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Parametric performance assessment of RC columns retrofitted by CFRP

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Abstract

Retrofitting deficient columns requires meticulous efforts and most of the retrofitting techniques gravely increase the size of the member. Many studies have performed numerical and experimental studies regarding the performance of various retrofitting techniques. However, carbon fiber reinforced polymer (CFRP) as a retrofitting technique is seldom considered in parametric studies so as to quantify the axial load and maximum stress capacity of reinforced concrete (RC) columns. To this end, we perform parametric analysis considering variation in load eccentricities and no. of CFRP plies. Finite element modeling is conducted to assess the performance of non-retrofitted and CFRP retrofitted columns. We conclude that CFRP retrofitting significantly increases axial load as well as stress capacity of RC columns even for eccentric loading. .

Keywords: CFRP; RC column; retrofitting; axial load capacity; parametric analysis.

1. Introduction

Dynamic actions such as earthquakes and wind can result in damage to structural components. Damage to structural components results in sudden decline of capacity leading to inoperability of structures in part or as a whole. Although dynamic action is the major factor responsible to reduce structural capacity or capacity of structural components, two additional scenarios also result in inadequacy of structural components. The first one is the change in regulations or codal practices that designate the existing components insufficient. The second scenario is capacity reduction over time due to extended service life or stiffness deterioration. All of these aspects require capacity enhancement to assure target performance hence retrofitting is required. Retrofitting is an approach to enhance capacity of structure as a whole or that of component by deploying additional arrangement or materials. Many retrofitting techniques have evolved over the decades and are being deployed per the availability of materials, workmanship, and design efficacy.

The column is one of the most critical components of structural system that is fundamentally exposed to compressive actions. In the seismic regions, column deficiencies are well noted in terms of inadequate shear capacity upon exposure to the lateral load. The compromised column capacity thus requires enhancement.

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So far, column capacity enhancements are practiced with column jacketing (RC), steel jacketing, and fiber reinforced polymer (FRP) reinforcing.

With the increase in load demands and research in the performance of structures under different loadings (seismic, wind or so on); moreover, the building codes are being updated with significant changes. Due to this reason many old buildings are considered substandard. The studies have shown that many existing buildings do not show adequate safety against dynamic loadings (Gautam et al. 2016). Therefore, retrofitting is a must to assure adequate seismic safety of existing building stocks. Common methods of retrofitting are concrete jacketing and steel jacketing. However, the improvement in ductility is relatively small in the case of concrete jacketing. It also changes the cross section of the section which increases the mass and stiffness. It leads to reduction in natural time period and higher seismic demands (Raza et al. 2019). The main problem for steel jacketing is rusting which compromises the strength of jackets. These issues are solved using CFRP retrofitting. CFRP is a rust-free technique and has high tensile as well as compressive strength (Zhang et al. 2016). The popularity of CFRP is mostly due to its high strength to weight ratio. Tabandeh and Gardoni (2014) concluded that the use of FRP composites is efficient in bond failure and also appreciably check flexural failure. Kyaure and Abed (2021) noted that the confinement by FRCM (fiber reinforced cementitious matrix) can restore the axial capacity of the column under concentric and eccentric loading conditions. Similarly, Dai et al. (2022) and Promis, Ferrier, and Hamelin (2009) report the performance of FRP retrofitting in RC members. Although several studies report experimental and analytical behavior of FRP under various loading conditions, the major missing aspect is the quantification of variation in terms of CFRP wrapping and eccentric loading. Thus, this study aims to quantify the performance of CFRP retrofitting considering the variation in eccentricity and no. of plies

2. Materials and methods

1.1. Material properties

We considered a typical column section 230×230 mm with 4-12Φ bars in the corners and 2-10Φ bars of yield strength 415 MPa. The typical cross-section is as shown in Fig. 1.

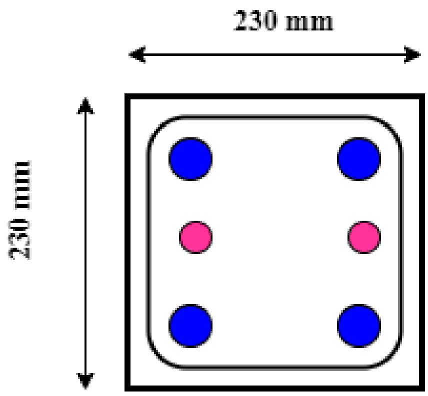

Fig. 1 Typical column cross-section with longitudinal rebars.

The ultimate strength of concrete (fcu) is taken as 24 MPa and cube strength is taken to be 20 MPa. Similarly, the fiber reinforced polymer properties for analysis were adopted from Sinha (2006). A summary of properties of FRP used for modeling is presented in Table 1.

Table 1. Properties of fiber reinforced polymer plies (Sinha 2006).

Parameters	Values
Longitudinal elastic modulus	133380 N/mm2
Transverse elastic modulus	8290 N/mm2
Thickness of CFRP ply	0.33 mm
Ultimate tensile strength	3792 N/mm2
Poisson's ratio (v›12)	0.26
Poisson's ratio (v›13)	0.424

1.2. Finite element modeling

The properties of CFRP, steel, and concrete were processed to prepare a model of a 230×230 mm RC column. The FE analytical models of the column were constructed in ABAQUS (Dassault Systems 2020). Two models with and without CFRP (Carbon Fiber Reinforced Polymer) were displaced axially under different eccentricities to get the load carrying capacity. Solid homogeneous and deformable elements were assigned for concrete, rebars, and stirrups. Concrete was modeled using concrete damaged plasticity model. A shell element was used for CFRP and was modeled in a controlled environment. Simple cuboidal elements were used for three-dimensional elements and rectangular elements were used for planar and two-dimensional elements for meshing. Rebars and stirrups were embedded in concrete and CFRP was connected to the column using tie. One end of column was fixed, and the other end was displaced under various eccentricity conditions. Reaction at fixed end weas used as the field variable.

CFRP confined RC elements were analyzed using Lam and Teng model (Lam and Teng 2003). The model proposes that after confinement the ultimate stress and strain of concrete is significantly improved. The column fails with the failing of FRP wrappings. The failure in CFRP is analyzed using Von Mises Stress. The analysis was repeated varying the number of CFRP plies as 2, 4, 6, 8, and 10. The failure point was determined using the primary stress contour of concrete block and Von Mises stress contour of CFRP layers. RC column fails at the ultimate stress of concrete whereas the confined column fails at ultimate tensile strength of FRP. For concrete blocks, 800 elements were deployed, and 1275 nodes were created. For CFRP, 300 elements were used, and 366 nodes were established. For rebars, 50 elements were deployed, and 51 nodes were assigned. Similarly, for stirrups, 12 elements with 12 nodes were constructed. An example of meshing with CFRP is shown in Fig. 2.

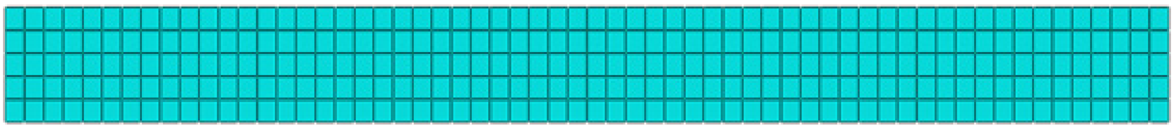

Fig. 2 An example of meshing in column wrapped with CFRP.

3. Results and discussions

The ultimate load capacities of a non-retrofitted and retrofitted column were assessed from finite element analysis. For ultimate load capacity, various eccentricities were also considered to depict the behavior of columns under eccentric loading. Concentric loading together with 5%, 10%, 20%, and 25% eccentricities were considered for comparison. Similarly, no. of CFRP plies were varied from 2 to 10 at the increment of 2. The load-axial deformation curve for concentric loading under various strengthening schemes is shown in Table 2.
Table 2: Ultimate load carrying capacity of RC column confined with CFRP

Eccentricity	Ultimate load carrying capacity of RC column (KN) for number of plies (n)					
	n = 0	n = 2	n = 4	n = 6	n = 8	n = 10
0%	1563.82	1702.91	1848.79	2040.99	2311.33	2605.11
5%	1317.52	1592.13	1739.24	1897.29	2124.62	2446.44
10%	1173.52	1470.8	1604.55	1753.08	2002.41	2303.64
20%	911.759	1220.3	1345.04	1481.65	1687.9	1925.89
25%	785.864	1100.5	1222.85	1358.93	1567.69	1784.58

Fig. 3 highlights that for a concentric loading, 2, 4, 6, 8, and 10 no. of plies increase the ultimate load capacity of the column by 8.89%, 18.22%, 39.51%, 47.8%, and 66.59%, respectively. Fig. 4 shows the load-axial deformation behavior of the column with 5% eccentricity. The ultimate load capacity of the retrofitted column with 5% eccentricity is increased by 20.84%, 32%, 44%, 61.26%, and 85.69% for 2, 4, 6, 8, and 10 CFRP plies when compared with the non-retrofitted column.

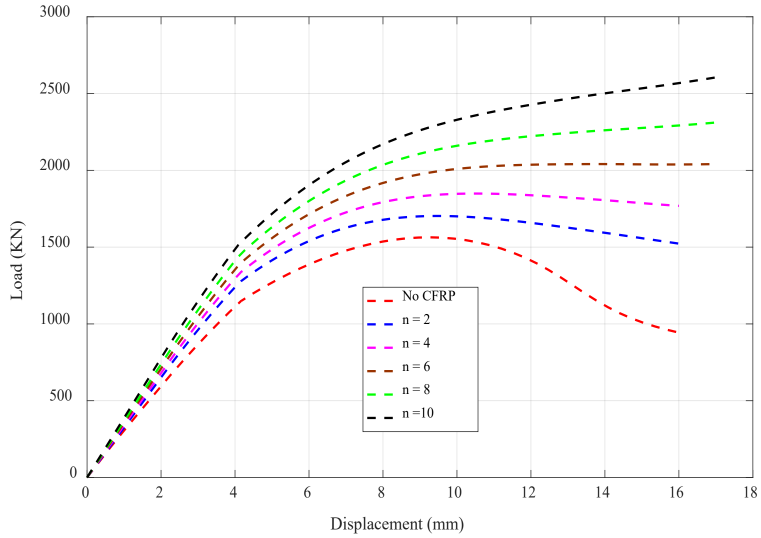

Fig. 3 Load vs. axial deformation plots for concentric loading.

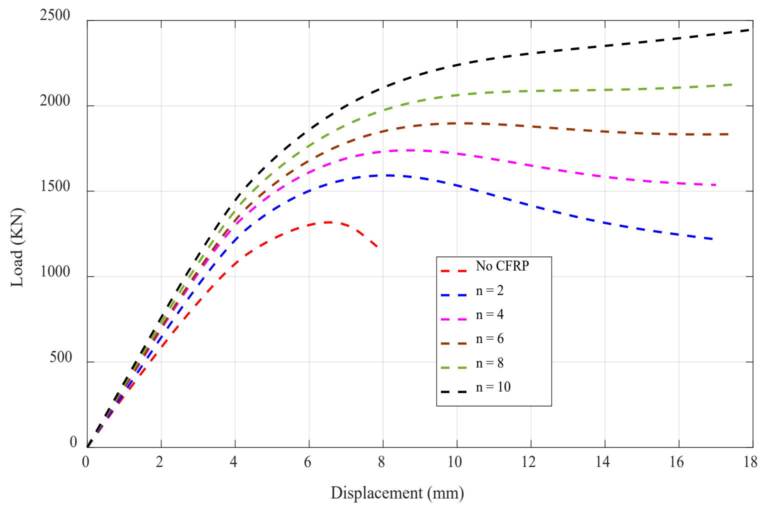

Fig. 4 Load vs. axial deformation plots for 5% eccentricity.

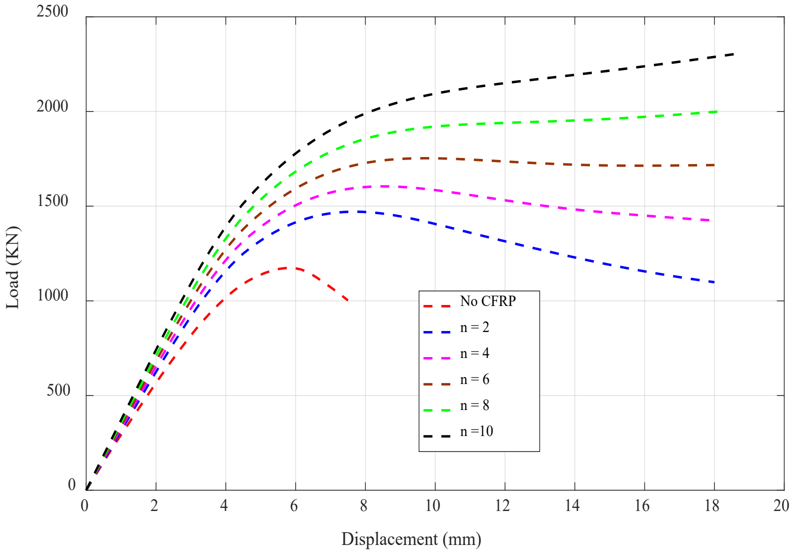

Fig. 5 Load vs. axial deformation plots for 10% eccentricity.

Fig. 5 shows the load-axial deformation curves for various retrofitting schemes for 10% eccentricity. For 10% eccentricity condition, the ultimate load capacity of the column is increased by 25.33%, 36.73%, 49.39%, 70.63%, and 96.3%, respectively for 2, 4, 6, 8, and 10 CFRP plies.

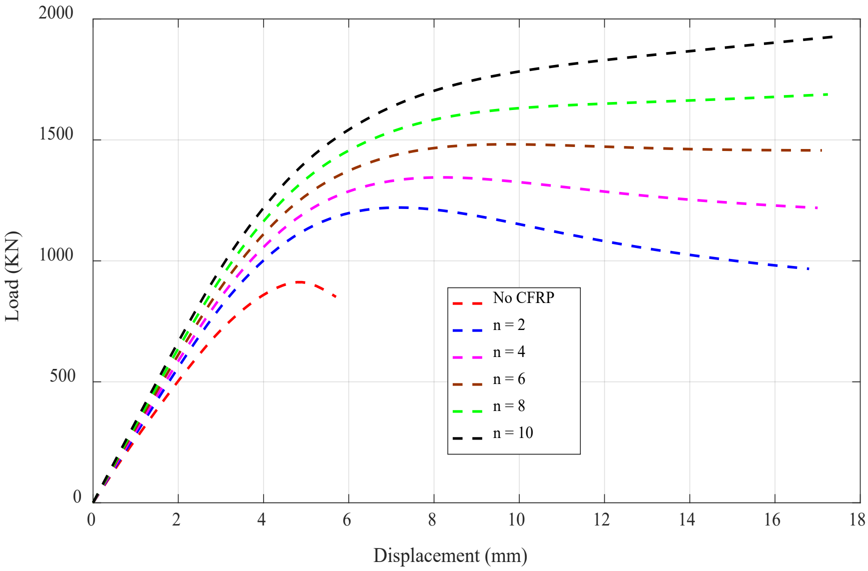

Fig. 6 Load vs. axial deformation plots for 20% eccentricity.

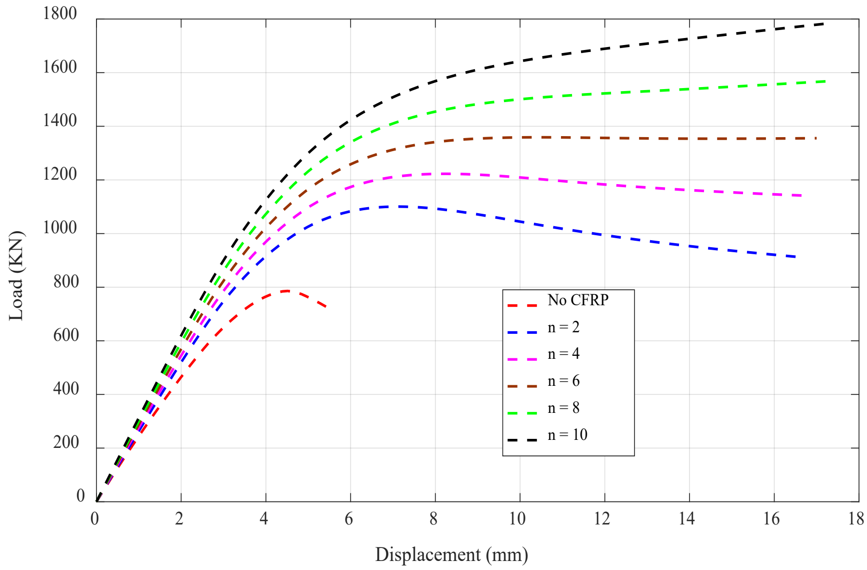

Fig. 7 Load vs. axial deformation plots for 25% eccentricity.

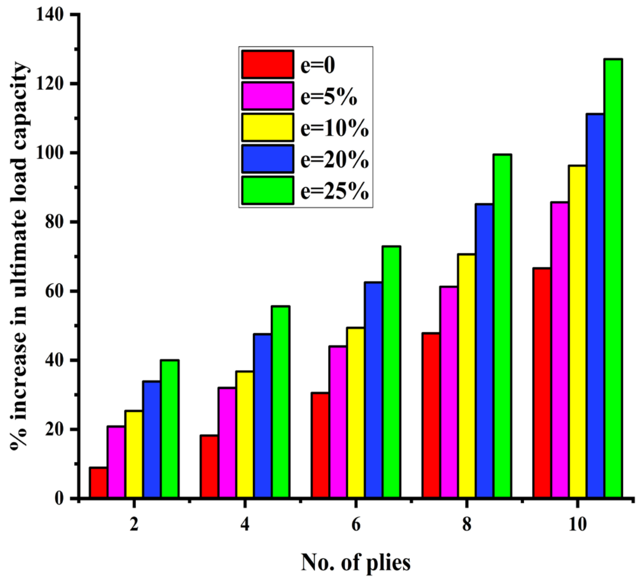

Fig. 8 Percentage increase in ultimate load capacity of strengthened column for various CFRP retrofitting schemes.

The load-axial deformation plots for various intervention schemes for 20% eccentricity are shown in Fig. 6. The ultimate capacity of the column for 2, 4, 6, 8, and 10 CFRP plies used for retrofitting is respectively increased by 33.84%, 47.52%, 62.5%, 85.13%, and 111.23%.

The load-axial deformation plots for various levels of retrofitting schemes for 25% eccentricity are shown in Fig. 7. The capacity enhancement assessed in terms of percentage increase in ultimate load carrying capacity with respect to the non-retrofitted column for 2, 4, 6, 8, and 10 plies is respectively 40%, 55.6%, 72.92%, 99.49%, and 127.09%.

To depict the sensitivity of number of plies in improving ultimate load capacity of the retrofitted column, the ultimate load carrying capacities for various eccentricity scenarios is presented in Fig. 8. The ultimate load capacity is found to be increased linearly as shown in Fig. 8, while increasing the number of plies. Although the load-axial deformation curve for non-retrofitted column shows relatively lower ultimate load carrying capacity, CFRP is found to be effective, even when eccentric loading occurs. For instance, the variation in ultimate load carrying capacity of retrofitted column is improved by 127.09% when compared with the non-retrofitted column for 25% eccentricity. It is found that eccentric loading significantly reduces the ultimate load capacity of non-retrofitted columns. However, retrofitted column is found to be effective in assuring the ultimate load capacity. Interestingly, ultimate load capacity shows linear variation while increasing no. of plies by 2 each time.

Apart from load-axial deformation analysis, we also assessed the impact of retrofitting in terms of Von Mises stress. The summary of the maximum stress under various eccentricities and number of plies in presented in Table 3.

Table 3: Maximum stress variation in column retrofitted by CFRP.

Eccentricity	**Maximum stress (MPa) in concrete wrapped with CFRP**					
	n = 0	**n = 2**	**n = 4**	**n = 6**	**n = 8**	**n = 10**
0%	24.67	26.43	28.34	29.3	30.28	30.88
5%	24.63	33.14	35.09	35.52	35.64	35.88
10%	24.73	34.06	36.14	36.71	37.07	37.24
20%	24.16	34.99	36.93	37.35	37.37	37.41
25%	24.13	34.99	36.91	37.53	37.84	37.91

Table 3 highlights that stress is not fluctuated under eccentric loading for non-retrofitted column. Whereas, in the case of retrofitted column, the variation is significantly observed. For instance, maximum stress is increased by 7.13%, 14.88%, 18.77%, 22.74%, and 25.17% for 5% eccentricity while deploying 2, 4, 6, 8, and 10 plies, respectively (Fig. 9). Similarly, for 5% eccentricity, maximum stress is found to be increased by 34.55%, 42.47%, 44.21%, 44.7%, and 45.68% when 2, 4, 6, 8, and 10 plies are used for retrofitting. For 10% eccentricity, the increase in maximum stress is found to be 37.73%, 46.14%, 48.44%, 49.90%, and 50.59%, respectively. At 20% eccentricity, the increase in maximum stress is found to be 44.83%, 52.86%, 54.59%, 54.68%, and 54.84% respectively when 2, 4, 6, 8, and 10 CFRP plies are used. Similarly, at 25% eccentricity, increase in 45%, 52.96%, 55.53%, 56.81%, and 57.1% respectively when 2, 4, 6, 8, and 10 CFRP plies are used. An example of stress distribution in column is shown in Fig. 10.

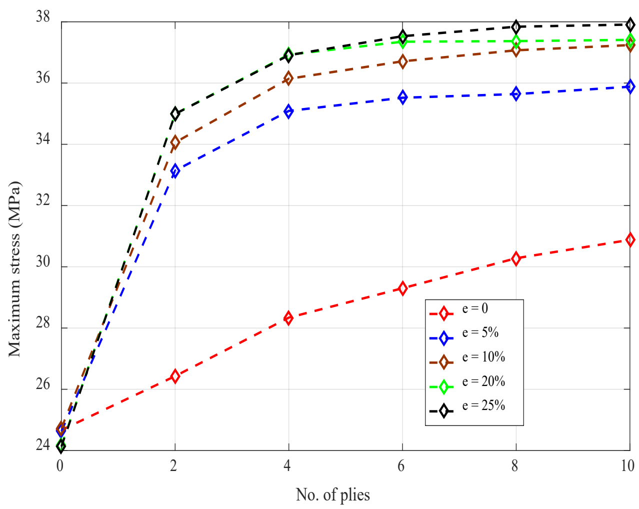

Fig. 9 Maximum stress in non-retrofitted and retrofitted column for various eccentricities.

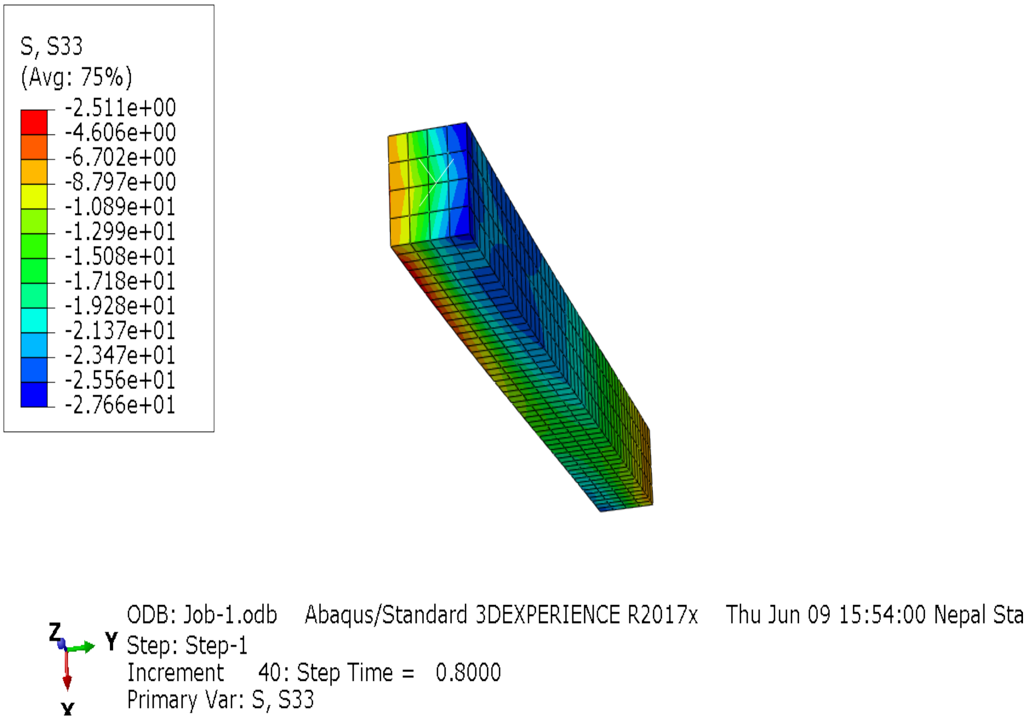

Fig. 10 Stress distribution in retrofitted column.

3. Conclusions

Aiming to quantify the parametric variation in performance of RC column retrofitted by CFRP, we conducted assessment of the ultimate load carrying capacity and maximum stress of columns considering variation in no. of plies and eccentricity. Based on the finite element results, we conclude that the non-retrofitted columns show relatively low axial load carrying capacity and maximum stress. However, when retrofitting is done, no. of plies is the most governing factor that controls the axial load carrying capacity. It is found that the load carrying capacity of a column is increased linearly while increasing the number of CFRP plies. Furthermore, it is interesting to note that eccentric loading is favorable when the column is wrapped with the CFRP plies. It is due to the fact that the CFRP plies will participate more rigorously in providing load carrying capacity under extreme condition. On the contrary, non-retrofitted columns are found to be showing marginal load carrying capacities only. The parametric analysis performed considering the maximum stress value for non-retrofitted and retrofitted condition highlights that there would be no significant variation in stress due to eccentric loading for non-retrofitted column. However, retrofitted column showed an increase of 57% for 10 CFRP plies. Introduction of 10 plies increases just 6.6 mm along one dimension of the column, which is only 2.16% increase in dimension. Similarly, for an increase of 2.16% dimension, the axial load carrying capacity is increased by 127%. These increments highlight that CFRP is one of the most effective retrofitting approaches for dry locations. Future research can perform sensitivity of other parameters such as dynamic loading, cost comparison, and benefit-cost analysis of CFRP retrofitting technique. Although we performed parametric analysis of the variation in ultimate load capacity and maximum stress, it would be pertinent to compare the analytical results with experimental ones. For this, experiments can be conducted.

Conflict of interest

Authors declare no conflict of interest.

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