The Honeycombed Damage Effect on UHPFRC Strengthened Short Column under Eccentric Load

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Abstruct

This research study aims to investigate the behavior of reinforced concrete columns with a honeycomb-damaged ratio under the effect of eccentric loading at the end of the effective length of the column. The experimental analyses were conducted on nine columns with a total height of 950 mm and a cross-section area of (120*120) mm to evaluate the impact of various factors on column behavior. The total columns had two corbel heads for applying the loads. All column specimens were tested under eccentric load until failure with an eccentricity ratio equal to (10/12). These factors include the defect ratio (35% and 70%) as a part of the specimen cross-sectional area at (L/4), strengthening of UHPFRC jacket thickness (15 and 30) mm and the side of strengthening (laminates 2-sides and full casting 4-sides). The honeycomb defect has been identified via foam slicing as an indicator of specimen failure. Furthermore, the bonding procedure between the new and old layers included roughening the old surface by grinding, followed by the application of epoxy resin for adhesion. The honeycombed specimens were repaired with UHPFRC before the test. According to the results of the tests, the application of the UHPFRC jacket to strengthen concrete columns resulted in improvements within the areas of ultimate load resistance, stiffness, energy absorption, and ductility. Additionally, the honeycomb-damaged ratio of the column specimens, the thickness of the UHPFRC jacket, and the side of strengthening all had a role in determining the amount of these increases. All of the column specimens failed when subjected to various levels of load. Depending on the experimental results, the gain in strength, stiffness, ductility, toughness, failure mode, and load versus displacement were recorded, illustrated and discussed.

Keywords: UHPFRC, Honeycomb Defect, Strengthening technique, Load Capacity.

1. Introduction

1.1. General

Currently, the advancement of concrete mixes in structural components is the primary focus of most researchers in this domain. The reinforced concrete (RC) columns are critical components in reinforced concrete buildings, offering resistance to horizontal loads and supporting vertical loads with or without moments. In reinforced concrete columns, damage may result from surface deterioration, surface deposits, deformation, cracks, and structural characteristics or faults. Prior to their total collapse due to any failure mode, the primary goal is to strengthen existing columns or structural elements. The column's strength is determined by the material's strength, namely the concrete's compressive strength, and the geometry of the cross-section [1]. Damage arises from both internal and exterior elements, posing a significant issue; it is not unusual for a structure to be destroyed. Demolition is the last alternative; it requires many stages, beginning with a root-cause assessment, which seeks to identify the primary elements leading to the concrete's breakdown. The issue of damage may be resolved by precise and appropriate application. The advantages of this study may serve as a reference for treating similar issues [2].

1.2. Honeycomb In Concrete Structure

Honeycombs are air spaces enclosed inside concrete as a result of segregation. Honeycombs may provide continuous channels that lead to significant water infiltration, and they are essential in water-retaining structures and tunnels [3]. These could appear on the surface of concrete and become obvious to the observer with the removal of the formworks. Inadequate vibration, the inclusion of bigger particles, not correctly consolidated due to poor vibrations or poor design of formwork, a few common in-situ testing techniques and the use of inflexible concrete may lead to honeycombing in concrete [4]. Honeycomb occurs when mortar insufficiently fills the voids between coarse aggregate particles. Understanding the root cause of concrete deterioration is important; the evaluation of unwanted defects such as honeycombing, cold joints, and surface cracks is essential since these imperfections will impact the durability and repair capacity of the building [5-6]. To identify the honeycomb and fractures with greater precision, it is essential to conduct tests including the ultrasonic pulse velocity (UPV) test, photometer analysis, and core drilling test [7-8]. Sasaki and Kobayashi conducted a cyclic loading test on reinforced concrete columns featuring repaired honeycombed concrete at the column base to evaluate the influence of the repaired section on deformation performance and interface behavior [9]. Dawari and Vesmawala conducted an experimental study on honeycomb damage identification in reinforced concrete beams. Methods have been validated based on the variances between modal curvature and modal flexibility. The study demonstrated that the method effectively identified damage and determined its location in both single and multiple beam scenarios. The numerical results demonstrated the efficacy of these methods in identifying damage scenarios in beams [10].

Previous studies indicate a lack of research regarding the performance of rehabilitated honeycombed reinforced concrete columns. The objective of this study is to examine the effects of the honeycomb deteriorate in the reinforced concrete columns, serving as a reference for solving issues related to honeycombing and cracking.

1.3. UHPFRC As Strengthening Material

The strengthening of residential buildings has become an important field in the development industry, utilizing various innovative materials extensively [11-12]. UHPFRC is used in engineering for the building of new roadways and the repair and strengthening of present structures, both nationally and globally [13-14]. Chun Ling Lu performed an practical investigation on the load compressive characteristics of UHPFRC columns. The study demonstrated that UHPFRC reinforcement significantly enhanced the load capacity and the index of ductility of the columns, with the increase in carrying capacity directly correlated to the thickness of the UHPFRC. Reinforced concrete columns seldom undergo pure axial compression forces in practical engineering situations. Consequently, it is essential to augment the material's ductility to raise the loading performance of the eccentrically compressed parts [15]. Xinling Wang evaluated eccentric load Reinforced concrete columns augmented with engineered cementitious composite for eccentric compression. The test results demonstrated the advantages of the very small ECC-reinforced low-eccentric compression reinforced concrete columns in comparison to plain mortar reinforced concrete columns [16]. Cho et al. applied high-performance fiber-reinforced cementitious composite (HPFRCC) mortar to the column's plastic hinge area and found that it improves the columns' overall force-displacement, energy dissipation, and stiffness degradation characteristics in addition to reducing bending and shear cracks [17]. Meda et al. advocated for the use of high-performance fiber-reinforced concrete (HPFRC) to rehabilitate corrosion-affected reinforced concrete columns, noting a significant improvement in the strength of the rehabilitated columns [18]. Dagenais et al. indicated that encasing columns with inadequate lap splices in reinforced concrete bridges using self-compacting ultra-high-performance fiber-reinforced concrete (UHPFRC) eradicated bond failure and concrete deterioration in the plastic hinge areas [19]. The making of UHPFRC requires essential parameters, including a significant cement content of 900 to 1200 kg/m3, silica fume (SF) constituting 10–30% by weight of the cement, the utilization of fine sand (0.15–0.40 mm) instead of gravel aggregates, a water-binder ratio (w/b) below 0.2, and the incorporation of an effective super plasticizer to maintain workability [20-25]. Typically, traditional UHPFRC utilizes a substantial quantity of cement without coarse aggregate to improve uniformity and remove intrinsic deficiencies, for instance, the interfacial transition zone (ITZ) defect occurring between the matrix and coarse aggregate [26-27].

1.4. Aim And Scope of Study

In structural engineering, the RC columns have been one of the most widely researched for about a century. So, skilled workers and treated materials from solid sources must be used to prevent failure in structural memberديوانية. The use of UHPFRC as a strengthening technology is crucial and should be considered during the enhancement of reinforced concrete building components or during the construction phase. In Iraq, a lot of reinforced concrete structures deteriorate over time owing to several reasons, including age, corroding materials, changing the building's purpose, unexpected failure, and poor design. The Iraqi governments should take into consideration implementing such strategies from the beginning, while keeping in mind unpredictable environmental factors as earthquakes and natural calamities.

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This research aims to evaluate the effectiveness of UHPFRC in augmenting the load-bearing capability of existing RC in its virgin condition.

1. To examine the total force capacity of the strengthened column specimens with UHPFRC full casting and laminates.

2. To understand the deflection response of the tested specimens.

3. To identify the phenomena of failure and cracks pattern of the tested specimens.

4. To examine the stiffness, ductility, toughness of the RC column strengthened with UHPFRC.

5. To bring out the advantage of using UHPFRC (laminates and full casting).

2. Methodology

2.1. Experimental programming

2.1.1. Material Properties

Conventional concrete

The cement used in this research is Ordinary Portland Cement (Type I) according to ASTM standards, manufactured in northern Iraq and commercially marketed as Karasta [28]. The fine and coarse aggregates were had the maximum particle size of 4.75 mm and 10 mm respectively, which in compatible with Iraqi standard requirements (IQS 45/2019) [29]. The mixing component were shown in Table 1.

Table 1 Normal concrete mixing proportion (kg/m3).

Cement	Fine Aggregate	Coarse Aggregate	Water
470	675	1030	200

Reinforcement steel bar

Typically, all the presented columns were reinforced with two types of steel bars, Ø10 mm in nominal diameter for the longitudinal direction and Ø8 mm in nominal diameter for the transverse direction and corbels. The reinforcement steel bars requirements were established in compliance with ASTM A370 [30], with the details illustrated in Table 2.

Table 2 Results of Steel Reinforcement Testing.

Bar Type	Nominal diameter (mm)	Measured diameter (mm)	Yield stress (MPa)	Ultimate strength (MPa)
Deformed	10	9.85	585	725
	8	8	523	694

UHPFRC

The manufacturing of UHPFRC requires a certain amount of cement. (OPC type I as used in conventional concrete). Very fine sand aggregate with grading (0.08-0.25 mm) was utilized, which is incompatible with “Iraqi Specification requirements IQS No.45/2019”. UHPFRC mixtures contain densified micro silica, a pozzolanic material with particle sizes of 0.15 µm. In terms of particle diameter, the average particle size is about 100 times smaller compared to Portland cement. Silica fume is produced in accordance with (ASTM C 1240/2020) standards [31]. Micro steel fibers SF conforming to ASTM A820 with a diameter of 0.20 mm, a length of 13 mm, an aspect ratio of 65, and a tensile strength exceeding 2500 MPa, modulus of elasticity 210 GPa were used in this work [32]. High range Water range-reducing admixture (super plasticizer) type (ViscoCrete-180Gs) conform with (ASTM C494, F) was used[33]. The last component was the clean water. Table 3 illustrates the UHPFRC mixtures used in this research study.

Table 3 UHPRFC mixing proportion (kg/m3).

Cement	Fine Aggregate	Silica Fume	Steel fiber	Water	Super plasticizer
900	775	200	154	198	45

2.1.2. Configuration of column specimens

Nine reinforced concrete columns were fabricated for this study, which have the same cross-section area of (120*120) mm and a total height of 950mm. The length of 750mm (effective length) which is localized between the cobbles. The corbels had been reinforced with supplementary steel bars to prevent premature failure in this section of the specimens during testing and to localize the failure in the central region. Depending on the parameter of the study, the column specimens were divided into three groups. The first group included one specimen unstrengthen as a reference column (C1) for comparison. The second and third groups included four column specimens (C2, C3, C4, C5, C6, C7, C8, C9) according to the honeycomb defect ratio (35% and 70%), the UHPFRC jacket thickness (15 and 30)mm, side of strengthening (full cast and laminates). All the column were tested under fixed load eccentricity which equal to 100mm. The details of specimens and testing program were summarized in Table 4 and Figure 1. Moreover, the schemes of the strengthened column specimens were shown in Figure 2.

Table 4 The configuration of column specimens.

Group	Specimen	Honeycomb ratio %	UHPFRC jacket thickness mm	Strengthening schemes	Eccentricity mm
a	C1	0.00	----	---	
b	C2	35.00	15	Full cast	
	C3	35.00	15	Partial cast (T and C)	
	C4	35.00	30	Full cast	
	C5	35.00	30	Partial cast (T and C)	100
c	C6	70.00	15	Full cast	
	C7	70.00	15	Partial cast (T and C)	
	C8	70.00	30	Full cast	
	C9	70.00	30	Partial cast (T and C)	

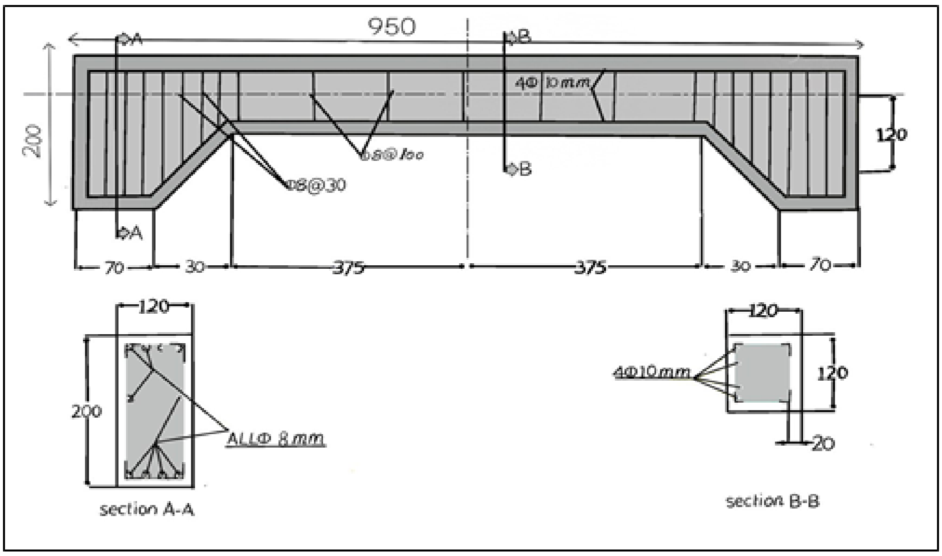

Figure 1. Measurements and reinforcement description of tested columns.

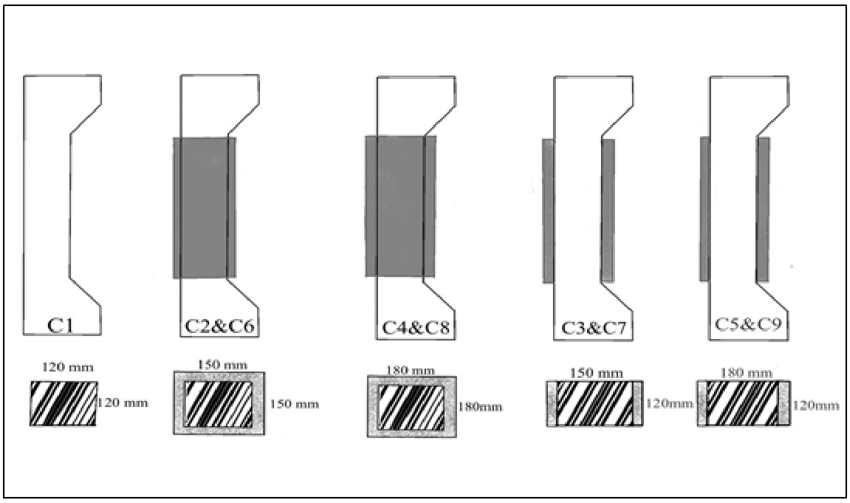

Figure 2. Measurements and reinforcement description of tested columns.

2.1.3. Strengthening procedures of the test specimens

Before strengthening process, the fabrication of the strengthened columns mainly includes the following steps:

1. Recasting RC columns with fixed dimensions and naturally curing for 28 days.

2. Clean the concrete residue and powder on the RC column interface after roughening it.

3. Finishing the secondary formwork for the column specimens, dusting Sikadure LB32 on the interface to guarantee good adhesion between the regular concrete and UHPFRC jackets, and strengthening with UHPFRC.

4. Use a tabletop electric vibrator to achieve optimal material properties, improved compaction, enhanced fiber dispersion, better surface finish, increased workability, and reliable defect detection.

5. Curing and testing of the strengthened specimens accordingly.

6. The above methods were repeated to cast jackets for all required specimens.

Additionally, to prevent adhesion with hardened (UHPFRC), all of the steel formworks were thoroughly cleaned, and their internal surfaces were lightly oiled. Steel formworks were made with very accurate specifications based on these requirements. Strengthening steps were shown in Figure 3.

Figure 3. UHPFRC strengthening procedure of tested columns.

Testing setup

All column specimens were tested in the structural laboratory at the College of Engineering, University of Missan by using an ALFA Testing Machine with a maximum compressive capacity of 5000 kN. Prior to testing, it was typical to clean the surface of the column specimen and apply a coating to improve cracking visibility and highlight the crack's path. Subsequently, the material was positioned vertically for testing. The centerline, supports, line loads, and LVDT were securely put in their designated locations. All necessary equipment for performing the tests was arranged as shown in Figure 4. One LVDT was positioned at a corner of the column to evaluate axial displacement, while the second LVDT was used to evaluate lateral displacement. The load was incrementally raised until failure occurred. Additionally, during the test, several measurements and data were documented and observed, including the load at first fracture, the final failure load, the axial displacement at the specimen's upper end, the lateral displacement at the mid-height of the specimen, and crack width. All columns' tests were performed at automatic loading step at loading rate of 1 kN/sec to provide the optimum testing conditions and prevent the initial failure or crushing the concrete due to the large step of loading.

Figure 4. Setup of typical tested specimen.

Experimental results and discussion

The experimental results were summarized in Table 5.

Table 5 The experimental results of column specimens.

Specimens	Pu (kN)	Δ_{axial} mm	$\Delta_{lateral}$ mm	Change Load Carrying Capacity (%)	Gain in stiffness (%)	Gain in ductility	TF
C1	115	8	7.85	0	0	-	1
C2	230	6	5.2	100.00	166.55	12.75	1.47
C3	140	5	3	21.74	94.71	63.73	0.96
C4	330	4.6	3.5	186.96	398.89	28.43	1.76
C5	194	5.3	3.03	68.70	154.52	71.57	1.2
C6	215	6	5.5	86.96	149.17	6.86	1.27
C7	125	6.25	2.95	8.70	39.08	22.55	1.08
C8	335	5.75	4.4	191.30	305.15	28.43	2.23
C9	270	4.8	3.2	134.78	291.17	47.06	1.56

Cracks patterns and failure modes

Figure 5 provided an illustration of the tested column specimens' failure phenomena and cracking paths. All reinforced columns exhibited no detachment of the new concrete layer, which is regarded as an advantage of this investigation. The control column C1 experienced failure due to concrete crushing at the top portion, resulting in the discoloration of the cover-core layers. The column C2 had local failure due to compression in the upper portion of the specimen, without detachment of the new concrete layer, followed by small cracks. The column specimen C3 failed due to its ductility. Cracks were seen when up to 90% of the full load-carrying capacity was used. The outside of the jacket exhibited warning signs before failure. In column C4, an initial crack commenced at 297 kN, followed by a sequence of surface cracks not exceeding 1.5 mm in width, which developed longitudinally from the lower portion of the column. As the applied load increased, both the crack width and depth escalated until final failure occurred at the ultimate load of 330 kN due to compression. The column specimen C5, UHPFRC jackets, and concrete substrate exhibited vertical shear cracks in the honeycomb fault region upper portion of column height upon attaining maximum failure load. Therefore, the main failure mode of this column was shear failure. The specimens (C6, C7, and C8) exhibited failure via compression and spalling of the concrete at both ends. The specimens failed because of vertical and horizontal cracks along the height of the column on both sides. Failure started with the appearance of very little cracks on the surface of the UHPFRC jacket, and then progressed to the substrate layer. Then, specimens failed due to compression. The column specimen C9 exhibited failure at a load value above that of the control column. Upon the initiation of cracks on both sides of the upper base at the front and back, the load at the first crack was 230 kN, and the concrete substrate displayed diagonal shear cracks in the top and bottom portion of the honeycomb defect zone of the column upon reaching the maximum failure load. Consequently, the primary mechanism of failure for this column was shear failure.

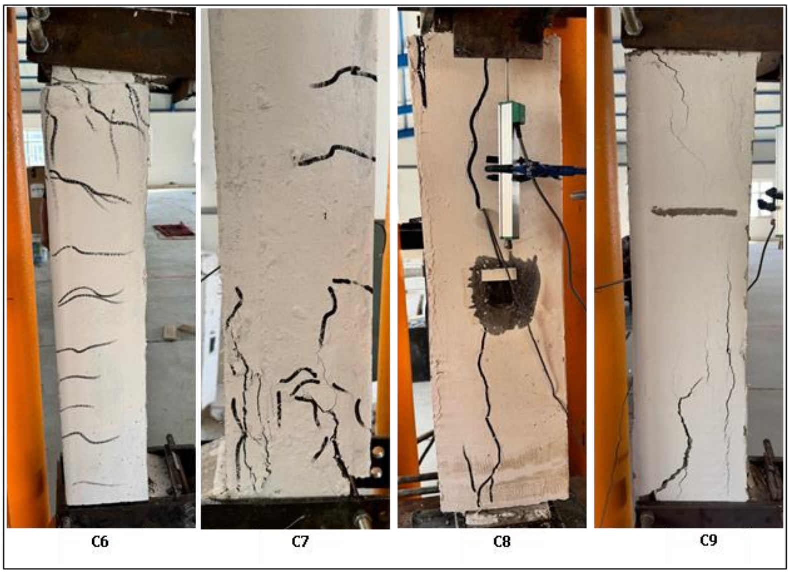

Figure 5. Crakes and failure phenomena of specimens.

Load-displacement relation

Figure 5 presents the load versus displacement curves for the column specimens (control and strengthened specimens), as well in Table 1 the magnitude of the axial and lateral displacement presented. The strengthened column specimens showed improvements in loading capacity, ductility, stiffness, and energy absorption. The entire casting process that utilized UHPFRC was more efficient than the laminates scheme. In general, the load displacement graphs may be distinguished into three phases. the first phase (uncracked stage), in which the displacement exhibited a nearly linear rise in response to the ascending load. the second stage, known as the (elastic-plastic stage), the gradient of the curve declines non-linearly. During the third phase (softening stage), the displacement gradually grew while the load remained constant. The inclination of the reinforced columns exceeds that of the control specimen at same eccentricity. In contrast, UHPFRC-jackets specimens exhibited ductile behavior due to the addition of steel fibers. The presence of fibers enhanced the ultimate loads and associated lateral displacement, evidenced by this investigation. The findings show that increasing the thickness of the UHPFRC jacket results in a decrease in displacements when the same load is applied.

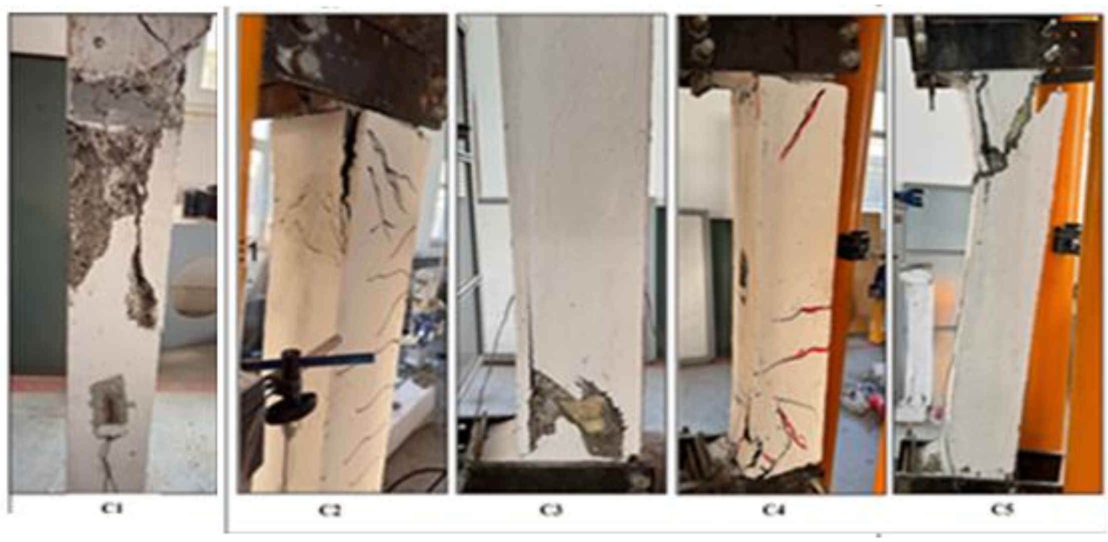

Figure 6. Axial and Lateral displacement curves of specimens.

Column Specimens load capacity

Table 5 illustrates the load capacity of the tested columns. Figure 7 illustrates the increase in load capacity of the reinforced specimens compared to the control column. The results indicate that the totally casting UHPFRC jacketing was an excellent approach for strengthening. In addition, the thickness of the UHPFRC jackets resulted in a modest improvement in the efficiency of the reinforced columns. The increase in capacity of strengthened specimens is directly related to the thickness of the UHPFRC jacket. The behavior of the tested columns was investigated to inspect the load capacity change of the strengthened columns. The control column exhibited a reduced load capacity compared to the other strengthened columns. The variance in capacity to bear load for the specimens (C2 to C4 and C6 to C8) when the UHPFRC jacket thickness full casting schemes increased from 15mm to 30mm were (100% to 186.96% and 86.96% to 191.3%) respectively. While the gain in strength for the column specimens (C3 to C5 and C7 to C9) when the UHPFRC jacket thickness increased as well, but with laminate schemes were (21.74% to 68.7% and 8.7% to 134.78%) respectively. The roughness of the column surface enhances the adhesion between the column core and the UHPFRC layer, resulting in a significant improvement in column force.

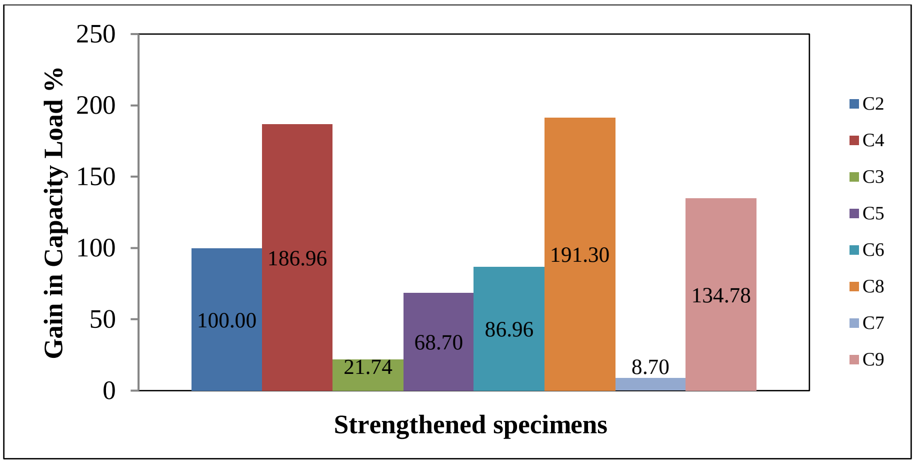

Figure 7. Gain in strength of strengthened specimens.

Stiffness

The stiffness is a function of applied loading and defined as the resistance of an elastic body to deflection. The stiffness is the ratio of maximum load (Pu) divided by the deflection of maximum load (Δu). stiffness refers to a material's resistance to deformation under an applied load. The stiffness magnitudes of the column specimens that were tested are shown in Table 5. Figure 8 illustrates the proportion of the increase in stiffness of the columns which had been strengthened by UHPFRC. Compared to the control specimens, the reinforced columns exhibit greater stiffness. The thickness of UHPFRC jackets significantly influences the percentage increase in stiffness. A comparison of the findings of strengthened columns in Figure 9 indicated that increasing the UHPFRC jacket thickness from 15mm to 30mm, with full casting strengthening of specimens (C2 to C4 and C6 to C8), led to an increase in stiffness gain of (38.33 to 71.74 and 35.83 to 58.26) respectively. In the other hand, the gain in stiffness for the strengthened specimens (C3 to C5 and C7 to C9) when the jacket thickness increased from 15mm to 30mm in two-sides (tension and compression) were (28 to 36.6 and 20 to 56.25) respectively. Moreover, the stiffness values increase with the increase in the size of the treated honeycomb because the ultimate strength increases when the honeycombed specimens are treated with high-strength materials.

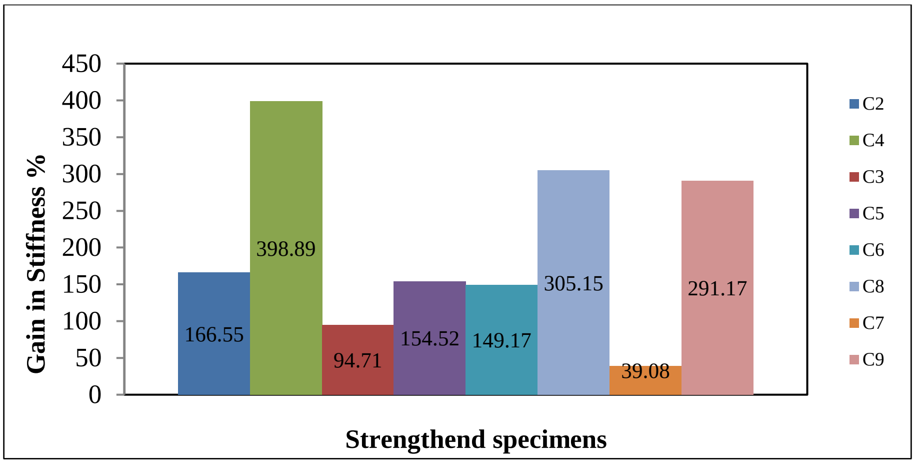

Figure 8. Gain in stiffness of strengthened specimens.

Ductility

Ductility is defined as the measure of a material's capacity to undergo plastic deformation prior to fracture. Ductility is a valuable structural characteristic since it facilitates load redistribution and warns of probable collapse. The ductility index (DI) is defined as the ratio of deflection at maximum load (Δu) to yield deflection (Δy) [34]. According to the data recorded in Table 5 and Figure 9, it can be seen that the increase of jacket thickness and strengthening technique (fully and partially) of the tested column specimens enhanced the ductility due to UHPFRC containing steel fibers, which in its role to enhance ductility and avoid sudden failure of specimens.

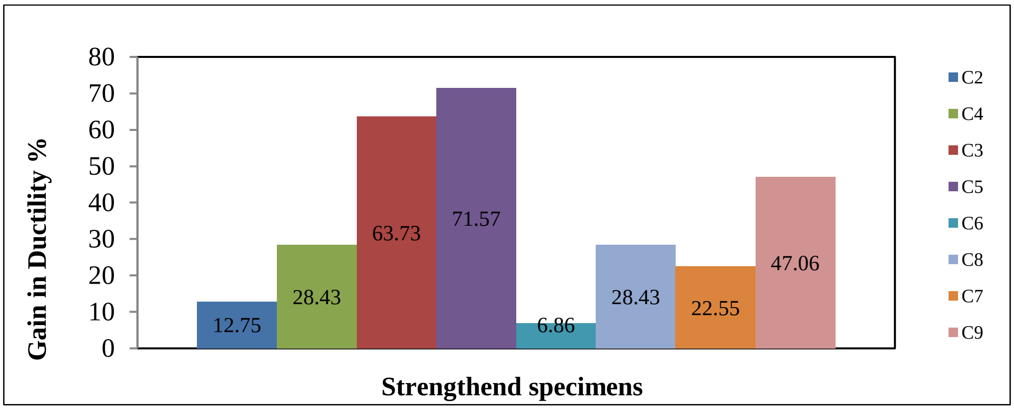

Figure 9. Gain in ductility of strengthened specimens.

Toughness

Toughness is defined as the ability to absorb considerable energy before cracking. This property is represented by the area under the whole curve. It is essentially resilience over every region. A large area under the curve indicates that the material has great toughness, enabling it to absorb significant energy prior to breaking. A material with high toughness should have a favorable balance of ductility and strength. Materials with poor strength and brittleness often exhibit low toughness. In term of toughness factor T.F, it could be defined as the ratio of the toughness of the strengthened specimen to that control specimen. The specimens that were strengthened with a full casting jacket (both sides) showed essential TF than those that were strengthened with a laminate scheme (tension and compression) accordingly. Additionally, the strengthening technique and jacket thickness were significant effect on the toughness factor of the tested specimens. In related to the Table 5 and Figure 10, which illustrated the results of the toughness factor of the strengthened column specimens, We can conclude that there is an improvement in the TF of columns that have been strengthened by UHPFRC, especially when changing the thickness of the strengthening layer from 15mm to 30mm for all sides (full casting) or only two sides (laminates), as follows: specimens (C2 to C4 and C6 to C8), resulted to an increase in TF of (1.47 to 1.76 and 1.27 to 2.23) respectively. While, the specimens (C3 to C5 and C7 to C9) resulted to an increase in TF of (0.96 to 1.2 and 1.08 to 1.56) respectively.

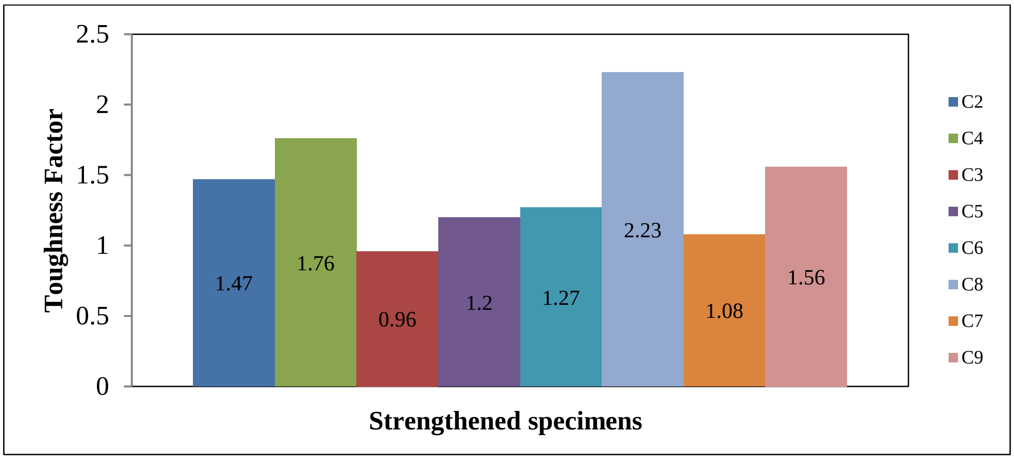

Figure 10. Toughness factor magnitude of strengthened specimens.

Conclusions

The experimental research could give the following results.

1. The UHPFRC approach offers an efficient approach for strengthening reinforced concrete columns subjected to eccentric loads.
2. The strengthening technique of full-cast jacketing was more efficient than that of the partial laminate scheme.
3. The increase in the UHPFRC jacketing from 15mm to 30mm results in an enhancement in load-bearing capacity, toughness, ductility, and stiffness.
4. To obtain the appropriate capacity of the strengthening columns for UHPRFC jackets, it is necessary to improve the roughening of the column surface and guarantee a bond between the UHPFRC mix and the column interface.
5. Because of their function as a bridge that inhibits fractures, steel fibers effectively postponed the initial appearance of cracks.
6. As the strengthening faces and thickness of UHPFRC jacketing increased the columns' mid-height lateral displacement and axial deformation reduced.
7. It was observed that the stiffness and ductility index of the rehabilitated honeycombed columns were too much affected by the presence of the honeycombed zone inside the columns, therefore, the reliance on the stiffness and ductility index, as often adopted when load testing is used, as an aid in assessment work can lead to safe assessment results because it supports and clearly shows the behavior of specimens.

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