

Strengthening and Repairing of the Circular Reinforced Concrete Columns Under Tensile Axial Load Using CFRP Sheet

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Abstract

This study examines strengthening and repairing of circular reinforced concrete columns exposed to axial tensile loads using CFRP sheets. The investigational program entails the casting and testing of eight specimens utilizing standard reinforced concrete throughout three phases as follows: Phase I: Control column specimens without preloading and without CFRP reinforcement; Phase II: Column specimens without preloading but with CFRP reinforcement; Phase III: Strengthened preloaded column specimens, which consist of columns reinforced with CFRP after being preloaded to 70% of the maximum load of the control column specimen. The selected primary parameters encompass the type of transverse reinforcement (tie or spiral), the influence of pre-damage, and the configuration of wrapping (completely or double helical). The experimental results demonstrate that changing the transverse reinforcement type from tie to spiral significantly affected the maximum load, resulting in a decrease of roughly 4.8% for the un-strengthened column and about 2.8% for the strengthened column. The column that has undergone pre-damage will possess a reduced load-carrying capacity compared to an undamaged column of equal specifications. Exposing the column to prior damage by loading it to 70% of the maximum load of the control column caused in a decrease of load carrying capacity by 10.8% and 10.77% for the tie and spiral reinforcement cases, respectively, in comparison to the analogous undamaged column. The pre-damaged specimen exhibits reduced initial stiffness compared to the other specimen due to the presence of pre-existing cracks.

Keywords: Circular Reinforced Concrete Columns; CFRP Sheets; Tensile Axial Load, Strengthening, Repairing.

1.INTRODUCTION

Columns are considered one of the important members in civil engineering constructions, through which loads are transferred from the higher floors to lower floors and then to the foundations [1]. A building's failure of an RC (Reinforced Concrete) column can have disastrous effects, ranging from progressive collapse, in which the failure of one component leads to the failure of the rest of the structure, to significant damage or even complete collapse, particularly when subjected to extreme loads like earthquakes or explosions [2].

In the past, it was assumed that structural components would sustain gravity loads to a great extent. These days, improvements in high-strength materials and structural design have reduced building weight, increasing slenderness, which necessitates careful consideration of lateral stresses, such as seismic and wind forces. Buildings are greatly affected by lateral loads brought on by wind and seismic activity, especially for tall structures, as their slenderness and flexibility increase. As a result, depending on the building's height, the right structural system must be chosen to withstand lateral loads [3]. In a Reinforced Concrete (RC) frame, tension can develop in the columns due to foundation settlement, dynamic loads, lateral loads and others, as will be mentioned later. When the column is subjected to tensile load, the concrete compressive strength is neglected in the design and it is supposed that the tension load is only resisted by the longitudinal steel reinforcement [4]. Because the concrete is strong in compression and weak in tension. There are numerous methods in which the basic weakness of concrete in tension may be overawed. One of this methods by using an epoxy admixtures or fibers [6]. Recently carbon fiber reinforced polymer FRP has gained popularity in civil engineering because of its advantageous properties, including great tensile strength, light weight, corrosion confrontation, low thermal constant, quick installation, and low maintenance charge [7]. The enhancement of existing reinforced concrete columns using (FRP) systems has evolved into the most favored method for retrofitting reinforced concrete buildings. CFRP materials often provide excellent stiffness/weight and strength/weight, while also presenting substantial potential for effective-cost and lasting lightweight solutions. The implementation of CFRP sheet systems resulted in a notable enhancement in the structural performance of the reinforced concrete structure [8]. The CFRP sheets enhanced the failure style and increased the capacity [9].

Tension may arise in the columns of RC frame for many causes [10,11]:

- 1- Axial Loads: Columns predominantly support axial loads (compression) from the beams and slabs situated above. Any irregularities in the load application, such as unequal loading or misalignment, may induce bending moments in the columns, resulting in tensile stresses on one side.
- 2- Temperature Effects: Fluctuations in temperature can induce the expansion or contraction of materials. When the frame is restricted and unable to expand or contract freely, it may result in tensile stress inside the columns.
- 3- Foundation Settlement: Uneven settlement of the foundation might generate moments in the columns, resulting in strain on one side of the column.

- 4- Shrinkage Cracking: Concrete undergoes shrinkage during the curing process. If this shrinkage is constrained (for instance, by reinforcement or connections), it may induce tensile stresses in the concrete, leading to fractures and tension inside the columns.
- 5- Dynamic Loads: In the absence of lateral forces, dynamic loads, such as vibrations from equipment or traffic, can generate tensile strains in the columns.
- 6- Construction Sequence: During construction, the application of loads that results in transient eccentricities or imbalanced forces may produce tensile stresses in the columns.
- 7- The explosion generates an uplift force that induces tensile strains in the column.
- 8- Lateral loading: Columns will experience bending under lateral loads, resulting in one side being in tension and the opposite side in compression.

Comprehending these aspects is important for maintaining the structural honesty of reinforced concrete frames and for constructing columns capable of safely bearing diverse pressures. A novel model for unconventionally loaded FRP circular concrete columns is introduced by [12]. Despite the fact that loads and strains change in three dimensions, the cross-section is built with finite elements, and the concrete is represented by a confinement-sensitive material law. The computational solution for this model was consistent with the findings from experiments published in the literature. Despite large differences in circumferential and hoop confinement strains, the supreme axial stresses in the section are nearly identical for both concentric and eccentric loadings. The literature shows that the suggested stress-strain curves may provide non-conservative results for eccentric loading; thus, based on our mathematical calculations, we offer new stress-strain curves. Jiang et al., [13] investigated reinforced concrete frame columns demonstrating tensile failure. A nonlinear failure equation for RC structure columns exposed to tension failure is developed using the relevant capacity models from American design standards, taking into account the impacts of mixed perpendicular and parallel loads. They find that the interaction curve of ultimate perpendicular and parallel loads has distinct characteristics; it is a nonlinear curve with specific positively correlated sections, which differs dramatically from the fundamental linear failure equation used in codes. The ratio of the optimistic association segment to the total curve is also considered. A realistic nonlinear failure model is then created using the sequence expansion method. Numerical reproduction demonstrates that the suggested model can produce correct reliability results, effectively anticipate reliability variations, and quickly forecast poor reliability occurrences. The results from this model reveal a notable discrepancy in the reliability of reinforced concrete columns designed with the same safety factors but differing design parameters, with reliability diminishing when the eccentricity caused by vertical load is minor.

Han et al., [14] examined the structural behavior of concrete full steel tubes subjected to axial tension. A total of 18 samples were examined. The primary criteria were the steel ratio, the type of concrete, and the bond status between the steel tube and its core concrete, whether bonded or unbonded. A finite element model was created to conduct analysis and investigations for concrete filled steel tubes subjected to axial stress. The tensile strength of steel tubes can be enhanced by the presence of core concrete in concrete filled steel tubes.

Zomorodian et al., [15] investigated the experimental results of uniaxial tensile testing on FRP-reinforced RC prisms, concentrating on crack width. The findings demonstrate that the behavior and crack width of FRP strengthened reinforced concrete components depend on factors such as wrapping schemes and ratios of FRP reinforcement, which are not covered in design standards for crack analysis. Yang et al., [16] investigated the experimental and analytical studies on the tensile stress-strain correlations of steel and concrete in FRP-strengthened reinforced concrete components. Conducted experimental and analytical studies on the tensile stress-strain correlations of steel and concrete in FRP strengthened reinforced concrete components. The findings indicate that the tensile properties of the steel and concrete are modified due to the externally attached FRP sheets. Several researches investigated the behavior of circular columns. Hadhood et al., [17] presented the findings of an experimental study on the concentric and eccentric behavior of full-scale circular high-strength concrete (HSC) columns reinforced with glass fiber reinforced polymer (GFRP) bars and spirals. Ten columns were evaluated under static loading with varying eccentricities. The test factors included the eccentricity/diameter and the reinforcement ratio. The compression failure in the concrete determined the ultimate capacity of specimens subjected to minimal eccentric force. A flexural/tension failure commenced in specimens subjected to significant eccentric loading, ultimately caused by excessive axial and lateral deformations and cracks on the tension side, until a stability failure and secondary compression ensued due to the strain constraints in the concrete. The moment and axial force diagrams were forecasted based on the principles of strain compatibility and internal force equilibrium. Barua and El-Salakawy [18] presented the test findings of seven circular concrete columns reinforced with steel or GFRP. The columns had a diameter of 355 mm and a length of 1,750 mm, and they were subjected to failure testing under concentric, eccentric, or four-point bending configurations. The test conditions encompassed the reinforcement type (steel, GFRP), the GFRP spiral pitch (50 and 85 mm), and $e/D=0, 0.085, 0.17, \text{ and } 0.34$. The axial capacity of the GFRP-reinforced concrete column was approximately 17% lower than that of the steel-reinforced concrete counterpart. For $e/D=0.085$, the GFRP-RC column with a reduced spiral pitch demonstrated roughly 10% greater axial capacity

compared to the column with an increased pitch. Cimesa et al., [19] examined the behavior of circular precast ultra-high-performance concrete UHPC columns reinforced with hoops and spiral reinforcement. The objectives of this research are twofold: firstly, to demonstrate the successful fabrication of four full precast UHPC columns utilizing an economical mixture and construction-scale production within a precast plant environment; and secondly, to compare the axial behavior of the fabricated circular columns featuring varying transverse reinforcement configurations. The study meticulously examines the selection of lateral confinement and spacing throughout the column's height, specifically regarding spiral and hoop reinforcement with spacings of 37 mm and 75 mm. The spirally restricted column with 37 mm spacing exhibited 26% greater ductility than the counter hoop reinforced column, while both designs demonstrated a substantial ductility increase of 34% when the transverse reinforcement spacing was decreased from 75 to 37 mm. Wang et al., [20] investigated the axial compressive behavior of concrete columns reinforced with GFRP bars and confined with CFRP strip ties. The experimental program looks at how loading type (static or cyclic) and volumetric ratio of strip ties (defined by tie spacing) affect column performance, with an emphasis on potential applications in bridge piers and building structures. The findings show that GFRP longitudinal reinforcement contributed 12.6% of the total peak load. Furthermore, reducing the tie spacing to fewer than eight times the bar diameter (8db) changed the failure mode from bar buckling to bar crushing, leading in considerable increases in ultimate strain and confined concrete strength.

Based on the literature review conducted, and to our knowledge, no research has been identified that examines the behavior of reinforced concrete columns strengthened with CFRP under tensile. This research aims to study the structural behavior of short reinforced concrete columns subjected to concentric tensile loads and method of strengthening and repairing them using carbon fiber reinforced polymers (CFRP) sheets. The study factors encompass the type of transverse reinforcement (tie or spiral), the impact of pre-damage, and the form of wrapping (fully or double helical).

2. EXPERIMENTAL PROGRAM AND MATERIAL PROPERTIES

The experimental program consisted of casting and testing a total of 8 specimens with normal reinforced concrete in three cases: The first case includes unstrengthened specimens, which were tested directly after completing the 28-day curing process to use them as a basis for comparing the results. The second case includes specimens strengthened by CFRP 28 days after casting, which were then tested to assess the effect of the strengthening only. The third case includes specimens that were initially subjected to a preload of 70% of their ultimate axial strength, then repaired by CFRP and retested to assess the remaining performance after the column was subjected to initial stresses before repairing.

2.1. DESCRIPTION OF SPECIMENS

The test specimen consisted of a circular reinforced concrete column with a diameter of 160 mm and a total length of 500 mm. The column was cast integrally with upper and lower end slabs, each with dimensions of 500×500×150 mm, to make the total length of the specimen 800 mm, as shown in Figure 1-a. Dimensions were selected to be compatible with the conditions of the laboratory and the capacity of the testing machine. All columns were reinforced with 7-Ø6 mm steel bars as longitudinal reinforcement with a transverse concrete cover of thickness 20 mm. In all columns (Ø5mm) deformed steel bars were used as transverse reinforcement spaced at 100 mm for ties or 75 mm for spiral, as shown in Figure 1b and c. The slabs were fabricated to apply tension load on the reinforced concrete columns indirectly and were made with adequate reinforcements to ensure their integrity and flawlessness during the test. If it contains two types of reinforcement: the first is the main mesh reinforcement, which used 6Φ12mm diameter bars at distance 85mm distributed in the longitudinal and transverse directions within the upper and lower layers for slabs, and the second is the shear reinforcement inclined at an angle of 45° which used 4Φ12mm diameter bars at distance 100mm distributed in both directions, in accordance with the requirements of vertical load resistance and shear, as shown Figure 2 .All columns and slabs have been designed according the specification (ACI Code 318, 2019) [21], as shown in Fig 1.

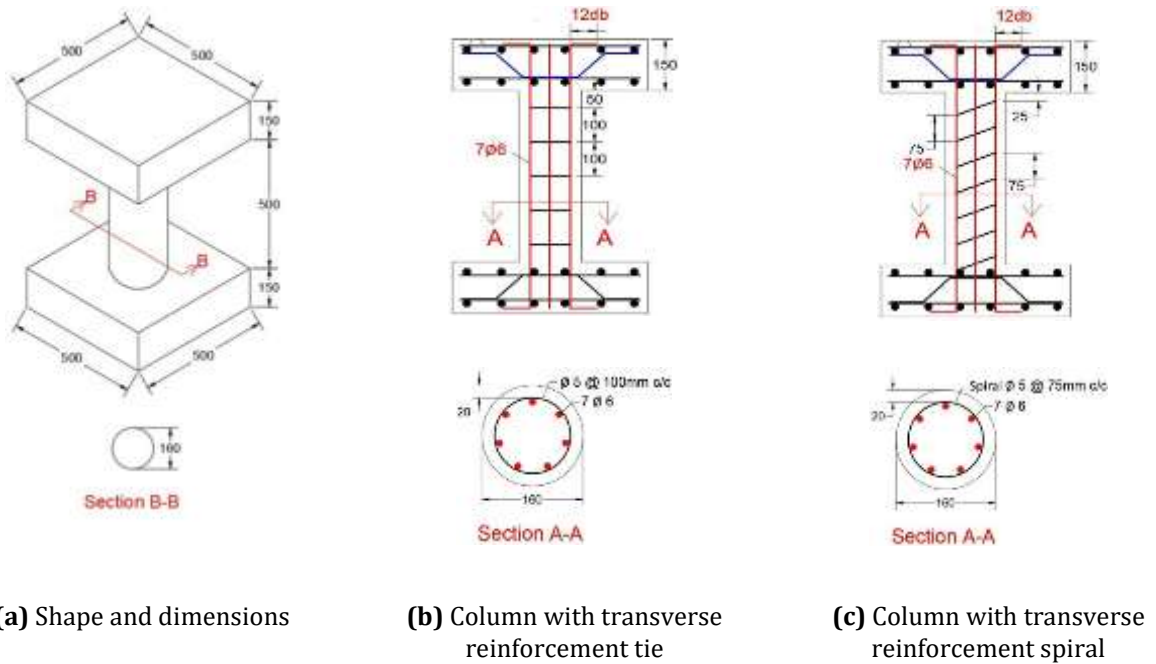


FIGURE 1. Shape, dimensions, and reinforcement details of specimens.

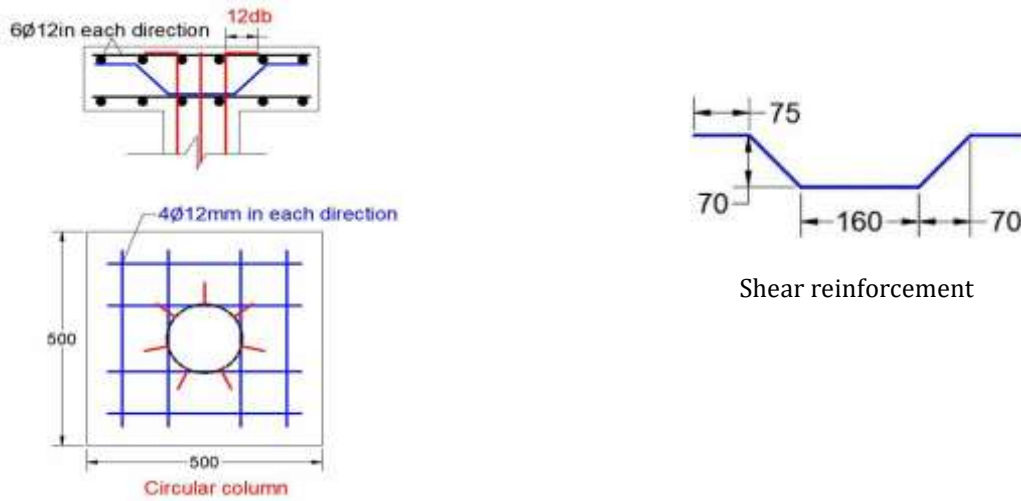


FIGURE 2. Dimensions and reinforcement details of slab.

Each symbol is referred in Fig. 3 which illustrate the naming convention used to identify the column specimens.

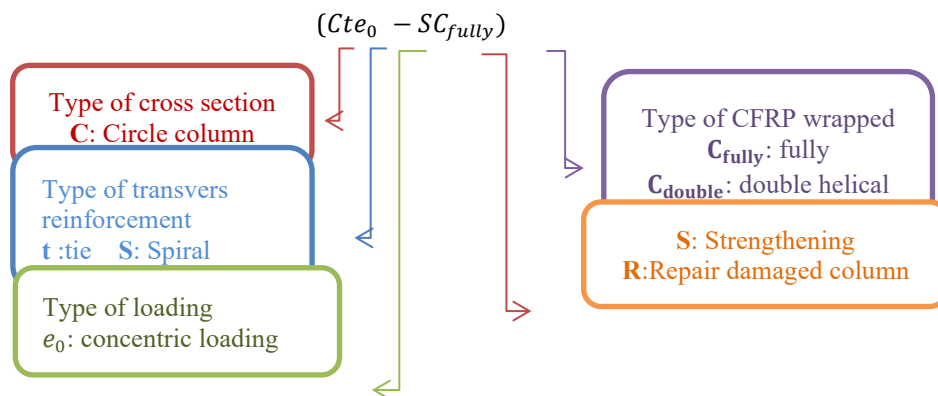
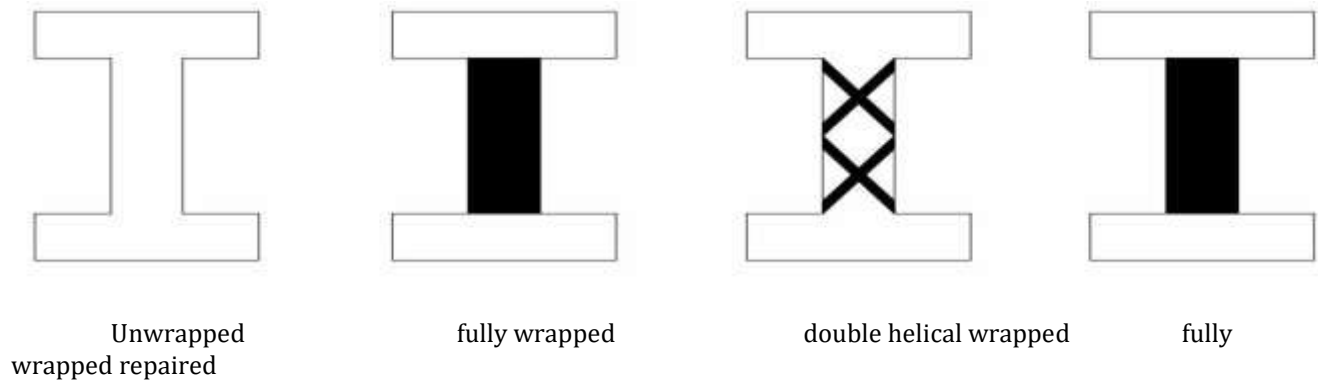


FIGURE 3. Naming convention used to identify the column specimens.

Tested specimens are divided into two groups according to the type of transverse reinforcement (ties or spiral). Each group consists of four columns, all subjected to axial tensile loading. The first column in each group is unwrapped and used as a control specimen (C_{te0-C_0} , C_{se0-C_0}). The second column is fully wrapped with CFRP with a length of 50cm and a width of 56 cm ($C_{te0-SC_{fully}}$, $C_{se0-SC_{fully}}$). The third column is partially wrapped with CFRP in the form of a double helical strip with a width of 5 cm and a length of 80 cm ($C_{te0-SC_{double}}$, $C_{se0-SC_{double}}$). The last column is called the repair columns, which are fully repaired with CFRP after preloading them to 70% of their ultimate axial strength ($C_{te0-RC_{fully}}$, $C_{se0-RC_{fully}}$), See Figure 4.

**FIGURE 4.** Details of CFRP sheets configuration.

2.2 CASTING AND CURING PROCESS

Initially, the reinforcing bars for the columns and slabs were cut according to the approved executive plans. The reinforcement bars of the columns were tied to the reinforcement bars of the slabs in an integrated manner to form a regular reinforcing mesh. Figure 5-b, shows the reinforcement details of the specimens. Then, the reinforcement was carefully placed inside the steel molds, using plastic spacers to achieve the required concrete cover, as shown in Figure 5-a and c. Before casting, prepared and weigh the materials used in this study according of the concrete mix volume. Oiled the internal surfaces of molds to prevent adhesion with concrete after hardening. When the mixing process was completed, all specimens were cast in 3 stages; the first stage included filling the bottom slab with concrete, then the rest of the mold was installed, and the process casting the column and the top slab was complete. At each of these stages, an internal electric vibrator is used, and the surface of top and bottom slab is smoothed using a hand trowel, as shown Figure 6. All specimens were removed from molds (48) hours after casting. Then, the specimens were wrapped entirely with jute bags and covered with agricultural nylon bags while keeping them wet for twenty-eight full days, as shown in Figure 7.

**FIGURE 5.** Molds of specimens and reinforcement details.



FIGURE 6. Stages of casting concrete for the specimens.



FIGURE 7. stages of curing concrete for the specimens.

2.3 TEST SETUP AND LOADING

All specimens were tested by using hydraulic testing machine with a maximum load capacity of (2000 KN) equipped with a central load cell that moves vertically (up and down). This allows for the application of axial loads with a high degree of accuracy, whether in tension or compression. A special loading system was manufactured, consisting of two upper and lower metal frames that act as intermediate elements to transfer loads from the testing machine to the specimens. The upper frame was designed to be responsible for transferring the tensile load to the top slab connected to the column, thus representing the main path for generating tensile force in the specimen during the test. While the lower frame was designed to act as the main support for generating the opposing tensile force. When installing the metal frames in the testing device, the upper frame fixed into the loading cell using a shear stud which is inserted into a matching hole in the upper frame and the metal element (steel anchor) that exists inside the loading cell to ensure that the load is transferred directly from the loading cell to the upper frame, as shown Figure 8. The lower frame is welded to the base of the testing device to act as a fixed and stable support. The specimens are placed in their correct position inside the device, ensuring that it is precisely aligned, and a LVDT is installed under the bottom surface of the upper slab to measure longitudinal deformations, as shown in Figure 9. When loading begins, loading cell moves upwards, pulling the upper frame with it, so that the upper slab is first subjected to direct tensile forces. As the loading cell continues to move, the load is gradually transferred to the concrete column, generating a tensile force in the column that represents the condition studied in this experiment.



FIGURE 8. Details installing the metal frames.

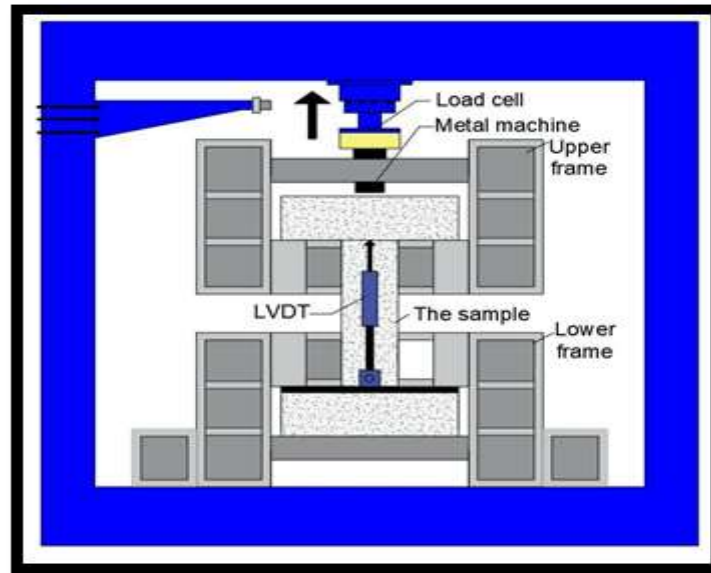


FIGURE 9. Test setup and loadin

2.4. MATERIAL PROPERTIES

2.4.1. Steel reinforcement

Deformed steel reinforcing bars of ($\emptyset 12$, $\emptyset 6$, $\emptyset 5$) mm were used in this study. Table 1 gives the result of tensile test for the used reinforcement bars according to (ASTM) A615, [22] and ASTM A496, [23].

TABLE 1. Test results of steel reinforcing bars.

Nominal Diameter (mm)	Yield Stress (MPa)	Ultimate Stress (MPa)	Elongation %
12	480	636	12.6
6	453	540	8.8
5	460	540	8.6

2.4.2. Carbon fiber reinforced polymer (CFRP) sheets and epoxy adhesive

Unidirectional carbon fibre from the SikaWrap® Hex-230C was utilised to reinforce concrete columns. The mechanical properties of CFRP sheets are presented in Table 2, according to the manufacturing specifications of Sika (2005). As for the adhesive material, a two-component epoxy of the SiKadur-330 type was used as a bonding agent for the CFRP sheet. Its properties are shown in the Table 2.

TABLE 2. Properties of CFRP sheets and epoxy adhesive.

Properties	Tensile strength (MPa)	E-modulus N/mm	Elongation at break (%)	Width (mm)	Thickness (mm)
SikaWrap Hex 230 c	4300	238	1.8	600	0.375
SiKadur-330	30	4500	0.9	--	--

2.4.3. Concrete

The concrete mixture comprises Portland cement OPC (Type 1), natural sand, crushed gravel with a maximum size of 10.5 mm, and potable water. Table 3 delineates the composition proportions of the concrete mix. Compressive strength was determined after 28 days by testing standard cubic specimens, where the strength reached 28MPa.

TABLE 3. Proportion of concrete mix.

Cement (Kg/m ³)	Water (Kg/m ³)	Sand (Kg/m ³)	Gravel (Kg/m ³)	W/C ratio
360	216	792	1116	0.6

3. RESULTS AND DISCUSSION

3.1. LOAD- AXIAL DISPLACEMENT RELATIONSHIPS OF COLUMN SPECIMENS

3.1.1. Effect of transverse reinforcement type (tie or spiral)

Figure 10 illustrates the impact of transverse reinforcement type on load-axial displacement relationships. When comparing two analogous columns with differing transverse reinforcement, the column with tie reinforcement will exhibit reduced stiffness relative to the column with spiral reinforcement, resulting in greater axial displacement under a constant load, particularly as the ultimate load stage is approached. Spiral reinforcement offers substantial confinement to the concrete core, enabling it to endure higher compressive loads and mitigate failure from buckling or crushing.

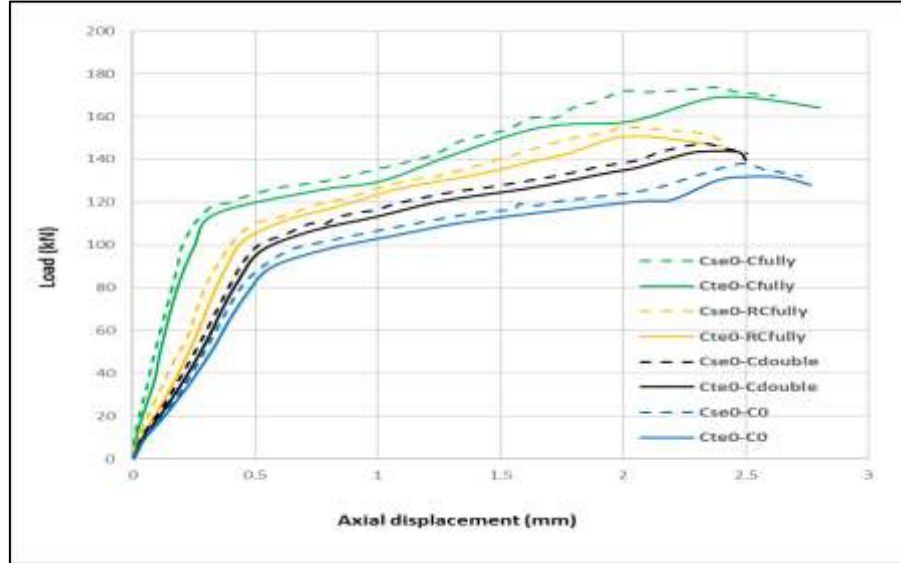
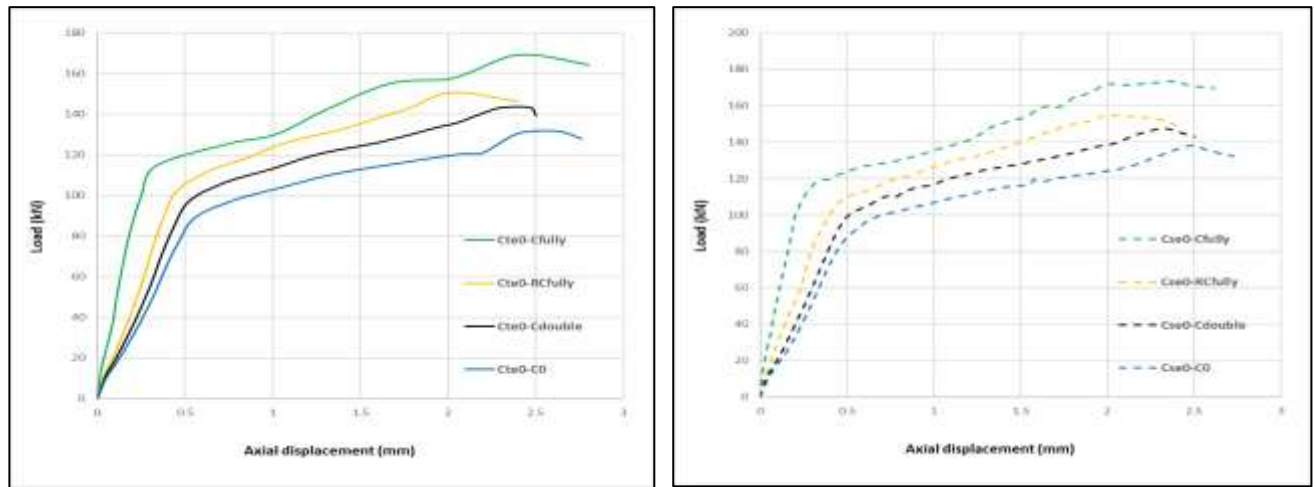


FIGURE 10. Effect of transverse reinforcement type on Load- axial displacement relationships.

3.1.2. Effect of the configuration of wrapping

The types of wrapping used in this study were fully or double helical. As shown in Fig. 11, the stiffness of the columns significantly depended on the type of wrapping. Where the stiffness of the columns increased in the following order according to the type of wrapping: not strengthened, double helical, pre-damaged fully, and fully.



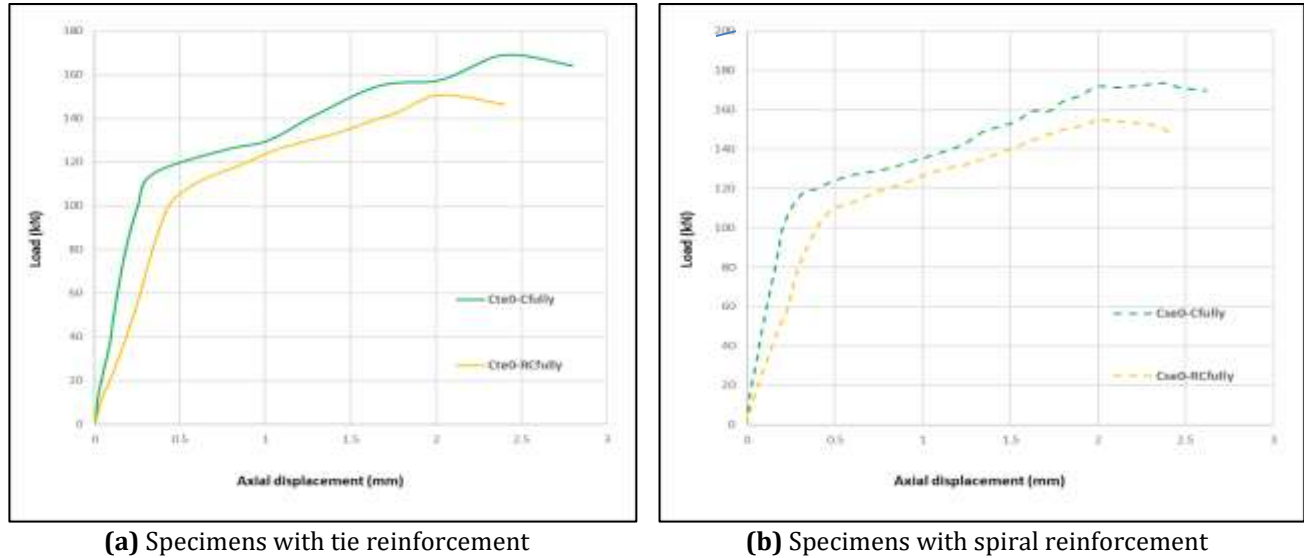
(a) Specimens with tie reinforcement

(b) Specimens with spiral reinforcement

FIGURE 11. Effect of types of wrapping on Load- axial displacement relationships.

3.1.3. Effect of pre-damage

Figure 12 illustrates that the column experiencing pre-damage exhibits reduced stiffness compared to an undamaged counterpart, resulting in greater axial displacement under constant load across all loading stages. The pre-damaged specimen exhibits reduced initial stiffness compared to the other specimen due to the presence of pre-existing cracks.

**FIGURE 12.** Effect of pre-damage on Load- axial displacement relationships.

3.2. LOAD CARRYING CAPACITY OF COLUMNS

3.2.1. Effect of transverse reinforcement type (tie or spiral)

The impact of altering the transverse reinforcement type from tie to spiral on the maximum load was evident, with a drop of approximately 4.8% for the un-strengthened column and around 2.8% for the strengthened column, as seen in Table 4.

Spiral transverse reinforcement provides continuous lateral restraint to the concrete, which reduces transverse shrinkage and maintains the integrity of the section resulting from the column being subjected to axial tension. Thus, columns with spiral reinforcement exhibit higher load than columns with tie transverse reinforcement.

TABLE 4. Effect of transverse reinforcement type on load carrying capacity.

Column ID	Axial displacement at ultimate load (mm)	Load carrying capacity P_u (kN)	% Increase in P_u
Cte0-C ₀	2.47	131.7	Ref.
Cse0-C ₀	2.48	138	4.8
Cte0-SC _{fully}	2.37	168.8	Ref.
Cse0-SC _{fully}	2.38	173.5	2.8
Cte0-SC _{double}	2.31	143.4	Ref.
Cse0-SC _{double}	2.32	147.4	2.78
Cte0-RC _{fully}	1.99	150.5	Ref.
Cse0-RC _{fully}	1.99	154.8	2.9

3.2.2. Effect of the configuration of wrapping

As shown in Table 5.

In relation to tie reinforcement specimens, the incorporation of CFRP sheets increases the load-carrying capacity by 28.2%, 8.9%, and 14.3% for the column with fully wrapping, double wrapping, and pre-damaged complete wrapping, respectively, in comparison to the reference un-strengthened column. The column with complete wrapping exhibits the highest load-carrying capacity. In relation to spiral reinforcement specimens, the incorporation of CFRP sheets leads to an increase in load-carrying capacity of 25.7%, 6.8%, and 12.2% for the fully wrapped, double wrapped, and pre-damaged fully wrapped columns, respectively, as compared to the reference un-strengthened column. The column with complete wrapping exhibits the highest load-carrying capacity. Fully wrapping gives the highest load – carrying capacity because the fibres are distributed over the complete section, so they all contribute to tensile strength and prevent weak areas from appearing, as in partial wrapping (double helical).

TABLE 5. Effect of the type of wrapping on load carrying capacity.

Transverse reinforcement type	Column ID	Axial displacement at ultimate load (mm)	Load carrying capacity P_u (kN)	% Increase in P_u
Tie	Cte0-C ₀	2.47	131.7	Ref.
	Cte0-SC _{fully}	2.37	168.8	28.2
	Cte0-SC _{double}	2.31	143.4	8.9

	Cte ₀ -RC _{fully}	1.99	150.5	14.3
Spiral	Cse ₀ -C ₀	2.48	138	Ref.
	Cse ₀ -SC _{fully}	2.38	173.5	25.7
	Cse ₀ -SC _{double}	2.32	147.4	6.8
	Cse ₀ -RC _{fully}	1.99	154.8	12.2

3.2.3. Effect of pre-damage

As shown in Table 6, the column subjected to pre damage will have less load-carrying capacity than the similar column without any damage. Whereas exposing the column to prior damage by loading it in the previous stage to 70% of the maximum load of the control column led to a decrease in the load-carrying capacity by 10.8% and 10.77% for the tie and spiral reinforcement cases, respectively, compared to the similar undamaged column. This is because the pre-damaged specimen has a lower initial stiffness than the other due to the pre-cracks.

TABLE 6. Effect of pre-damage on load carrying capacity.

Transverse reinforcement type	Column ID	Axial displacement at ultimate load (mm)	Load carrying capacity Pu (kN)	% Decrease in Pu
Tie	Cte ₀ -SC _{fully}	2.37	168.8	Ref.
	Cte ₀ -RC _{fully}	1.99	150.5	10.8
Spiral	Cse ₀ -SC _{fully}	2.38	173.5	Ref.
	Cse ₀ -RC _{fully}	1.99	154.8	10.77

3.3. failure mode of columns

Figures 13 shows the failure modes of the tested specimens; the failure modes of the specimens were as follows: For un-strengthened specimen with tie reinforcement, the failure mode was shear failure. This is a critical concern due to its brittle nature and potential for sudden collapse. Diagonal tension cracks characterize it and can lead to a significant reduction in the column's axial load capacity. While for un-strengthened specimen with spiral reinforcement, the failure mode was tensile failure, where cracks initiate and propagate due to the concrete's limited tensile strength. This can manifest as a brittle failure, where the concrete fractures suddenly after reaching its tensile capacity. Where The cracks were in the form of continuous rings around the perimeter of the column section and are separated from each other and along the column's length specially at the ends of the column. For fully wrapping specimens (pre damaged or not), whether the Transverse reinforcement was tie or spiral, the failure mode was separation of the CFRP sheet and the removal of a part of the concrete cover at the ends of the column, and then the tensile failure occurred with the formation of cracks in the form of continuous rings at the ends of the column. For double helical wrapping specimens, whether the transverse reinforcement was tie or spiral, the failure mode was separation of the CFRP sheet at the ends of the column, followed by tensile failure with the formation of cracks in the form of continuous rings at the ends of the column and in the concrete areas not bonded with the CFRP sheet.

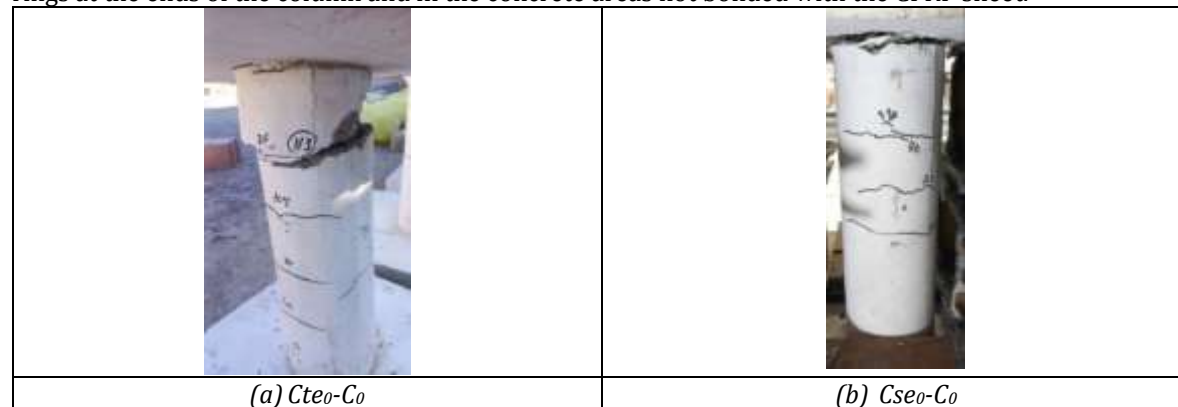




FIGURE 13. Failure modes of the tested specimens.

4. CONCLUSION

From the previous experimental results, the following can be concluded:

- The impact of altering the transverse reinforcement type from tie to spiral on the maximum load was evident, with a drop of approximately 4.8% for the un-strengthened column and around 2.8% for the strengthened column.
- In relation to tie reinforcement specimens, the incorporation of CFRP sheets increases the load-carrying capacity by 28.2%, 8.9%, and 14.3% for the column with fully wrapping, double wrapping, and pre-damaged complete wrapping, respectively, in comparison to the reference un-strengthened column. The column with complete wrapping exhibits the highest load-carrying capacity.
- In relation to spiral reinforcement specimens, the incorporation of CFRP sheets leads to an increase in load-carrying capacity of 25.7%, 6.8%, and 12.2% for the fully wrapped, double wrapped, and pre-damaged fully wrapped columns, respectively, as compared to the reference un-strengthened column. The column with complete wrapping exhibits the highest load-carrying capacity.
- The column subjected to pre damage will have less load-carrying capacity than the similar column without any damage. Whereas exposing the column to prior damage by loading it in the previous stage to 70% of the maximum load of the control column led to a decrease in the load-carrying capacity by 10.8% and 10.77% for the tie and spiral reinforcement cases, respectively, compared to the similar undamaged column. This is because the pre-damaged specimen has a lower initial stiffness than the other due to the pre-cracks.
- For un-strengthened specimen with tie reinforcement, the failure mode was shear failure. This is a critical concern due to its brittle nature and potential for sudden collapse. Diagonal tension cracks characterize it and can lead to a significant reduction in the column's axial load capacity. While for un-strengthened specimen with spiral reinforcement, the failure mode was tensile failure, where cracks initiate and propagate due to the concrete's limited

tensile strength. This can manifest as a brittle failure, where the concrete fractures suddenly after reaching its tensile capacity. Where The cracks were in the form of continuous rings around the perimeter of the column section and are separated from each other and along the column's length specially at the ends of the column.

- The effect of the type of wrapping was very clear on the failure mode.

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