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Numerical Analysis of Retrofitted RC Column under Lateral Load

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ABSTRACT

One of the most common retrofitting processes for columns is reinforced concrete (RC) jacketing. This process enhances the ductility, stiffness, flexural capacity, and shear capacity of columns, and increases the axial load-carrying capacity of the RC column when subjected to an axial load. According to previous research, the most typical way to improve the lateral capacity of a column in composite action is column retrofitting with RC jacketing. The lateral strength of a single RC column and a single bay, single-story RC frame (retrofitted with concrete jacketing) is numerically analyzed in this work. To obtain a complete overview, an RC frame analysis is conducted even though a single column represents the column in the frame. Finally, parametric analysis is performed to assess the influence of reinforcement ratio, compressive strength of jacket concrete, and yield strength of reinforcement. The axial load carrying capacity and flexural capacity of retrofitted columns increase with the increase in RC jacket compressive strength, reinforcement percentage, and yield strength of the reinforcement. If the compressive strength of the jacket concrete stays constant, 1% reinforcement increment leads to a 10% to 20% increase in the axial capacity of the column. The parametric study reveals that retrofitted columns and frames exhibit a substantial increase in lateral capacity (10 to 12 times) compared to existing columns.

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1. Introduction

Retrofitting of structures is intended for strengthening existing structures for multiple reasons, including seismic loads. Seismic Retrofitting of the old structures has become a vital aspect of structural engineering. Previous studies proposed several methods for retrofitting the existing structures to make them more resilient. The capacity of the vertical element has the major influence on structural integrity. Therefore, vertical elements like columns and walls are the main focused area to be retrofitted for seismic strengthening [1]. Choosing the appropriate strengthening approach is a challenging task. The engineer must choose between various distinct techniques and procedures, some of which are new or require specialized personnel to accomplish. One of the most prevalent retrofitting procedures in use is column jacketing. For jacketing, additional concrete, steel, fiber-reinforced polymers (FRP), or textile-reinforced mortar (TRM) are employed. The traditional method of strengthening and repairing concrete structures, known as concrete jacketing (RC jacketing), has been largely replaced by FRP and TRM in modern techniques. This is due to several advantages of FRP and TRM over concrete, including their high strength-to-weight ratio, flexibility, and durability. These materials are lighter, more resistant to deformation, and highly resistant to corrosion, making them ideal for use in areas subject to high loads. Several numerical analyses using artificial techniques were also conducted to evaluate compressive strength behavior of columns retrofitted with FRP [2–4]. However, FRP composites are very flammable and have unsustainable production methods [5]. On the other hand, failure mechanisms of TRM composites, are complex, have thickness constraints, and are susceptible to moisture and climatic conditions [5].

For the enhancement of ductility and shear capacity along with the prevention of bond failure of RC column, steel jacketing, and fiber reinforced polymer (FRP) are extensively used [1,6–8]. However, concrete jacketing shows ductility, bending and shear capacity improvement of RC column [9–15]. Again, for considerable stiffness requirement, concrete jacketing is a common solution. Sezen and Miller (2011) [16] reported that RC jacketing improved the axial load carrying capacity of the RC column when the axial load is applied to the column and RC jacket cross-section. Similar behavior of load carrying capacity and load transfer mechanism were found by Achillopoulou et al. [17,18]. Tayeh et al. [19] repaired the damaged column using normal strength concrete and ultra-high performance fiber reinforced concrete and found 2 to 3 times axial capacity improvement in comparison with the unjacketed reference column. A numerical study was conducted by Anand et al. [20] considering no slippage between old and new concrete of RC jacketed column and the result shows a substantial increment of load bearing capacity. Julio et al. [14] conducted an experimental investigation considering the 0.04 m^2 area, 1.35 m height of the original column, and 3 mm thickness of the RC jacket. They claimed that the adhering RC jacket contributed to an increase in lateral capacity of 86% to 90%. According to past research, column retrofitting using RC jacketing is the most common method to improve lateral capacity of the column in composite action. The behavior of concrete-jacketed columns under lateral loads is intricate. It depends on several aspects, notably the concrete and steel reinforcing characteristics, the thickness and stiffness of the jacketing material, and the type and extent of the loading. Numerical modeling can assist in better understanding this behavior and optimizing the design of retrofitting methods. In this study, a numerical analysis of the lateral strength of a single RC column and a single bay, single-story RC frame (retrofitted using concrete jacketing) is conducted. Additionally, a parametric study is conducted to evaluate the impact of reinforcement ratio, new concrete's compressive strength, and reinforcement's yield strength.

2. Research significance

Seismic strengthening of the structure is required to enhance the lateral capacity of the existing frames. Of all the retrofitting techniques, column retrofitting with RC jackets is the most practiced. RC retrofitting of columns increases the axial capacity as well as the lateral capacity. This study focuses on the effect of longitudinal reinforcement percentage, reinforcement yield strength, and compressive strength of jacket concrete on the lateral and axial performance of the retrofitted columns and frames. This study will give a clear understanding of the RC retrofitting of columns which can be utilized in design practices.

3. Methodology

3.1. Material properties and size

For numerical analysis, two types of old existing columns of 3 m height were chosen considering Ø20 mm and Ø25 mm longitudinal reinforcement and having a cross-section of 300 × 300 mm. RC jacket thickness was chosen 127 mm along both directions of the original column to form a symmetrical cross-section (Fig. 1). Detailed material properties and reinforcement of old original column and retrofitted columns are shown in Table 1. Regarding the field application, the compressive strength of jacket concrete is chosen between 24 MPa to 35 MPa. Again, the yield strength of reinforcement used in the jacket concrete is selected as 415 MPa and 500 MPa.

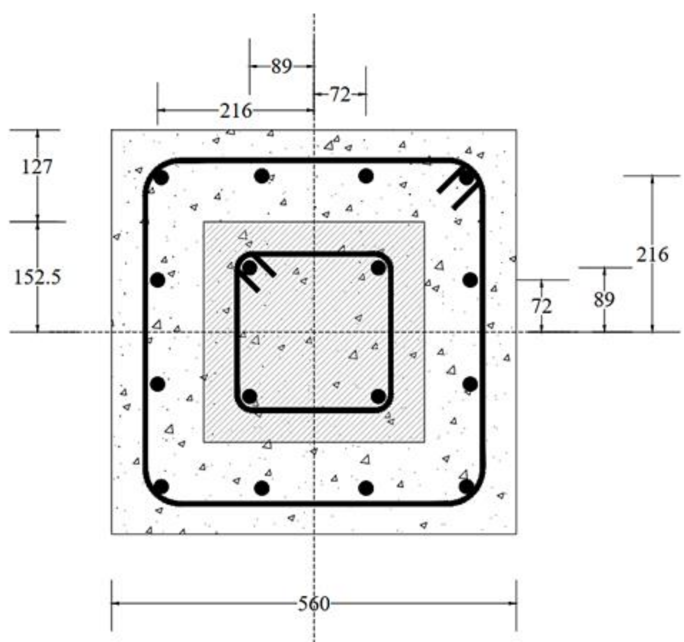


Fig. 1. Cross-section of the retrofitted column (unit: mm).

Table 1
Model description showing the material properties of original column and RC jacket.

Column	Frame	Original column		RC jacket		Reinforcement of retrofitted column	
		f_y (MPa)	f_c'(MPa)	f_y (MPa)	f_c'(MPa)	% Rebar	Nos. & Diameter (mm)
RC1	BF1	415	17.24	415	24.13	1.60	4-Ø20 mm +12 -Ø20mm
RC2	BF2					2.60	4-Ø25 mm +12 -Ø25mm
RC3	BF3				27.58	1.60	4-Ø20 mm +12 -Ø20mm
RC4	BF4					2.60	4-Ø25 mm +12 -Ø25mm
RC5	BF5				31.03	1.60	4-Ø20 mm +12 -Ø20mm
RC6	BF6					2.60	4-Ø25 mm +12 -Ø25mm
RC7	BF7				34.47	1.60	4-Ø20 mm +12 -Ø20mm
RC8	BF8					2.60	4-Ø25 mm +12 -Ø25mm
RC9	BF9			500	24.13	1.60	4-Ø20 mm +12 -Ø20mm
RC10	BF10					2.60	4-Ø25 mm +12 -Ø25mm
RC11	BF11				27.58	1.60	4-Ø20 mm +12 -Ø20mm
RC12	BF12					2.60	4-Ø25 mm +12 -Ø25mm
RC13	BF13				31.03	1.60	4-Ø20 mm +12 -Ø20mm
RC14	BF14					2.60	4-Ø25 mm +12 -Ø25mm
RC15	BF15				34.47	1.60	4-Ø20 mm +12 -Ø20mm
RC16	BF16					2.60	4-Ø25 mm +12 -Ø25mm

3.2. Interaction diagram for retrofitted column

To plot the load moment interaction diagram manual calculation is done according to ACI code considering the composite action of old and new concrete. At first the area of the jacket concrete is transformed using the ratio of compressive strength of jacket concrete and old confined concrete. Later the manual calculation is compared with the interaction diagram obtained from section designer of ETABS.

3.3. Modelling in Opensees for lateral capacity of retrofitted column

To simulate the lateral behavior of cantilever original and retrofitted column OpenSees version 3.2.2 is used [21]. Columns are modelled using fiber sections and inelastic behavior is depicted by nonlinear Force-Based Beam-Column Elements (nonlinearBeamCoumn) considering numerical interaction options in OpenSees which incorporate plasticity and plastic hinge integration. Uniaxial material *Concrete 01* (Fig. 2a) from OpenSees library is used to model the old concrete and RC jackets. In Opensees, the *Concrete01* material is defined as a zero-tensile strength material. Again, *Steel01* (Fig. 2b) is utilized for modeling of reinforcement. *Steel01* is a uniaxial bilinear material object with kinematic hardening. The interface between the existing concrete and the new RC jacket is an exigent issue for numerical modelling to obtain the real behavior of the Retrofitted column. In practical scenario, friction or sliding at the old and new concrete interface may affect the lateral capacity of the retrofitted column. Different surface techniques including increasing surface roughness, dowel bars, shear connectors, and use of bonding agent can be used for the connection of old and RC jacket [22]. Naci Caglar et al. [23] used different slip/friction coefficients to reduce the yield strength of the reinforcing steel. They formulate the numerical models for the experimental studies conducted by Bousias et al. [24], Julio and Branco [25], and Vandoros & Dritsos [26]. They concluded that in the inelastic range the effect of slip is minimal and can be neglected. Therefore, zero slip is considered between old concrete and RC retrofit for this research. The base of the columns is restrained in horizontal and vertical directions as shown in Fig. 3. A constant axial load of 500 kN is applied at the free end of all 16 columns. Horizontal displacement is gradually applied at the free end of the cantilever column incorporating displacement control integrator in OpenSees with an increment of 0.1 mm up to the essential number of load steps.

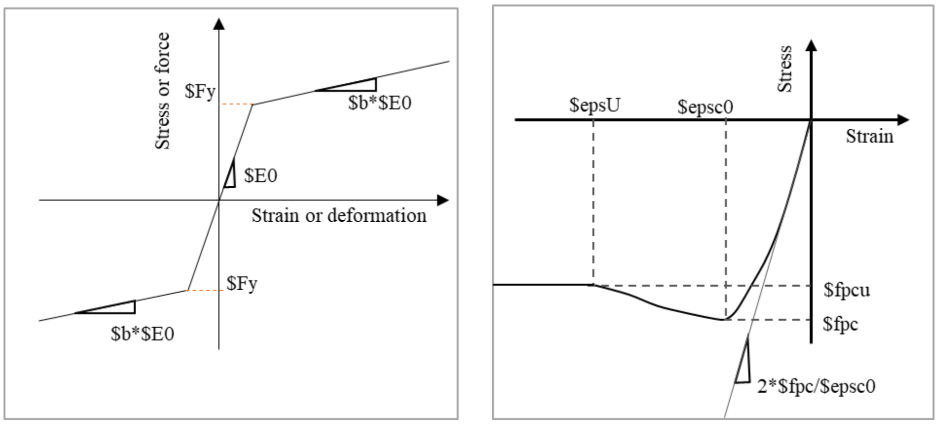


Fig. 2. (a) *Steel01* and (b) *Concrete 01* material model in Opensees [27,28].

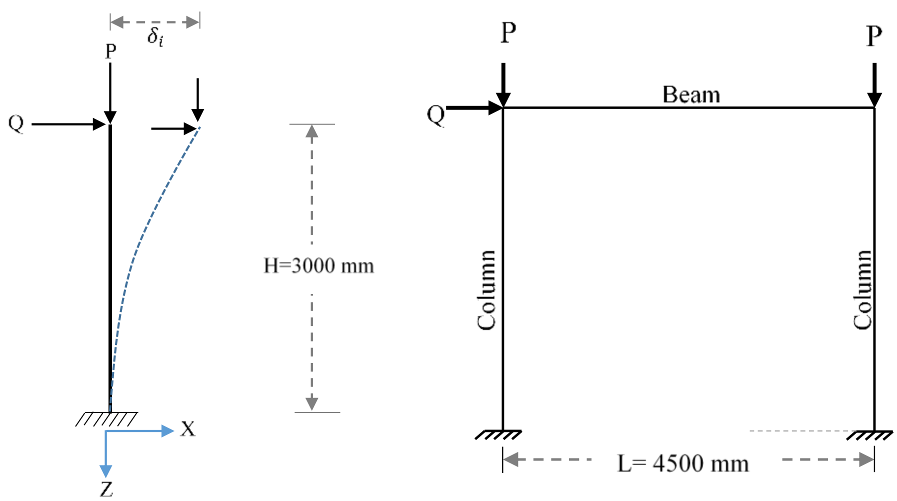


Fig. 3. (a) Cantilever column and (b) Bare frame for numerical modelling in OpenSees.

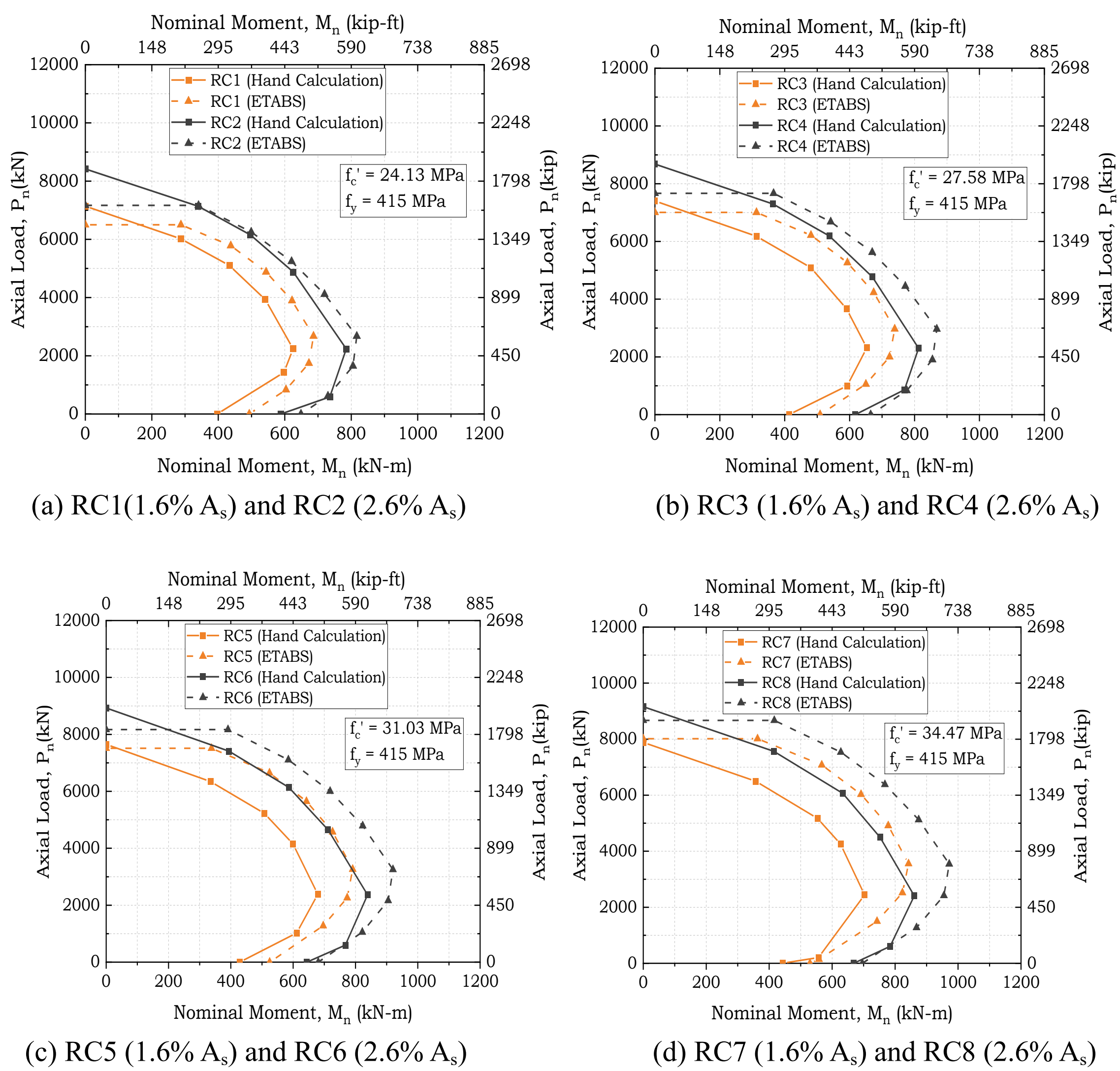
A parametric study is also conducted for all columns to have a clear conception of lateral performance of the column in a one bay one story bare frame. The dimensions and other properties of the beam are taken same as the old unjacketed column. Fig. 3 shows the dimensions, boundary conditions and loadings of one bay one story retrofitted bare frame.

4. Results and discussion

For retrofitted single-column analysis manual calculation of the load-moment interaction, the diagram is compared with the interaction diagram from ETABS. Again, the lateral capacity of the single retrofitted column is validated with the available experimental data from existing literature. Finally, a parametric study is done to have a clear idea of the effect of material properties on the retrofitted single column and retrofitted single bay single-story bare frame.

4.1. Load-moment interaction diagram of retrofitted column

When RC jacketing is added to a column, the axial load-bearing capacity of the column increases. Fig. 4 and Fig. 5 illustrate the load-moment interaction graphs for all 16 columns. Hand computation of the interaction diagram yields a conservative result when compared to the interaction diagram generated by the ETABS section designer.



(a) RC1(1.6% A_s) and RC2 (2.6% A_s)

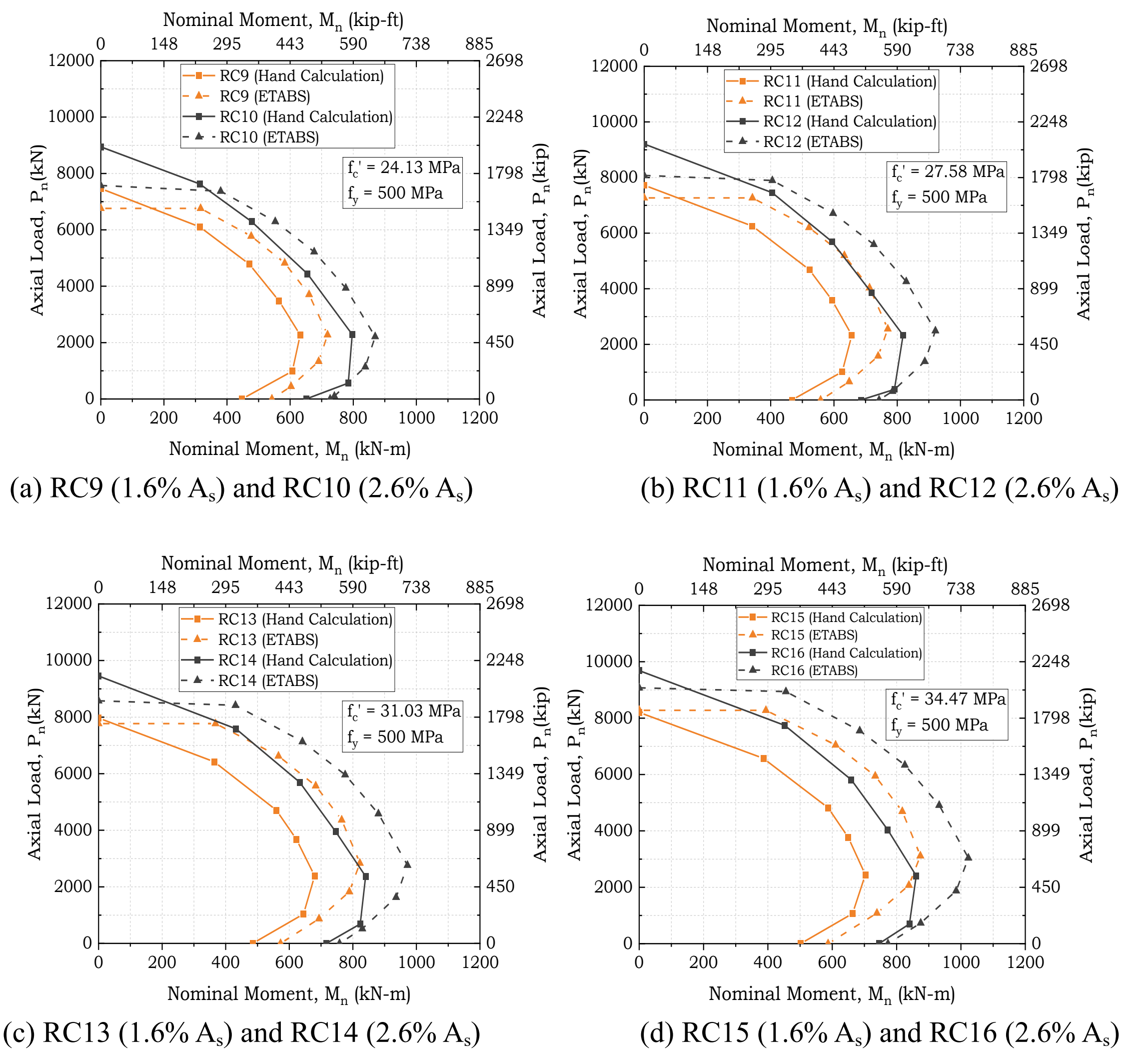
(b) RC3 (1.6% A_s) and RC4 (2.6% A_s)

(c) RC5 (1.6% A_s) and RC6 (2.6% A_s)

(d) RC7 (1.6% A_s) and RC8 (2.6% A_s)

Fig. 4. Load-moment interaction diagram of retrofitted columns having yield strength of reinforcement, f_y = 415 MPa.

The transformation of jacket concrete utilizing the ratio of compressive strength of jacket concrete and old confined concrete in the manual calculation might be the probable cause of this cautious outcome. Furthermore, when weighted average compressive strength is employed for old confined and jacket concrete, the ETABS interaction diagram remains identical. The axial load capacity rises with increasing compressive strength of jacket concrete and reinforcement yield strength for pure compression and balanced condition of retrofitted columns (Fig. 6). Similar behavior is found for flexural capacity of retrofitted columns under pure bending and balanced condition (Fig. 7). If the compressive strength of the jacket concrete stays constant, the axial capacity increases by 10% to 20%, attributed to a 1% increase in reinforcement while considering pure compression of the column (Fig. 6a). The behavior is also comparable for compression controlled, balance condition, tension controlled and pure bending failure ranges.



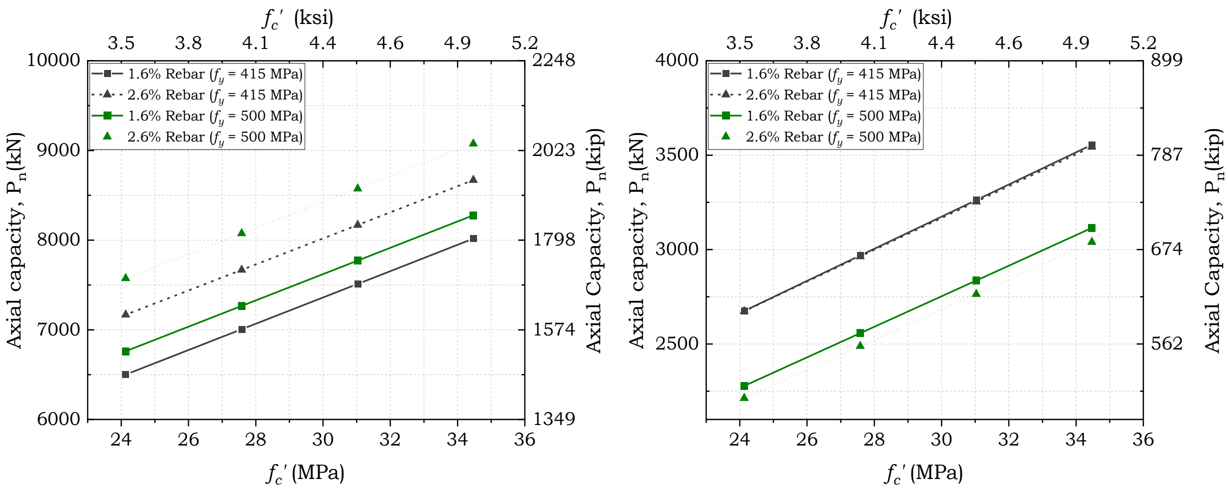
(a) RC9 (1.6% A_s) and RC10 (2.6% A_s)

(b) RC11 (1.6% A_s) and RC12 (2.6% A_s)

(c) RC13 (1.6% A_s) and RC14 (2.6% A_s)

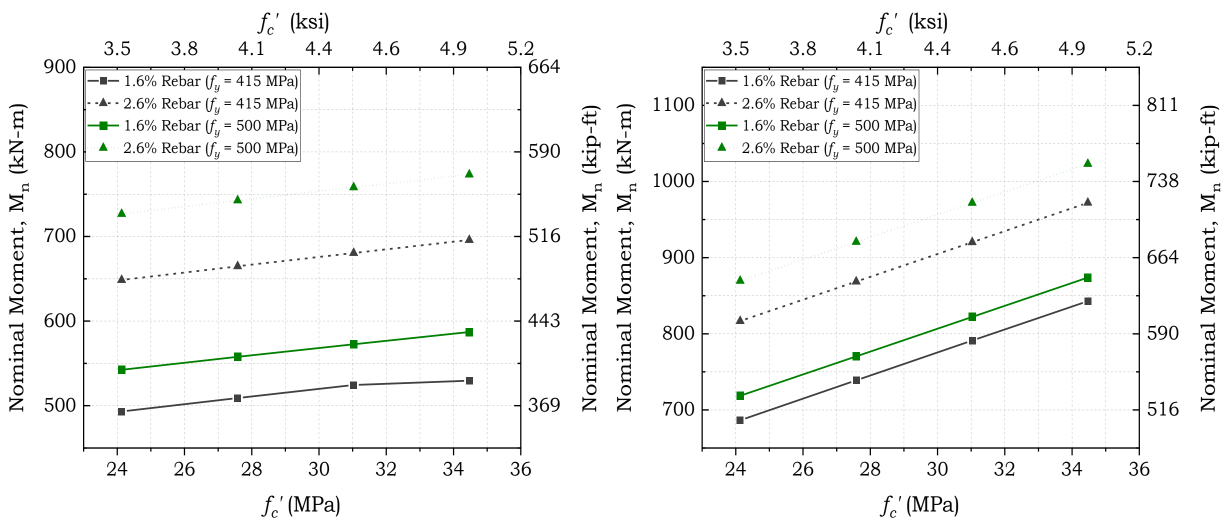
(d) RC15 (1.6% A_s) and RC16 (2.6% A_s)

Fig. 5. Load-moment interaction diagram of retrofitted columns having yield strength of reinforcement, f_y = 500 MPa.



(a) (b)

Fig. 6. Comparison of axial capacity of retrofitted column with compressive strength of concrete for (a) pure compression and (b) balanced condition for different % of reinforcement and yield strength of longitudinal reinforcement.



(a) (b)

Fig. 7. Comparison of flexural capacity of retrofitted column with compressive strength of concrete for (a) pure bending and (b) balanced condition for different % of reinforcement and yield strength of longitudinal reinforcement.

4.2. Lateral capacity increment of single retrofitted column

4.2.1. Validation of the numerical modelling

Three reference test specimens are chosen to validate the numerical simulation of the lateral capacity of the existing column and the retrofitted column taking lateral capability into account. Dimensions and the material properties of these reference test specimens are shown in Table 2 and Table 3. Fig. 8 shows the experimental and numerical initial stiffness of the single retrofitted column and the old column is almost identical. Therefore, this numerical modelling approach can be employed to simulate the lateral capacity of the old existing column and RC jacketed column. Again, numerical modelling depicts conservative prediction of lateral strength and higher prediction of initial stiffness for BMR1-R and R-RCL3 reference specimens. However, the numerical model of the reference specimen M6 shows a modest overprediction of lateral capacity in the post-peak region than the corresponding experimental model due to the uniaxial material modelling using *Steel01* and *Concrete01* in the OpenSees library. Although the simulation of the post-peak region could not represent the experimental condition, the qualitative difference in behavior remains the same.

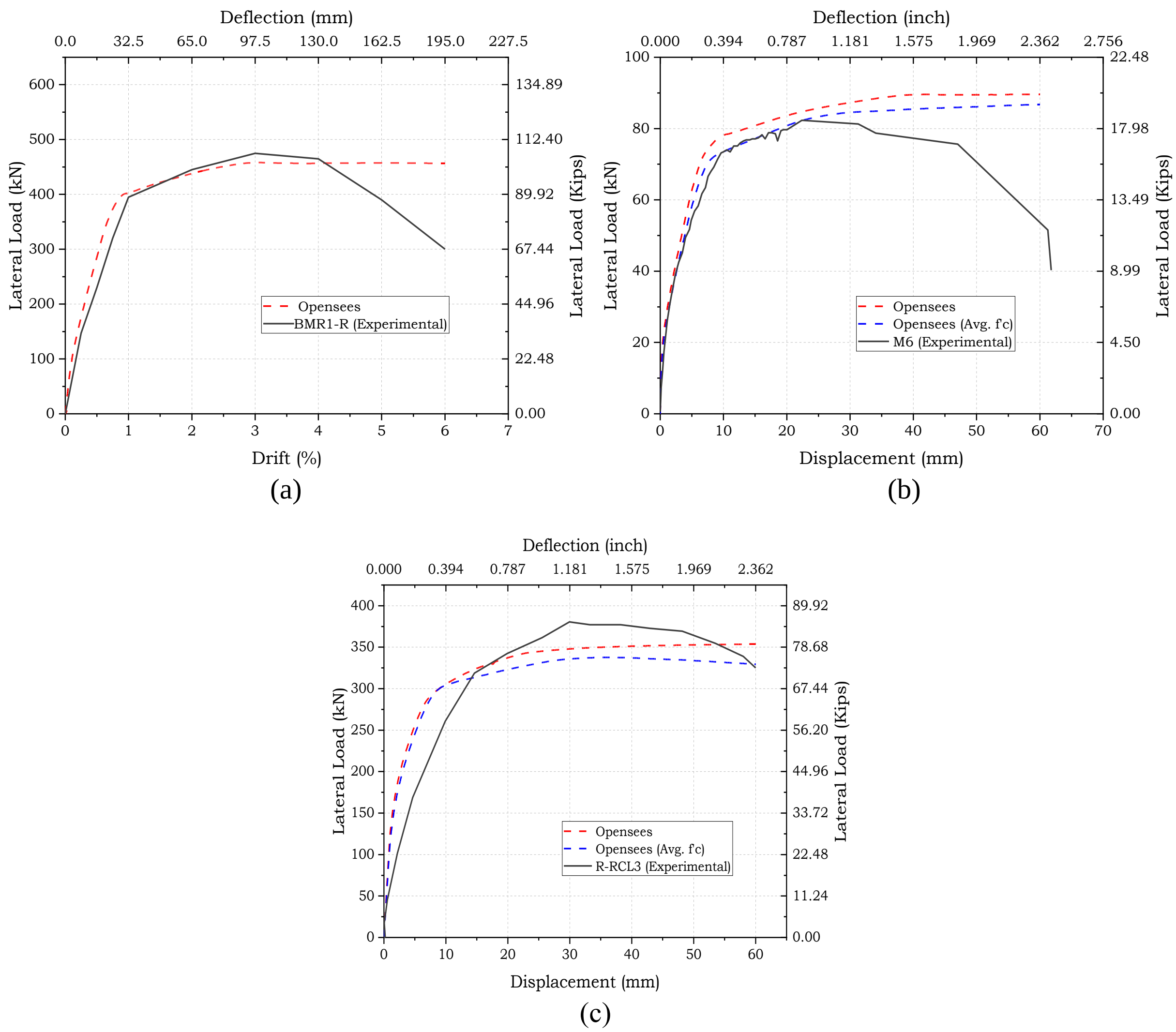


Fig. 8. Comparison of the numerical modelling with the experimental test of existing column without retrofitting (a) BMR1-R [29]and retrofitted columns (b) M6 [25] & (c) R-RCL3 [30].

Table 2
Dimensions of reference test specimens used for validation of numerical modelling in OpenSees for lateral behavior.

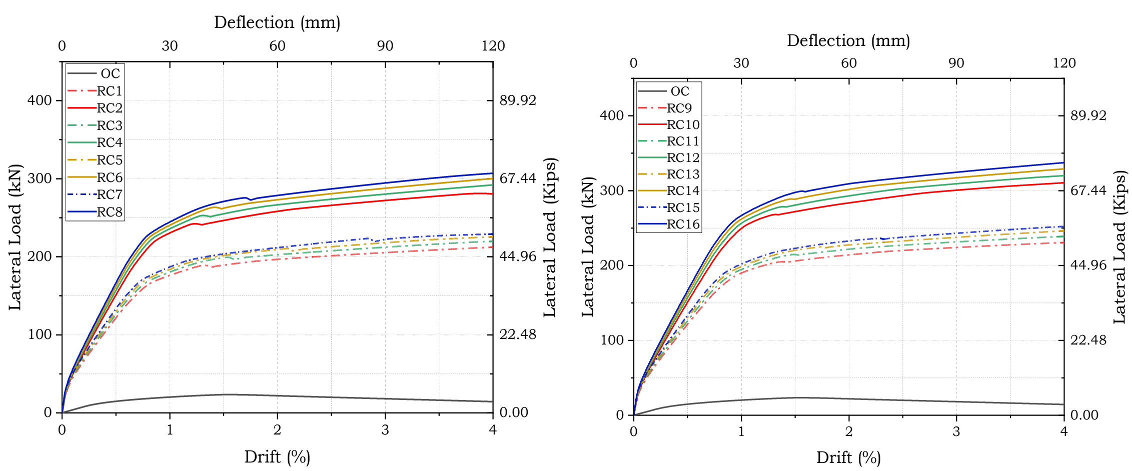
Dimensions/Size	BMR1-R [29]	M6 [25]	R-RCL3 [30]
Cross-section (mm)	750×600	200×200	500×250
Thickness of RC jacket (mm)	-	35	75
Height of column (mm)	3250	900	1600
Cover (mm)	25	25	30

Table 3
Material, reinforcement, and axial load detailing of reference test specimens.

Model	Material Properties (MPa)				Longitudinal Reinforcement		Axial Load (kN)
	Existing column		RC jacket		Existing Column	RC Jacket	
	f_y	f_c'	f_y	f_c'			
BMR1-R	436.8	22.05	-	-	32-Ø19 mm	-	1400
M6	520	35.17	520	79.96	6-Ø10 mm	6-Ø10 mm	170
R-RCL3	514	36.8	514	55.8	4-Ø18 mm	6-Ø18 mm	957.5

4.2.2. Performance of single retrofitted column for various reinforcement ratio, f_y and f_c'

A parametric study is carried out to assess the influence of jacket compressive strength of concrete, longitudinal reinforcement yield strength, and reinforcement percentage on the lateral capacity of a single retrofitted column. Fig. 9 shows that the compressive strength of the jacket concrete has minimal influence on the initial stiffness of the column. However, the initial stiffness rises as the percentage of reinforcement increases. For 1.6% reinforcement ratio and up to 2% lateral drift (Fig. 10), the average lateral capacity increases 9.17 to 9.96 times compared to the lateral capacity of the old existing column. Again, in contrast to the old existing column with a 2.6% reinforcement ratio, the average lateral capacity rises 12.01 to 13.16 times. For 3 to 4% lateral drift, further increment of the normalized lateral capacity of the retrofitted column is found.

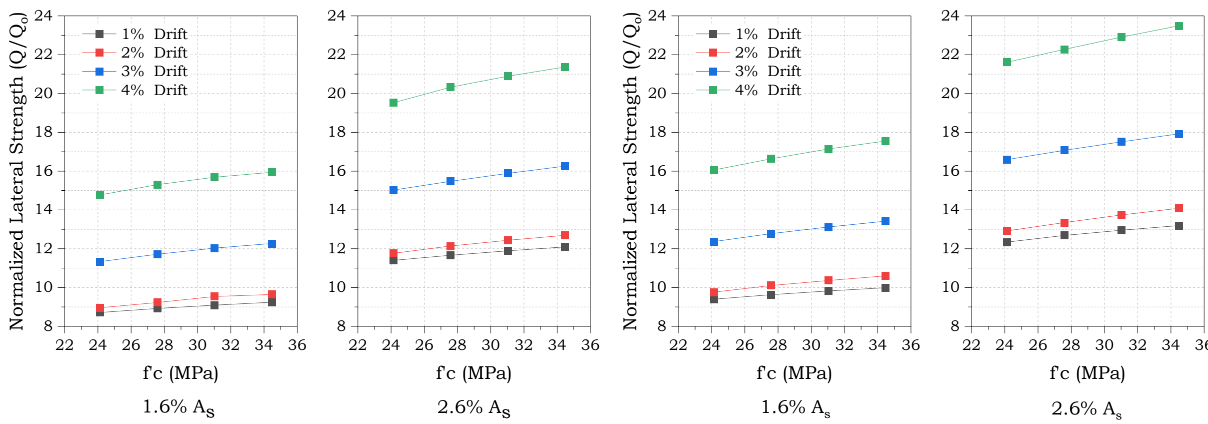


(a) (b)

Fig. 9. Lateral Capacity of Retrofitted single column for various steel percentages and f_c' considering (a) f_y = 415 MPa (b) f_y = 500 MPa.

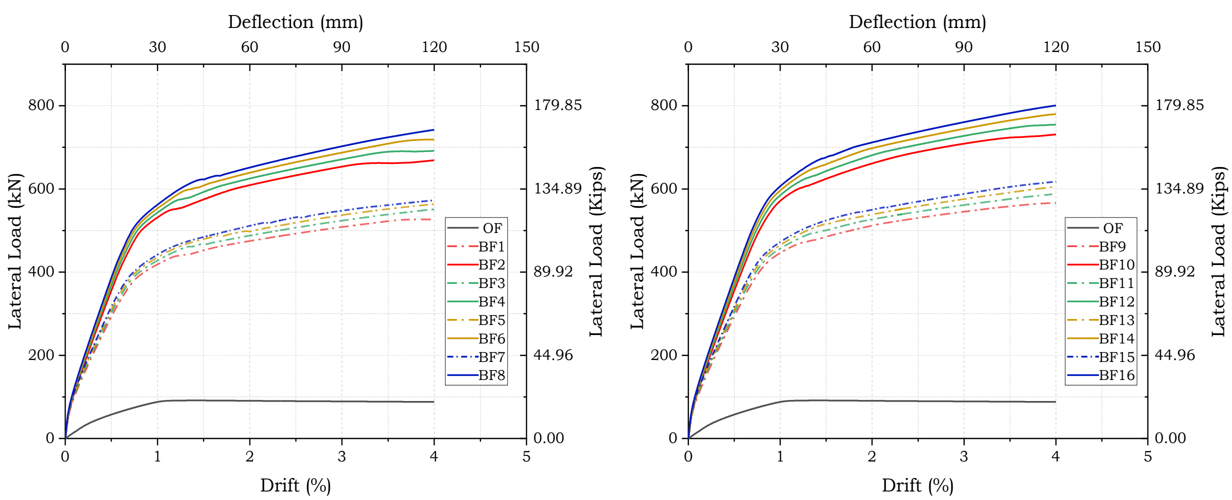
4.3 Performance of retrofitted single story single bay bare frame

A parametric analysis of single-bay single-story retrofitted frames utilizing these 16 types of retrofitted columns is also carried out. Finally, the result is compared to the lateral capacity of the existing frame. The axial load on the columns is assumed to be 500 kN, and the beam is considered a non-retrofitted element. Fig. 11 shows the lateral capacity increment of the retrofitted frames compared to the lateral capacity of the old frame. Bare frame with retrofitted columns shows higher initial stiffness and higher lateral capacity than the initial stiffness and lateral capacity of the non-retrofitted bare frame. Again, concrete compressive strength has minimal effect on the lateral capacity of the retrofitted frame. However, increasing the percentage of longitudinal reinforcements results in a considerable increase in lateral capacity.



(a) (b)

Fig. 10. Relation of normalized lateral strength with compressive strength of jacket concrete of the retrofitted columns having (a) f_y = 415 MPa (b) f_y = 500 MPa.



(a) (b)

Fig. 11. Lateral Capacity of Retrofitted one story one bay bare frame for various steel percentages and f_c' considering (a) f_y = 415 MPa (b) f_y = 500 MPa.

5. Conclusions

This study represents a parametric study of RC retrofitted columns focusing on load moment interaction diagram from ETABS and manual calculation considering different percentages of longitudinal reinforcement, compressive strength of concrete, and yield strength of reinforcement. Again, a numerical parametric study is also performed focusing lateral capacity of the retrofitted column and retrofitted bare frame. An old existing column specimen and two retrofitted column specimens with RC jacketing from the existing literature have been utilized and modeled in OpenSees to simulate the lateral behaviour of axially loaded cantilever columns under gradually increasing displacement. The results from the numerical modelling show a satisfactory agreement with the experimental result for initial stiffness, lateral strength, and ductility. The numerical investigation leads to the following findings:

- The axial load carrying capacity and flexural capacity of retrofitted columns increase as RC jacket compressive strength and longitudinal reinforcement yield strength increase. When the percentage of reinforcement in the jacketed column rises, the axial compression capacity and flexural capacity increase significantly.
- When evaluating the lateral capacity of retrofitted columns, it is observed that the compressive strength of the jacket concrete has minimal impact on the initial stiffness of the column. However, the initial stiffness increases with the increase in the percentage of reinforcement.
- For a 1.6% reinforcement ratio and up to 2% lateral drift, the average lateral capacity rises ten times compared to the old existing column. Again, for 2.6% reinforcement ratio, the average lateral capacity increases up to 13 times compared to the old column. A further increase in the normalized lateral capacity of the retrofitted column is discovered for 3 to 4% lateral drift.
- Similar behaviour is found for a single-story single bay retrofitted frame. The lateral performance of the frame improves when the columns are retrofitted with RC jackets.

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Conflicts of interest

The authors declare no conflict of interest.

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