A refined procedure for the seismic evaluation and retrofit of reinforced concrete buildings

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Abstract: In the present study, a refined procedure for the seismic evaluation and retrofit of reinforced concrete (RC) buildings based on the "Quadrants assessment method" and "Material strain limit approach" is proposed and numerically investigated. The Quadrants assessment method involves the performance point, design base shear, and threshold damage limit state. Herein, four existing RC buildings (Model-1, Model-2, Model-3, and Model-4) are considered from the Koyna-Warna region (Zone-IV, India). These four buildings are analyzed with nonlinear static adaptive pushover analysis by using the SeismoStruct software. Based on the Quadrants assessment method, the three-storey RC building (Model-1) is retrofitted with RC jacketing, while the other three RC buildings do not need to be retrofitted. Also, the significant seismic design parameters like ductility, overstrength factor, response reduction factor, etc., are evaluated before and after the retrofit. The results depict that the combination of the "Quadrants assessment method" and "Material strain limit approach" is a rapid, reliable and refined procedure for the seismic evaluation and retrofit of RC buildings.

Keywords: Reinforced concrete buildings; Seismic evaluation; Retrofit; Quadrants assessment method; Material strain limit approach; Adaptive pushover analysis

1. Introduction

A reinforced concrete (RC) building is one of the recent trends in the construction industry. Nowadays, a natural disaster, namely an earthquake, comes at any time, so the quality of the construction should be good enough. Seismic evaluation and retrofit are the best options to avoid the loss of infrastructure and life. Most of the constructions are not able to sustain the seismic load due to their design and construction deficiency, etc. So, there is a need to go for a retrofitting option. Retrofitting can be 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. This study aims to evaluate the seismic performance of RC buildings and suggest retrofit solutions based on their deficiencies.

Ghobarah (2000)[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 (2001)[2] and Sengupta *et al.* (2004)[3] observed that pushover analysis is a simple and efficient approach for the evaluation of existing structures, and the time history analysis method is generally used for complex structures. Vielma *et al.* (2012)[4] and Vielma *et al.* (2013)[5] presented the Quadrants method to be suitable for rapid and reliable evaluation of the seismic performance of existing buildings with a low calculation effort. El-Betar (2018)[6] observed that the priority of the seismic evaluation must be given to the old and non-engineered buildings in high seismic regions. Kontoni and Farghaly (2019)[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.* (2021)[8] worked on RC column and beam members subjected to a variety of loads under damaged condition and strengthened by using carbon and glass fiber reinforced polymer (FRP) wraps. Shendkar et al. (2021)[9] worked on the effect of lintel beam on seismic performance of RC buildings with semi-interlocked and unreinforced masonry infills, and the results showed that the building shows a good seismic performance with lintel beam. Shendkar *et al.* (2021)[10] worked on the seismic evaluation and retrofit of RC buildings with masonry infills based on a newly developed material strain limit approach, and the results showed that the material strain limit approach is an effective method for the seismic assessment of structures. Shendkar et al. (2021)[11] evaluated the seismic risk assessment of RC buildings in Koyna-Warna region through the EDRI method, where the authors showed the different damage states of RC buildings based on rapid visual screening. Shendkar et al. (2022)[12] studied the influence of masonry infill on the seismic design factors of RC buildings, considering three different values of the compressive strength of the masonry infill, and the results showed that the response reduction factors (R) of all RC infilled frames were decreased when the compressive strength of the masonry infill reduced.

In the present study, a new refined seismic evaluation procedure is proposed based on the "Quadrants assessment method" and "Material strain limit approach". The results depict that the combination of the Quadrants assessment method and Material strain limit approach is a rapid, reliable and refined procedure for the seismic evaluation and retrofit of RC structures.

2. Proposed Seismic Evaluation Methods

In recent years, the application of adaptive pushover analysis has been widely used to check the nonlinear response of the structures. It represents a significant alternative solution for the nonlinear dynamic analysis of structures. In this study, advanced pushover analysis, i.e., adaptive pushover analysis, is used. Antoniou and Pinho (2004)[13] employed a force-based adaptive pushover analysis, in which the lateral load is continuously revised at every single step during the eigenvalue analysis. In the present study, the response spectrum (Figure 1) of the Koyna–Warna region is used for the spectral amplification purpose, which was obtained from the "Seismic activity - Indian Scenario" by Ramaliigeswara Rao (2015)[14].

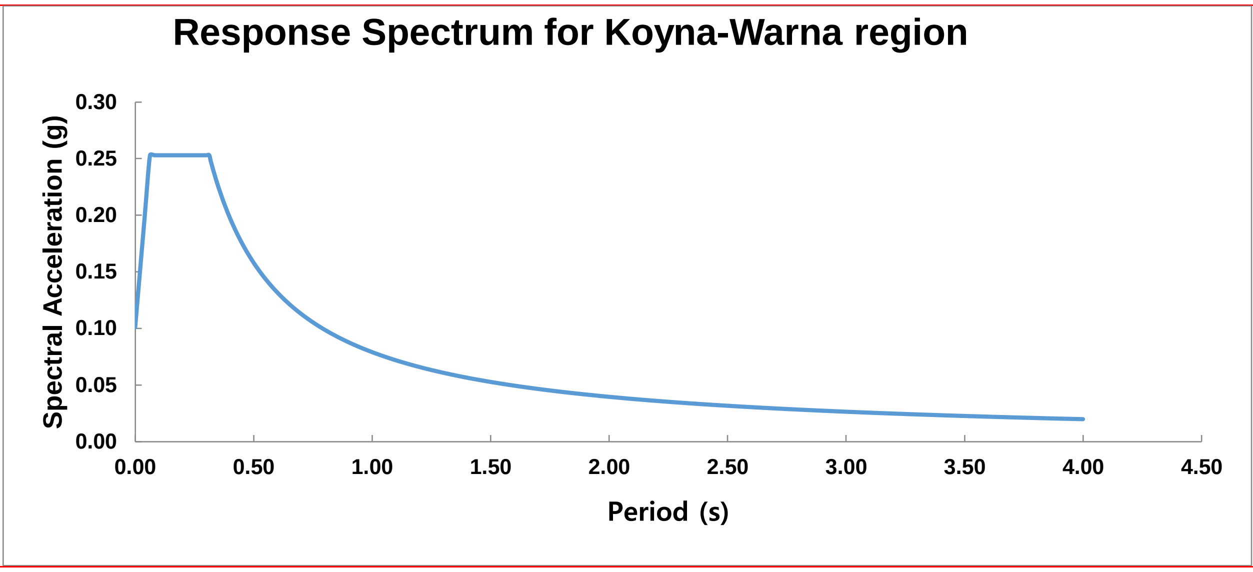


Figure 1. Acceleration Response Spectrum for Koyna-Warna Region.

2.1 Quadrants Assessment Method

Vielma *et al.* (2012)[4] and Vielma *et al.* (2013)[5] have presented the Quadrants method as an effective procedure for the evaluation of the seismic performance of existing buildings. The Quadrants method is based on the results of the nonlinear static pushover analysis, and this generates the capacity curve, which represents the overall capacity of the whole structure against lateral forces.

In this study, this method has been modified as "Quadrants assessment method" based on two structural parameters. The first one is the design base shear, obtained from the seismic weight of the structure as per IS 1893 Part-1 (2016)[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 are used to 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, as shown in Figure 2.

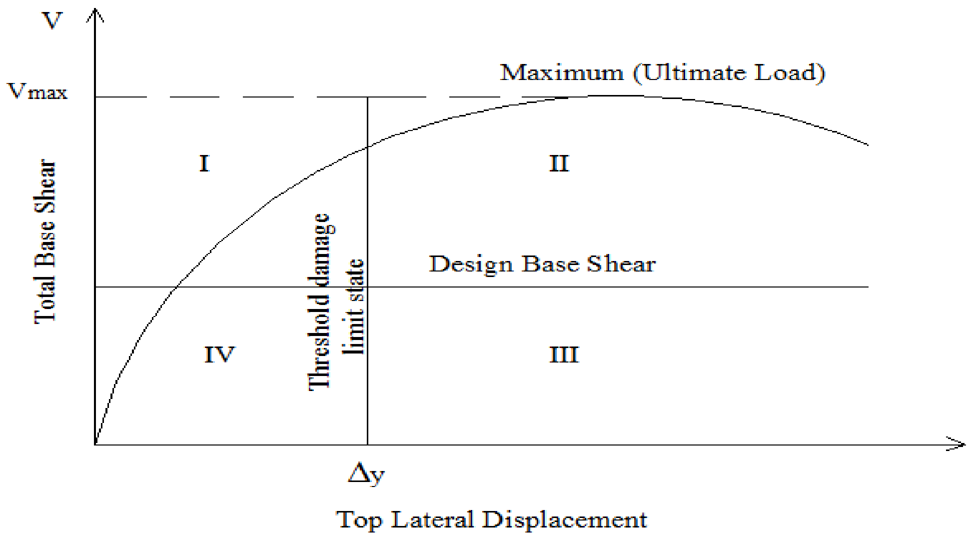


Figure 2. The capacity curve and the axes that define the Quadrants assessment method.

The performance point of the structure is calculated as per 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 by 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.

2.2 Material Strain Limits 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 in 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. Material strains are usually the best parameter for the identification of the performance state of a given structure as compared to other existing methods. It is possible in the SeismoStruct program because, in this software, the distributed inelasticity is given to each structural member, so it is easy to identify the actual damage phenomena 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: (1) crushing strain limit for unconfined concrete in beam: 0.0035[18], (2) crushing strain limit for unconfined concrete in column: 0.002[18], (3) crushing strain limit for confined concrete: 0.008[19-23], (4) yield strain limit for steel: 0.0025[17, 20-23], and (5) fracture strain limit for steel: 0.06[17, 20-23].

2.3 Refined procedure for the 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 buildings, involving the two seismic evaluation methods, namely, the “Quadrants assessment method” and “Material strain limit approach”. The Material strain limit approach is the micro-level evaluation used for the identification of deficient members. The identification of the deficient members is based on the provisions of ASCE 41-06[16] is shown in Table 1, and the RC structure is to be strengthened by using local or/and global retrofitting techniques.

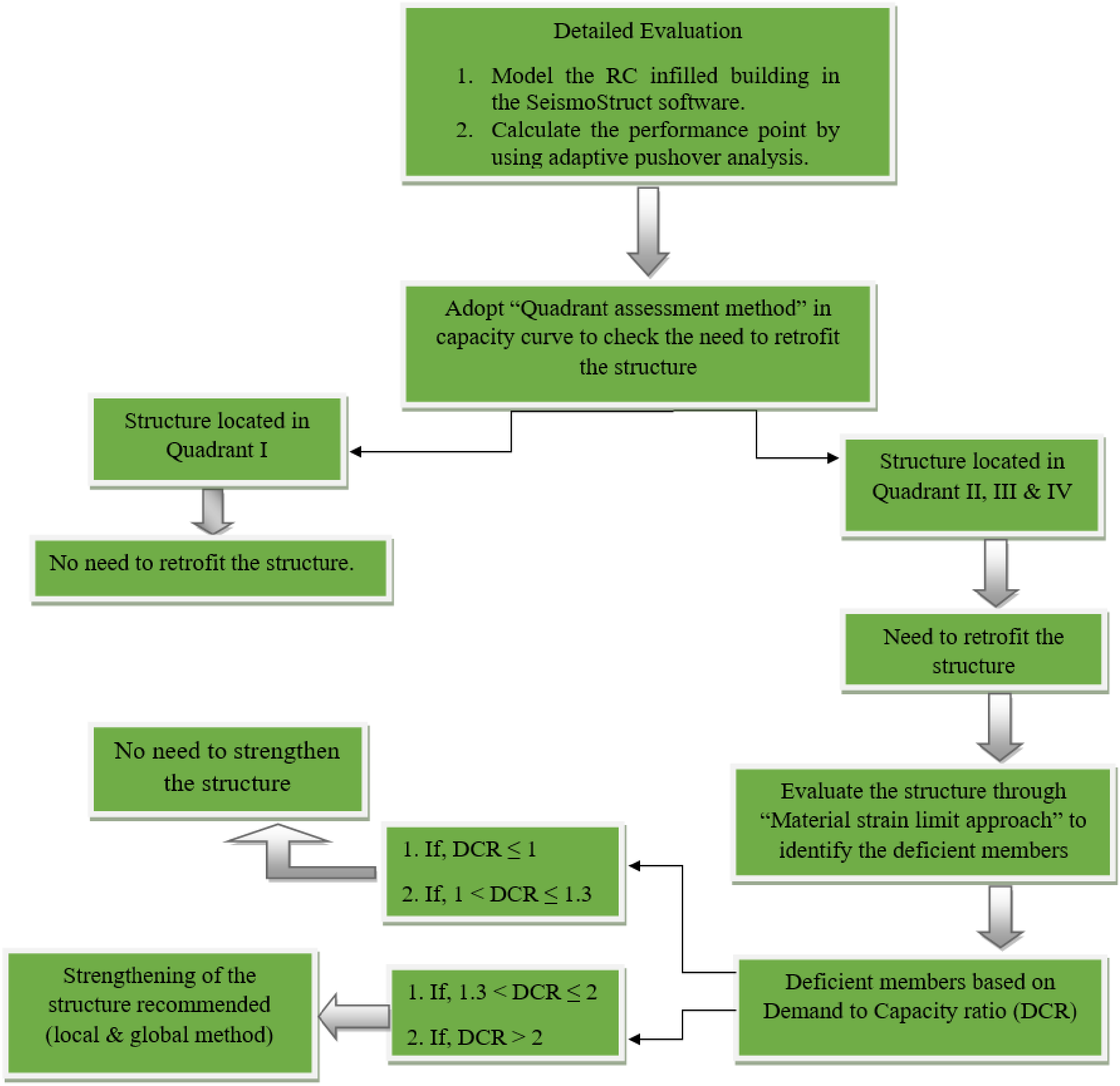


Figure 3. Flow chart of the proposed refined procedure for the seismic evaluation and retrofit of RC buildings.

117

Table 1. Criteria for Demand to Capacity Ratio

Condition	Demand to Capacity Ratio (DCR)	Remark
Safe	If, DCR ≤ 1	No need for rehabilitation
Marginally Inadequate	If, 1 < DCR ≤ 1.3	
Significant damage / failure	If, 1.3 < DCR ≤ 2	Need for rehabilitation
	If, DCR > 2	

118

The “Quadrants assessment method” is a global approach for the seismic evaluation of structures based on the performance point. The “Quadrants assessment method” checks the need for intervention/retrofit of a structure, so the rapid seismic evaluation of a structure can be possible through this method. After this evaluation, the “Material strain limit method” is the local approach for the seismic assessment of the RC structure based on the threshold strain limit of concrete and steel to identify the actual damage state of structural members, i.e., micro-level evaluation. Ultimately, the proposed combination of these two methods can provide a rapid, reliable and refined procedure for the seismic evaluation and retrofit of RC structures.

3. Seismic Evaluation of RC Buildings

India has experienced several devastating earthquakes in the past, resulting in massive damage to the buildings and huge deaths. Particularly, the Koyna-Warna region in the state of Maharashtra, India, is one of the most significant worldwide examples of reservoir-induced seismicity. The seismic activity in the Koyna-Warna region (Zone-IV) has been experienced continuously for more than 50 years. There have been nine earthquakes of $M > 5$, about 96 earthquakes of $4 \leq M < 5$, and thousands of smaller earthquakes since 1963; the integrated Koyna seismic network graph is shown in Figure 4 (Seismic activity in Koyna region, 2018-2019)[24].

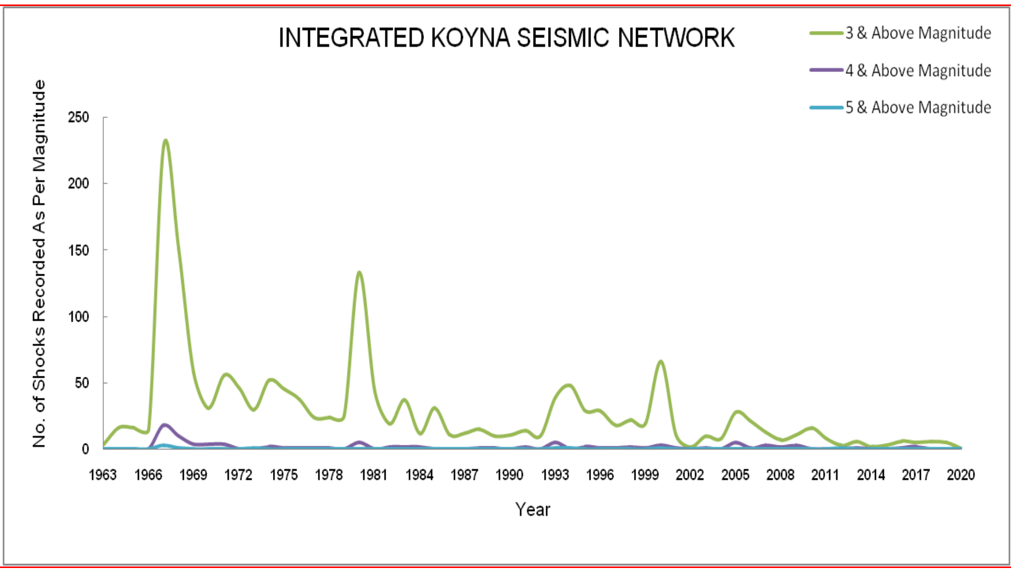


Figure 4. Integrated seismic activity of the Koyna region.

In this study, the type of soil is considered as “medium” soil. Four existing RC buildings are considered from the Koyna-Warna region. These buildings are modeled and analyzed with nonlinear static adaptive pushover analysis by using the SeismoStruct (2020)[17] software.

3.1 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 5-6), located in Zone IV (Koyna-Warna Region) as per IS 1893 Part-1:2016 code[15]. It is an open ground storey building. Table 2 shows the material and sectional details obtained from available structural drawings.

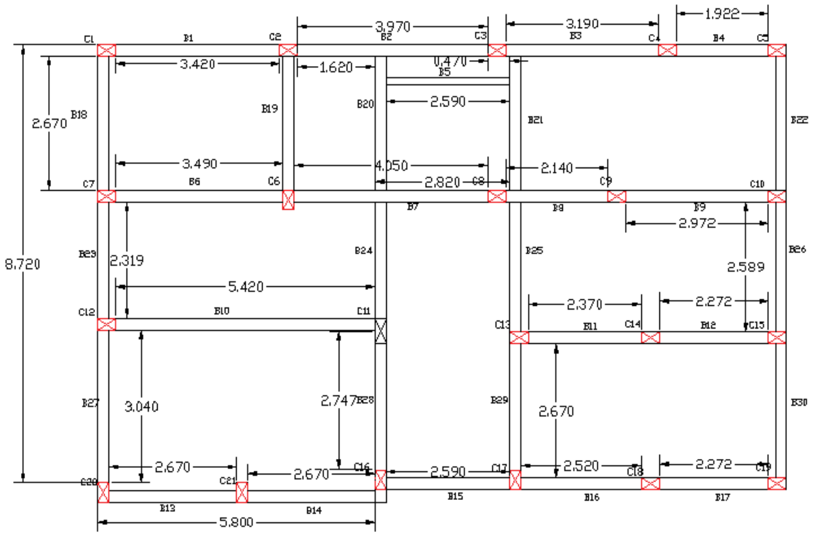


Figure 5. The plan of the three-storey RC building (Model-1) (units in m).

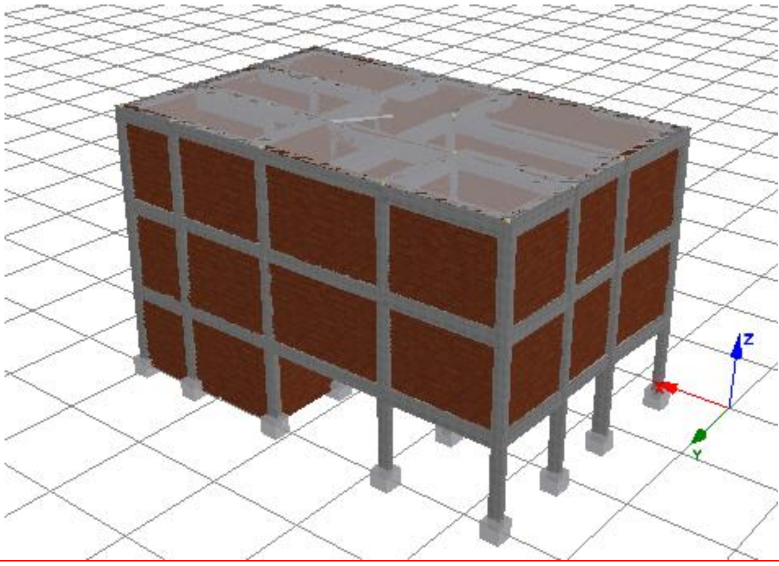


Figure 6. The model of the three-storey RC building (Model-1).

Table 2. Material and sectional details of the three-storey RC building (Model-1)

Structural system	Ordinary moment resistant RC frame
Number of total storeys	3
Height of stories (m)	3
Year of construction	2019
Name of building	Abdul Mukadam building (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) Reinforcement:	230×380, 230×450, 4-12 Ø at corners and 4-12 Ø along longer side, 6 Ø @150 c/c, 4-16 Ø at corners and 4-12 Ø along longer side, 6 Ø @150 c/c
Size of beams (mm) Reinforcement:	230×380, 230×450, 230×530, 230×750 2-12 Ø at top and bottom, 6 Ø @150 c/c, 2-12 Ø at top and bottom, 6 Ø @150 c/c, 2-16 Ø at bottom and 2-12 Ø at top, 6 Ø @150 c/c, 4-16 Ø at bottom and 2-12 Ø at top, 6 Ø @150 c/c
Thickness of slabs (mm)	125

3.2 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 7-8), located in Zone IV (Koyna-Warna Region). Table 3 shows the material and sectional details obtained from available structural drawings.

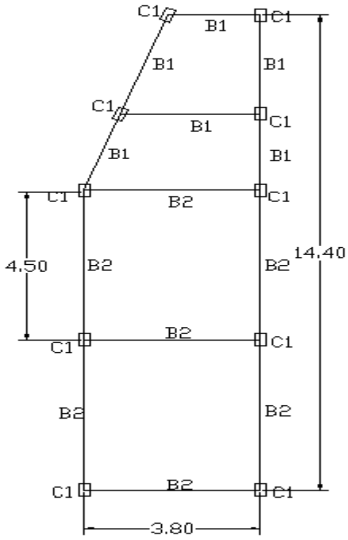


Figure 7. The plan of the four-storey RC building (Model-2) (units in m).

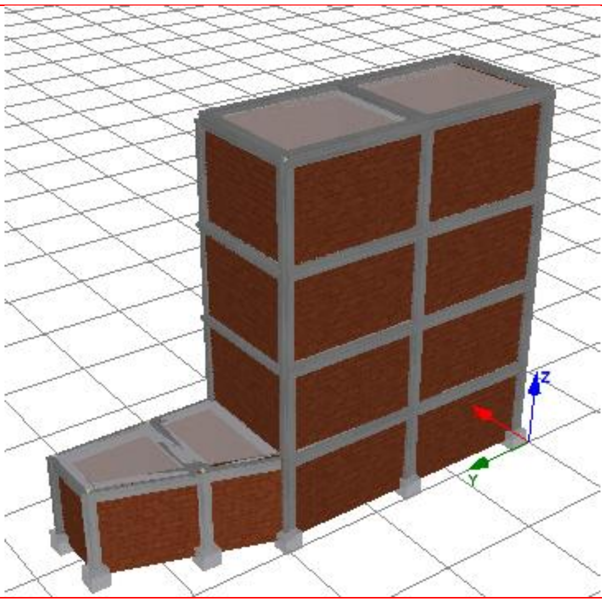


Figure 8. The model of the four-storey RC building (Model-2).

Table 3. Material and sectional details of the four-storey RC building (Model-2)

Structural system	Ordinary moment-resisting frame
Number of total storeys	4
Height of stories (m)	3
Year of construction	2007
Name of building	Dnyandeep building (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) Reinforcement:	230×380 4-16 Ø at corners and 4-16 Ø along longer side, 6 Ø @150 c/c
Size of beams (mm) Reinforcement:	230×350, 230×400 2-16 Ø at bottom and 2-12 Ø at top, 6 Ø @ 200 c/c, 2-16 Ø at bottom and 2-12 Ø at top, 6 Ø @ 200 c/c
Thickness of slabs (mm)	125

3.3 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 9-10), located in Zone IV (Koyna-Warna Region). Table 4 shows the material and sectional details obtained from available structural drawings.

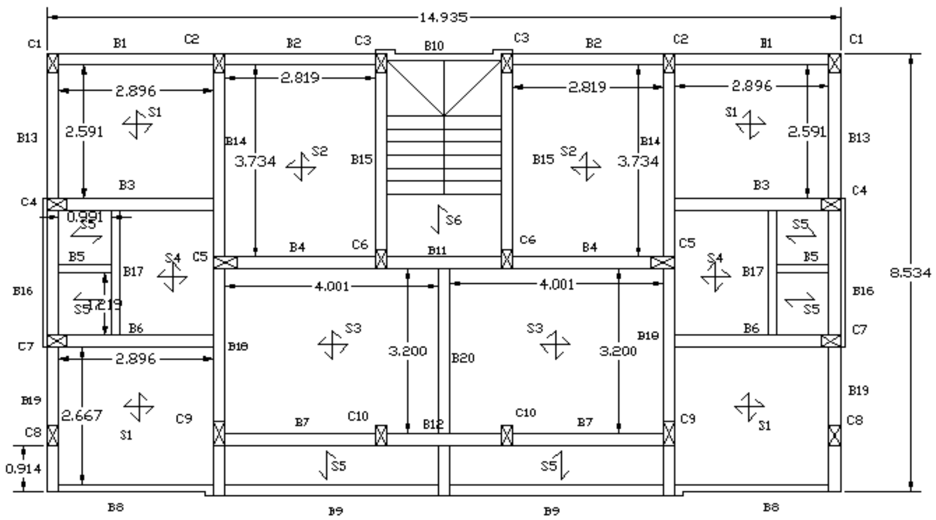


Figure 9. The plan of the four-storey RC building (Model-3) (units in m).

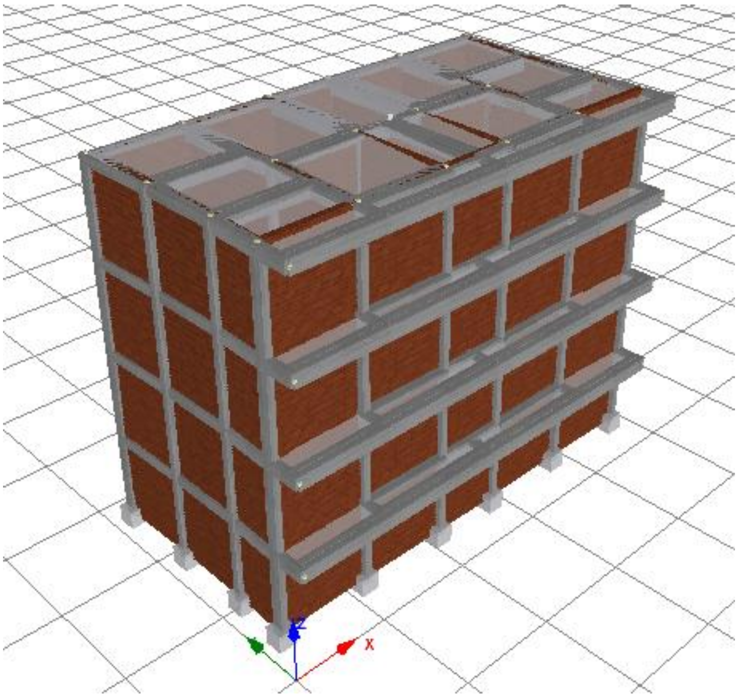


Figure 10. The model of the four-storey RC building (Model-3).

Table 4. Material and sectional details of the four-storey RC building (Model-3)

Structural system	Ordinary moment-resisting frame
Number of total storeys	4
Height of stories (m)	3
Year of construction	2018
Name of building	Ghadge Haribhau building (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 500
Size of columns (mm) Reinforcement:	230×380, 230×450 4-12 Ø at corners and 2-12 Ø along longer side, 6 Ø @150 c/c, 4-16 Ø at corners and 4-16 Ø along longer side, 6 Ø @150 c/c
Size of beams (mm) Reinforcement:	230×300, 230×380, 230×450 2-12 Ø at bottom and 2-12 Ø at top, 6 Ø @ 150 c/c, 2-12 Ø at bottom and 2-12 Ø at top, 6 Ø @ 150 c/c, 2-12 Ø at bottom and 2-12 Ø at top, 6 Ø @ 150 c/c
Thickness of slabs (mm)	150

3.4 Single-storey RC building in the Koyna-Warna Region (Model-4)

The fourth building presented in this study is a school ordinary moment-resisting RC framed building (Figures 11-12), located in Zone IV (Koyna-Warna Region). Table 5 shows the material and sectional details obtained from available structural drawings.

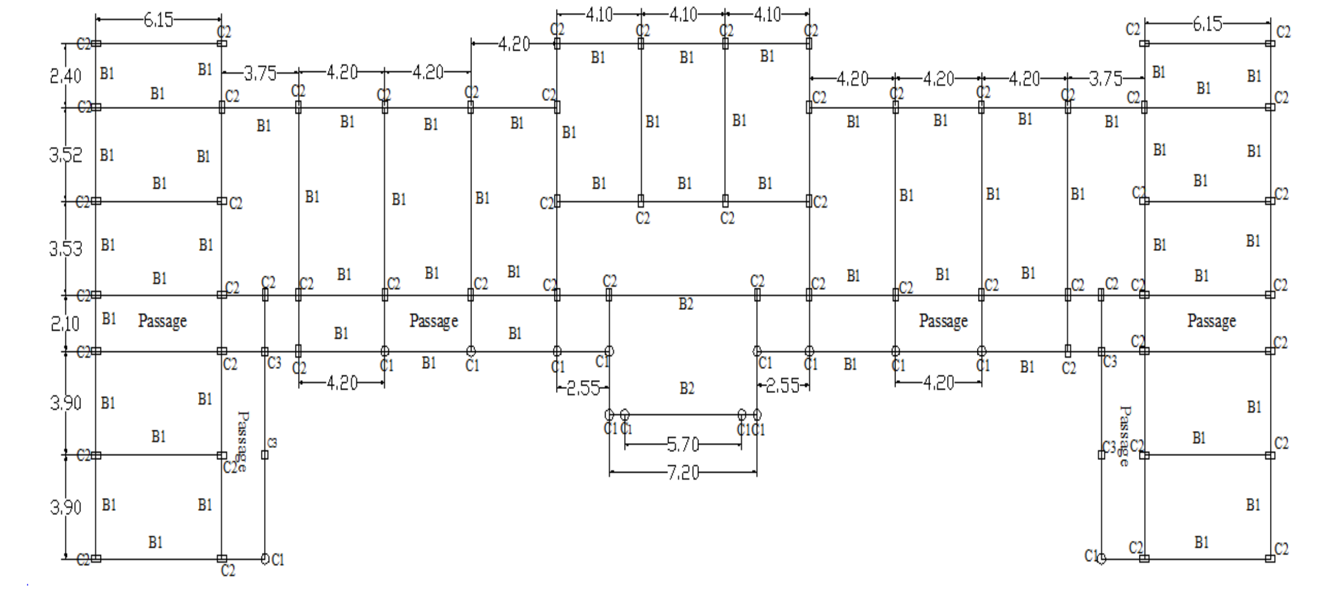


Figure 11. The plan of the Single-storey RC building (Model-4) (units in m).

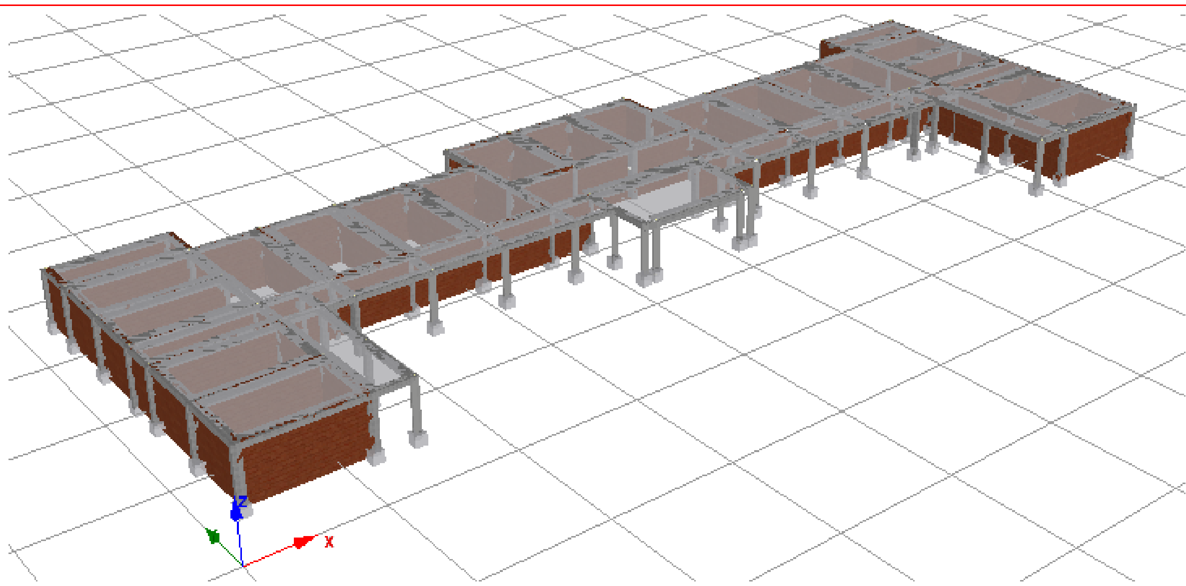


Figure 12. The model of the single-storey RC building (Model-4).

Table 5. Material and sectional details of the single-storey RC building (Model-4)

Structural system	Ordinary moment-resisting frame
Number of total storeys	1
Height of stories (m)	3.1
Year of construction	2007
Name of building	Guruvarya Lalasaheb Patankar Vidyalay (School building)
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) Reinforcement:	250×450, 300×300, 400 mm dia. circular column 4-16 Ø at corners and 2-12 Ø along longer side, 8 Ø @180 c/c, 4-16 Ø at corners, 8 Ø @170 c/c, 8-18 Ø at peripheral, 8 Ø @150 c/c
Size of beams (mm) Reinforcement:	250×300, 250×400 2-20 Ø at bottom and 2-12 Ø at top, 8 Ø @ 200 c/c, 2-20 Ø at bottom and 2-12 Ø at top, 8 Ø @ 200 c/c
Thickness of slabs (mm)	150

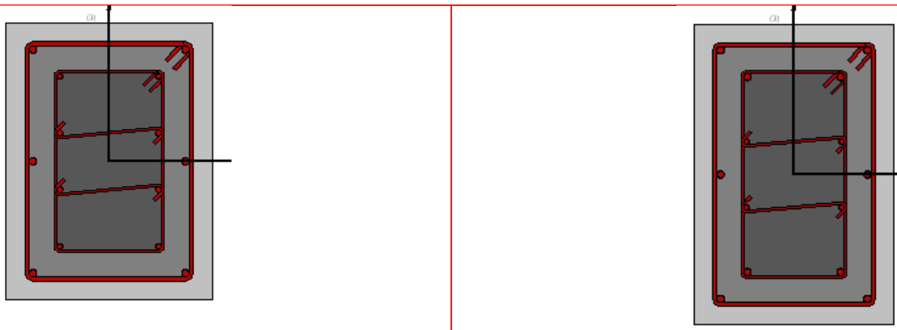
4. Retrofit Strategy

As it will be shown in section 5, the three-storey RC building (Model-1) needs to be retrofitted.

A retrofit strategy in accordance with IS 15988:2013[25] is used to strengthen a structure based on its current deficiencies. Several retrofit strategies may be selected as a retrofit scheme for the structure:

1. Local retrofit: RC jacketing, steel jacketing, FRP sheet wrapping, etc.
2. Global retrofit: Addition of infills, shear walls, steel braces, energy dissipation devices, etc.

Among the above different strategies, RC jacketing is used for the deficient column members having a crush of the confined concrete and fractured steel failure. In this retrofit technique, the M25 concrete is used for jacketing, and the addition of steel is used at the corners and middle (6 no. of 16 mm diameter steel) and 8 mm diameter of stirrups used at 100 mm spacing c/c. The size of the retrofitted columns is 430×580 mm and 430×650 mm, as shown in Figures 13(a) and 13(b), respectively. Also, the retrofitted plan is shown in Figure 14.



(a) (b)

Figure 13. The cross-sections of the columns after the retrofit: (a) 430×580 mm; (b) 430×650 mm.

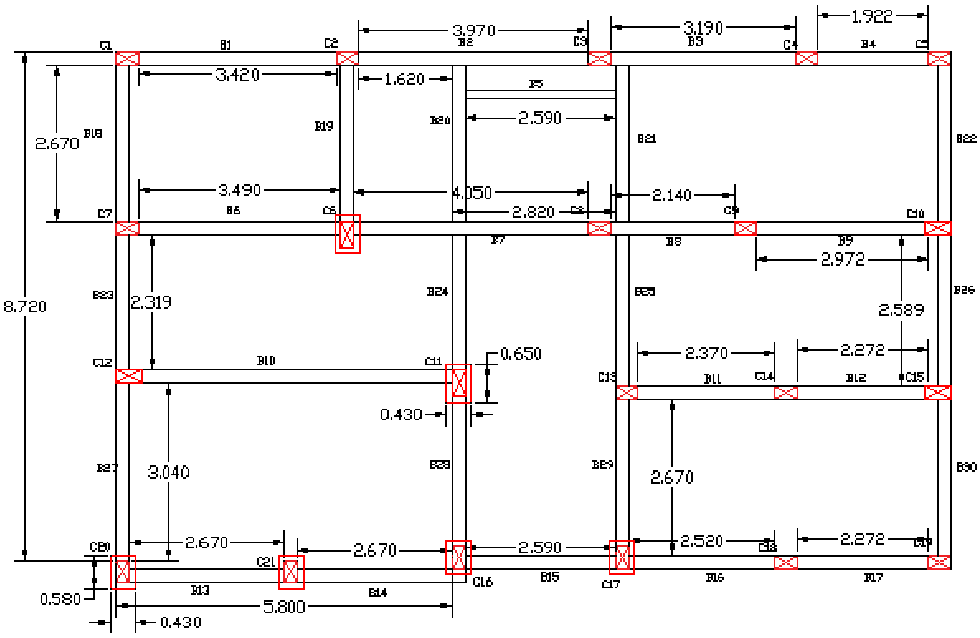


Figure 14. Retrofitted plan of Model-1 (units in m).

5. Results and Discussion

5.1 Seismic Investigation and Retrofit of the three-Storey RC Building (Model-1)

5.1.1 Pushover curves of the three-storey RC building before and after the retrofit

As shown in Figure 15, the ultimate capacity of the building is increased after the retrofit in the X as well as the Y direction, and the remaining parameters are discussed in Table 6.

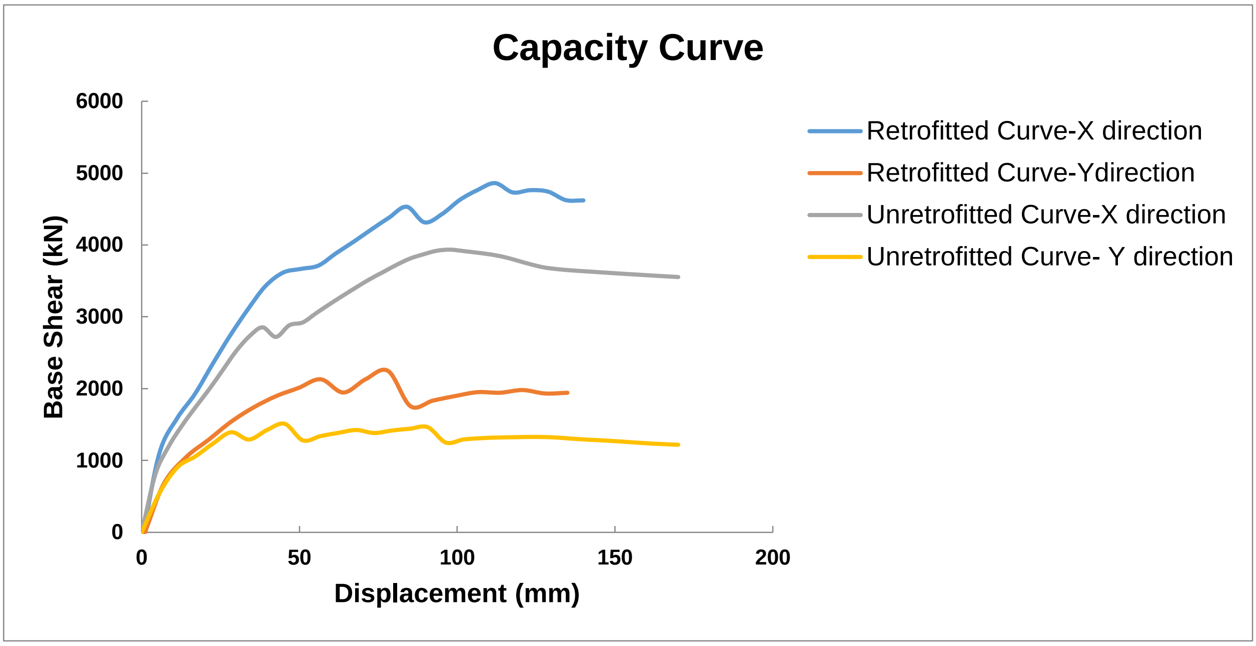


Figure 15. Pushover curve of the three-storey RC building with and without retrofit.

Figure 16 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 a displacement of 4.25 mm. The first yielding of steel occurred at a base shear of 1983.86 kN and a displacement of 21.25 mm. The first crushing of the unconfined concrete column occurred at a base shear of 2247.24 kN and a displacement of 25.5 mm. And the first crushing of confined concrete occurred at a base shear of 3868.66 kN and a displacement of 89.25 mm.

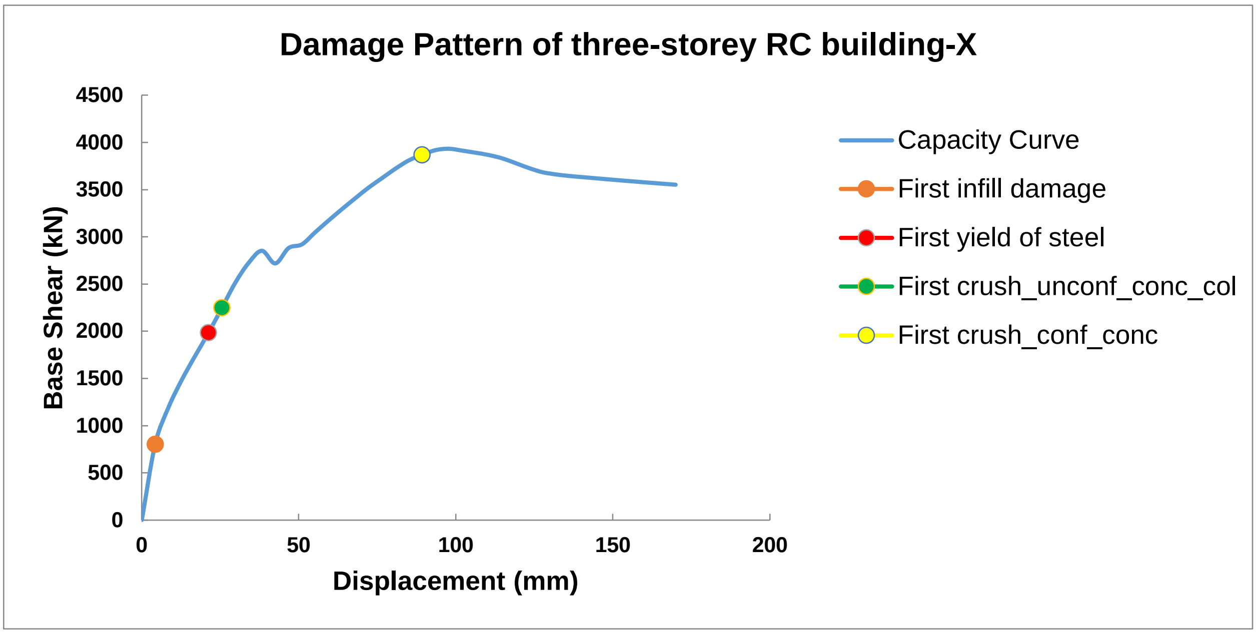


Figure 16. Damage pattern of the three-storey RC building without retrofit in the X direction.

Figure 17 shows the damage pattern of the three-storey RC building without retrofit in the Y direction (Model-1). The first infill damage and the first yielding of steel occurred at a base shear of 551.28 kN and a displacement of 5.67 mm. The first crushing of the unconfined concrete beam occurred at a base shear of 907.55kN and a displacement of 11.33 mm. The first crushing of the unconfined concrete column occurred at a base shear of 1240.44kN and a displacement of 22.67 mm, the first fracture of steel occurred at a base shear of 1393.48 kN and a displacement of 28.33 mm, and the first crushing of confined concrete occurred at a base shear of 1417.97 kN and a displacement of 79.33 mm.

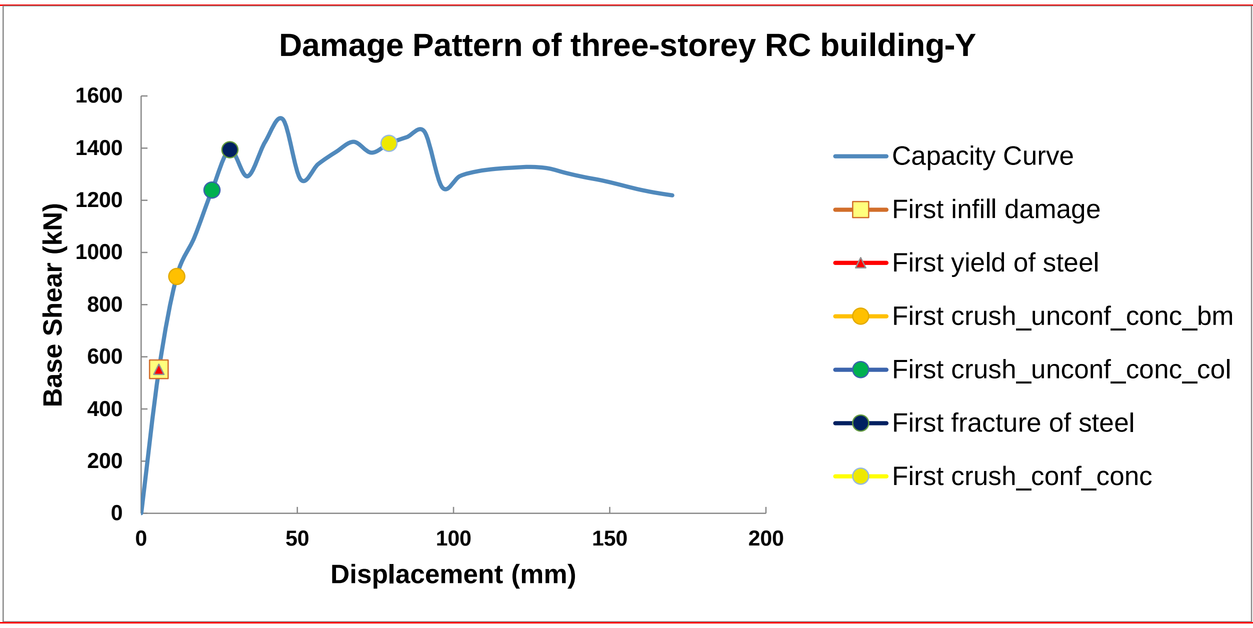


Figure 17. Damage pattern of the three-storey RC building without retrofit in the Y direction.

Table 6 Comparison of different parameters of the three-storey RC building (Model-1)					
Parameters	Before retrofit		After retrofit		Remarks
	In X-axis	In Y-axis	In X-axis	In Y-axis	
Ultimate capacity (kN)	3933.15	1510.65	4861.01	2244.71	After the retrofit, the ultimate capacity is increased by1.23 times in X-axis and 1.48 times in Y-axis.
Yield displacement (mm)	26.40	13.10	36.06	23.12	After the retrofit, the yield displacement is increased by 1.36 times in X-axis and 1.76 times in Y-axis.
Maximum Displacement (mm)	97.75	45.33	112	78.10	After the retrofit, the maximum displacement is increased by1.14 times in X-axis and 1.72 times in Y-axis.
Ductility	3.70	3.46	3.11	3.38	After the retrofit, the ductility is decreased by 15.94% in X-axis and 2.31% in the Y-axis.
Ductility Reduction Factor	2.53	2.43	2.28	2.40	After the retrofit, the ductility reduction factor is decreased by 9.88% in X-axis and 1.23 % in Y-axis.
Overstrength factor	7.77	2.99	9.47	4.37	After the retrofit, the overstrength factor is increased by 1.21 times in the X-axis and 1.46 times in Y-axis.
Time period (s)	0.39	0.39	0.34	0.34	After the retrofit, the time period is decreased by 12.82 % in X-axis and Y-axis.
R-factor	9.82	3.63	10.79	5.25	After the retrofit, the R-factor is increased by 1.09 times in X-axis and 1.45 times in Y-axis.

5.1.2 Performance point of the three-storey RC 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 the retrofit of a structure depends on the location of the performance point in the "Quadrants assessment method". In this study, the performance point is calculated based on ASCE 41-06[16].

Based on Table 7, the performance points before the retrofit in X and Y directions are located in the Ist and IInd Quadrants, respectively, as shown in Figure 18 and Figure 19, so there is a need to retrofit the building according to the "Quadrants assessment method".

Table 7 Performance points of the three-storey RC building before the retrofit in X and Y directions (Model-1)				
Performance level	Displacement (mm)		Corresponding Base Shear (kN)	
	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

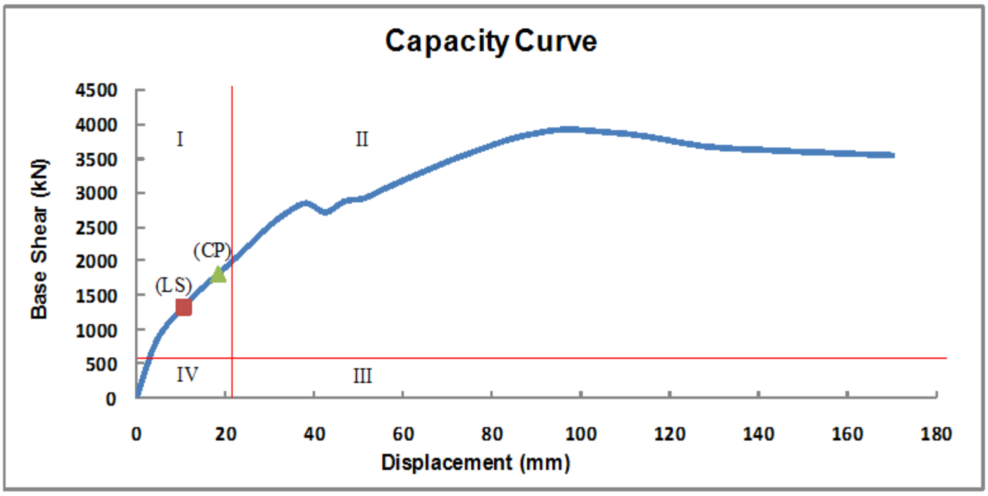


Figure 18. Location of performance points of the three-storey RC building before the retrofit in X direction.

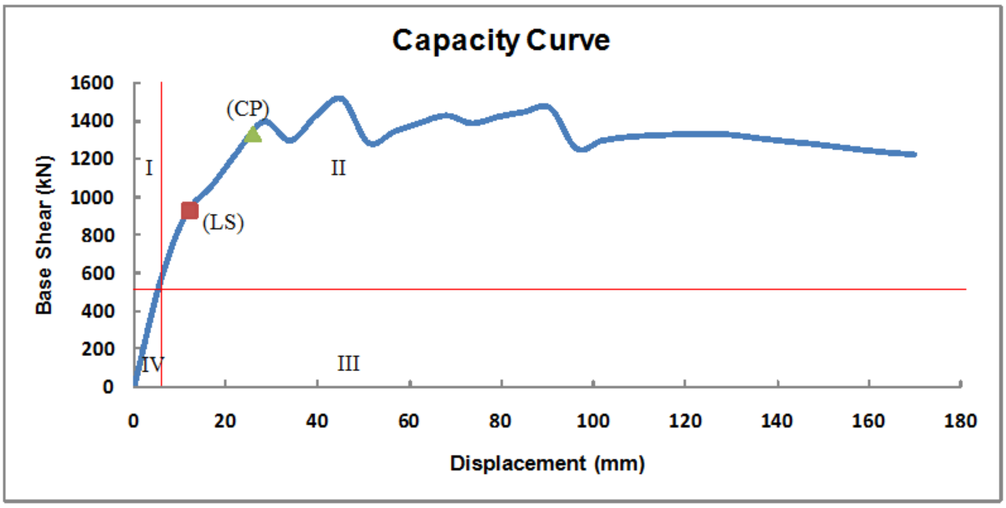


Figure 19. Location of performance points of the three-storey RC building before the retrofit in Y direction.

Based on Table 8, the performance points after the retrofit in the X and Y direction are located in the Ist Quadrant, as shown in Figure 20 and Figure 21, so the building is in safe mode after the retrofit according to the "Quadrants assessment method".

Table 8 Performance points of the three-storey RC building after the retrofit in X and Y directions (Model-1)

Performance level	Displacement (mm)		Corresponding Base Shear (kN)	
	X direction	Y direction	X direction	Y direction
Life Safety	7.62	7.9	1278.68	705.53
Collapse Prevention	13.53	17.85	1725.63	1171.97

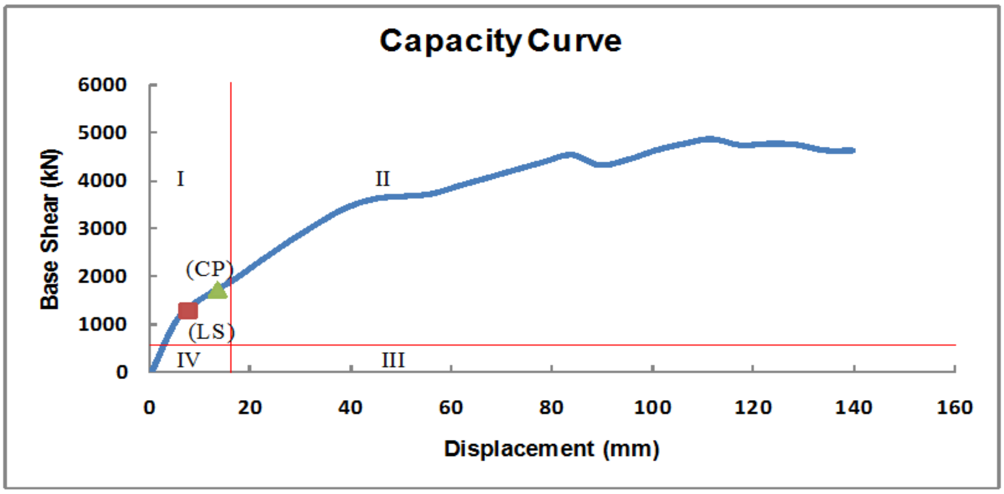


Figure 20. Location of performance points of the three-storey RC building after the retrofit in X direction.

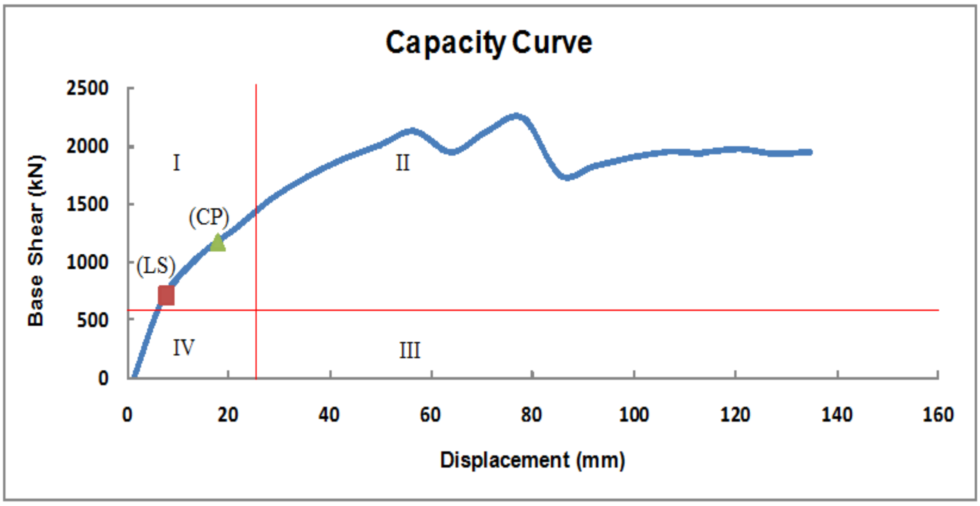


Figure 21. Location of performance points of the three-storey RC building after the retrofit in Y direction.

5.2 Seismic Investigation of the Four-Storey RC Building (Model-2)

5.2.1 Pushover curves of the four-storey RC building

As shown in Figure 22, the ultimate capacity of the building is higher in the Y direction as compared to the X direction due to the structural configuration of the building, and the remaining parameters are discussed in Table 9.

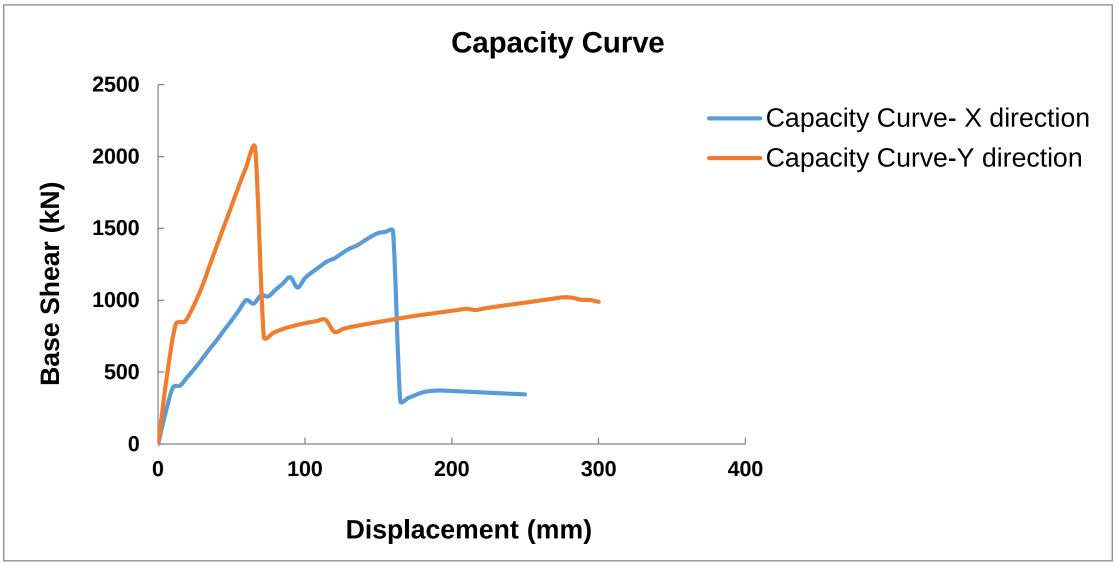


Figure 22. Pushover curves of the four-storey RC building.

Figure 23 shows the damage pattern of the four-storey RC building in the X direction. The first infill damage occurred at a base shear of 390.85 kN and displacement of 9.90 mm. The first yielding of steel occurred at a base shear of 1000.78 kN and displacement of 61.76 mm, and the first crushing of the unconfined concrete column occurred at a base shear of 1000.78 kN and displacement of 61.76 mm.

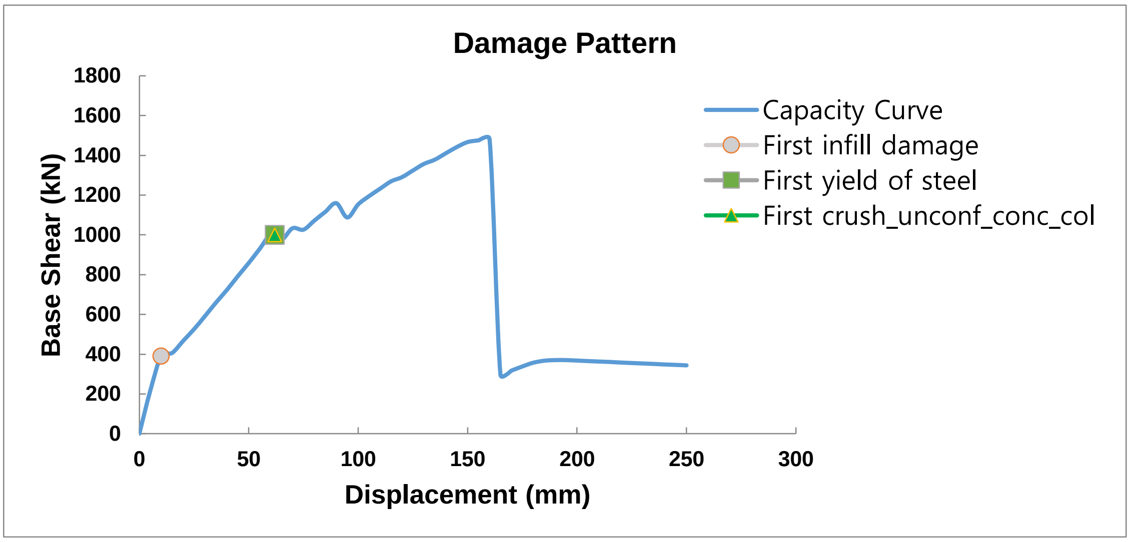


Figure 23. Damage pattern of the four-storey RC building in the X direction.

Figure 24 shows the damage pattern of the four-storey RC building in the Y direction. The first infill damage occurred at a base shear of 833.03 kN and displacement of 12 mm. The first yielding of steel and the first crushing of the unconfined concrete column occurred at a base shear of 1601.07 kN and displacement of 48 mm. The first crush of confined concrete occurred at a base shear of 814.94 kN and displacement of 90 mm, and the first fracture of steel occurred at a base shear of 906.21 kN and displacement of 186 mm.

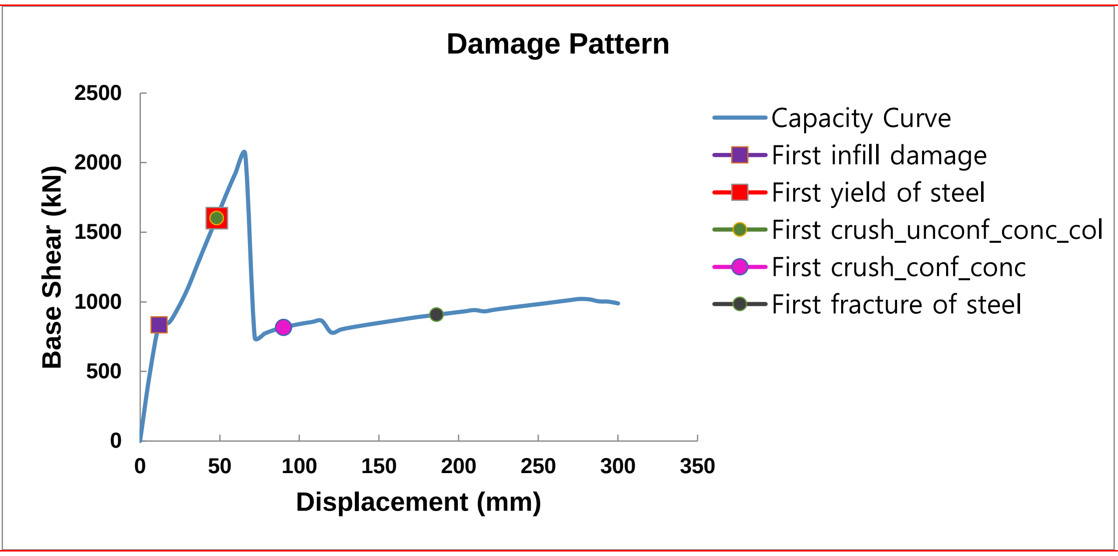


Figure 24. Damage pattern of the four-storey RC building in the Y direction.

Table 9. Comparison of different parameters of the four-storey RC building (Model-2)

Parameters			Remarks
	In X-axis	In Y-axis	
Ultimate capacity (kN)	1482.71	2060.55	The ultimate capacity is increased by 1.38 times in Y-axis as compared to X-axis
Yield displacement (mm)	63.85	47.69	The yield displacement is decreased by 25.30% in Y-axis as compared to X-axis
Maximum Displacement (mm)	160	66.00	The maximum displacement is decreased by 58.75 % in Y-axis as compared to X-axis
Ductility	2.51	1.38	The ductility is decreased by 45.02 % in Y-axis as compared to X-axis
Ductility Reduction Factor	2.00	1.33	The ductility reduction factor is decreased by 33.5 % in Y-axis as compared to X-axis
Overstrength factor	5.26	7.31	The overstrength factor is increased by 38.97 % in Y-axis as compared to X-axis
Period (s)	0.41	0.41	The time period is same in X and Y direction
R-factor	5.26	4.86	The R-factor is increased by 8.23 % in X-axis as compared to Y-axis

Based on Table 10, the performance points of the four-storey RC building in X and Y directions (Model-2) are located in the I[st] 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 as per the "Quadrants assessment method".

Table 10. Performance points of the four-storey RC building in X and Y directions (Model-2)

Performance level	Displacement (mm)		Corresponding Base Shear (kN)	
	X direction	Y direction	X direction	Y direction
Life Safety	16.5	14.49	424.58	839.58
Collapse Prevention	27.13	23.44	554.19	947.49

5.3 Seismic Investigation of the Four-Storey RC Building (Model-3)

5.3.1 Pushover curves of the four-storey RC building

As shown in Figure 25, the ultimate capacity of the building is higher in the X direction as compared to the Y direction due to the structural configuration of the building, and the remaining parameters are discussed in Table 11.

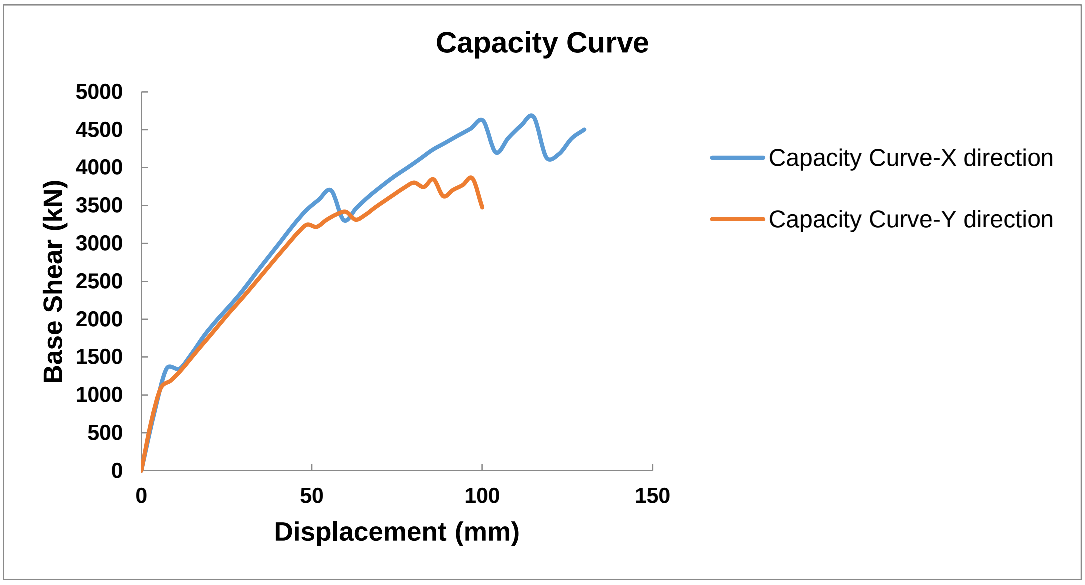


Figure 25. Pushover curves of the four-storey RC building.

Figure 26 shows the damage pattern of the four-storey RC building in the X direction. The first infill damage occurred at a base shear of 1348.41kN and displacement of 7.43 mm. The first yielding of steel occurred at a base shear of 2178.67 kN and displacement of 26 mm. The first crushing of the unconfined concrete column occurred at a base shear of 2809.10 kN and displacement of 37.14 mm. The first crushing of the unconfined concrete beam occurred at base shear 3237.65 kN and displacement of 44.57 mm, and the first crushing of confined concrete occurred at base shear 4618.11 kN and displacement of 100.29 mm.

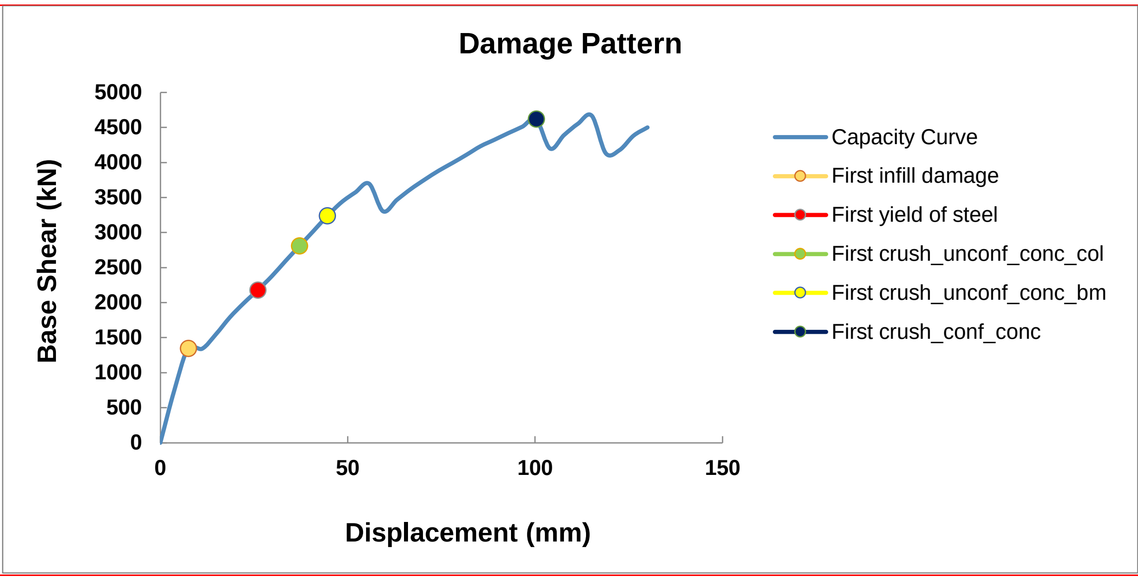


Figure 26. Damage pattern of the four-storey RC building in the X direction.

Figure 27 shows the damage pattern of the four-storey RC building in the Y direction. The first infill damage occurred at a base shear of 1091.62 kN and displacement of 5.71 mm. The first yielding of steel occurred at a base shear of 2374.34 kN and displacement of 31.43 mm. The first crushing of the unconfined concrete column occurred at a base shear of 2527.10 kN and displacement of 34.29 mm, and the first crushing of the unconfined concrete beam occurred at a base shear of 3621.97 kN and displacement of 88.57 mm.

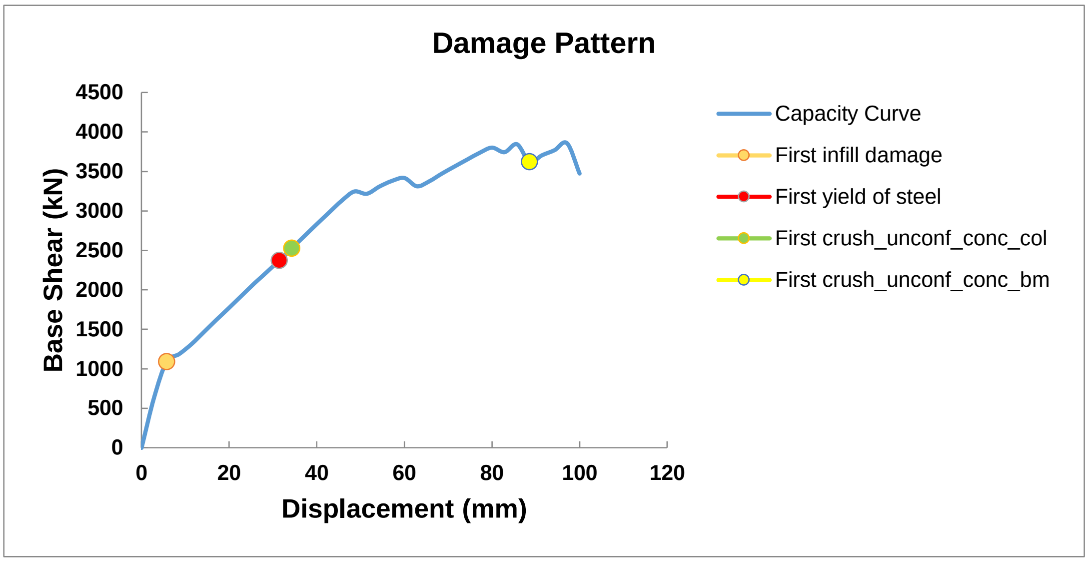


Figure 27. Damage pattern of the four-storey RC building in the Y direction.

Table 11. Comparison of different parameters of the four-storey RC building (Model-3)

Parameters			Remarks
	In X-axis	In Y-axis	
Ultimate capacity (kN)	4667.1	3857.04	The ultimate capacity increases by 1.21 times in X-axis as compared to Y-axis
Yield displacement (mm)	43.50	40.14	The yield displacement decreases by 7.72 % in Y-axis as compared to X-axis
Maximum Displacement (mm)	115.14	97.14	The maximum displacement decreases by 15.63 % in Y-axis as compared to X-axis
Ductility	2.65	2.42	The ductility decreases by 8.67 % in Y-axis as compared to X-axis
Ductility Reduction Factor	2.07	1.96	The ductility reduction factor decreases by 5.31 % in Y-axis as compared to X-axis
Overstrength factor	6.11	5.05	The overstrength factor increases by 21% in X-axis as compared to Y-axis
Period (s)	0.36	0.36	The time period is same in X and Y direction
R-factor	6.32	4.95	The R-factor increases by 27.67 % in X-axis as compared to Y-axis

Based on Table 12, the performance points of the four-storey RC building in X and Y directions (Model-3) are located in the Ist Quadrant only based on the design base shear (763.57 kN) and threshold damage limit state (26 mm in the X direction, 31.43 mm in the Y direction), so there is no need to retrofit the building as per the “Quadrants assessment method”.

Table 12. Performance points of the four-storey RC building in X and Y directions (Model-3)				
Performance level	Displacement (mm)		Corresponding Base Shear (kN)	
	X direction	Y direction	X direction	Y direction
Life Safety	11.52	11.61	1342.10	1316
Collapse Prevention	20.02	20.73	1870.09	1813.71

5.4 Seismic Investigation of the Single-Storey RC Building (Model-4)

5.4.1 Pushover curves of the single-storey RC building

As shown in Figure 28, the ultimate capacity of the building is higher in the X direction as compared to the Y direction due to the structural configuration of the building, and the remaining parameters are discussed in Table 13.

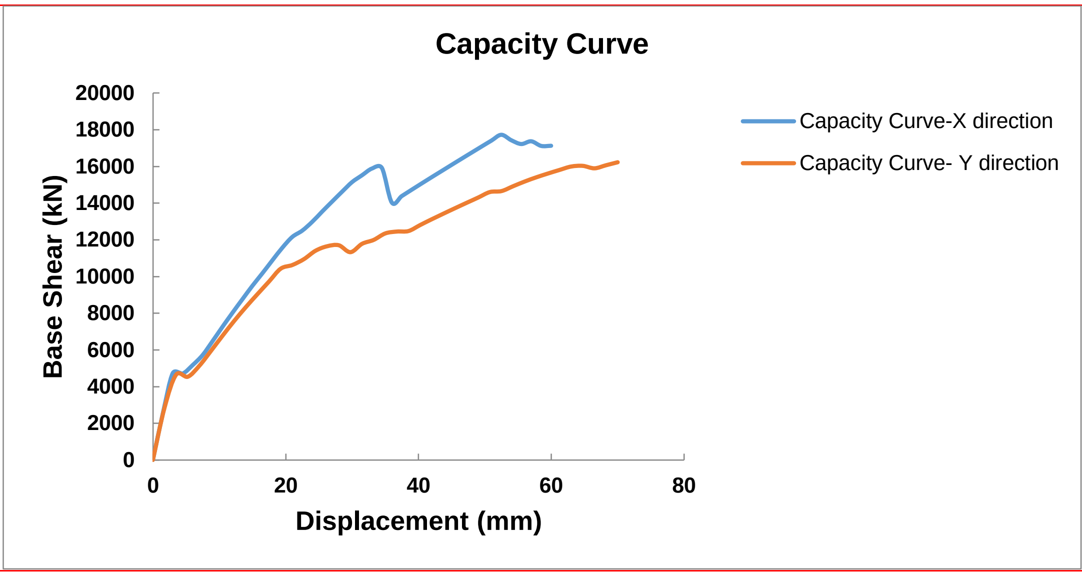


Figure 28. Pushover curves of the single-storey RC building.

Figure 29 shows the damage pattern of the single-storey RC building in the X direction. The first infill damage occurred at a base shear of 4734.32 kN and displacement of 3 mm. The first yielding of steel occurred at a base shear of 5721.94 kN and displacement of 7.50 mm. The first crushing of the unconfined concrete column occurred at a base shear of 8030.94 kN and displacement of 12 mm. The first crushing of the unconfined concrete beam occurred at a base shear of 14629.58 kN and displacement of 28.50 mm, and the first crushing of confined concrete occurred at a base shear of 17381.19 kN and displacement of 57 mm.

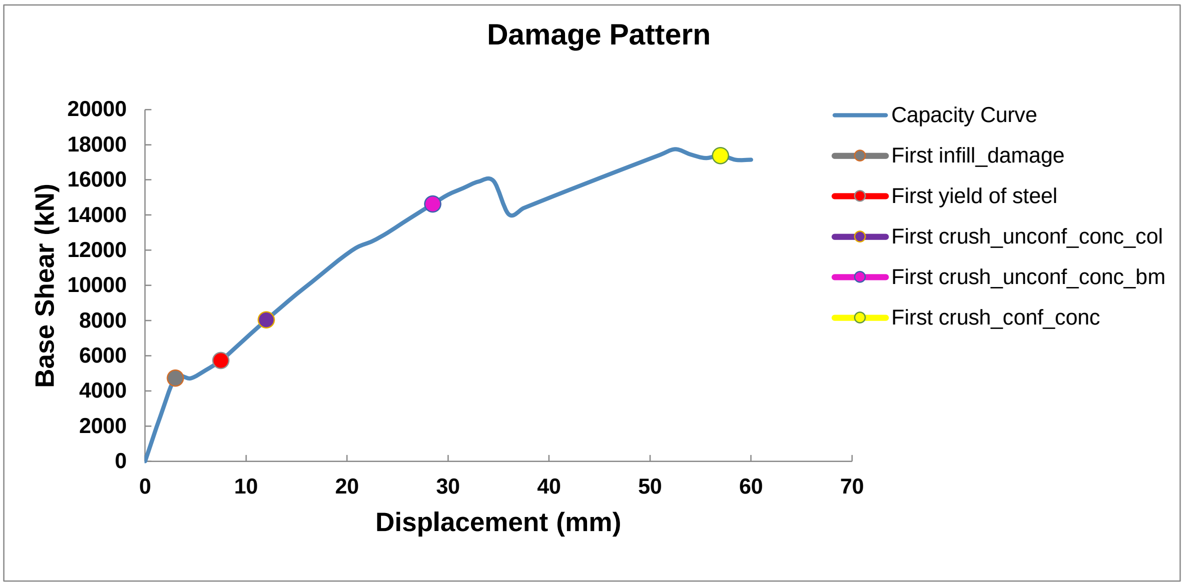


Figure 29. Damage pattern of the single-storey RC building in the X direction.

Figure 30 shows the damage pattern of the single-storey RC building in the Y direction. The first infill damage and the first yielding of steel occurred at a base shear of 4649.33 kN and displacement of 3.50 mm. The first crushing of the unconfined concrete column occurred at a base shear of 9040.66 kN and displacement of 15.75 mm, and the first crushing of the unconfined concrete beam occurred at a base shear of 11706.41 kN and displacement of 28 mm.

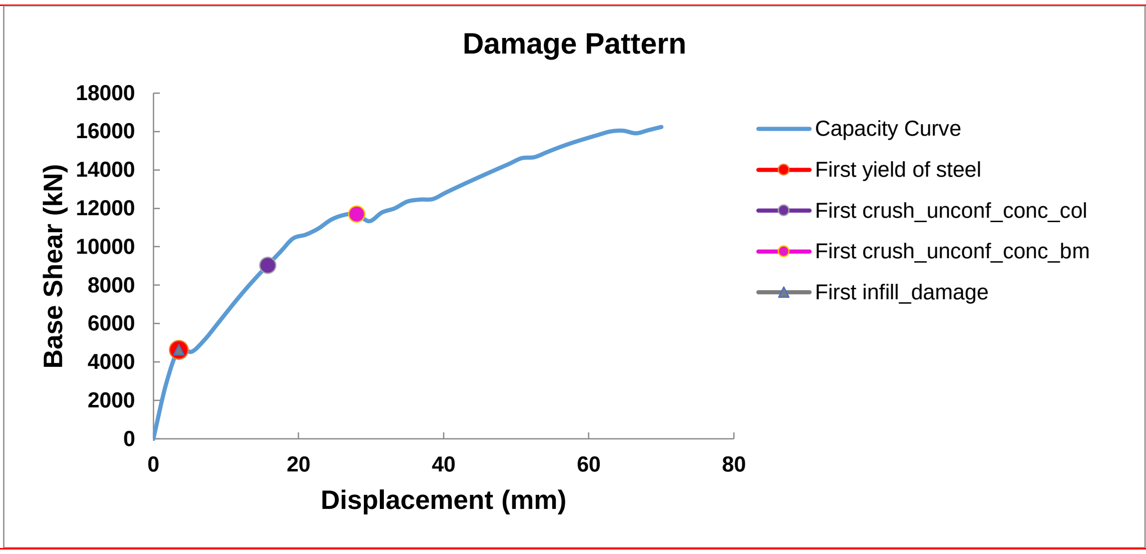


Figure 30. Damage pattern of the single-storey RC building in the Y direction.

Table 13. Comparison of different parameters of the single-storey RC building (Model-4)			
Parameters			Remarks
	In X-axis	In Y-axis	
Ultimate capacity (kN)	17735.47	16232.99	The ultimate capacity increases by 1.09 times in X-axis as compared to Y-axis
Yield displacement (mm)	23.01	19.76	The yield displacement decreases by 14.12% in Y-axis as compared to X-axis
Maximum Displacement (mm)	52.5	70	The maximum displacement increases by 33.33 % in Y-axis as compared to X-axis
Ductility	2.28	3.54	The ductility increases by 55.26% in Y-axis as compared to X-axis
Ductility Reduction Factor	1.00	1.00	The ductility reduction factor is same in X-axis and Y-axis
Overstrength factor	16.11	14.74	The overstrength factor decreases by 8.50% in Y-axis as compared to X-axis
Period (s)	0.13	0.13	The time period is same in X and Y direction
R-factor	8.05	7.37	The R-factor increases by 9.22% in X-axis as compared to Y-axis

Based on Table 14, the performance points of the single-storey RC building in X and Y directions (Model-4) are located in the Ist 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 as per the "Quadrants assessment method".

Table 14. Performance points of the single-storey RC building in X and Y directions (Model-4)				
Performance level	Displacement (mm)		Corresponding Base Shear (kN)	
	X direction	Y direction	X direction	Y direction
Life Safety	1.88	1.87	3094.82	2969.42
Collapse Prevention	2.28	2.25	3680.36	3361.05

6. Conclusions

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 different existing RC buildings from the Koyna-Warna region are seismically evaluated. The following conclusions can be drawn:

The three-storey RC existing 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 to resist earthquakes due to the absence of irregularities in these structures. These issues are proved through the “Quadrants assessment method” and “Material strain limit approach”. The ultimate capacity of the retrofitted three-storey RC building (Model-1) is increased by 1.23 times in the X direction and 1.48 times in the Y direction, respectively, as compared to the unretrofitted building, due to the RC jacketing of the deficient columns, and the ductility parameter is decreased by 15.94 % and 2.31 % in X and Y directions, respectively, due to the increased stiffness. The performance point of the three-storey RC existing building (Model-1) is transferred from the II^{nd} Quadrant to the I^{st} Quadrant due to the application of RC jacketing. The performance points of the other three RC buildings (Model-2, Model-3, and Model-4) are located in the I^{st} Quadrant due to their inherent structural integrity, so there is no need to retrofit these RC buildings based on the “Quadrants assessment method”.

Based on the present study, it is 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.

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EDITABLE VERSION OF FIGURE 3 (in the paper above was given as "PICTURE" format):