A refined procedure for seismic evaluation and retrofitting of reinforced concrete buildings

Mangeshkumar R. Shendkar[1], Denise-Penelope N. Kontoni[2,3,*], Ramancharla Pradeep Kumar[4], Ahmed Abdelraheem Farghaly[5], Sasankasekhar Mandal[1] and Pabitra Ranjan Maiti[1]

[1]Department of Civil Engineering, Indian Institute of Technology (BHU), Varanasi 221 005, India
[2]Department of Civil Engineering, School of Engineering, University of the Peloponnese, GR-26334 Patras, Greece
[3]School of Science and Technology, Hellenic Open University, GR-26335 Patras, Greece
[4]Earthquake Engineering Research Centre, International Institute of Information Technology, Hyderabad 500 032, India
[5]Department of Civil and Architectural Constructions, Faculty of Technology and Education, Sohag University, Sohag 82524, Egypt

In the present study, a refined procedure for the seismic evaluation and retrofitting of reinforced concrete (RC) buildings based on the 'quadrants assessment method' and 'material strain limit approach' is proposed and numerically analysed. The quadrants assessment method involves the performance point, design base shear and threshold damage limit state. Herein, four existing RC buildings (models 1–4) are considered from the Koyna–Warna region, Maharashtra (zone-IV, India). These four buildings were studied using nonlinear static adaptive pushover analysis employing the SeismoStruct software. Based on the quadrants assessment method, the three-storey RC building (model-1) was retrofitted with RC jacketing, while the other three RC buildings did not need to be retrofitted. Also, significant seismic design parameters like ductility, over strength factor, response reduction factor, etc. were evaluated before and after retrofitting. The results depict that the combination of the 'quadrants assessment method' and 'material strain limit approach' is a rapid, reliable and refined procedure for seismic evaluation and retrofitting of RC buildings.

Keywords: Adaptive pushover analysis, material strain limit approach, quadrants assessment method, reinforced concrete buildings, seismic evaluation.

A reinforced concrete (RC) building is a recent trend in the construction industry. Nowadays, a natural disaster, e.g. an earthquake, occurs at any time; so the quality of construction should be good. Seismic evaluation and retrofitting are the best options to prevent loss of life and damage to infrastructure. Most constructions cannot sustain the seismic load due to their design construction deficiency, etc. So, there is a need for retrofitting. This is defined as the process of modification of an existing structure to improve its seismic performance. These retrofitting strategies are especially needed in an earthquake-prone area. The present study aims to evaluate the seismic performance of RC buildings and suggests retrofitting solutions based on their deficiencies.

Ghobarah[1] worked on the seismic assessment of existing RC structures. The need for seismic evaluation basically depends on the vulnerability of the existing structures. Sinha and Shaw[2] and Sengupta *et al.*[3] observed that pushover analysis is a simple and efficient approach for evaluating existing structures, and the time-history analysis method is generally used for complex structures. Vielma *et al.*[4,5] reported that the quadrants method was suitable for rapid and reliable evaluation of the seismic performance of existing buildings with less calculation. El-Betar[6] found that priority must be given to the seismic evaluation of old and non-engineered buildings in high seismic regions. Kontoni and Farghaly[7] studied the effect of base isolation and tuned mass dampers (TMDs) on the seismic response of RC high-rise buildings considering soil–structure interaction. Ebadi-Jamkhaneh *et al.*[8] worked on RC columns and beam members subjected to various loads under damaged conditions and strengthened using carbon and glass fibre reinforced polymer (FRP) wraps. Shendkar *et al.*[9] worked on the effect of the lintel beam on the seismic performance of RC buildings with semi-interlocked and unreinforced masonry infills and found that the buildings showed good seismic performance with the lintel beam. Shendkar *et al.*[10] worked on the seismic evaluation and retrofit of RC buildings with masonry infills based on a newly developed material strain limit approach and showed that this is an effective method for the seismic assessment of structures. Shendkar *et al.*[11] evaluated the seismic risk assessment of RC buildings in the Koyna–Warna region, Maharashtra, India, using the EDRI method, where they showed the different damage states of RC buildings based on rapid visual screening. Shendkar *et al.*[12] studied the influence of masonry infill on the seismic design factors of RC buildings, considering three different values of compressive strength of the masonry infill. They showed that the response reduction factor (R-factor) of all RC in filled frames had decreased with a decrease in the compressive strength of the masonry infill.

*For correspondence. (e-mail: kontoni@uop.gr)

In the present study, a novel, refined seismic evaluation procedure is proposed based on the 'quadrants assessment method' and 'material strain limit approach'. The results showed that combining these two methods is a rapid, reliable and refined procedure for the seismic evaluation and retrofit of RC structures.

Proposed seismic evaluation methods

In recent years, adaptive pushover analysis has been widely used to check the nonlinear response of structures. It represents a significant alternative solution for the nonlinear dynamic analysis of structures. In the present study, we have used adaptive pushover analysis. Antoniou and Pinho[13] used a force-based adaptive pushover analysis, in which the lateral load was continuously revised at every step during eigenvalue analysis. In the present study, the response spectrum of the Koyna–Warna region was used for spectral amplification (Figure 1), which was obtained by Ramaliigeswara Rao[14].

Quadrants assessment method

Vielma *et al.*[4,5] have presented the quadrants method as an effective procedure for evaluating the seismic performance of existing buildings. This method is based on the results of the nonlinear static pushover analysis and generates the capacity curve which represents the overall capacity of the whole structure against lateral forces.

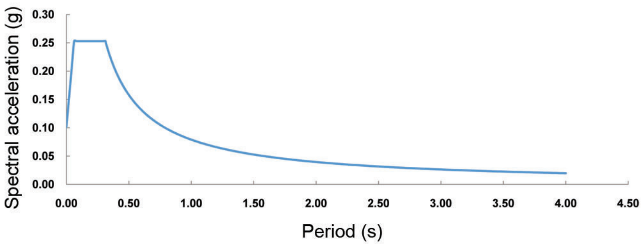

Figure 1. Acceleration response spectrum for the Koyna–Warna region.

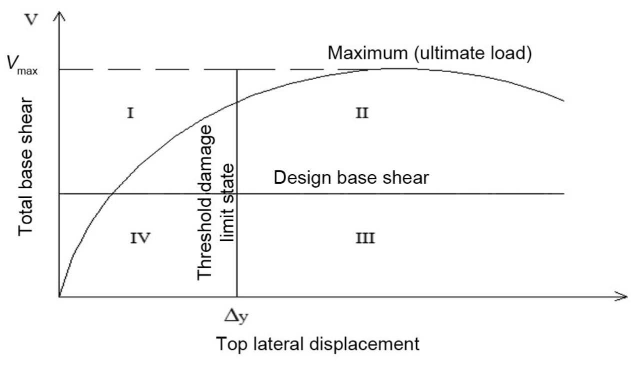

Figure 2. The capacity curve and axes that define the quadrants assessment method.

In the present study, this has been modified as the 'quadrants assessment method' based on two structural parameters. The first is the design base shear, obtained from the seismic weight of the structure according to IS 1893 Part-1 (ref. 15). The second parameter is the threshold damage limit state (i.e. first yield point) obtained from the material strain limit approach to define yield deformation of RC framed buildings. Both values define two axes over the capacity curve; the design base shear defines a horizontal axis and the threshold damage limit state defines a vertical axis. So ultimately, the capacity curve is divided into four quadrants (Figure 2).

The performance point of the structure was calculated according to ASCE 41-06 (ASCE/SEI 41-06, 2006)[16] for life safety and collapse prevention purposes. The intersection of the demand and capacity curves (i.e. the performance point) is a general procedure to evaluate the seismic performance of a structure under a specific demand. If the performance point is in quadrant I, the structure has enough lateral strength and stiffness; so it does not need to be reinforced. If the structure is in quadrant II, it is necessary to provide additional stiffness using RC or steel jacketing. If the performance point is in quadrant III or IV, the structure requires a more radical intervention, adding stiffness and lateral strength.

Material strain limit approach

Engineers must be capable of identifying the instants at which different performance limit states (e.g. structural damage) are reached. This can be efficiently carried out using SeismoStruct[17] software through the definition of performance criteria, whereby the attainment of a given threshold value of material strain is monitored during the analysis of a structure[17]. Material strains are usually the best parameter for identifying the performance state of a given structure compared to other existing methods. The material strain limit approach is possible in the SeismoStruct program because, in this software, the distributed inelasticity is assigned to each structural member and so it is easy to identify the actual damage based on the material in a structure.

To check the damage patterns of the structures, the performance criteria based on material strain used in the present numerical simulation are: (i) crushing strain limit for unconfined concrete in beam: 0.0035 (ref. 18), (ii) crushing strain limit for unconfined concrete in column: 0.002 (ref. 18), (iii) crushing strain limit for confined concrete: 0.008 (refs 19–23), (iv) yield strain limit for steel: 0.0025 (refs 17, 20–23) and (v) fracture strain limit for steel: 0.06 (refs 17, 20–23).

Refined procedure for seismic evaluation and retrofit of RC buildings

Figure 3 presents the flow chart of the proposed refined procedure for the seismic evaluation and retrofit of RC

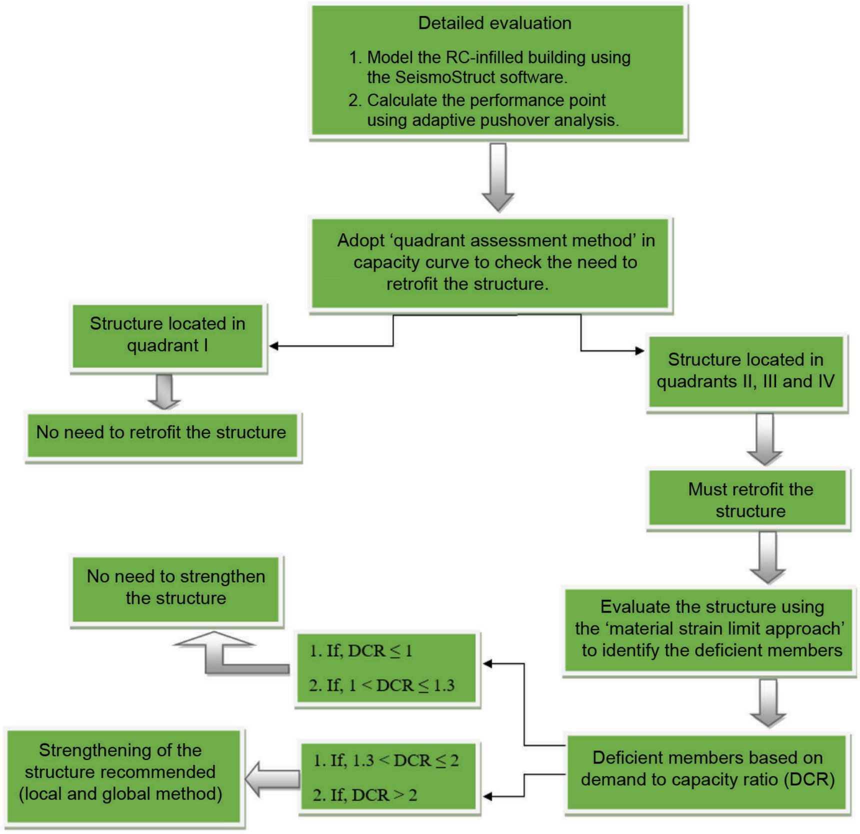

Figure 3. Flow chart of the proposed refined procedure for seismic evaluation and retrofitting of RC buildings.

buildings, involving two seismic evaluation methods. The material strain limit approach is a micro-level evaluation used to identify deficient members. This identification is based on the provisions of ASCE 41-06 (ref. 16), and the RC structure needs to be strengthened using local and/or global retrofitting techniques.

The 'quadrants assessment method' is a global approach for the seismic evaluation of structures based on the performance point. This method determines the need for intervention/retrofitting of a structure, enabling a rapid seismic evaluation of a structure. The 'material strain limit method' is a local approach for the seismic assessment of RC structures based on the threshold strain limit of concrete and steel to identify the actual damage state of structural members, i.e. micro-level evaluation. Combining these two methods can provide a rapid, reliable and refined procedure for the seismic evaluation and retrofitting of RC structures.

Seismic evaluation of RC buildings

India has experienced several devastating earthquakes, resulting in massive damage to buildings and several deaths. Particularly, the Koyna–Warna region is a significant example of reservoir-induced seismicity. Seismic activity has been experienced continuously for more than 50 years in this region (zone-IV). There have been nine earthquakes of $M > 5$, about 96 earthquakes of $4 \leq M < 5$, and thousands of minor earthquakes since 1963 (ref. 24).

In this study, the soil is considered a 'medium' type. Four existing RC buildings have been considered from the Koyna–Warna region. These buildings are modelled and analysed using nonlinear static adaptive pushover analysis employing SeismoStruct[17].

Three-storey RC building in the Koyna–Warna region (model-1)

The first building presented in this study is an ordinary residential moment-resisting, RC-framed building (Figures 4 *a* and 5 *a*), located in zone IV (Koyna–Warna region) according to IS 1893 Part-1:2016 code[15]. It is an open ground-storey building. Table 1 shows the material and sectional details obtained from available structural drawings.

Four-storey RC building in the Koyna–Warna region (model-2)

The second building presented in this study is an ordinary residential, moment-resisting RC-framed building (Figures

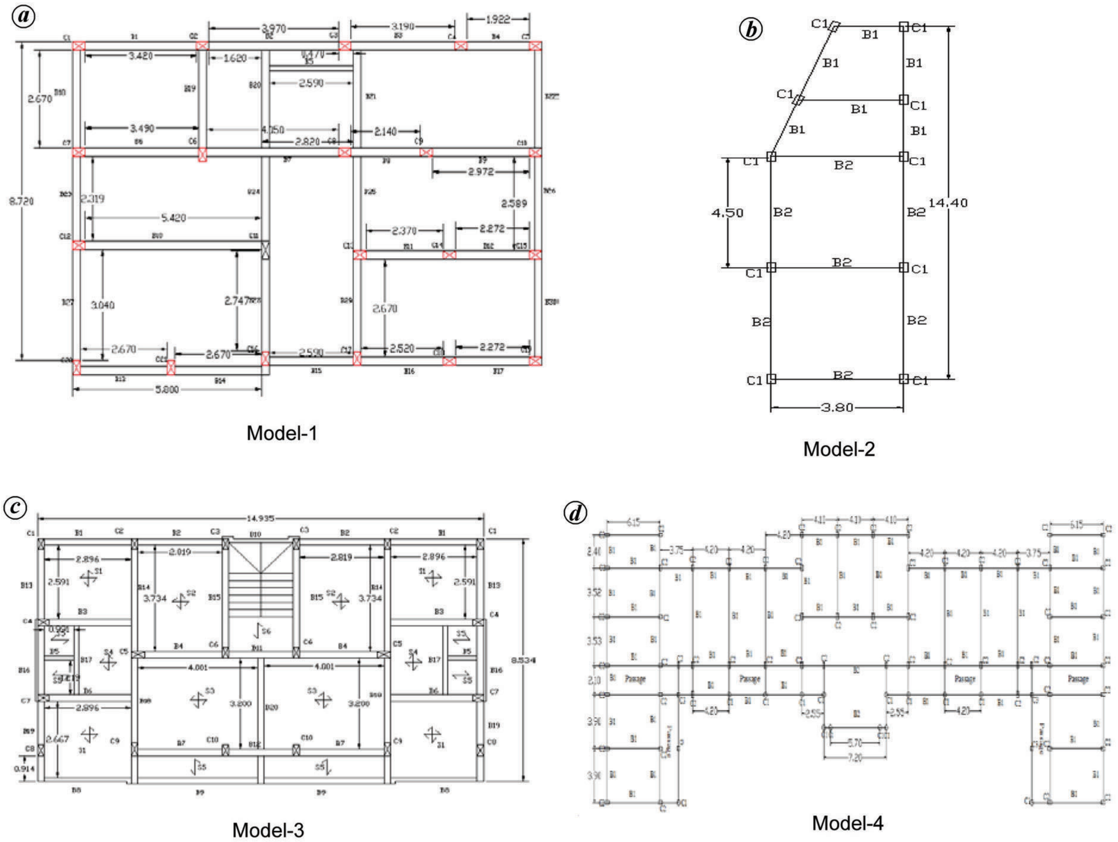

Figure 4. The plan of the RC building.

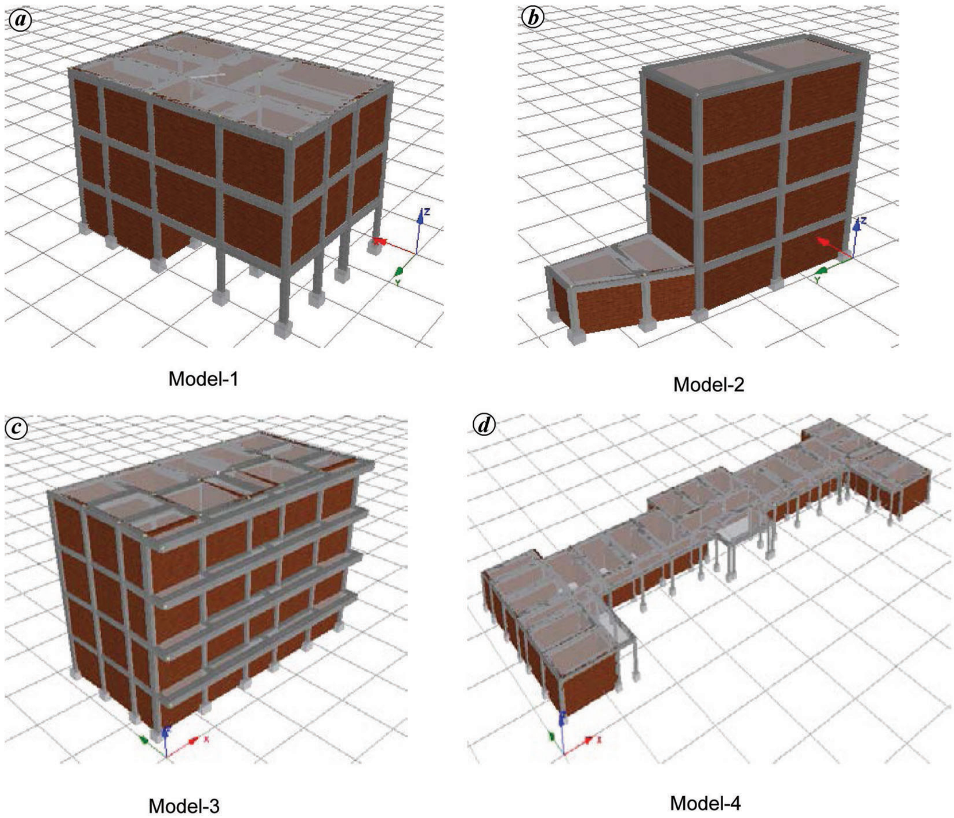

Figure 5. The model of the RC building.

Table 1. Material and sectional details of the three-storey RC building (model-1)

Structural system	Ordinary moment-resisting RC frame
Total number of storeys	3
Height of stories (m)	3
Year of construction	2019
Building name	Abdul Mukadam (residential)
Diagonal compressive strength of infill (f_m; MPa)	1.32
Thickness of infill (mm)	230 external, 115 internal
Concrete grade	M20
Reinforcement grade	Fe 415
Size of columns (mm)	230 × 380, 230 × 450
Reinforcement	4–12 ∅ at the corners and 4–12 ∅ along the longer side, 6 ∅ @150 c/c, 4–16 ∅ at the corners and 4–12 ∅ along the longer side, 6 ∅ @150 c/c
Size of beams (mm)	230 × 380, 230 × 450, 230 × 530, 230 × 750
Reinforcement	2–12 ∅ at the top and bottom, 6 ∅ @ 150 c/c, 2–12 ∅ at the top and bottom, 6 ∅ @150 c/c, 2–16 ∅ at the bottom and 2–12 ∅ at the top, 6 ∅ @150 c/c, 4-16 ∅ at the bottom and 2–12 ∅ at the top, 6 ∅ @150 c/c.
Thickness of slabs (mm)	125

Table 2. Material and sectional details of the four-storey RC building (model-2)

Structural system	Ordinary moment-resisting frame
Total number of storeys	4
Height of stories (m)	3
Year of construction	2007
Building name	Dnyandeep (residential)
f_m (MPa)	1.32
Thickness of infill (mm)	230 (external), 115 (internal)
Concrete grade	M20
Reinforcement grade	Fe 415
Size of columns (mm)	230 × 380
Reinforcement	4–16 ∅ at the corners and 4–16 ∅ along the longer side, 6 ∅ @ 150 c/c
Size of beams (mm)	230 × 350, 230 × 400
Reinforcement	2–16 ∅ at the bottom and 2–12 ∅ at the top, 6 ∅ @ 200 c/c, 2–16 ∅ at the bottom and 2-12 ∅ at the top, 6 ∅ @ 200 c/c
Thickness of slabs (mm)	125

4 *b* and 5 *b*), located in zone IV (Koyna–Warna region). Table 2 shows the material and sectional details obtained from available structural drawings.

Four-storey RC building in the Koyna–Warna region (model-3)

The third building presented in this study is an ordinary residential, moment-resisting, RC-framed building (Figures 4 *c* and 5 *c*), located in zone IV (Koyna–Warna region). Table 3 shows the material and sectional details obtained from available structural drawings.

Single-storey RC building in the Koyna–Warna region (model-4)

The fourth building presented in this study is an ordinary moment-resisting, RC-framed school building (Figures 4 *d* and 5 *d*), located in zone IV (Koyna–Warna region). Table 4 shows the material and sectional details obtained from available structural drawings.

Retrofit strategy

The three-storey RC building (model-1) needs to be retrofitted, as discussed later in the text.

A retrofit strategy in accordance with IS 15988:2013 (ref. 25) is used to strengthen a structure based on its current deficiencies. Several strategies may be selected as a retrofit scheme for the structure. (i) Local retrofit: RC jacketing, steel jacketing, FRP sheet wrapping, etc. (ii) Global retrofit: Addition of infills, shear walls, steel braces, energy dissipation devices, etc.

Among the above strategies, RC jacketing is used for the deficient column members having a crush of confined concrete and fractured steel failure. In this retrofit technique, M25 concrete is used for jacketing; steel is used at the corners and middle (six numbers of 16 mm diameter steel) and 8 mm diameter stirrups are used at 100 mm spacing c/c.

Table 3. Material and sectional details of the four-storey RC building (model-3)

Structural system	Ordinary moment-resisting frame
Total number of storeys	4
Height of stories (m)	3
Year of construction	2018
Building name	Ghadge Haribhau building (residential)
f_m (MPa)	1.32
Thickness of infill (mm)	230 (external), 115 (internal)
Concrete grade	M20
Reinforcement grade	Fe 500
Size of columns (mm)	230 × 380, 230 × 450
Reinforcement	4–12 ∅ at the corners and 2–12 ∅ along the longer side, 6 ∅ @150 c/c, 4–16 ∅ at the corners and 4–16 ∅ along the longer side, 6 ∅ @150 c/c
Size of beams (mm)	230 × 300, 230 × 380, 230 × 450
Reinforcement	2–12 ∅ at the bottom and 2–12 ∅ at the top, 6 ∅ @ 150 c/c, 2–12 ∅ at the bottom and 2–12 ∅ at the top, 6 ∅ @ 150 c/c, 2–12 ∅ at the bottom and 2–12 ∅ at the top, 6 ∅ @ 150 c/c
Thickness of slabs (mm)	150

Table 4. Material and sectional details of the single-storey RC building (model-4)

Structural system	Ordinary moment-resisting frame
Total number of storeys	1
Height of stories (m)	3.1
Year of construction	2007
Building name	Guruvarya Lalasaheb Patankar Vidyalay (school building)
f_m (MPa)	1.32
Thickness of infill (mm)	230 (external), 115 (internal)
Concrete grade	M20
Reinforcement grade	Fe 415
Size of columns (mm)	250 × 450, 300 × 300, 400 mm diameter circular column
Reinforcement	4–16 ∅ at the corners and 2–12 ∅ along the longer side, 8 ∅ @180 c/c, 4-16 ∅ at the corners, 8 ∅ @170 c/c, 8–18 ∅ at the periphery, 8 ∅ @150 c/c
Size of beams (mm)	250 × 300, 250 × 400
Reinforcement	2–20 ∅ at the bottom and 2–12 ∅ at the top, 8 ∅ @ 200 c/c, 2–20 ∅ at the bottom and 2–12 ∅ at the top, 8 ∅ @ 200 c/c
Thickness of slabs (mm)	150

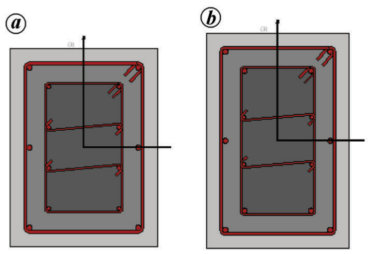

Figure 6. The cross-sections of the columns after the retrofitting: ***a***, 430 × 580 mm; ***b***, 430 × 650 mm.

The size of the retrofitted columns is 430 × 580 mm and 430 × 650 mm (Figure 6*a* and *b* respectively). Figure 7 shows the retrofitted plan.

Results and discussion

Seismic evaluation and retrofit of the three-storey RC building (model-1)

Pushover curves of the three-storey RC building before and after retrofit: As shown in Figure 8, the ultimate capacity of the building is increased after retrofitting in the *X*- as well as *Y*-directions. Table 5 shows a comparison of different parameters.

Figure 9 shows the damage pattern of the three-storey RC building without retrofit in the *X*-direction (model-1). The first infill damage occurred at a base shear of 801.10 kN and displacement of 4.25 mm. The first yielding of steel occurred at a base shear of 1983.86 kN and displacement of 21.25 mm. The first crushing of the unconfined concrete column occurred at a base shear of 2247.24 kN and displacement of 25.5 mm. The first crushing of confined concrete occurred at a base shear of 3868.66 kN and displacement of 89.25 mm.

Figure 10 shows the damage pattern of the three-storey RC building without retrofit in the *Y*-direction (model-1). The first infill damage and first yielding of steel occurred at a base shear of 551.28 kN and displacement of 5.67 mm. The first crushing of the unconfined concrete beam occurred at a base shear of 907.55 kN and displacement of 11.33 mm. The first crushing of the unconfined concrete column occurred at a base shear of 1240.44 kN and displacement of 22.67 mm. The first fracture of steel occurred at a base

Table 5. Comparison of different parameters of the three-storey RC building (model-1)

Parameters	Before retrofit		After retrofit		Remarks
	In the *X*-axis	In the *Y*-axis	In the *X*-axis	In the *Y*-axis	
Ultimate capacity (kN)	3933.15	1510.65	4861.01	2244.71	After retrofit, ultimate capacity increased by 1.23 times in the *X*-axis and 1.48 times in the *Y*-axis.
Yield displacement (mm)	26.40	13.10	36.06	23.12	After retrofit, yield displacement increased by 1.36 times in the *X*-axis and 1.76 times in the *Y*-axis.
Maximum displacement (mm)	97.75	45.33	112	78.10	After retrofit, maximum displacement is increased by the 1.14 times in the *X*-axis and 1.72 times in the *Y*-axis.
Ductility	3.70	3.46	3.11	3.38	After retrofit, ductility decreased by 15.94% in the *X*-axis and 2.31% in the *Y*-axis.
Ductility reduction factor	2.53	2.43	2.28	2.40	After retrofit, ductility reduction factor decreased by 9.88% in the *X*-axis and 1.23% in the *Y*-axis.
Overstrength factor	7.77	2.99	9.47	4.37	After retrofit, overstrength factor increased by 1.21 times in the *X*-axis and 1.46 times in the *Y*-axis.
Time period (sec)	0.39	0.39	0.34	0.34	After retrofit, time period decreased by 12.82% in the *X*-axis and the *Y*-axis.
R-factor	9.82	3.63	10.79	5.25	After retrofit, *R*-factor is increased by 1.09 times in the *X*-axis and 1.45 times in the *Y*-axis.

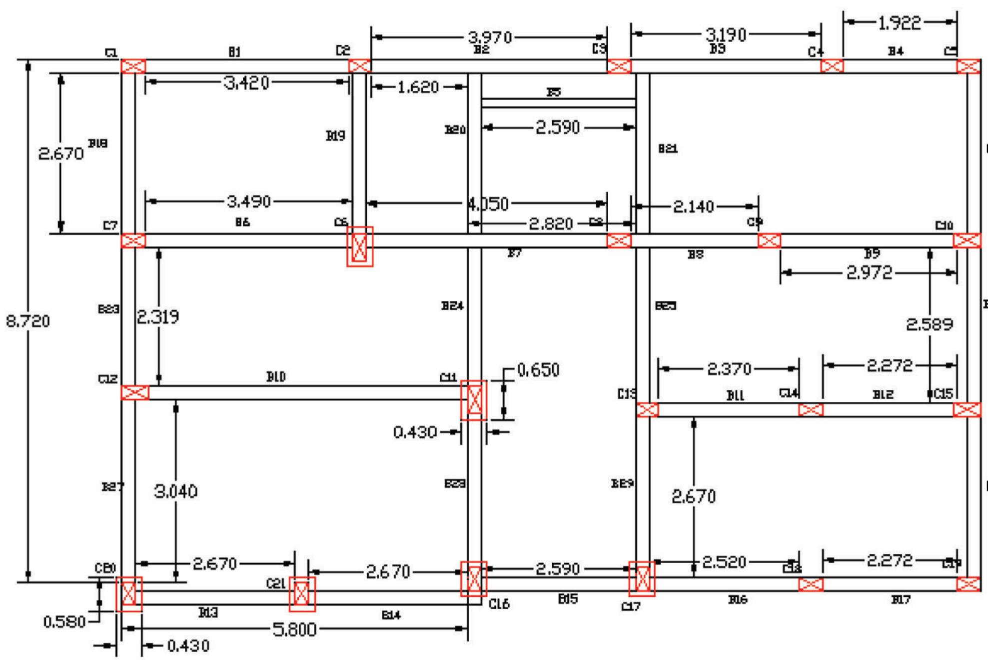

Figure 7. Retrofitted plan of model-1 (units in m).

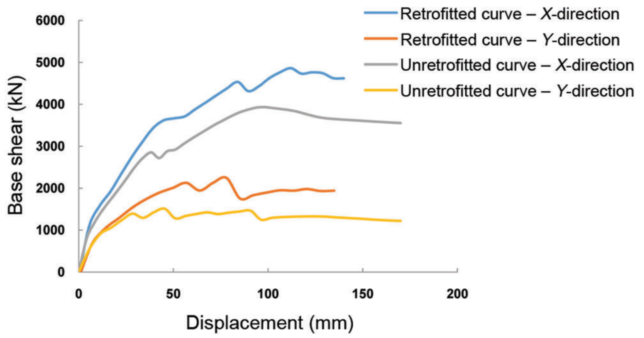

Figure 8. Pushover curve of the three-storey RC building with and without retrofitting.

shear of 1393.48 kN and displacement of 28.33 mm. The first crushing of confined concrete occurred at a base shear of 1417.97 kN and displacement of 79.33 mm.

Performance point of the building (model-1): The performance point is the intersection of the demand and capacity curve. The 'quadrants assessment method' is purely based on the performance point. The need for retrofit of a structure depends on the location of the performance point in the 'quadrants assessment method'. In this study, the performance point was calculated based on ASCE 41-06 (ref. 16).

Based on Table 6, the performance points before retrofitting in the *X*- and *Y*-directions are located in the first and

Table 6. Performance points of the three-storey RC building before retrofit in the *X*- and *Y*-directions (model-1)

	Displacement (mm)		Corresponding base shear (kN)	
Performance level	*X*-direction	*Y*-direction	*X*-direction	*Y*-direction
Life safety (LS)	10.62	12.07	1338.91	927.15
Collapse prevention (CP)	18.22	25.96	1809.94	1328.97

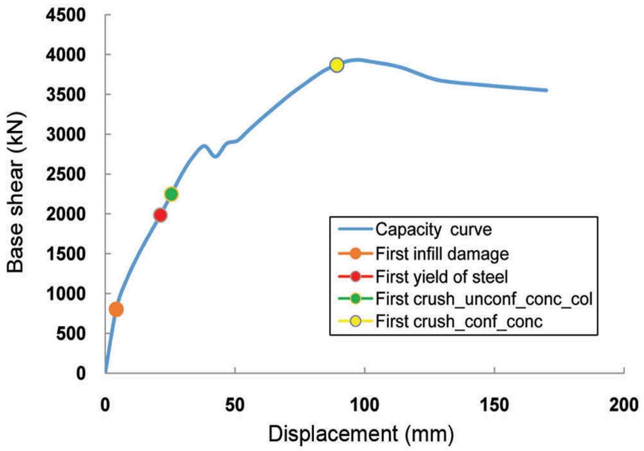

Figure 9. Damage pattern of the three-storey RC building without retrofit in the *X*-direction.

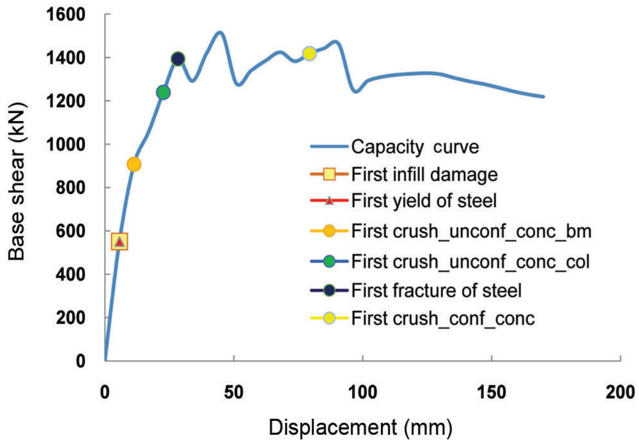

Figure 10. Damage pattern of the three-storey RC building without retrofit in the *Y*-direction.

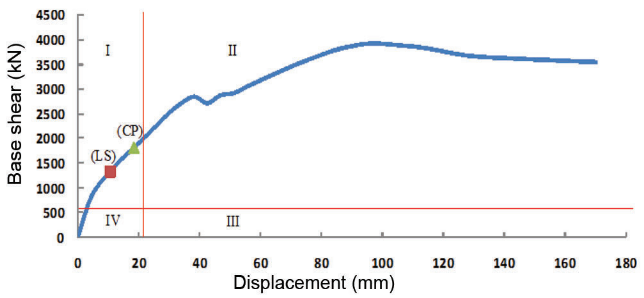

Figure 11. Location of performance points of the three-storey RC building before retrofit in the *X*-direction.

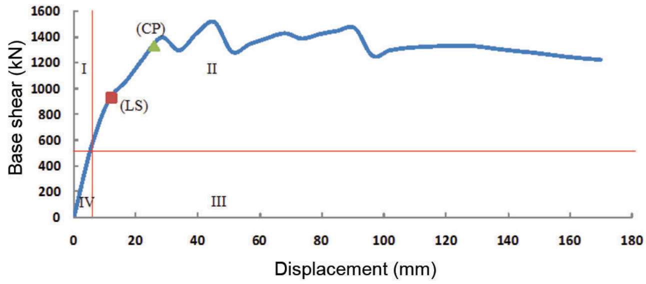

Figure 12. Location of performance points of the three-storey RC building before retrofit in the *Y*-direction.

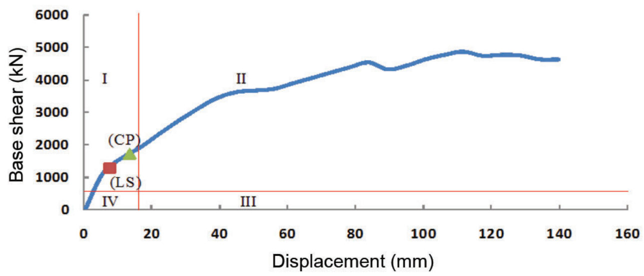

Figure 13. Location of performance points of the three-storey RC building after retrofit in the *X*-direction.

second quadrants respectively (Figures 11 and 12 respectively), so there is a need to retrofit the building according to the 'quadrants assessment method'.

Based on Table 7, the performance points after retrofitting in the *X*- and *Y*-directions as located in the first quadrant (Figures 13 and 14 respectively). So the building is in safe mode after retrofit according to the 'quadrants assessment method'.

Seismic evaluation of the four-storey RC building (model-2)

Pushover curves of the building: As shown in Figure 15, the ultimate capacity is higher in the *Y*-direction compared to the *X*-direction due to the structural configuration of the building. Table 8 shows a comparison of different parameters.

Based on Table 9, the performance points of the four-storey RC building in the *X*- and *Y*-directions (model-2) are located in the first quadrant only based on the design base shear (282 kN) and threshold damage limit state (61.76 mm in the *X*-direction, 48 mm in the *Y*-direction). So there is no need to retrofit the building according to the 'quadrants assessment method'.

Table 7. Performance points of the three-storey RC building after retrofit in X- and Y-directions (model-1)

	Displacement (mm)		Corresponding base shear (kN)	
Performance level	X-direction	Y-direction	X-direction	Y-direction
LS	7.62	7.9	1278.68	705.53
CP	13.53	17.85	1725.63	1171.97

Table 8. Comparison of different parameters of the four-storey RC building (model-2)

	Parameters		
	In the X-axis	In the Y-axis	Remarks
Ultimate capacity (kN)	1482.71	2060.55	Ultimate capacity increased by 1.38 times in the Y-axis compared to the X-axis.
Yield displacement (mm)	63.85	47.69	Yield displacement decreased by 25.30% in the Y-axis compared to the X-axis.
Maximum displacement (mm)	160	66.00	Maximum displacement decreased by 58.75% in the Y-axis compared to the X-axis.
Ductility	2.51	1.38	Ductility decreased by 45.02% in the Y-axis compared to the X-axis.
Ductility reduction factor	2.00	1.33	Ductility reduction factor decreased by 33.5% in the Y-axis compared to the X-axis.
Overstrength factor	5.26	7.31	Overstrength factor increased by 38.97% in the Y-axis compared to the X-axis.
Period (sec)	0.41	0.41	Time period was the same in the X- and Y-directions.
R-factor	5.26	4.86	R-factor increased by the 8.23% in the X-axis compared to the Y-axis.

Table 9. Performance points of the four-storey RC building in X- and Y-directions (model-2)

	Displacement (mm)		Corresponding base shear (kN)	
Performance level	X-direction	Y-direction	X-direction	Y-direction
LS	16.5	14.49	424.58	839.58
CP	27.13	23.44	554.19	947.49

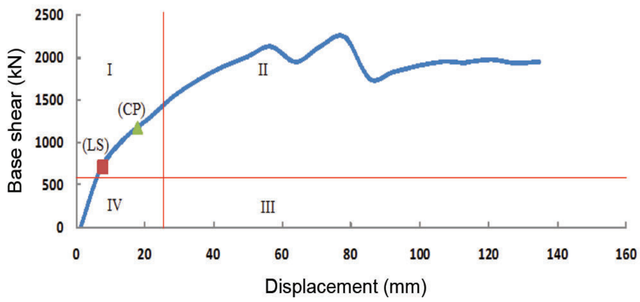

Figure 14. Location of performance points of the three-storey RC building after retrofit in the Y-direction.

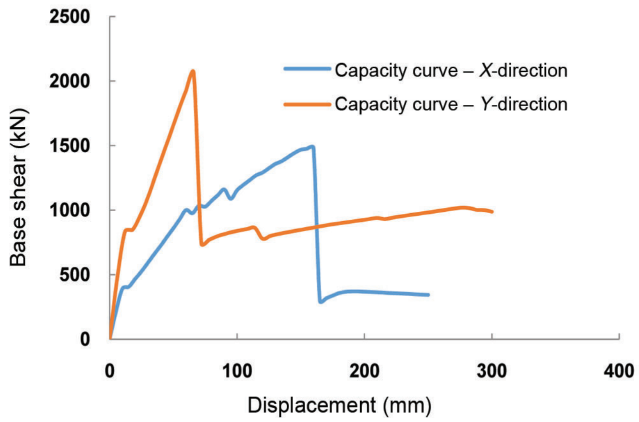

Figure 15. Pushover curves of the four-storey RC building.

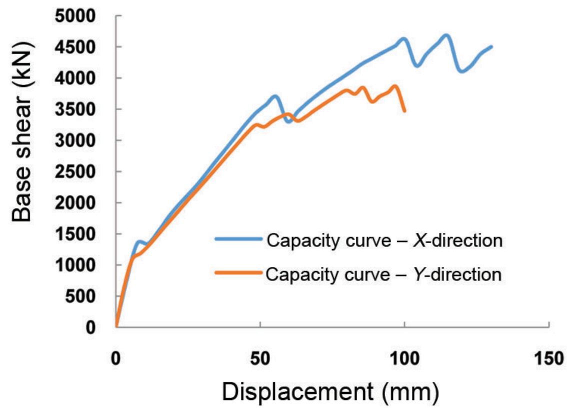

Figure 16. Pushover curves of the four-storey RC building.

Seismic evaluation of the four-storey RC building (model-3)

Pushover curves of the building: As shown in Figure 16, the ultimate capacity is higher in the X-direction compared to the Y-direction due to the structural configuration of the building. Table 10 shows a comparison of different parameters.

Based on Table 11, the performance points of the four-storey RC building in the X- and Y-directions (model-3) are located in the first quadrant only based on the design base shear (763.57 kN) and threshold damage limit state (26 mm

Table 10. Comparison of different parameters of the four-storey RC building (model-3)

	Parameters		Remarks
	In the *X*-axis	In the *Y*-axis	
Ultimate capacity (kN)	4667.1	3857.04	Ultimate capacity increased by 1.21 times in the *X*-axis as compared to the *Y*-axis.
Yield displacement (mm)	43.50	40.14	Yield displacement decreased by 7.72% in the *Y*-axis compared to the *X*-axis.
Maximum displacement (mm)	115.14	97.14	Maximum displacement decreased by 15.63% in the *Y*-axis compared to the *X*-axis.
Ductility	2.65	2.42	Ductility decreased by 8.67% in the *Y*-axis compared to the *X*-axis.
Ductility reduction factor	2.07	1.96	Ductility reduction factor decreased by 5.31% in the *Y*-axis compared to the *X*-axis.
Overstrength factor	6.11	5.05	Overstrength factor increased by 21% in the *X*-axis compared to the *Y*-axis.
Period (sec)	0.36	0.36	Time period was the same in the *X*- and *Y*-directions.
R-factor	6.32	4.95	*R*-factor increased by 27.67% in the *X*-axis compared to the *Y*-axis.

Table 11. Performance points of the four-storey RC building in the *X*- and *Y*-directions (model-3)

	Displacement (mm)		Corresponding base shear (kN)	
Performance level	*X*-direction	*Y*-direction	*X*-direction	*Y*-direction
LS	11.52	11.61	1342.10	1316
CP	20.02	20.73	1870.09	1813.71

Table 12. Comparison of different parameters of the single-storey RC building (model-4)

	Parameters		Remarks
	In the *X*-axis	In the *Y*-axis	
Ultimate capacity (kN)	17,735.47	16,232.99	Ultimate capacity increased by 1.09 times in the *X*-axis compared to the *Y*-axis.
Yield displacement (mm)	23.01	19.76	Yield displacement decreased by 14.12% in the *Y*-axis compared to the *X*-axis.
Maximum displacement (mm)	52.5	70	Maximum displacement increased by 33.33% in the *Y*-axis compared to the *X*-axis.
Ductility	2.28	3.54	Ductility increased by 55.26% in the *Y*-axis compared to the *X*-axis.
Ductility reduction factor	1.00	1.00	Ductility reduction factor was same in the *X*-axis and *Y*-directions.
Overstrength factor	16.11	14.74	Overstrength factor decreased by 8.50% in the *Y*-axis compared to the *X*-axis.
Period (sec)	0.13	0.13	Time period was the same in the *X*- and *Y*-direction.
R-factor	8.05	7.37	*R*-factor increased by the 9.22% in the *X*-axis compared to the *Y*-axis.

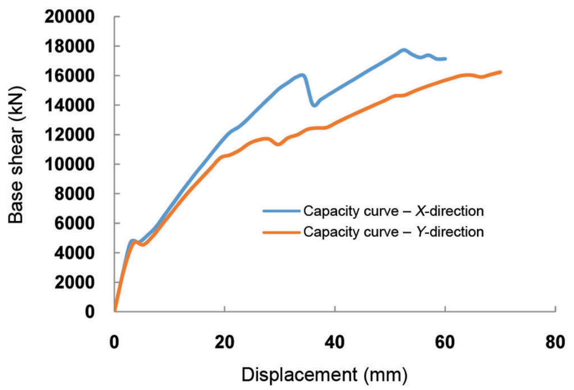

Figure 17. Pushover curves of the single-storey RC building.

in the *X*-direction, 31.43 mm in the *Y*-direction). So there is no need to retrofit the building according to the 'quadrants assessment method'.

Seismic evaluation of the single-storey RC building (model-4)

Pushover curves of the building: As shown in Figure 17, the ultimate capacity is higher in the *X*-direction compared to the *Y*-direction due to the structural configuration of the building. Table 12 shows a comparison of different parameters.

Based on Table 13, the performance points of the single-storey RC building in the *X*- and *Y*-directions (model-4) are located in the first quadrant only based on the design base shear (1101.19 kN) and threshold damage limit state (7.50 mm in the *X*-direction, 3.50 mm in the *Y*-direction). So there is no need to retrofit the building according to the 'quadrants assessment method'.

Conclusion

This study proposes a refined procedure for the seismic evaluation of RC buildings based on the combination of the 'quadrants assessment method' and 'material strain limit approach'. Herein, four existing RC buildings from the Koyna–Warna region have been seismically evaluated. The following conclusions can be drawn from this study.

The existing three-storey RC building (model-1) is vulnerable to earthquakes due to the soft storey effect. So there is a need to retrofit this structure based on the 'quadrants assessment method'. On the other hand, the three other buildings (model-2, model-3 and model-4) are found

Table 13. Performance points of the single-storey RC building in the *X*- and *Y*-directions (model-4)

	Displacement (mm)		Corresponding base shear (kN)	
Performance level	*X*-direction	*Y*-direction	*X*-direction	*Y*-direction
LS	1.88	1.87	3094.82	2969.42
CP	2.28	2.25	3680.36	3361.05

to resist earthquakes due to the absence of irregularities in them. These issues are proved using the 'quadrants assessment method' and 'material strain limit approach'. The ultimate capacity of the retrofitted three-storey RC building (model-1) increased by 1.23 times in the *X*-direction and 1.48 times in the *Y*-direction compared to the unretrofitted building due to RC jacketing of the deficient columns. The ductility parameter decreased by 15.94% and 2.31% in the *X*- and *Y*-directions respectively, due to increased stiffness. The performance point of the existing three-storey RC building (model-1) was transferred from the second quadrant to the first quadrant due to RC jacketing. The performance points of the other three RC buildings were located in the first quadrant due to their inherent structural integrity. So there is no need to retrofit these RC buildings based on the 'quadrants assessment method'.

From the present study, it can be concluded that the proposed combination of the 'quadrants assessment method' and 'Material strain limit approach' can give a rapid, reliable and refined procedure for the seismic evaluation and retrofit of any RC structure.

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

1. Ghobarah, A., Seismic assessment of existing RC structures. *Prog. Struct. Eng. Mater.*, 2000, **2**(1), 60–71; https://doi.org/10.1002/(SICI)1528-2716(200001/03)2:1<60::AID-PSE8>3.0.CO;2-O.
2. Sinha, R. and Shaw, R., The Bhuj earthquake of 26 January 2001 – consequences and future challenges. Indian Institute of Technology, Bombay and Earthquake Disaster Mitigation Research Center, Japan, 2001.
3. Sengupta, A. K., Reddy, C. S., Badari Narayanan, V. T. and Asokan, A., Seismic analysis and retrofit of existing multi-storied buildings in India – an overview with a case study. In Proceedings of the 13th World Conference on Earthquake Engineering, Vancouver, Canada, 2004.
4. Vielma, J. C., Martinez, Y., Barbat, A. H. and Oller, S., The quadrants method: a procedure to evaluate the seismic performance of existing buildings. In Proceedings of the 15 World Conference on Earthquake Engineering, Lisbon, Portugal, 2012.
5. Vielma, J. C., Barbat, A. H., Ugel, R. and Herrera, R. I., Seismic evaluation of low rise RC framed building designed according to Venezuelan codes. In *Engineering Seismology, Geotechnical and Structural Earthquake Engineering*, IntechOpen Limited, London, UK, 2013, pp. 283–300; http://dx.doi.org/10.5772/55158.
6. El-Betar S. A., Seismic vulnerability evaluation of existing RC buildings. *Housing Build. Natl. Res. Center J.*, 2018, **14**(2), 189–197; http://dx.doi.org/10.1016/j.hbrcj.2016.09.002.
7. Kontoni, D.-P. N. and Farghaly, A. A., The effect of base isolation and tuned mass dampers on the seismic response of RC high-rise buildings considering soil–structure interaction. *Earthq. Struct.*, 2019, **17**(4), 425–434; https://doi.org/10.12989/eas.2019.17.4.425.
8. Ebadi-Jamkhaneh, M., Homaioon-Ebrahimi, A. and Kontoni, D.-P. N., Numerical finite element study of strengthening of damaged reinforced concrete members with carbon and glass FRP wraps. *Comput. Concr.*, 2021, **28**(2), 137–147; http://dx.doi.org/10.12989/cac.2021.28.2.137.
9. Shendkar, M. R., Kontoni, D.-P. N., Mandal, S., Maiti, P. R. and Gautam, D., Effect of lintel beam on seismic response of reinforced concrete buildings with semi-interlocked and unreinforced brick masonry infills. *Infrastructures*, 2021, **6**(1), 1–18; https://doi.org/10.3390/infrastructures6010006.
10. Shendkar, M. R., Kontoni, D.-P. N., Mandal, S., Maiti, P. R. and Tavasoli, O., Seismic evaluation and retrofit of reinforced concrete buildings with masonry infills based on material strain limit approach. *Shock Vib.*, 2021, **2021**, 1–15; https://doi.org/10.1155/2021/5536409.
11. Shendkar, M. R., Pradeep Kumar, R., Mandal, S., Maiti, P. R. and Kontoni, D.-P. N., Seismic risk assessment of reinforced concrete buildings in Koyna–Warna region through EDRI method. *Innov. Infrastruct. Sol.*, 2021, **6**(3), 1–25; https://doi.org/10.1007/s41062-021-00505-0.
12. Shendkar, M. R., Kontoni, D.-P. N., Işık, E., Mandal, S., Maiti, P. R. and Harirchian, E., Influence of masonry infill on seismic design factors of reinforced-concrete buildings. *Shock Vib.*, 2022, **2022**, 1–15; https://doi.org/10.1155/2022/5521162.
13. Antoniou, S. and Pinho, R., Advantages and limitations of adaptive and non-adaptive force-based pushover procedures. *J. Earthq. Eng.*, 2004, **8**(4), 497–522; https://doi.org/10.1080/13632460409350498.
14. Ramaliigeswara Rao, B., *Seismic Activity – Indian Scenario*, Buddha Publisher, Hyderabad, 2015.
15. IS 1893, Criteria for earthquake resistant design of structures, Part 1: General provisions and buildings (sixth revision). Bureau of Indian Standards, New Delhi, 2016.
16. ASCE/SEI 41-06, Seismic rehabilitation of existing buildings. American Society of Civil Engineers, Virginia, USA, 2006.
17. SeismoStruct, A computer program for static and dynamic nonlinear analysis of framed structures. Seismosoft Ltd, Pavia, Italy, 2020; https://seismosoft.com/.
18. IS 456, Plain and reinforced concrete, code of practice. BIS, New Delhi, 2000.
19. Chen, L., Lu, X., Jiang, H. and Zheng, J., Experimental investigation of damage behavior of RC frame members including non-seismically designed columns. *Earthq. Eng. Eng. Vib.*, 2009, **8**(2), 301–311.
20. Aswin Prabhu, T., Seismic evaluation of 4-story reinforced concrete structure by non-linear static pushover analysis. B.Tech. thesis, National Institute of Technology, Rourkela, 2013.
21. Shendkar, M. R., Mandal, S. and Pradeep Kumar, R., Effect of lintel beam on response reduction factor of RC-infilled frames. *Curr. Sci.*, 2020, **118**(7), 1077–1086; 10.18520/cs/v118/i7/1077-1086.
22. Shendkar, M., Mandal, S., Pradeep Kumar, R. and Maiti, P. R., Response reduction factor of RC-infilled frames by using different methods. *Indian Concr. Inst. J.*, 2020, 14–23.
23. Shendkar, M. R., Pradeep Kumar, R. and Maiti, P. R., Effect of aspect ratio on response reduction factor of RC framed structures with semi-interlocked masonry and unreinforced masonry infill. *Indian Concr. J.*, 2020, **94**(12), 7–16.
24. Seismic activity in Koyna region – Annual Report. Water Resources Department, Government of Maharashtra, 2018–2019.
25. IS 15988, Seismic evaluation and strengthening of existing reinforced concrete buildings-guidelines. BIS, New Delhi, 2013.

Received 27 December 2021; re-revised accepted 23 June 2022

doi: 10.18520/cs/v123/i8/1020-1030