime. In this investigation, a four-storied (G+3) RC building structure in Warangal city, Telangana State, India, has been selected as a case study. Furthermore, the structure is to be extended vertically by two stories above the existing configuration. The structural and material inputs to the analytical model are updated from visual inspection and nondestructive tests, followed by an analytical study. From the analytical study, the seismic capacity of the existing gravity load-designed structure itself is found to be inadequate for seismic requirements. Since the structure is to be extended vertically, the existing building needs to be strengthened appropriately to withstand additional loads and remain functional throughout its lifetime. The outcome of the seismic analysis is checked for conformity using demand and capacity requirement of the structural components of the six-storied (G+5) structure. This behavior mimics the current scenario of existing RC buildings in this locality, which needs to be appropriately strengthened. It has been observed from the analysis that the RC building was vulnerable to the seismic forces and needed retrofitting to remain functional during its service life.

Keywords Response spectrum · Nonlinear static analysis · Nondestructive testing · Demand–capacity ratio

1 Introduction

Earthquakes are pronounced to be one of the devastating natural hazards that have the potential to create a disaster. Hence, mitigation of the effects of these hazards on infrastructure is the only preventive approach to save the economy of a nation and mankind. Most of the urban habitat consists of midrise (G+3 to G+5) RC buildings (with and without irregularities) to cater to their inherent functional needs, viz., parking lots and ventilation. These RC structures were designed according to existing Indian standard codes prior to the development of the seismic design concept. It has been reported in Earthquake Disaster Risk Index report that about 59 percent area of India is vulnerable to moderate to major earthquakes. It is evident from past earthquakes occurred in India such as Manipur (2016), Nepal (2015), Sikkim (2011), Kashmir (2005), Bhuj (2001), Chamoli (1999), Jabalpur (1997) and Latur (1993) that all type of buildings sustain damage if not designed properly. It has been reported in the literature that more than 90% of the casualties in past earthquakes in India have occurred due to the collapse of numerous commercial and residential structures [1]. The loss of life and property can be minimized significantly by ensuring better code

✉ Praveen Oggu, opraveen@student.nitw.ac.in | [1]Department of Civil Engineering, National Institute of Technology Warangal, Warangal, Telangana 506004, India.

compliance of upcoming constructions and undertaking seismic retrofitting of existing buildings, thereby making them earthquake resilient. Hence, there is an indispensable need for seismic resistance evaluation, identification of deficiencies, before designing any repair or rehabilitation or strengthening for these existing RC buildings. The performance of these structures needs to be evaluated before and after strengthening to remain functional throughout its serviceable lifetime and to prevent a disaster. The earthquake risk at any location depends on the seismic hazard and vulnerability characteristics of the structures. Seismic vulnerability evaluation for existing buildings is necessary as buildings might be inadequately designed to resist seismic forces or the buildings are designed prior to the existence of seismic design codes. In view of this, these structures become vulnerable whenever a seismic hazard is encountered, paving the way for a catastrophe.

Recently, many Indian standard codes for designing RC buildings including the seismic design codes have undergone revisions incorporating an additional requirement of strong column–weak beam design (SCWB) to prevent global failure of the building [2, 3]. It has been shown in the literature that the strong column–weak beam (SCWB) concept has a significant influence on the seismic performance of RC buildings (with and without infills and irregularities) [4–6]. Further, it is perceived to be a cost-effective measure of improving the seismic performance by increasing the strength of the column, without a significant increase in the beam strength for RC frame buildings. In the present study, a G+3 RC frame structure in Warangal city has been considered as a case study. The existing building location corresponds to seismic zone III, and the soil test performed at the site confirms medium soil profile as per BIS 1893 (Part 1).

This building structure has been designed prior to the existence of seismic codes and is proposed to be extended now vertically for another two floors (i.e., G+3 to G+5) above the existing. Hence, this RC building model is modeled and analyzed for the structural floor plan with inputs from the field visit (which includes visual inspection, collection of structural drawings, verification of structural configuration and NDT rebound hammer test) for the seismic resistance evaluation in the present and proposed configurations.

2 Seismic resistance assessment methodology

The weaknesses in the structural system and deficiencies in the structural steel reinforcement of existing RC buildings have a potential influence on the failure modes, which directly influences the RC building's ability to withstand the loads and remain stable. Seismic vulnerability of a structure is usually expressed as a relationship between intensity measure (spectral displacement, spectral velocity or spectral acceleration) and damage measure (various damage states, viz., slight, moderate, extensive and collapse) [5–9]. The overall methodology for seismic resistance assessment evaluation of existing RC building adopted in this work to withstand seismic loads pertaining to zone III requirements is depicted in Fig. 1.

Seismic vulnerability evaluation is usually done either qualitatively or quantitatively using certain empirical procedures, viz., rapid visual screening procedures and P25 scoring method, followed by nondestructive tests (NDT). The seismic strengthening/retrofitting is conducted in accordance with the guidelines of BIS 15988: 2013 [10] and IITK-GSDMA Guidelines for Seismic Evaluation and Strengthening of Buildings [11], in addition to CPWD handbook [12]. Considering the importance of the structure, this qualitative evaluation is generally followed by analytical evaluation approaches used for seismic design. In this work, a field visit is carried out to verify the existing structural configurations with the structural plan collected. Visual inspection is carried out to understand the visual signatures of damage, deterioration, etc., by means of walk around the building approach, followed by a nondestructive rebound hammer test, to ascertain the compressive strength of the structural components. This input is utilized for the analytical model development of existing G+3 and proposed G+5 RC building structure using SAP2000 software. Seismic strengthening and retrofitting of RC buildings using several approaches have been reported in literature [13–18]. A similar study of retrofitting a gravity load designed RC building using external steel concentric bracing systems using SAP2000 was performed [19].
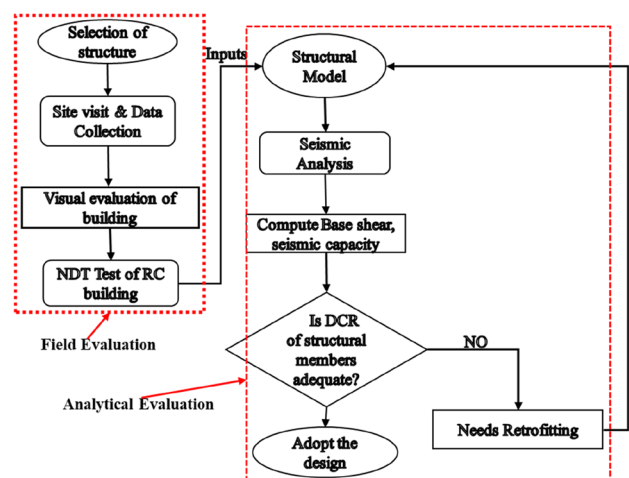

Fig. 1 Methodology of the study

3 Case study

A G+3 story RC building situated in Warangal city, Telangana state, India, as shown in Fig. 2 is selected to understand the seismic resistance capability. The total height of the existing building configuration is 12.8 m with floor height as 3.2 m each for all the stories (G+3). The structural floor plan for the selected building configuration is depicted in Fig. 3. The floor area comprises of 57.2 m × 17.6 m and consists of five categories of beam sections and six categories of column sections as given in Table 1. This building has been designed and constructed as a gravity load-designed building as per BIS 456 [20], without seismic provisions and is proposed to be extended vertically from existing G+3 to G+5 configuration.

4 Modeling and analysis

The structural model is developed using SAP2000 software [21], for the structural floor plan shown in Fig. 3, and the component details are given in Table 1 prepared as per the structural drawings provided during the field visit. Material properties are updated after visual inspection and nondestructive rebound hammer test performed on all the structural components. Around 1000 data points comprising of all the structural components including beams, columns and slabs have been recorded using rebound hammer to ascertain the compressive strength of the structural components as depicted in schematic shown in Fig. 4 (beams: on Face 1, Face 3, Face 6; columns: on Face 1, Face 2, Face 3 and Face 4; and slabs).

The RC building frames are modeled as three-dimensional ordinary moment-resisting frame (OMRF) structure with the fixed base condition. The infill walls load are taken as a distributed load on corresponding beams. Beam and column elements are modeled as nonlinear frame elements with lumped plasticity by defining plastic hinges at both ends of the beams and columns [22, 23]. Plastic hinge behavior of structural members, i.e., beams (M3 hinges) and columns (P-M2-M3 hinges), was defined using default hinges in SAP2000 as per FEMA 356 [22]. The slabs are modeled as a rigid diaphragm, and slab thickness of 100 mm is adopted based on field measurements. The dimensions and cross-sectional details of beams and columns were also ascertained during field visits, as shown in Fig. 5. Rigid diaphragms are assigned by constraining the nodes belonging to the same story throughout the structure for each floor level. The self-weights of the slab and floor finishing are taken as a distributed load on to the respective beams. Material characteristics considered for modeling and analysis, after field study, are M30 grade concrete and Fe415 grade steel rebars. Mander material model is used to characterize the stress–strain behavior of concrete [24], and the constitutive model used to characterize stress–strain behavior of steel rebars is Park stress–strain model, as depicted in Fig. 6. The cross section and components design details of the case study building are given in Table 1. The seismic zone of Warangal city is zone III as per BIS 1893 (Part 1) and soil profile corresponds to medium soil as per the soil investigation report provided for the considered site. Further, the loads considered for seismic analysis as per BIS 875 (Part I) [25] and BIS 875 (Part II) [26] are presented in Table 2. Fixed base analysis was performed, ignoring soil flexibility. Furthermore, to account for the safety of the foundation, the safe bearing capacity of the soil has been evaluated, and the foundation of the retrofitted structure has been found safe against sliding, overturning, one-way and two-way shear checks as per IS code.

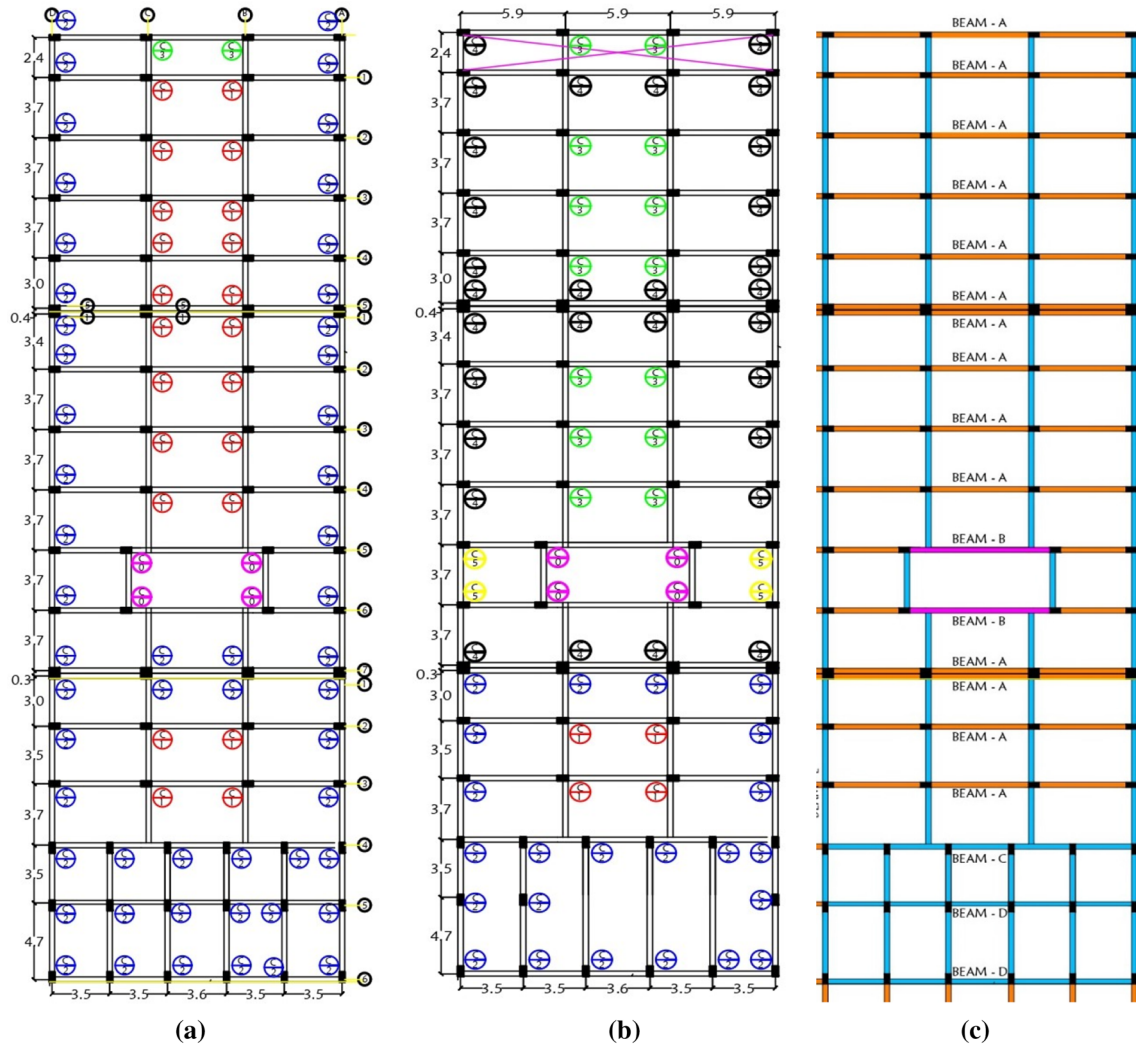**Fig. 2** Photographs of the existing RC frame building

Fig. 3 Building structural floor plan. **a** Location of columns from the ground level, **b** location of columns from G+2 level, **c** location of beams

Table 1 Design details for the existing case study building

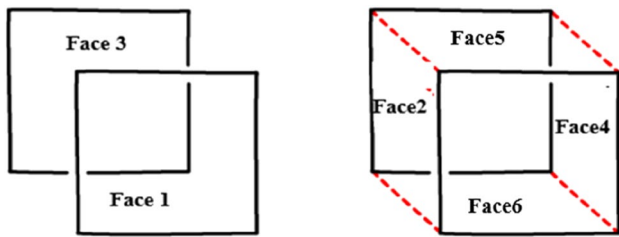| S. No.	Structural component	Type	Existing size (mm)	Existing reinforcement details	
				Top (mm φ)	Bottom (mm φ)
1	Beam	A	230×480	6–16	6–16
2		B	280×640	3–25	3–25
				2–20	2–20
3		C	230×430	1–16	1–16
				2–12	2–12
4		D		1–16	1–16
				2–12	2–12
5		E		1–16	1–16
				2–12	2–12
6	Column	C_0	300 x 610	10–25	
7		C_1		12–20	
8		C_2		10–20	
9		C_3	230 x 530	6–20 and 4–16	
10		C_4		12–16	
11		C_5		10–20	

Fig. 4 Schematic representing nondestructive test pattern

The analytical study involves modeling and seismic analysis of existing and proposed building design. The dynamic analysis for all types of building structures in zone III may be performed either using the time history method or response spectrum method. Hence, response spectrum analysis has been carried out on the existing building model in addition to nonlinear static analysis, which is carried out for various performance limit states defined as per FEMA-356 [22]. The response spectrum is chosen from BIS 1893 (Part 1) for zone III medium soil profile. Further, in view of inherent deficiencies involved in the

Fig. 5 Verification of dimensions and cross-sectional details of beams and columns during field visits
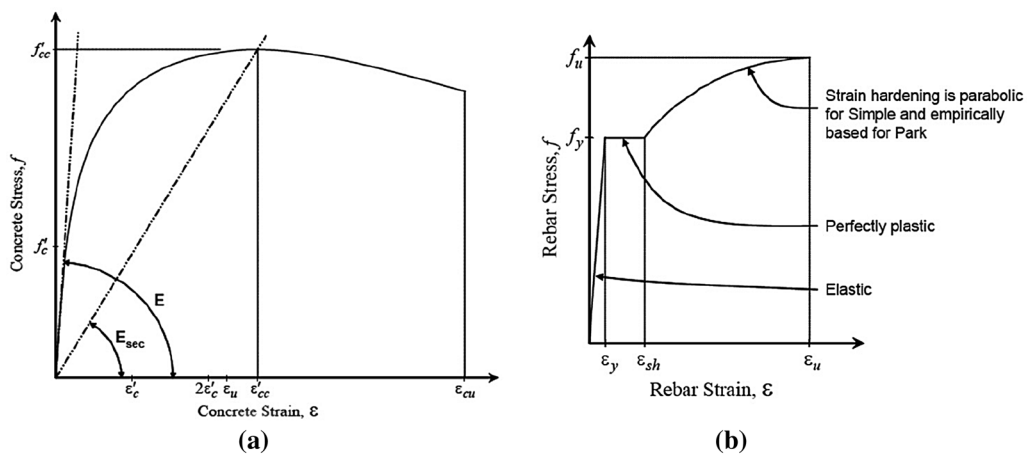

Fig. 6 **a** Mander confined concrete stress–strain curve, **b** Park stress–strain model

Table 2 Details of loads considered for seismic analysis

S. No.	Particulars	Description
1	Dead load	Self-weight of the structure
2	Live load	3 kN/m^2
3	Floor finish	1 kN/m^2
4	Roof treatment	1.5 kN/m^2
4	Outer wall load	230 mm thick: 14.2 kN/m
5	Inside wall load	150 mm thick: 9.6 kN/m
6	Wall load roof	1.5 m high and 150 mm thick: 4.5 kN/m
7	Seismic load	BIS 1893 (Part 1):2016
8	Importance factor	1
9	Soil type	Medium
10	Type of structure	RCC frame structure
11	Response reduction factor	3 for OMRF

nonlinear static analysis procedure, the demand–capacity ratios (DCR) are also computed to confirm the seismic capacity of structural components obtained from nonlinear static analysis. Moreover, seismic analysis comprising of response spectrum analysis and nonlinear static analysis of this structure should also consider the proposed vertical extension loads before designing any repair or strengthening measure adopted. This observation can be verified with the difference in base shear values computed for both G+3 and G+5 configurations. Base shear for G+3 configuration is found to be 3681.2 kN, and for G+5 configuration, it is found to be 4678.51 kN for seismic zone III requirements. Hence, seismic analysis is performed (a) on the existing structure (G+3), (b) on G+5 building structure, considering the additional design loads of proposed extension of two floors (G+3 to G+5) and also (c) after strengthening/repair/retrofit of the existing structure to withstand the proposed extension and checked for adequacy using DCR as mentioned in Fig. 1 [3, 27]. Further, the components belonging to the collapse limit state are termed as inadequate or seismically deficient components and are shown in Table 3. These structural components need to be appropriately strengthened/repaired/retrofitted, as discussed in Sect. 6 before extending the existing structure.

5 Results and discussion

The results corresponding to the outcome of the response spectrum analysis performed on the existing building G+3 building model is shown in Fig. 7. The legend in Fig. 8 describes different damage states of plastic hinges (i.e., IO: immediate occupancy, LS: life safety, CP: collapse prevention, C: collapse) with appropriate labels and colors, as per

Table 3 Structural components to be retrofitted in existing G+3 configuration

S. No.	Structural component	Type	Total number of components	Components need retrofitting
1	Beam	A	172	0
2		B	8	0
3		C	20	12
4		D	40	40
5		E	272	272
6	Column	C_0	16	0
7		C_1	70	12
8		C_2	160	30
9		C_3	18	0
10		C_4	30	0
11		C_5	4	0

FEMA 356 [22]. It can be observed from the plastic hinge formulation that certain components are in the collapse (C) limit state in Fig. 8. The DCR contour plot indicating the stress levels (0: unstressed to 1: fully stressed) also confirms this observation, as shown in Fig. 9 for load combination 1.5(DL + EQ) in zone III. The components have DCR greater than one which indicates the failure of the member. The total number of components indicated as failed or in collapse limit state for the existing structure and needs retrofitting are presented in Table 3. Further, seismic analysis is again repeated for G+5 storied building considering a load combination of 1.5(DL + EQ) zone III medium soil profile to ascertain its seismic resistance capability of withstanding the additional two stories on the existing structure.
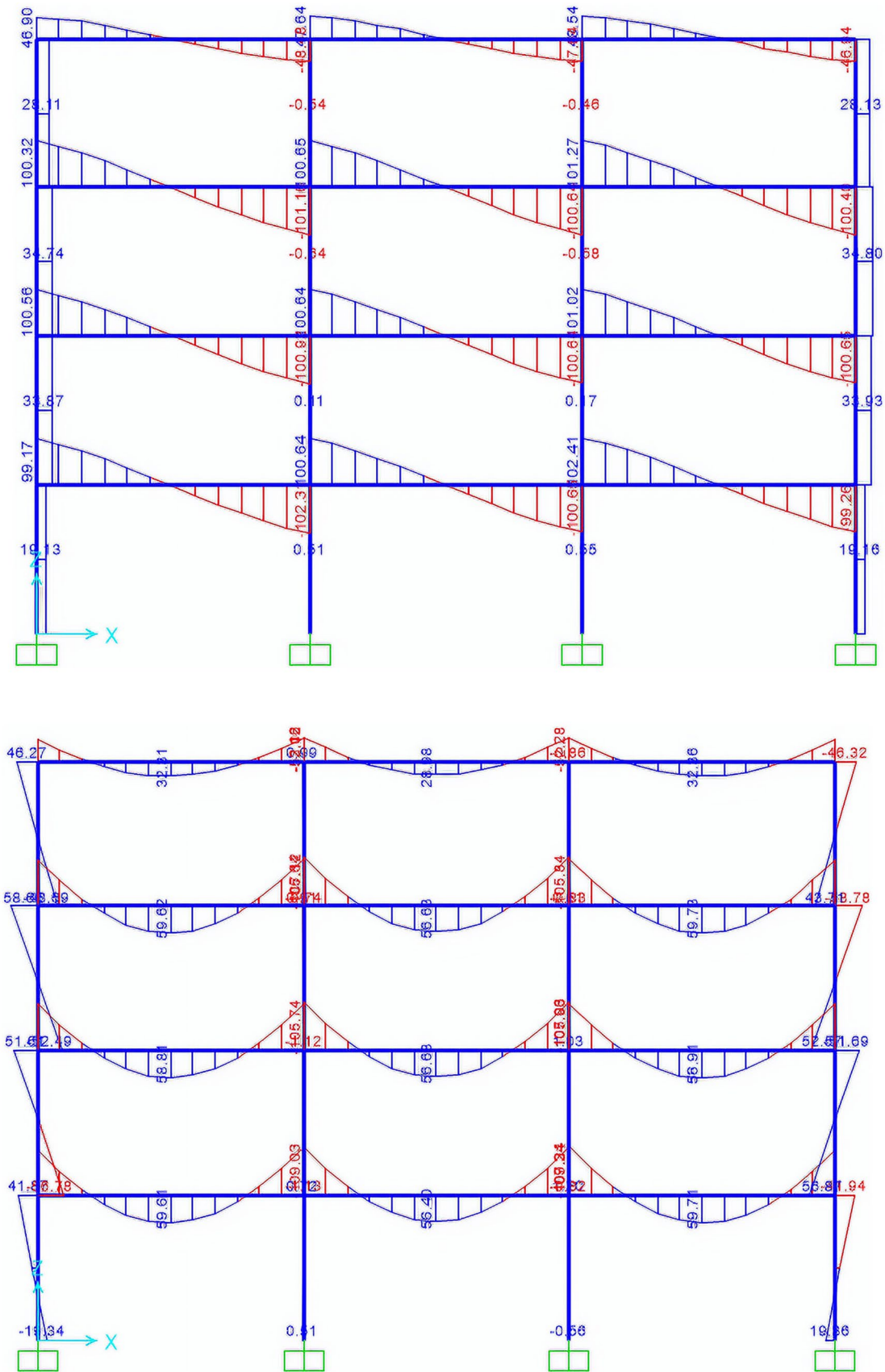
Fig. 7 SFD and BMD of a typical frame in G+3 building for load combination (1.5(DL + EQ)) for zone III
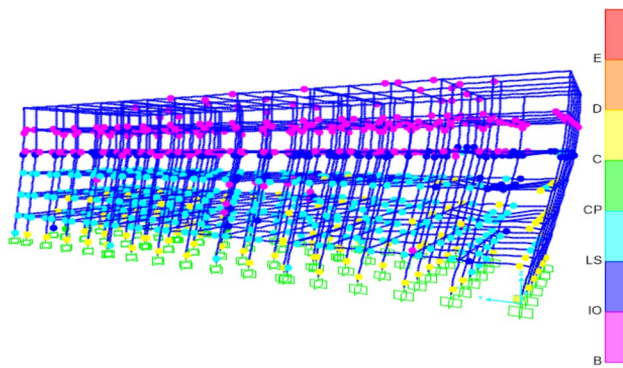
Fig. 8 Plastic hinge formation in the G+3 building model for zone III seismic load

These results are confirmed by checking the DCR ratios of the structural components which can be seen from the results shown in Figs. 10 and 11 (indicating the stress levels (0: unstressed to 1: fully stressed). From the results, it can be concluded that the structural components that need strengthening/retrofitting to withstand for seismic zone III requirements are present only in the existing G+3 structure. Therefore, the extended portion from G+3 to G+5 appears meeting the design requirements and the existing design shown in Table 1 can be adopted after strengthening the G+3 building.

6 Retrofitting of beams and columns

The seismic analysis carried out on the existing structural configuration and the structural components having inadequate seismic capacity is identified and presented in Table 3. The retrofitting of the deficient components is

carried out right from the ground floor (G) to the top floor (G+3) of the existing building.

Steel plate bonding is the most commonly used strengthening technique. This is perceived to be an inexpensive, versatile and advanced technique for rehabilitation, upgradation of concrete structures by mechanically connecting MS plates by bolting and gluing to their surfaces with epoxy. Furthermore, it is reported in the literature that plate bonding can substantially increase strength, stiffness, ductility and stability of the reinforced concrete elements and can be used effectively for seismic retrofitting [12]. Hence, the plate-bonding technique is adopted for strengthening the beam and column components with appropriate sizes of steel plates for the existing G+3 building. This technique was adopted considering the seismic-resistant design provisions of the entire G+5 building configuration. Tables 4 and Fig. 12 represent the retrofitting strategy adopted for deficient beam and column components in the existing structure.

Further, these modified sections in the existing G+3 configuration are modeled using the section designer in SAP2000 software, and the model is extended vertically for two more stories with proposed structural design including the reinforcement details and member sizes as given in Table 1 with the configuration shown in Fig. 3.

Seismic analysis is repeated on this new configuration (G+5) for zone III medium soil profile, and seismic resistance capability of the structural components is confirmed by checking the DCR ratios of the structural components. From the results shown in Figs. 13 and 14 (indicating the stress levels (0: unstressed to 1: fully stressed), it can be observed that the capacity of the building components has enhanced from collapse limit state (C) to life safety limit state (LS) due to strengthening of the existing RC building.

Fig. 9 DCR contour for G+3 building for zone III seismic load in **a** elevation, **b** plan
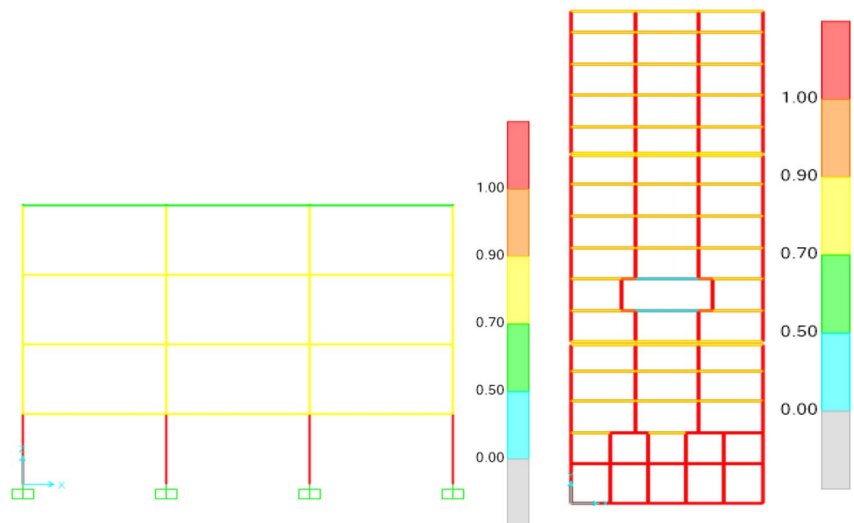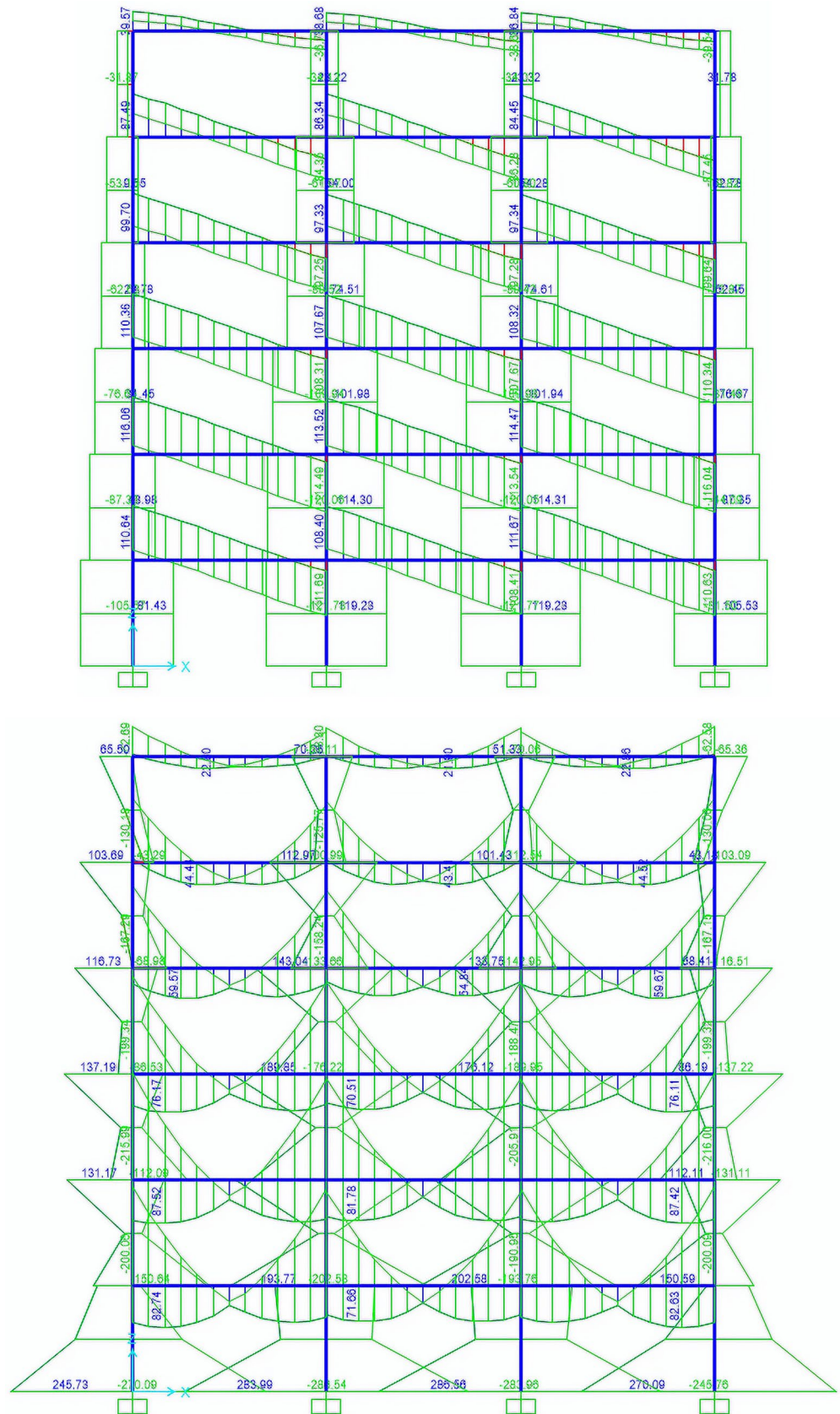
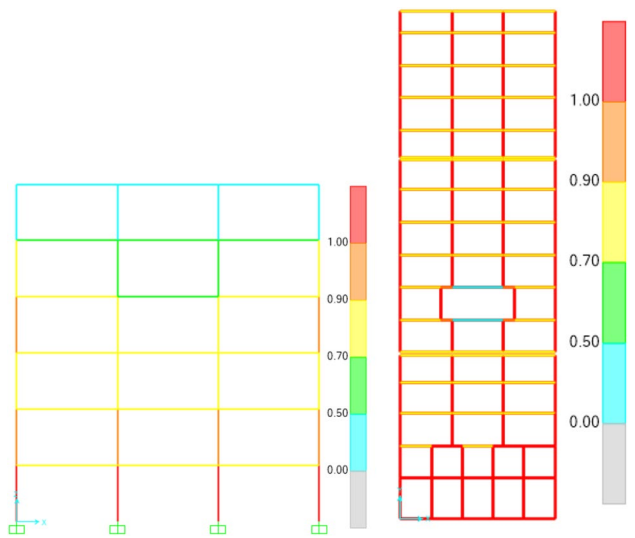**Fig. 10** SFD and BMD of a typical frame in G+5 building for load combination (1.5(DL+EQ)) for zone III

Fig. 11 DCR contour for G+5 building for zone III seismic load before strengthening existing G+3 configuration in **a** elevation, **b** plan

7 Summary and conclusions

The gravity load-designed RC frame buildings are reported to be vulnerable in the literature in view of low lateral strength and limited ductility for the seismic loading conditions, and this observation can be clearly envisaged in the case study presented. From the plastic hinge pattern arrived during nonlinear static analysis performed on the existing G+3 structure, it can be detected that certain structural components were inadequate. This observation is clearly pronounced from the analysis G+5 structure before repair/retrofitting and also from the DCR calculations performed for earthquake load case. In the seismic analysis performed on G+5 configuration, inadequate structural components, i.e., components in collapse limit state, were found to be present in G+3 configuration only. These components are strengthened with steel bonding technique for flexural and shear strength enhancement in beams and axial strength and moment carrying capacity enhancement in

Table 4 Retrofit/strengthening strategy for the existing G+3 building

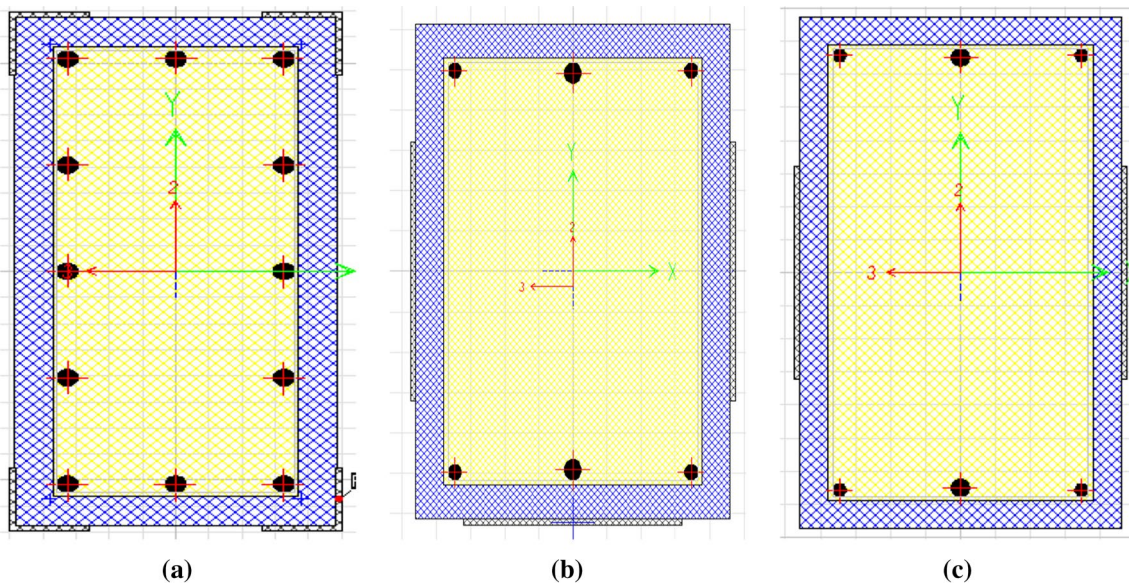| S. No.	Component	Type	Retrofitting adopted in addition to existing reinforcement
1	Beam	C	MS flat 200 mm × 5 mm on two side faces of the beam as shown in Fig. 12c
2		D	
3		E	MS flat 200 mm × 5 mm on three faces of the beam excluding the top face as shown in Fig. 12b
4	Column	C_1	Four angle sections, ISA 75 mm × 75 mm × 5 mm as shown in Fig. 12a
5		C_2	

(a)   (b)   (c)

Fig. 12 Plate-bonding technique for strengthening: **a** column, **b** beam on three faces, **c** beam two side faces

Fig. 13 SFD and BMD of a typical frame in G+5 building after strengthening under load combination 1.5(DL + EQ) for zone III
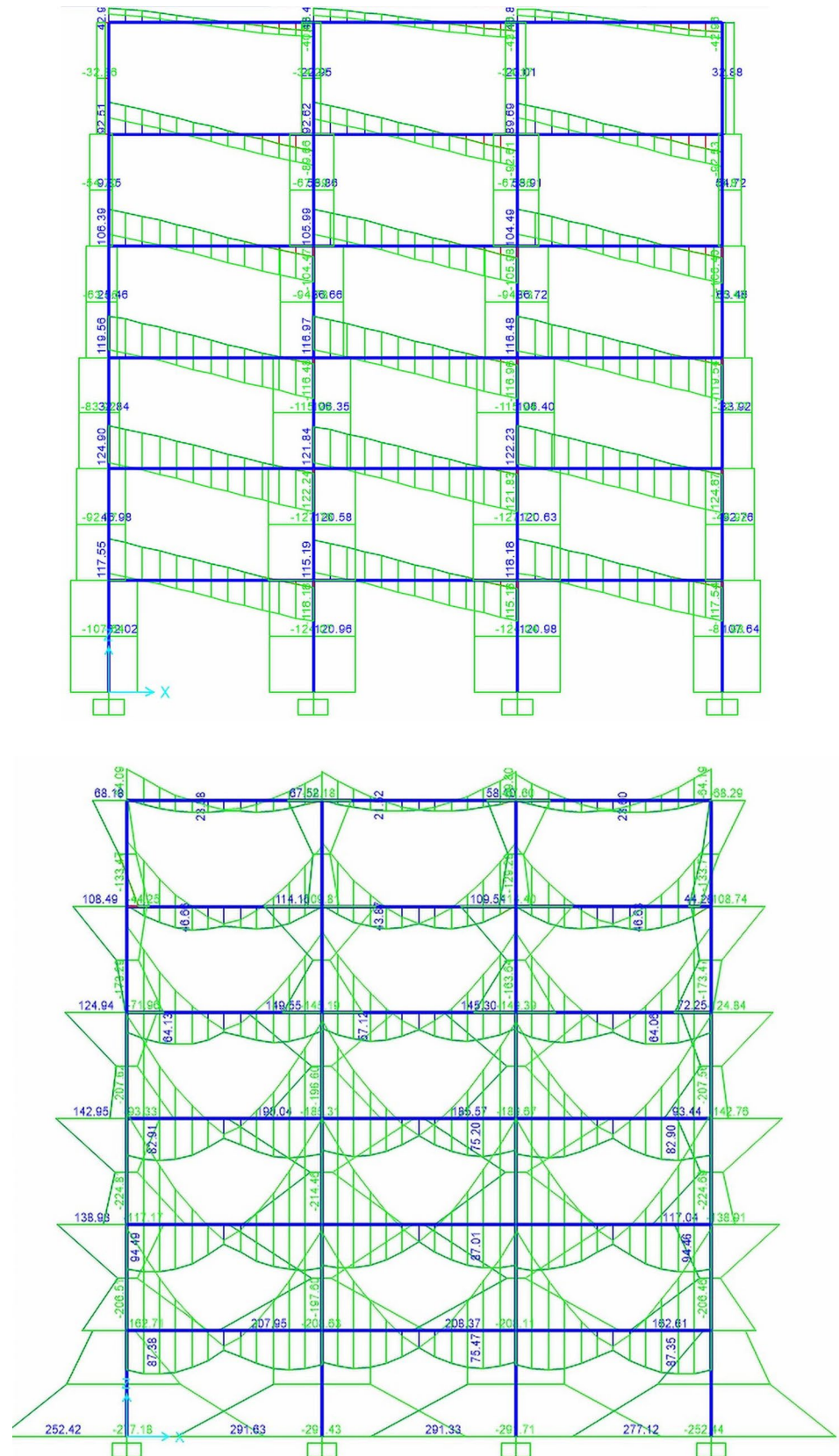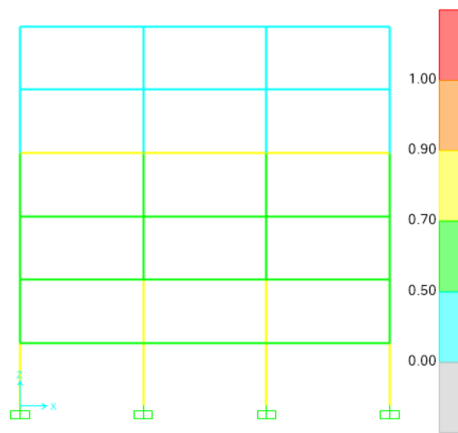
Fig. 14 DCR contour for G+5 building for zone III seismic load after strengthening existing G+3 configuration

columns, as given in Table 4 and Fig. 12. Furthermore, the strengthened G+3 structure can be extended vertically to G+4 and G+5 adopting the structural design as mentioned in Table 1 with the configuration shown in Fig. 3. After strengthening, the performance level of these components enhanced from collapse (C) limit state to life safety (LS) limit state and overall G+5 building structure satisfies the design limits for seismic requirements of the building location, i.e., zone III requirements with medium soil profile as per BIS 1893 (Part 1).

This study has significant importance in current scenario of existing buildings in India. It deals with evaluating existing buildings with the current design practice and suggests a methodology to repair/strengthen existing buildings to sustain any coming eventuality like an earthquake.

Compliance with ethical standards

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

References

1. Earthquake Disaster Risk Index Report (2019) A publication of the National Disaster Management Authority, Government of India. National Disaster Management Authority, New Delhi
2. IS 1893 (2002) Criteria for earthquake resistant design of structures. Part 1—general provisions and buildings. Bureau of Indian Standards, New Delhi
3. IS 1893 (2016) Criteria for earthquake resistant design of structures. Part 1—general provisions and buildings. Bureau of Indian Standards, New Delhi
4. Oggu P, Kumar VK, Gopikrishna K (2016) Seismic fragility analysis of vertical setback RC structures. In: Proceedings of the international conference on the trends and recent advances in civil engineering (TRACE-2016), 11–12 Aug 2016, Amity University, Noida, India
5. Oggu P, Gopikrishna K (2017) Seismic behavior and its influence on damage probabilities of irregular R.C. buildings. In: Proceedings of the international conference on composite materials and structures-ICCMS 2017, 27–29 Dec 2017, Hyderabad, India
6. Pisode M, Surana M, Haldar P, Singh Y (2017) Comparative assessment of seismic fragility of RC frame buildings designed for older and revised Indian standards. ISET J Earthq Technol 54(1):17–29
7. Gautham A, Gopikrishna K (2017) Fragility analysis—a tool to assess seismic performance of structural systems. Mater Today Proc 4(9):10565–10569. https://doi.org/10.1016/j.matpr.2017.06.421
8. Oggu P, Mehulkumar P, Gopikrishna K (2019) Influence of real ground motion records in performance assessment of RC buildings. Int J Eng 32(12):1745–1752. https://doi.org/10.5829/ije.2019.32.12c.07
9. Oggu P, Gopikrishna K (2020) Assessment of three-dimensional RC moment-resisting frames under repeated earthquakes. Structures 26:6–23. https://doi.org/10.1016/j.istruc.2020.03.039
10. IS 15988 (2013) Seismic evaluation and strengthening of existing reinforced concrete buildings—guidelines. Bureau of Indian Standards, New Delhi
11. Rai DC (2005) Seismic evaluation and strengthening of existing buildings. IIT Kanpur and Gujarat State Disaster Mitigation Authority, Gandhinagar
12. CPWD (2002) Handbook on repair and rehabilitation of RCC buildings. Central Public Works Department, Government of India, New Delhi
13. Masi A (2003) Seismic vulnerability assessment of gravity load designed R/C frames. Bull Earthq Eng 1(3):371–395. https://doi.org/10.1023/B:BEEE.0000021426.31223.60
14. Zhang Y, Hu X (2012) Seismic retrofitting of reinforced concrete frame structures using GFRP-tube-confined-concrete composite braces. Earthq Eng Eng Vib 11(1):91–105. https://doi.org/10.1007/s11803-012-0101-9
15. Li G, Jiang Y, Zhang S, Zeng Y, Li Q (2015) Seismic design or retrofit of buildings with metallic structural fuses by the damage-reduction spectrum. Earthq Eng Eng Vib 14(1):85–96. https://doi.org/10.1007/s11803-015-0008-3
16. Laterza M, D'Amato M, Braga F, Gigliotti R (2017) Extension to rectangular section of an analytical model for concrete confined by steel stirrups and/or FRP jackets. Compos Struct 176:910–922. https://doi.org/10.1016/j.compstruct.2017.06.025
17. Eldin MN, Dereje AJ, Kim J (2019) Seismic retrofit of RC buildings using self-centering PC frames with friction-dampers. Eng Struct. https://doi.org/10.1016/j.engstruct.2019.109925
18. Van Cao V, Nguyen TQ (2019) Effects of CFRP/GFRP flexural retrofitting on reducing seismic damage of reinforced concrete frames: a comparative study. Asian J Civ Eng 20(8):1071–1087. https://doi.org/10.1007/s42107-019-00173-7
19. Formisan A, Massimilla A, Di Lorenzo G, Landolfo R (2020) Seismic retrofit of gravity load designed RC buildings using external steel concentric bracing systems. Eng Fail Anal. https://doi.org/10.1016/j.engfailanal.2020.104485
20. IS 456 (2000) Plain and reinforced concrete—code of practice. Bureau of Indian Standards, New Delhi
21. CSI (2016) SAP2000—analysis reference manual. Computers and Structures Inc., Berkeley
22. ASCE (2000) Prestandard and commentary for the seismic rehabilitation of buildings. Prepared for Federal Emergency Management Agency, FEMA Publication No. 356. Washington, DC

23. Inel M, Ozmen HB (2006) Effects of plastic hinge properties in nonlinear analysis of reinforced concrete buildings. Eng Struct 28:1494–1502. https://doi.org/10.1016/j.engstruct.2006.01.017

24. Mander JB, Priestley MJN, Park P (1989) Theoretical stress–strain model for confined concrete. J Struct Eng 114(8):1804–1826. https://doi.org/10.1061/(ASCE)0733-9445(1988)114:8(1804)

25. IS 875 (1987) Code of practice for design loads other than earthquake for buildings and structures. Part I—dead loads–unit weights of building. Bureau of Indian Standards, New Delhi

26. IS 875 (1987) Design loads (other than earthquake) for buildings and structures—part II. Imposed loads—code of practice. Bureau of Indian Standards, New Delhi

27. Agrawal P, Shrikhande M (2006) Earthquake resistant design of structures. PHI Learning Pvt. Ltd., New Delhi