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*Research Article*

# Performance Analysis of CFRP Composite Strips Confined RC Columns under Axial Compression

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In an attempt to mitigate the high cost of FRP composite strengthening, an experimental investigation was carried out that sought to achieve efficient and most favorable FRP strengthening using CFRP composite strips. 50 mm wide CFRP composite strips were used in two different spacings (20 mm and 40 mm) to confine columns. The test results of the column confined with smaller spacing (20 mm) showed significant restraint of axial deformation of the column and enhanced the strength capacity to a maximum of 99.20% compared to that of reference column. In contrast, the column confined by strips with larger spacing (40 mm) failed by crushing of concrete alone, which occurred even before the CFRP strips reached their ultimate strain. In addition, the embodied energy that exists in the CFRP strips could not be utilized effectively. The stress and strength enhancement ratio of this present study was compared with the previous research that has been conducted on columns confined with full wrapping. From the obtained results, it is recommended that CFRP strips with a spacing of 20 mm be used to improve the strength capacity of the RC column; in addition, this wrapping technique provides economic benefits compared to a column confined with full wrapping.

## 1. Introduction

Over the past several decades, the innovative application of FRP composites has gained popularity as a method of upgrading/strengthening the deteriorated RC structures in the construction industry due to their high resistance to corrosion and their high strength-to-weight ratio. In addition, FRP composites are lightweight and durable and have high tensile strength, stiffness, and fatigue strength [1]. The external confinement provided by the FRP composites prevents Poisson's effect and enhances the strength capacity and ultimate strain of the concrete. Deterioration of RC structures can be caused by a variety of factors, including fire, ageing, environmental degradation, cracking, corrosion and yielding of steel, and large deformation because of overloading. Traditionally, steel jacketing using steel plates was often used to improve the performance of an RC column, and the effectiveness of this technique has been demonstrated through various strengthening applications [2–4]. Even though the technique was successful in practice, it had some problems, including the addition of self-weight, corrosion of the steel plate, the need for skilled labour, and a higher cost. In addition, this method can be applied only to the square and rectangular columns and is not possible to apply to the circular columns. The research outcomes of Wu et al. [2] revealed that the bonding of linear steel jackets was ineffective in providing confinement pressure, and ACI 440.2 R-02 [5] does not recommend this technique due to this fact. In contrast, the use of fibre reinforced polymer (FRP) composites for rehabilitation does not have any of these drawbacks, and moreover, it enables the upgrading of deteriorated members without significantly altering the appearance of the member [6]. The outcomes of most of the pioneer research work carried out by researchers Xiao and Wu [7], Maruyama et al. [8], Toutanji and Deng [9], Chaallal et al. [10], Mukherjee et al. [11], Zaki [12], Yaqub and Bailey [13], Wu et al. [14], Park et al. [15], Bouchelaghem et al. [16], Pan et al. [17], Wu et al. [18], Mouring et al. [19], Attari et al. [20], Sun et al. [21], and Sen and Reddy [22] revealed that FRP confinement significantly enhances the strength, stiffness, and ductility of the RC structures. Recently, several researchers [23–26] have performed studies on analytical and numerical modelling of FRP strengthened RC structures subjected to various loads. The strengthening/upgrading of RC columns through fully bonding the external surface with FRP composites has led to the increased utilization of FRP composites, thus increasing the cost of the strengthening technique. Thus, studies should be carried out to identify the most favorable FRP wrapping scheme to improve the performance of the RC column members. In order to resolve this issue, a feasibility investigation was carried out on the utilization of CFRP composites in the form of strips to confine the column. Unlike the aforementioned bonding methods, this approach provides an economical solution. Unidirectional CFRP strips having a width of 50 mm were used in this study, and the experimental parameters were effective spacing between the CFRP strips and number of CFRP layers. The columns were tested under concentrical compression load, and the tests were performed until failure of the column. The test results of the columns confined by CFRP strips were compared with the previous studies, specifically Abdollahi et al. [27], Au and Buyukozturk [28], Pon et al. [29], Bisby et al. [30], Aire et al. [31], Silva [32], Almusallam [33], Silva and Rodrigues [34], Benzaid et al. [35], Smith et al. [36], Erdil et al. [37], Akogbe et al. [38], Miyauchi et al. [39], Wang and Wu [40], Hosotani et al. [41], Shehata et al. [42], Santarosa et al. [43], Thériault et al. [44], Valdmanis et al. [45], Wang and Wu [46], Wang and Hsu [47], Hadi [48], Punurai et al. [49], Quiertant and Clement [50], Pham et al. [51], Li et al. [52], Siddiqui et al. [53], and Sharma et al. [54] conducted on RC columns externally confined by full wrapping, in terms of stress and strength enhancement ratio.

## 2. Experimental Program

*2.1. Material Properties*

*2.1.1. Cement and Aggregates.* Locally available ordinary/commercial Portland cement was used as a binding material. According to IS 8112:2013 [56], the specific gravity of the cement was tested, and the value obtained was about 3.13. Natural river sand passing through 4.75 mm was used as fine aggregate and crushed blue metal about 10 mm in size was used as a coarse aggregate. Crushed blue metal jelly is the blue-gray hard stone, bluish in color, which is crushed and used for concrete production in the southern part of India. The sieving analysis of both fine and coarse aggregate was carried out according to IS 2386(1):1963 [57] and the specific gravity of the sand and the coarse aggregate was about 2.48 and 2.67, respectively.

*2.1.2. Steel Reinforcement.* Commercial high yield strength deformed (HYSD) bars having a yield strength of 415 N/mm$^2$ were used as reinforcement. Six 8 mm diameter bars were used as longitudinal/vertical/main reinforcement for all columns. For rings/stirrups, 6 mm diameter was used, and the effective spacing between the stirrups was about 100 mm.

*2.1.3. Fibre and Matrix Material.* A unidirectional carbon fibre called Sikawrap-230 C, fabricated by SIKA India Inc., was used in this study to strengthen the column. Carbon fibre was selected for its superior mechanical and durability properties. The stiffness and tensile strengths of the fibre, as provided by the manufacturer, were 230 GPa and 4300 MPa, respectively. The thickness of the fibre was 0.131 mm. It is a fabric type of fibre and can be tailored into any desired shape. An epoxy impregnation resin called Sikadur-330 supplied by SIKA India Inc. was used in this study to make the effective bond between concrete and CFRP. It is a two-part system that includes resin and hardener, and the mixing ratio was 100 : 25 (B : H).

*2.2. Concrete.* Based on the aggregated properties obtained according to the aforementioned IS standards, the concrete mix proportions were designed to achieve the strength of 25 N/mm$^2$ (M25) according to the procedure described in IS 10262:2009 [63]. The mix proportion of the concrete was 1 : 1.6 : 2.9. A constant water-to-cement ratio (W/C) was observed for all mixtures, and the value was about 0.40. A test was performed to determine the 28 days' compressive strength of concrete using 150 mm × 150 mm × 150 mm cubes. The average concrete strength obtained was about 36.5 Mpa.

*2.3. Specimen Fabrication.* A total of seven columns having a cross-sectional dimension of 125 mm diameter and a height of 800 mm were fabricated. Of the six specimens excluding the reference column, three columns were externally confined by 50 mm width CFRP strips having a spacing of 20 mm, and the remaining three columns were confined with the spacing of 40 mm using 50 mm width CFRP strips. The specimen fabrication procedure followed in this study was very similar to the procedure followed in [55]. For concrete mixtures, cement and aggregates were weighed in dry condition and mixed together in a 30-litre omni mixer for 60 seconds. Later, the required amount of water was added and the mixture was mixed together for 180 seconds. With the required cover specified in IS 456-2000, the fabricated reinforcement was placed in the mould. Following this, the mould was filled with concrete layer by layer, and each layer of concrete was effectively compacted by the needle vibrator to ensure the concrete was free from air gaps and flaws. After 24 hours, the moulds were removed and the columns were allowed to membrane-cure for 28 days. Surface preparation of a column is very important to achieve an effective bond between the concrete and FRP composites. Thus, after 28 days' curing, the external surface of all the columns was subjected to sand blasting using coarse sand in order to make the surface rough. After sandblasting, all of the columns were covered with plastic sheets immediately and kept in an airtight room. They were then strengthened with CFRP composite strips with two different wrapping schemes, and the different spacings are shown in Figure 1. Before the columns were strengthened with FRP composites, acetone was used to clean the surface

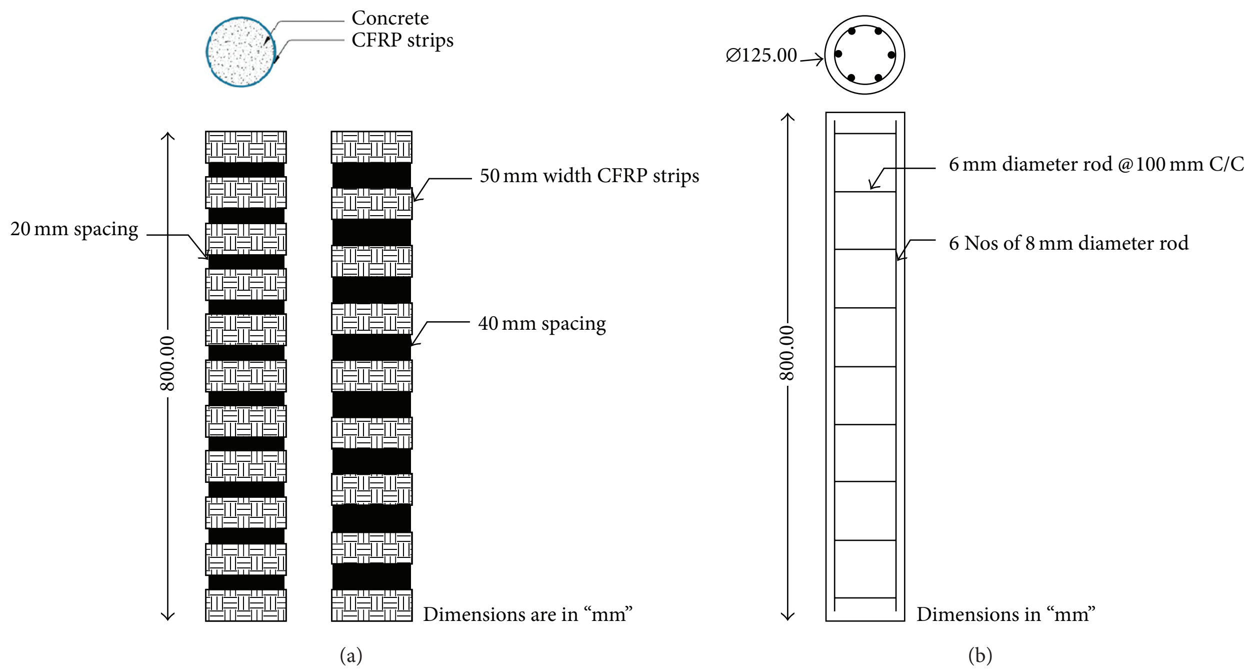


Figure 1: (a) CFRP strips wrapping scheme and (b) column reinforcement details.

to remove the contaminated material, and a steel roller was used in the direction of the fibre to remove the air gaps and excessive resin, as shown in Figure 2.

*2.4. Axial Loading Setup.* A compression testing machine with a capacity of 2000 kN was used to test the column specimens under concentrically axial compression. The column member was placed on the supports, and care was taken to ensure that its centerline was exactly in line with the axis of the machine. Linear voltage displacement transducers (LVDTs) were used to measure the axial and lateral deformation of the column and the 2000 kN load cell was used to monitor the load. Both load cell and LVDTs were connected to the 16-Channel Data Acquisition System to store the data. The load was applied to the columns using an electronic jack and they were tested until failure. The experimental observation includes the nature of the failure, axial deformation, and ultimate load. To identify the specimens easily and for discussion, the columns were designated with names such as NC-CC, NC-20-1, NC-20-2, NC-20-3, NC-40-1, NC-40-2, and NC-40-3. For example, the name of specimen NC-40-2 specifies that the normal strength column was strengthened by two (2) layers of 50 mm width CFRP strip with the spacing of 40 mm. The control column is specified as NC-CC.

## 3. Results and Discussions

*3.1. Behaviour and Failure Modes.* The reference column showed linear behaviour initially; in addition, the first crack was initiated near to the supports at the respective 50% of its ultimate load. Loading further, the cracks were increased, and new compressive cracks were observed on all sides of the column. Finally, the column failed by crushing of concrete, with concrete spalling observed at the supports occurring at the load of 252 kN. It was an explosive failure, accompanied by loud noise, due to the brittle failure of the concrete, as shown in Figure 3. For the column confined with 50 mm CFRP strips with 20 mm spacing (NC-20-2 and NC-20-3), at the respective 60% (155 kN) ultimate load of the reference column (approximately), there were no cracks observed in the unbonded area (on concrete surface); however, a cracking sound was observed due to the removal of excessive resin on the outside of the CFRP strips. Loading further, the columns failed by rupture of fibre followed by crushing of concrete, as shown in Figures 4 to 6; furthermore, it was a very sudden and catastrophic failure when compared to the reference column. As uniform pressure is applied on the top surface of the column, the concrete core expands laterally due to Poisson's effect and this load effect transfers to the CFRP composite strips through adhesion by the shear stress mechanism [64] (see Figure 7). In this way, the load transmitted between column and fibre via the intermediate adhesive layer. The CFRP prevents Poisson's effect on the concrete by providing confining pressure (see Figure 7) and is subjected to tension in the hoop direction, thus enhancing the compressive strength and stiffness of the concrete. Furthermore, the concrete zone near to the CFRP strips becomes more rigid due to the greater confinement pressure exerted by the CFRP strips. When the CFRP strips no longer resist Poisson's effect, rupture of CFRP occurs, followed by the crushing of concrete. The catastrophic failure mode of the strengthened column is attributed to the abrupt absence of confining pressure exerted by the CFRP composites caused

(a) (b) (c)

(d)

Figure 2: Wrapping procedure [55]: (a) applying resin coating; (b) wrapping CFRP strips; (c) removing excessive resin using steel roller; (d) all strengthened beams.

by the rupture of FRP composites. The increase in the spacing between the CFRP strips from 20 mm to 40 mm transforms the failure mode from CFRP rupture to crushing of concrete which occurred in the unbonded area, as shown in Figures 8 to 10. When the spacing between CFRP strips is increased, the unbonded area is subjected to more strain due to the absence of confining pressure; in addition, the plastic hinges ($M_p$) were formed on the unbonded area [64] (see Figure 11) due to there being a quite high effective spacing between the FRP strips. As a result, the crushing of concrete occurred on the unbonded area even before the CFRP composites reached their ultimate strain. It was concluded that the embodied energy that exists in the CFRP strips can be effectively utilized when the spacing between the CFRP strips is quite small.

*3.2. Axial Stress-Strain Behaviour.* The ultimate axial deformation ($\Delta_u$) and the percentage of enhancement of the restraint effect against the axial deformation of the strengthened column when compared to the reference column are summarized in Table 1. The ultimate axial deformation ($\Delta_u$) of the column is the axial deformation of the column when the load falls to 80% of its ultimate load. The lateral confinement provided by the CFRP strips showed positive effects in terms of restraining the deformation of the column at both spacings, as shown in Figures 12 to 14; in addition, that restraint effect further promoted the axial stress of the column, which is evident from Figure 14. Column NC-20-1 exhibited quite comparable stress-strain behaviour to the reference column; however, the axial stress was slightly higher than the reference column. Nevertheless, the columns NC-20-2 and NC-20-3 showed a large amount of restraint against axial deformation (see Figure 12) from the initial stage; in addition, a significant improvement in axial stress was observed when compared to the control column. Furthermore, until the respective failure load of the reference column was reached, columns NC-20-2 and NC-20-3 behaved elastically and then started to behave plastically when the load of the columns reached approximately 65% to 70% (240 kN to 351 kN) of ultimate

Table 1: Experimental result of all specimens.

| Designation of columns | Failure load (kN) | Ultimate axial deformation ($\Delta_u$) | % of the restraining effect against axial deformation compared to reference column | Displacement ductility, $\mu_\Delta = \Delta/\Delta_y$ | % of increase in axial load carrying capacity | The maximum stiffness value of all columns (kN/mm) | Theoretical $P_{theo}$ [39] | Percentage of error, $\Delta = ((P_{exp} - P_{theo})/P_{exp}) \times 100$ (%) |
|---|---|---|---|---|---|---|---|---|
| NC-CC | 252.13 | 2.72 | — | 1.012 | — | 81.78 | — | — |
| NC-20-1 | 338.45 | 4.95 | 16.67 | 0.956 | 34.12 | 99.45 | 309.33 | 8.48 |
| NC-20-2 | 400.23 | 3.94 | 82.60 | 1.002 | 58.73 | 148.47 | 366.66 | 8.33 |
| NC-20-3 | 502.09 | 3.52 | 197.87 | 1.284 | 99.20 | 265.91 | 424.12 | 15.54 |
| NC-40-1 | 261.14 | 3.48 | 1.22 | 0.932 | 3.57 | 78.12 | 296.21 | 13.64 |
| NC-40-2 | 310.19 | 3.73 | 40.67 | 0.97 | 23.02 | 108.12 | 341.18 | 10.06 |
| NC-40-3 | 339.72 | 2.81 | 92.15 | 1.061 | 34.74 | 180.14 | 385.77 | 13.80 |


Figure 3: Failure pattern of reference column.

Figure 5: Failure pattern of NC-20-2.


Figure 4: Failure pattern of NC-20-1.

Figure 6: Failure pattern of NC-20-3.

load. This phenomenon indicates that the increase in the CFRP layers increases the composite plate's thickness, and as a result the confining pressure provided by the CFRP strips increased, significantly controlling Poisson's effect of the concrete, and enhanced the confinement provided by the steel stirrups. It is concluded that a minimum of two layers of CFRP strips should be applied to the RC column in FRP strips strengthening in order to acquire better enhancement of axial deformation control. At the failure load of the reference column, columns NC-20-1, NC-20-2, and NC-20-3 showed an axial deformation of 3.61 mm, 2.34 mm, and 1.41 mm, respectively, which is 16.66%, 82.61%, and 197.87% higher than that of the reference column, respectively. From Figure 15, it can be understood that the enhancement in the restraint of axial deformation was linear when the number of CFRP layers was increased. Compared to columns NC-20-1 and NC-20-2, column NC-20-3 had a restraining effect that was increased by 288.65% and 152.14%, respectively. It was observed that the column confined with 40 mm spacing (NC-40-1, NC-40-2, and NC-40-3) showed inferior effects (see Figures 13 and 14) in terms of restraining axial deformation due to the increased spacing between the CFRP strips. Column NC-40-1 did not show any axial deformation control; in addition, the stress-strain behaviour of the column was very similar to that of the reference column (see Figure 13). As discussed earlier, the absence of confining pressure in the unbonded area and the increased effective spacing between the FRP strips led to the formation of plastic hinges ($M_p$) on the unbonded area (see Figure 11). As a result, the crushing of concrete occurred, even before the CFRP strips reached their ultimate strain. Thereby, the embodied energy existing in the CFRP strips has not been effectively utilized. Columns NC-40-2 and NC-40-3 showed a 40.61% and 75.12% enhancement in deformation control, respectively, at the failure load of the reference column. From Figure 14, it can be understood that column NC-40-3 showed equal stress-strain behaviour to that of column NC-20-1. This tendency indicates that the formation of a restraint effect against axial deformation depends upon the effective spacing between the CFRP strips.

The test results of the columns confined by CFRP strips were compared with the previous studies conducted

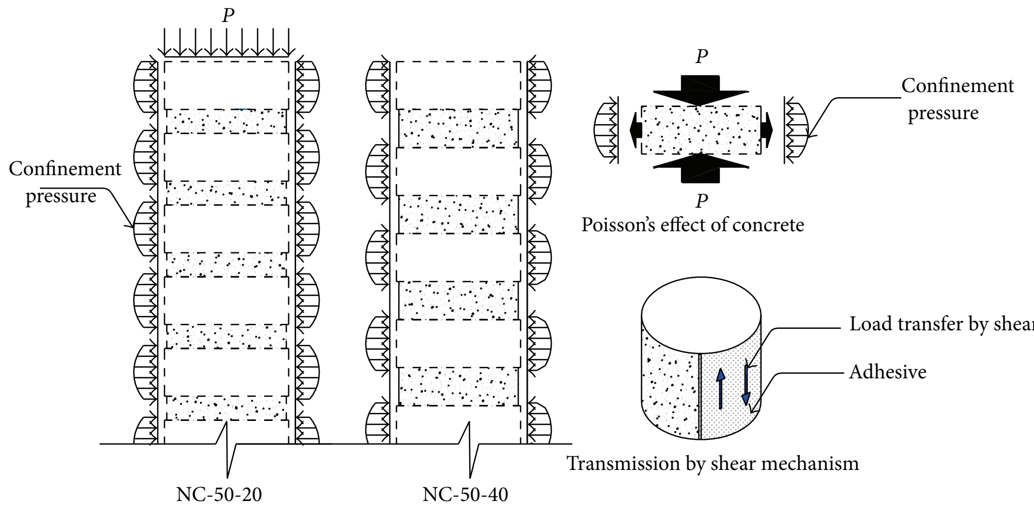


Figure 7: Confinement provided by CFRP strips and transmission by shear mechanism.

Figure 8: Failure pattern of NC-40-1.


Figure 9: Failure pattern of NC-40-2.

Figure 10: Failure pattern of NC-40-3.

on RC columns externally confined by full wrapping, in terms of stress and strength enhancement ratio. Among these studies, few studies were performed on plain concrete confined using different types of FRP with different strengths and modulus. The stress enhancement ratio of some of the previous studies conducted on RC columns externally confined by full wrapping is summarized in Table 2 and the results were compared with the present study as is shown in Figure 16. From Figure 16, it can be understood that the stress enhancement ratio value in the present study is essentially equal to the previous studies [27–46]; in addition, in many cases [28, 30–33, 35–37, 40–42, 45] the stress enhancement ratio value of the present study was quite high. From this, it can be concluded that wrapping with the strips rather than conventional wrapping can be used to enhance the stress capacity of the RC columns, while providing an economic advantage.

*3.3. Ductility Performance.* The displacement ductility index of the FRP confined column is an important structural property due to the rupture and catastrophic failure mode of the FRP composites. From the idealized bilinear curve obtained from the load deformation behaviour of the column, the displacement ductility index of all the columns was

Table 2: Test results of previous studies: stress enhancement ratio.

| Paper | Diameter of the column, $D$ (mm) | Height of the column, $H$ (mm) | Compressive stress value of unconfined column ($f_{sucon}$), N/mm$^2$ | Confinement type | Type of fibre | Stress enhancement ratio, $f'_{scc}/f_{sucon}$ |
|---|---|---|---|---|---|---|
| Abdollahi et al. [27] | 150 | 300 | 41.7 | Full wrap | Normal modulus CFRP | 3.32 |
| Au and Buyukozturk [28] | 150 | 375 | 24.2 | Full wrap | GFRP | 1.81 |
| Pon et al. [29] | 150 | 1200 | 9.6 | Full wrap | CFRP | 3.26 |
| Bisby et al. [30] | 150 | 300 | 34.4 | Full wrap | CFRP | 1.28 |
| Aire et al. [31] | 150 | 300 | 42 | Full wrap | CFRP and GFRP | 2.57 |
| Silva [32] | 150 | 750 | 26.21 | Full wrap | Normal modulus CFRP | 1.56 |
| Almusallam [33] | 150 | 300 | 50.80 | Full wrap | Normal modulus CFRP | 2.10 |
| Silva and Rodriguez [34] | 250 | 750 | 31.2 | Full wrap | CFRP | 3.03 |
| Benzaid et al. [35] | 160 | 320 | 49.5 | Full wrap | Normal modulus CFRP | 2.55 |
| Smith et al. [36] | 250 | 500 | 35 | Full wrap | CFRP | 1.69 |
| Erdil et al. [37] | 150 | 300 | 20.8 | Full wrap | CFRP | 2.96 |
| Akogbe et al. [38] | 300 | 600 | 26.5 | Full wrap | CFRP | 3.19 |
| Miyauchi et al. [39] | 100 | 200 | 31.2 | Full wrap | CFRP | 3.26 |
| Wang and Wu [40] | 150 | 300 | 30.9 | Full wrap | CFRP | 2.41 |
| Hosotani et al. [41] | 200 | 600 | 41.72 | Full wrap | CFRP | 2.23 |
| Shehata et al. [42] | 225 | 450 | 34 | Full wrap | CFRP | 2.41 |
| Santarosa et al. [43] | 150 | 300 | 28.1 | Full wrap | CFRP | 3.05 |
| Thériault et al. [44] | 304 | 608 | 37 | Full wrap | CFRP and GFRP | 3.89 |
| Valdmanis et al. [45] | 150 | 300 | 44.3 | Full wrap | CFRP | 2.60 |
| Wang and Wu [46] | 194 | 582 | 51.6 | Full wrap | AFRP | 3.37 |
| Present study | 125 | 800 | 20.54 | Strip wrap (20 mm spacing) | Normal modulus CFRP | 2.99 |

$f'_{scc}$: stress value of FRP confined column.

evaluated [4] using (1), where $\mu_\Delta$ is the ductility index of the column; $\Delta$ is the axial deformation of the column when the load falls to 85% of the ultimate load; $\Delta_y$ is the deformation at the respective yield load of the column (deformation at the respective load falls to 75% of the ultimate load):

$$\mu_\Delta = \frac{\Delta}{\Delta_y}. \quad (1)$$

The evaluated displacement ductility index of the strengthened columns has ranged from 0.93 to 1.28. From Figure 17, it can be understood that the presence of CFRP strips enhances the ductility performance of the column; however, the enhancement was not significantly higher. In addition, the increase in the effective spacing between the CFRP strips decreases the displacement ductility index of the column. The columns confined with three layers in 20 mm

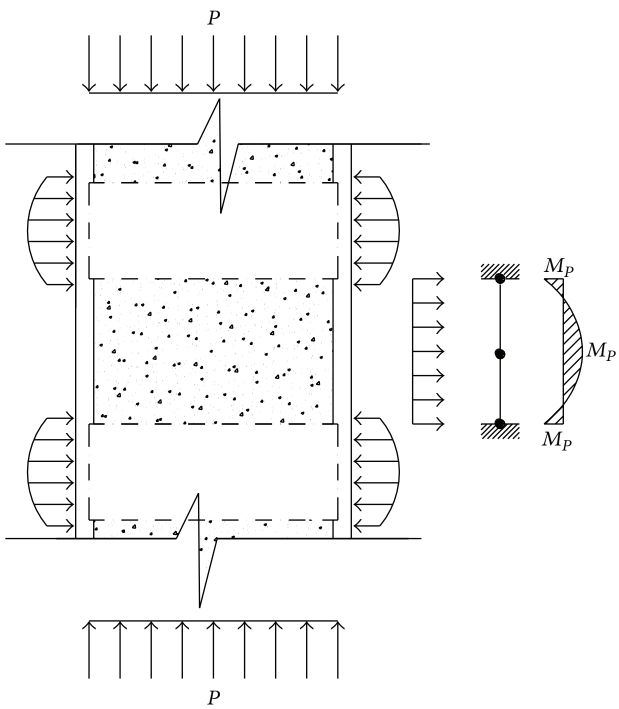


Figure 11: Crushing failure of concrete.

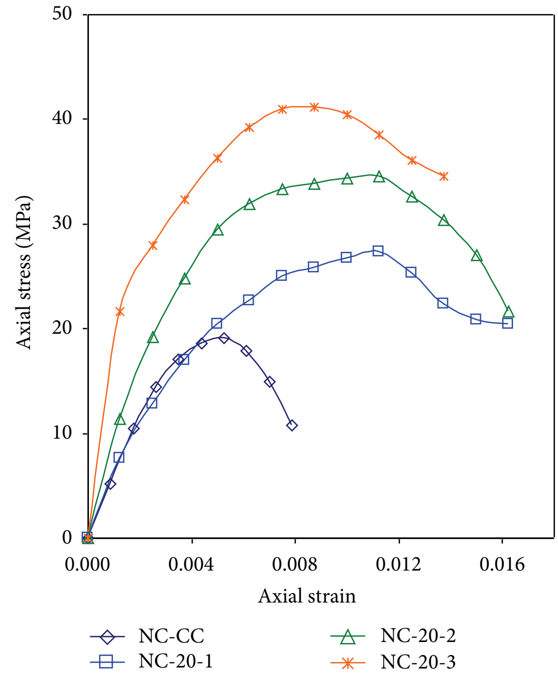


Figure 12: Axial stress-strain behaviour of columns confined with 20 mm spacing, comparison.

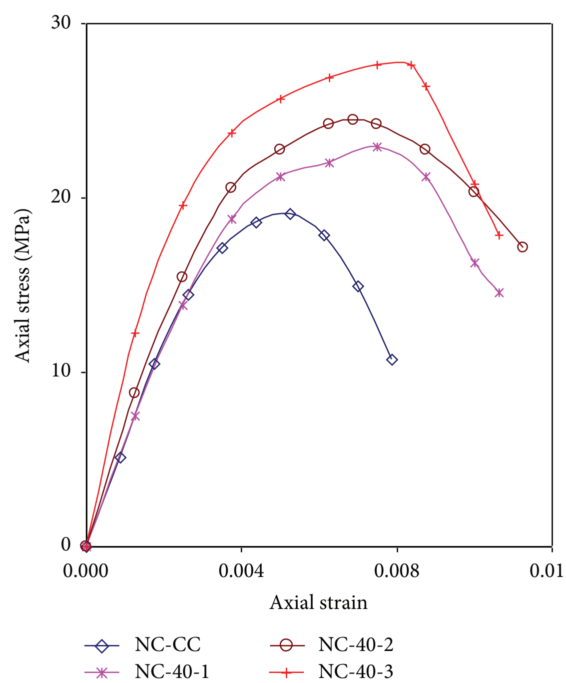


Figure 13: Axial stress-strain behaviour of columns confined with 40 mm spacing, comparison.

spacing showed a more beneficial effect on the ductility response when compared to the column confined with one and two layers. The displacement ductility index of column NC-20-3 was increased by 26.41% compared to the reference column. However, column NC-40-3 showed only a 4.71% enhancement compared to the reference column. From this, it is concluded that increasing to a high spacing between the CFRP strips results in the wrapping having only a superficial effect on the ductility behaviour of the column. It is suggested that the CFRP material with smaller spacing can be used as a strengthening material to improve the performance of the RC column without affecting the ductility performance.

*3.4. Ultimate Strength and Stiffness.* The measured ultimate strength of all strengthened columns and their enhancements in strength compared to the reference column are presented in Table 1. Figure 18 clearly shows that the external confinement provided by the CFRP strips composites enhances the strength capacity of the RC column; however, the enhancement was only high for the columns confined with more layers and smaller spacing, which is evident from Figure 18. For the column confined with 20 mm spacing, in comparison with the reference column, the column strengthened with one layer of CFRP strips did not show any significant increase in strength, and furthermore it has enhanced its strength by only 34.12% compared to that of the reference column. However, the columns NC-20-2 and NC-20-3 increased their strength capacity by 58.73% and 99.20%, respectively, compared to that of the reference column. The increase in the composite plate thickness provides more confinement pressure during Poisson's effect of the concrete and keeps the concrete in a state of three-dimensional stress, and as a result the compressive strength and stiffness of the concrete are increased. This mechanism led to an increase in the strength capacity of the column. This tendency exposed the fact that having more than one layer of CFRP strips provides a significant improvement in the strength capacity of

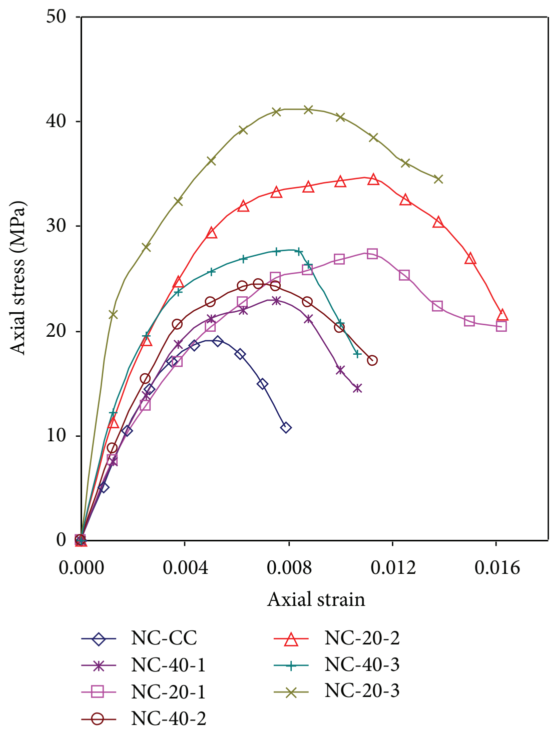


FIGURE 14: Axial stress-strain behaviour of all columns, comparison.

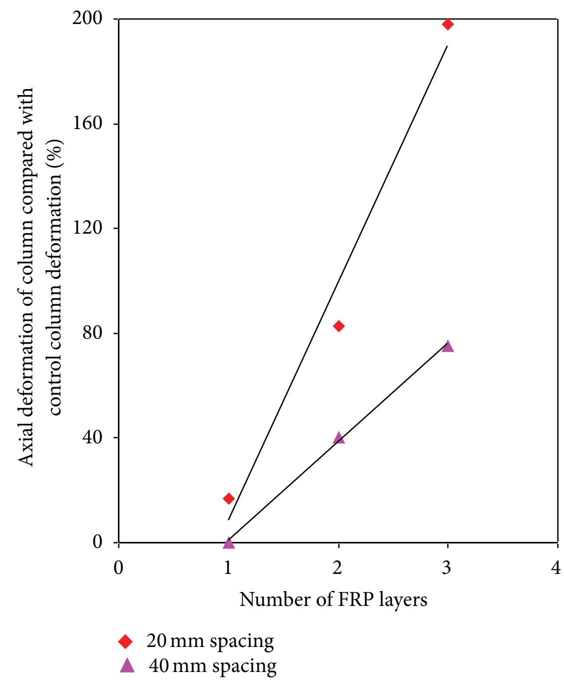


FIGURE 15: Relation between axial deformation control and number of CFRP layers.

the column. It is interesting to note that while the strength capacity of the columns was increased with the increases in the number of layers, the enhancement was not proportional, as is shown in Figure 19. As was discussed earlier, this could be attributed to the crushing failure of resin between the CFRP composite strips. In contrast, the enhancement in the strength of the column confined with 40 mm spacing was not significant (see Figure 18), and the column confined with one and two layers showed a strength capacity nearly equal to that of the reference column. The columns NC-40-1, NC-40-2, and NC-40-3 showed a strength capacity that was enhanced by 3.57%, 23.02%, and 34.74%, respectively, when compared to the reference column. These outcomes lead us to the conclusion that the increase in strength capacity can be achieved only with a smaller spacing. The column's capacity to provide a restraint effect against deformation during loading can be referred to as stiffness of the column [65]. The stiffness of the columns was evaluated from the obtained load deformation value, and the values are listed in Table 1 and presented in Figure 20. All the columns showed higher stiffness during initial loading; however, the stiffness of the columns started to decrease with the increase in the applied load. The column confined with CFRP strips had high stiffness throughout the entire loading compared to the reference column, due to the prevention of Poisson's effect of concrete through the additional confining pressure provided by the CFRP strips. However, increasing the effective spacing between the strips decreased the stiffness of the column when compared to the column confined with smaller spacing, as is shown in Figure 20. In comparison to the column with three layers in 40 mm spacing (NC-40-3), the column NC-20-3 showed an increase in stiffness of 68.98%, and this increase in strength is high.

The strength enhancement ratios found in some of the previous studies performed on RC columns externally strengthened by full wrapping are summarized in Table 3 and are compared with this present study in Figure 21. Table 3 covers the geometric properties of the specimen (size and height): strength value of unconfined column ($f_{ucon}$), confinement type, type of fibre, number of layers ($n$), and strength value of FRP confined column ($f_{cc}$). From Table 3 and Figure 21, it can be understood that the strength enhancement ratio of this present study is very close to the RC column confined by full wrapping, and thus it can be concluded that the confinement provided by the FRP strips is relatively equal to the confinement provided by the full wrapping. From the test results, it is suggested that CFRP strips with the spacing of 20 mm can be used to improve the strength capacity of the RC column. In addition, the CFRP strips strengthening technique provides a cost-effective solution in place of the column confined with full wrapping.

## 4. Evaluating the Ultimate Strength of FRP Confined RC Column Based on Existing Models

Over the past several decades, various researchers suggested many expressions to evaluate the strength capacity of the FRP confined column. However, expression (2) proposed by Richart et al. [66] is widely accepted by many researchers.

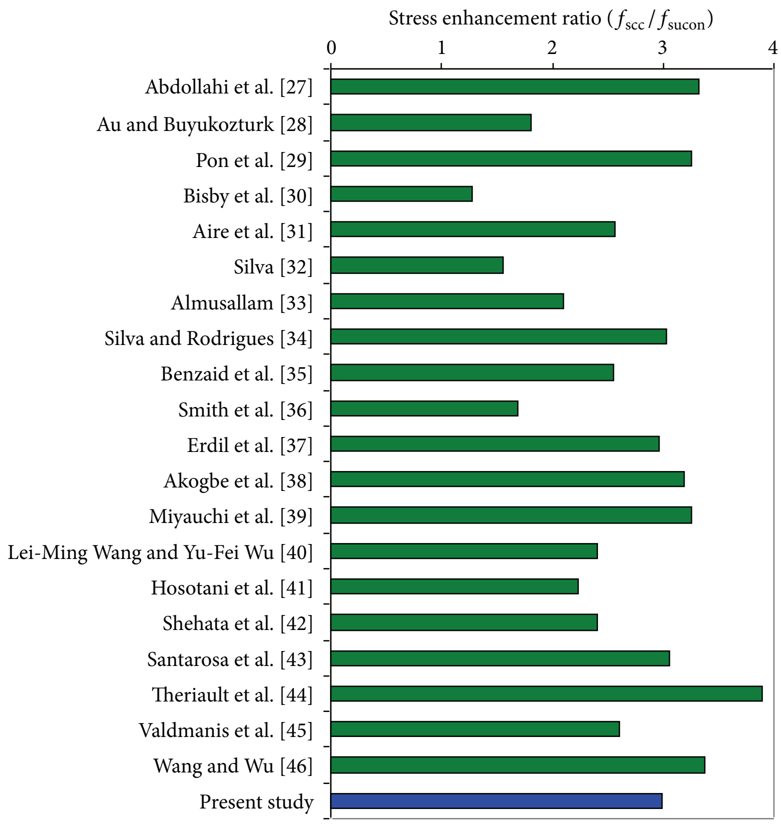


FIGURE 16: Stress enhancement ratio of present and previous studies, comparison.

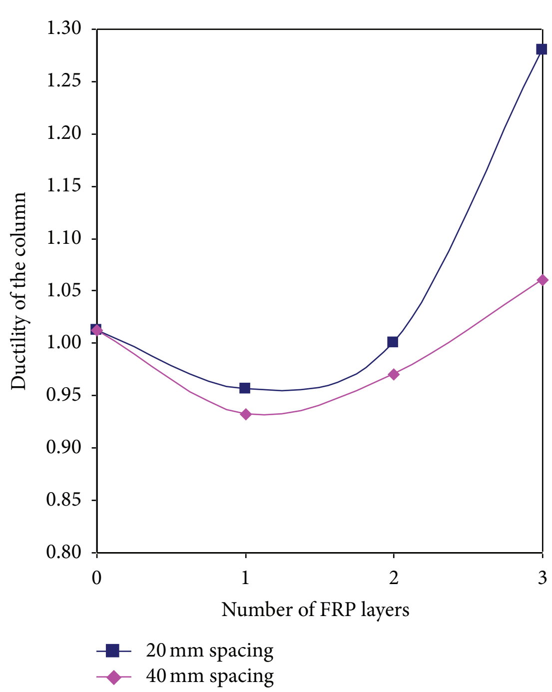


FIGURE 17: Displacement ductility behaviour of all columns, comparison.

Table 3: Test results of previous studies: strength enhancement ratio.

| Paper | Dimension or diameter of the column (mm) | Height of the column, $H$ (mm) | Confinement type | Type of fibre | Number of layers ($n$) | Strength value of unconfined column ($f_{ucon}$) kN | Strength value of FRP confined column ($f'_{cc}$) kN | Strength enhancement ratio $f_{cc}/f_{ucon}$ |
|---|---|---|---|---|---|---|---|---|
| Silva [32] | 150 | 750 | Full wrap | Normal modulus CFRP | 3 | 468.40 | 732.99 | 1.56 |
| Wang and Wu [40] | 150 | 300 | Full wrap | Normal modulus CFRP | 2 | 545.77 | 1317.79 | 2.41 |
| Wang and Hsu [47] | 300 | 900 | Full wrap | GFRP | 6 | 2127 | 4025 | 1.89 |
| Hadi [48] | 205 | 925 | Full wrap | Normal modulus CFRP | 3 | 552 | 871.3 | 1.58 |
| Punurai et al. [49] | 76 | 1200 | Full wrap | Normal modulus CFRP | 3 | 36.5 | 59.64 | 1.63 |
| Yaqub and Bailey [13] | 200 | 1000 | Full wrap | High modulus CFRP | 2 | 826 | 1356 | 1.64 |
| Quiertant and Clement [50] | 200 × 200 | 2500 | Full wrap | Normal modulus CFRP | 2 | 1211 | 1578 | 1.30 |
| Pham et al. [51] | 212 | 800 | Full wrap | High modulus CFRP | 3 | 942 | 2109 | 2.24 |
| Li et al. [52] | 152.4 | 609.6 | Full wrap | E Glass Fibre | 2 | 652.91 | 866.93 | 1.33 |
| Siddiqui et al. [53] | 150 | 1200 | Full wrap | Normal modulus CFRP | 3 | 258 | 647.12 | 2.51 |
| Sharma et al. [54] | 125 × 125 | 1200 | Full wrap | GFRP sheet | 2 | 303 | 596.11 | 1.97 |
| Present study | 125 | 800 | Strip wrap (20 mm spacing) | Normal modulus CFRP | 2 | 252.13 | 401.23 | 1.58 |
| Present study | 125 | 800 | | Normal modulus CFRP | 3 | 252.13 | 502.09 | 1.99 |

$f_{ucon}$: strength value of unconfined column; $f'_{cc}$: strength value of FRP confined column.

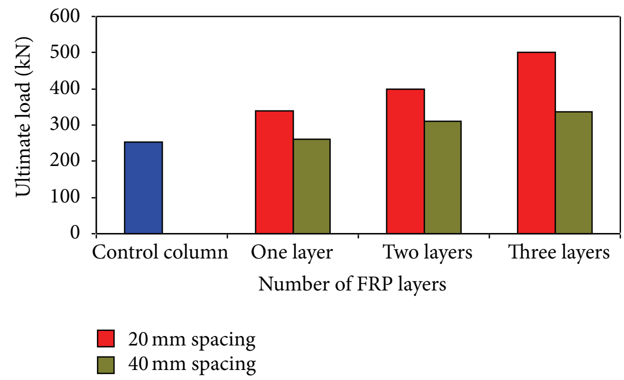


Figure 18: Ultimate axial strength of all strengthened columns, comparison.

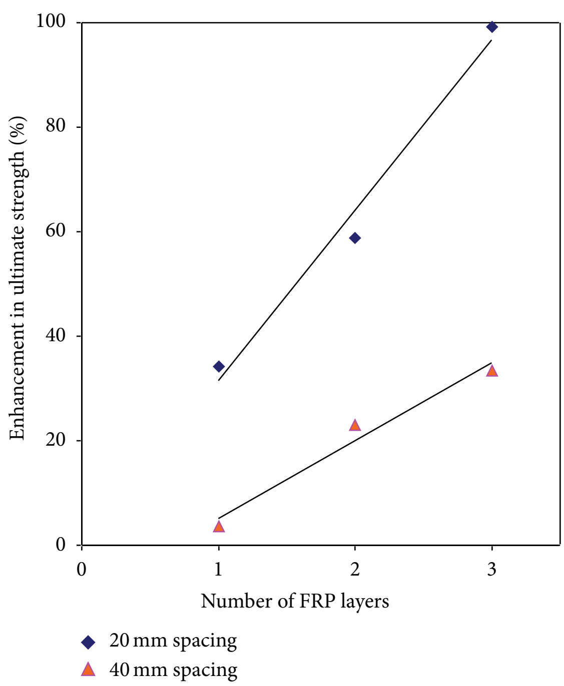


Figure 19: Relation between enhancement in ultimate strength and number of CFRP layers.

It is a simple equation, and the confinement coefficient can be adjusted based on the type of fibre used:

$$\frac{f_{cc}}{f_{ucon}} = 1 + k\frac{f_{lc}}{f_{ucon}}, \quad (2)$$

where $f_{cc}$ is the compressive strength of FRP confined column; $f_{lc}$ is lateral confinement pressure exerted by the FRP composites; and $f_{ucon}$ and $k$ are unconfined compressive strength of the column and effective confinement coefficient, respectively. Based on the model proposed by Siddiqui et al. [53], numerous expressions were proposed in previous research, and a summary of some of the expressions found in the literature [14, 39, 58–62, 67, 68], for estimating the strength capacity of the FRP confined column, is considered in this study. From (2), it can be understood that the strength capacity of the FRP confined column depends upon the confinement ratio ($f_{lc}/f_{ucon}$) in addition to confinement pressure ($f_{lc}$) exerted by the FRP composite affecting the strength performance of the FRP confined concrete. Among the few models [14, 39, 58–62, 67, 68], the model proposed by Miyauchi et al. [39] was considered in this study to evaluate the ultimate strength capacity of the FRP confined RC column, since the models proposed by various studies showed a lower prediction, which is shown in Figure 22; in addition, the percentage of difference of the studies was also very high (see Table 4). The modes proposed by Miyauchi et al. [39] are as follows:

$$f_{cc} = f_{ucon}\left[1 + 3.5\left(\frac{f_{lc}}{f_{ucon}}\right)\right]. \quad (3)$$

When the column is subjected to uniform pressure on the top of the surface of the column, the concrete starts to expand laterally due to Poisson's effect on the concrete, while the FRP strips in the outer limits prevent Poisson's effect by providing confinement pressure as they are subjected to tension in the hoop direction. As the axial stress increases, the corresponding lateral strain increases and the FRP develops its maximum tensile hoop stress, which is equal to the ultimate tensile strength of CFRP ($f_{frp}$) balanced by the lateral pressure ($f_{lc}$) as shown in Figure 23. By considering the equilibrium, (4) [1] can be derived to find the lateral confinement pressure ($f_{lc}$) provided by the FRP composites:

$$f_{lc} = \frac{\rho_{frp} f_{frp}}{2}, \quad (4)$$

where $f_{lc}$ is the lateral confinement pressure exerted by the CFRP strips; $f_{frp}$ is the tensile strength of FRP in the hoop direction; $\rho_{frp}$ is the FRP volumetric ratio to concrete for the column wrapped with CFRP strips (Figure 1) and can be determined by the following equation:

$$\rho_{frp} = \frac{8 t_{frp} b_{frp}}{D\left(b_{frp} + s_{frp}\right)}, \quad (5)$$

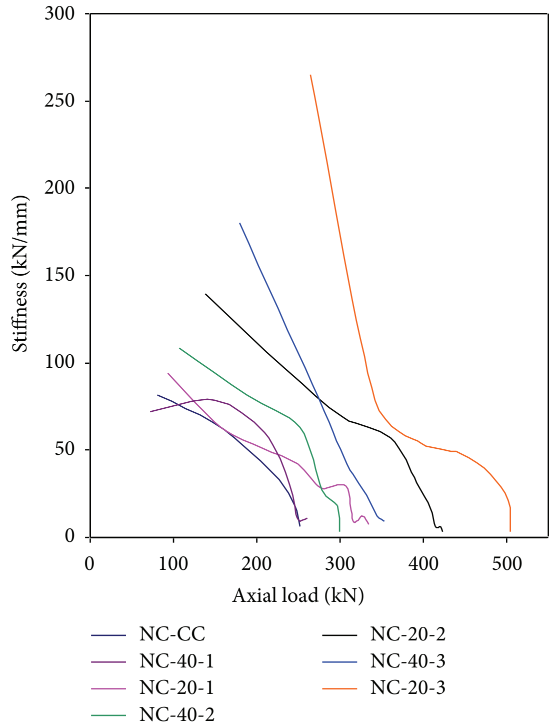


FIGURE 20: Stiffness value of all strengthened columns, comparison.

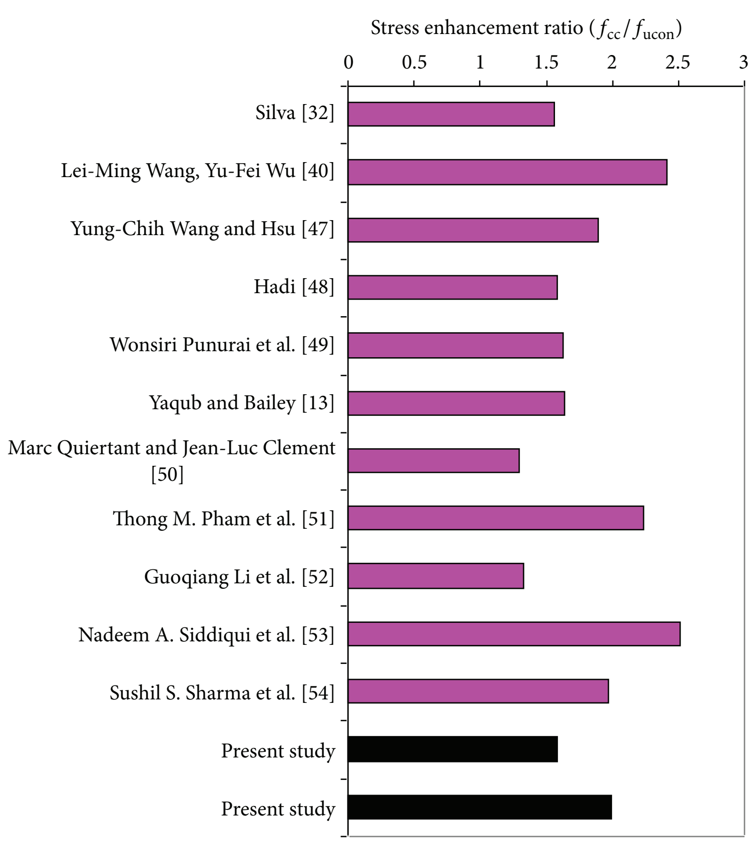


FIGURE 21: Strength enhancement ratio of present and previous studies, comparison.

Table 4: Percentage of error (PE) of some models used to predict the peak axial strength of concrete columns.

| Designation of columns | Percentage of difference (%) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Wu et al. [14] | Miyauchi et al. [39] | Benzaid and Mesbah [58] | Shehata et al. [59] | Tamuzs et al. [67] | Karbhari and Gao [60] | Youssef et al. [68] | Toutanji [61] | Wei and Wu [62] |
| NC-20-1 | 28.52 | 8.48 | 14.33 | 15.75 | 5.09 | 10.92 | 14.54 | −0.12 | 12.88 |
| NC-20-2 | 26.69 | 8.33 | 20.19 | 20.62 | 2.60 | 14.58 | 18.57 | −1.93 | 16.63 |
| NC-20-3 | 31.75 | 15.54 | 30.97 | 30.22 | 8.69 | 24.38 | 27.77 | 6.02 | 26.04 |
| NC-40-1 | 11.94 | −13.64 | −8.21 | −6.31 | −17.05 | −11.66 | −7.54 | −23.29 | −9.40 |
| NC-40-2 | 12.72 | −10.06 | 1.15 | 2.27 | −15.81 | −4.54 | 0.22 | −21.86 | −2.04 |
| NC-40-3 | 8.57 | −13.80 | 3.09 | 3.11 | −21.69 | −4.59 | 0.29 | −26.70 | −2.11 |

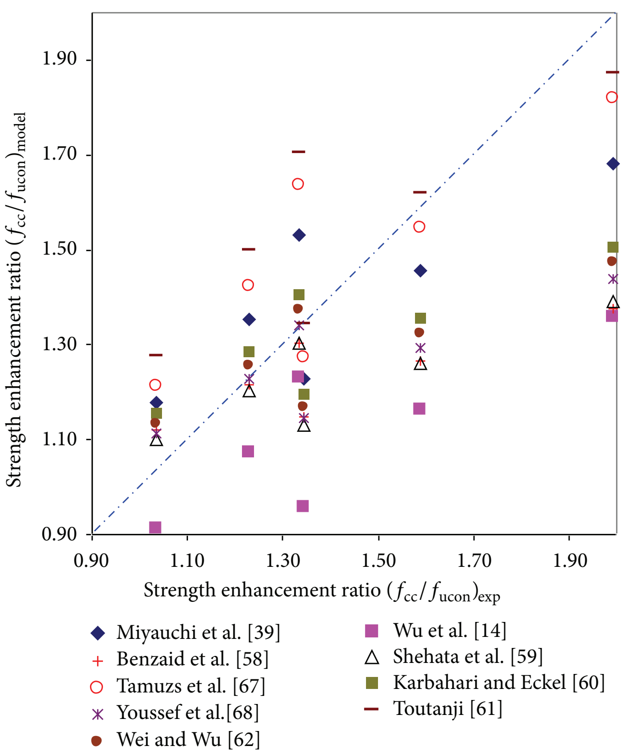


Figure 22: Correlation between theoretical strength enhancement ratio using various existing models and experimental strength enhancement ratio.

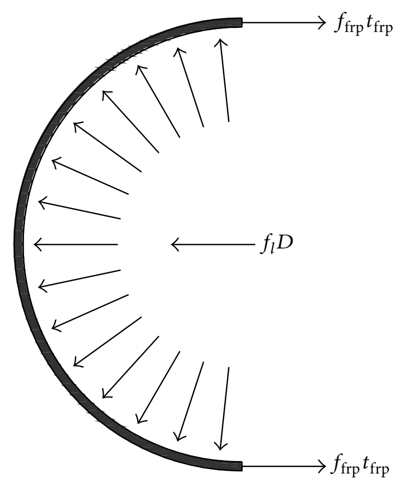


Figure 23: Confinement pressure provided by the CFRP strips CFRP layers.

where $b_{frp}$ and $t_{frp}$ are the width of CFRP strips and thickness of the FRP confinement, respectively; $D$ and $s_{frp}$ are the diameter of the column and clear spacing between the CFRP strips. The load carrying capacity of the FRP confined columns was evaluated through (3) [39] and listed in Table 1. The correlation between the measured and theoretical strengths of the FRP confined column is quite strong, as shown in Figure 24.

## 5. Conclusion

The effectiveness and economic advantages of using CFRP composite strips to strengthen RC columns were investigated. The parameters used included effective spacing between the CFRP strips and number of FRP layers. Based on the test results obtained, the following conclusions can be drawn:

(1) Columns confined with smaller spacing (20 mm) showed a greater restraint of Poisson's effect on the concrete, and this enhanced the strength capacity of the column significantly. In comparison with the reference column, the columns with 20 mm spacing showed a restraint of Poisson's effect and a strength capacity that were increased by 197.87% and 99.20%, respectively. An increase in the number of layers improved the performance of the column further; however, this improvement was not linear. In addition, the presence of CFRP layers increased the ductility performance of the column; in particular, the columns confined with three layers showed a more beneficial effect.

(2) The increase in the spacing between the CFRP strips from 20 mm to 40 mm showed excessively inferior effects in terms of restraining in axial deformation, ductility performance, and strength capacity of the column when compared to the column confined with

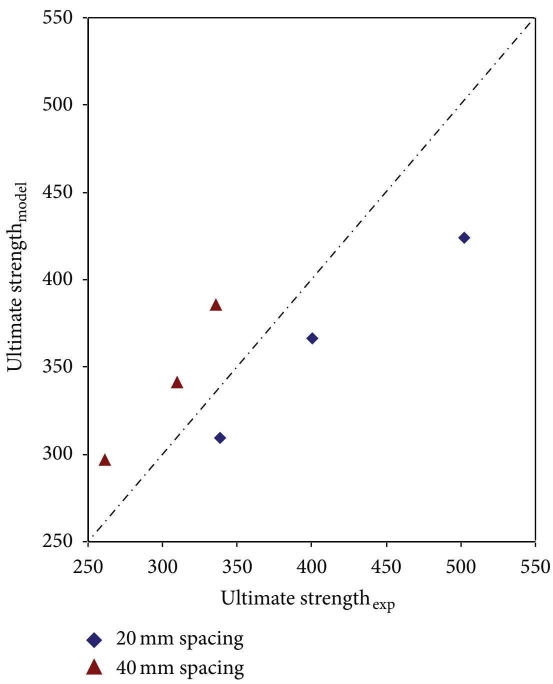


FIGURE 24: Correlation between experimental and theoretical strength enhancement ratios.

20 mm spacing. All the columns failed by crushing concrete alone without any rupture of CFRP composites. In addition, the embodied energy that exists in the CFRP strips was not effectively utilized due to the above mentioned effect. The columns showed an enhancement in the strength capacity of up to 33.33% when compared to the reference column.

(3) The ultimate strength capacity of the strengthened columns predicted using Miyauchi et al.'s [39] expression fairly agreed with the experimental results.

(4) The stress and strength enhancement ratio of this present study is very close to the findings related to RC columns confined by full wrapping, and it is suggested that the CFRP strips with smaller spacing (20 mm) can be used to improve the strength capacity of the RC column. In addition, this CFRP strip strengthening technique provides a solution that is 40% more cost-effective than confining a column with full wrapping.

## Notations

$\Delta_u$: Ultimate axial deformation
$\mu_\Delta$: Ductility index of the column
$\Delta$: Axial deformation of the column
$\Delta_y$: Deformation at the respective yield load of the column
$f_{ucon}$: Strength value of unconfined column
$n$: Number of layers
$f_{cc}$: Strength value of FRP confined column
$f_{lc}$: Lateral confinement pressure exerted by the FRP composites
$k$: Effective confinement coefficient
$f_{frp}$: Ultimate tensile strength of CFRP
$\rho_{frp}$: FRP volumetric ratio
$b_{frp}$: Width of CFRP strips
$t_{frp}$: Thickness of the FRP confinement
$D$: Diameter of the column
$s_{frp}$: Clear spacing between the CFRP strips.

## Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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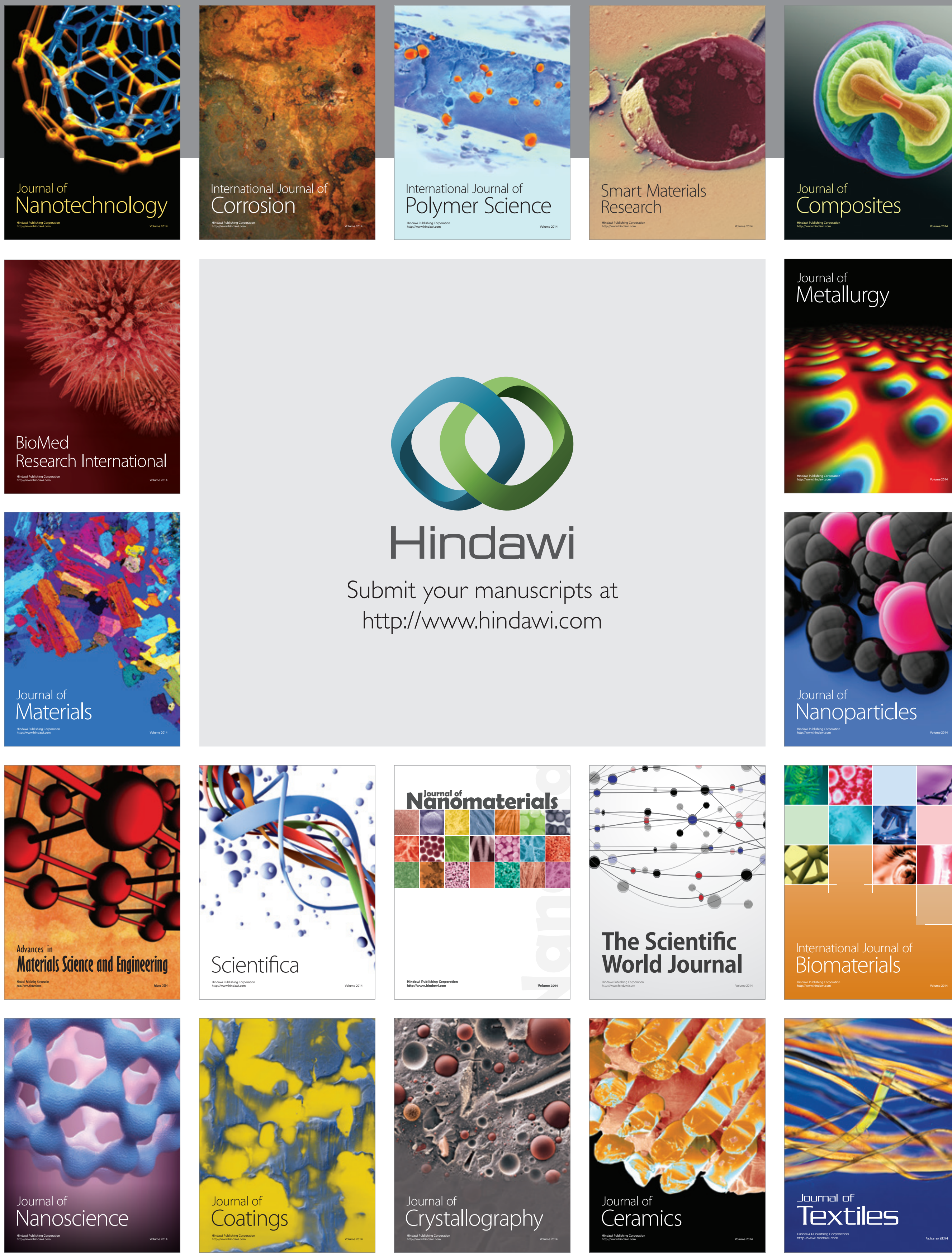
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