

Integrating CFRP U-Wrapping and Spike Anchors in the Applications of Flexural Strengthening of RC Beams

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Abstract

This research examines the dual role of Carbon Fiber Reinforced Polymer (CFRP) U-shaped wrapping and spike anchors (SA), installed laterally or vertically, in enhancing stress transfer at the concrete-laminate interface and mitigating premature debonding. In addition to the RC control beam, eight beams organized into three groups were investigated. Group 1 evaluated the strength gain provided by Externally Bonded Reinforcement (EBR) alone or EBR supplemented with a single anchorage system, either a U-wrap or spike anchor, to secure the CFRP laminate. Group 2 investigated EBR with a single end U-wrap paired with either double lateral or single vertical bottom SAs. Group 3 employed double end U-wraps alone or in combination with single or double lateral SAs per sheet. The results revealed that incorporating spike anchors alone was more effective than U-wrapping. Flexural capacity increased by over 81% compared to the control beam and by 50% relative to the beam strengthened solely with EBR. On the other hand, hybrid configurations of spike anchors and U-wraps showed limited additional benefit, except for the case of double U-wraps combined with double lateral SAs, which achieved flexural strength gains of over 96% and 62% compared to the control and EBR-only beams, respectively. Anchoring also resulted in an enhanced flexural behaviour where most of the anchored specimens failed by CFRP rupture rather than CFRP debonding, indicating a better utilization of CFRP material.

Keywords

CFRP strengthening, Debonding, Spike anchors, u-wrapping, flexural

1. Introduction

It has been reported in the literature that one of the main limitations of implementing the externally bonded carbon fibre in rehabilitation, retrofitting or strengthening RC elements is the premature debonding of carbon fibre from the surface of substrate material such as concrete before utilizing the full capacity of CF material (Alkhateeb & Hejazi, 2022; Al-Mamory & Al-Ahmed, 2022; Bai et al., 2025; Fu et al., 2017; Wang et al., 2024). To overcome this structural problem, however, and to enhance the efficiency of such materials for the purpose it used for, some potential solutions have been recommended based on experimental (Abdallah et al., 2023; Abed et al., 2022; Gu et al., 2022) or analytical (Abed et al., 2021; Cui et al., 2024; Wang et al., 2024) studies.

Among the mostly robust solutions to overcome the CFRP premature debonding is the use of mechanical anchorage systems such as metal bolts, Ultra High Performance Concrete (UHPC) jacketing, or carbon fibre U-wrapping (Abdallah et al., 2023; Akbarzadeh Bengar & Shahmansouri, 2020; Bai et al., 2025; Fu et al., 2017; Liu et al., 2024; Saeed et al., 2025; Spadea et al., 1998; Wang et al., 2024; Zhou et al., 2020). The results provided by such proposals are promising where it has been reported that such anchoring systems can significantly improve the strength, ductility, stiffness and overall performance of strengthened elements (Ababneh et al., 2020; Abed et al., 2022; Aykac et al., 2013; Bai et al., 2025). However, most of these proposals may increase the dimensions and weight of RC elements which is generally undesirable. In addition, due to the difference in material properties (i.e., CFRP vs. steel or UHPC), achieving full bond between steel and CF is difficult. Moreover, metal plates and anchors are highly vulnerable to corrosion problem which promotes additional durability problems.

Based on the above limitations of steel anchoring, U-shaped carbon fibre wrapping has been considered in many of the recent applications (Abed et al., 2021; Al-Mamory & Al-Ahmed, 2022; Bai et al., 2025; Cui et al., 2024). It has been shown that such anchoring technique can significantly enhance the flexural performance of RC beams by prolonging CFRP debonding (Abdallah et al., 2023; Bai et al., 2025; Mcguirk, n.d.).

Another solution recently proposed by researchers is the implementation of longitudinal grooving techniques, such as Externally Bonded Reinforcement In Grooves (EBRIG) or Externally Bonded Reinforcement On Grooves (EBROG) (Fig. 1) (Kaur et al., 2025; Mashrei et al., 2019; Mostofinejad & Mahmoudabadi, 2010; Sanginabadi et al., 2022). These grooving techniques increase the contact area between the FRP material and the concrete substrate, thereby enhancing the flexural performance of strengthened reinforced concrete (RC) elements. Although several studies report that either technique can significantly improve the flexural strength of RC beams, extensive surface grooving can be time-consuming and labour-intensive. Furthermore, grooving the concrete cover may compromise the structural integrity of the section, particularly in cases of excessive grooving or when poor-quality concrete is being strengthened.

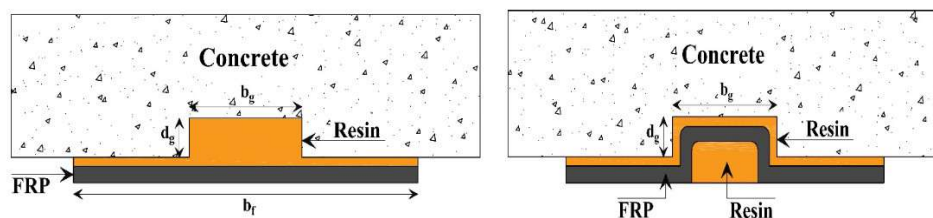


Figure 1: Strengthening of RC beams by EBROG (Left) and EBRIG (right) techniques (Sanginabadi et al., 2022)

The most recent and promising solution that overcomes many of the drawbacks of the systems mentioned above is the use of carbon fibre spike anchors (Assad et al., 2024; del Rey Castillo, Dizhur, et al., 2019; del Rey Castillo, Kanitkar, et al., 2019; Sun et al., 2020). Similarity in properties of anchoring and strengthening materials (both are carbon fibre) and ease of installation can effectively influence the performance of such anchoring technique. Moreover, dimensions, weight, quality of the concrete section are not altered through implementing of such anchoring system. In addition, the installation of CF spike anchors, if performed correctly, is much easier, faster, and requires less efforts as compared to other solutions.

(Rasheed et al., 2024) have conducted an experimental program for flexural strengthening of five full-scale T-girders with external CFRP materials. While the CFRP configuration was kept identical across all specimens, the number of CFRP anchors was varied. The results obtained highlighted the role of CFRP anchors in delaying the failure load beyond the classical intermediate cracking (IC) failure mode. More recently, (Alhelal et al., 2026) studied the effects of spike anchor parameters such as anchors placement, dowel diameter, and fan length on the effectiveness of such FRP anchors in mitigation of intermediate crack debonding failure. The results demonstrated the effectiveness of spike anchors particularly when positioned solely within the shear span. Additionally, it has been reported that end anchors have improved the peak displacement at failure by 40%.

Although some research has been conducted to date regarding the efficacy of the aforementioned bonding techniques, the most recent version of ACI 440.2-23 (ACI PRC 440.2, 2023) clearly stated that: “*further research is needed to provide information in areas that are still unclear or are in need of additional evidence to validate performance.*” Among the suggested areas, the code has suggested studying the effects different types of anchoring system that could provide for better bonding between fibre reinforced polymer and the substrate materials and clearly stated that this area is still in need for further research that can accurately address the debonding problem and possible solutions.

While most anchoring techniques have been examined individually, this study seeks to evaluate the combined effect of spike anchors and U-wrapping, and to determine the extent to which such integration can enhance the flexural capacity, ductility, stiffness and toughness of the strengthened RC beams.

2. Experimental Program

To achieve the objectives of the research, a total of ten beams of different strengthening and anchoring configurations were fabricated and tested. This section provides information about the used material properties, specimen’s design, installation of CFRP sheets and anchors and testing procedures. The overall experimental setup is illustrated schematically with further details in Section 2.3.

2.1. Steel and Concrete

To better represent the concrete type of most of the existing RC buildings, tested beams were fabricated using a concrete mix of designated compressive strength of 30 MPa. All concrete ingredients such as cement, coarse and fine aggregates had been individually tested and verified according to relevant specifications prior to use. On the other hand, 8 mm diameter steel bars had also been tested and verified as per the BS 4449-05 (BS 4449:2005+A3, 2016) to be used for both flexural and shear reinforcement. In addition to the material properties listed above, a total of six standard cubes of 150x150x150mm were casted and tested under compression as per the BS EN 12390-3 (BS EN 12390-3:, 2019) to estimate the actual compressive strength of concrete prior to beams casting. Table 1 shows some of the most important proprieties of the steel and concrete used.

Table 1: Steel and concrete properties

Steel, conformation with BS 4449-16				
Diameter [mm]	Yield stress, R_e [MPa]	Ultimate stress, R_m [MPa]	R_m/R_e	Elongation [%]
8	575	646	1.123	12.8
Limits	$485 < R_e < 650$	-	>1.06	>4
Concrete mix [kg/m ³]				
Cement	Fine aggregate	Coarse aggregate	Water	Viscocrete [5930]
410	740	1035	170	3.28
Concrete strength [MPa]				
Sample 1	Sample 2	Sample 3	Average	
32.0	31.4	31.7	31.7	

2.2. Carbon Fiber and Epoxy

A 0.13 mm unidirectional woven Carbon Fiber (CF), commercially known as SikaWrap-230C, has been implemented for longitudinal strengthening and u-anchors. This fibre type has been applied to the concrete surface by using a paste-like epoxy resin designed for manual application of carbon fibre known as Sikadur-330. These materials are shown in Figure 2.

On the other hand, a 10 mm diameter (impregnated) unidirectional structural carbon fibre cord, known as SikaWrap Fx-50C, has been utilized as spike anchor which has been manufactured specifically for such applications. These anchors, as will be discussed later, had been impregnated first by using a low viscosity impregnation epoxy resin commercially known as Sikadur-52LP before inserting inside the predrilled anchors' holes. Figure 2 also shows the anchors fabric and epoxy materials used in this research. In addition, some of the most important technical properties of these materials are provided in Table 2.



Figure 2: Carbon fibre and epoxy materials used in this research

Table 2: Technical properties of strengthening materials

Material	Description	Property	Results ¹
SikaWrap-230C	Unidirectional CFRP fabric	Thickness [mm]	0.13
		Tensile modulus [MPa]	238×10^3
		Elongation at break [%]	1.8
		Tensile strength [MPa]	4300
Sikadur-330 @7 days, 30 °C	Epoxy resin	Elastic modulus [MPa]	3489
		Tensile strength [MPa]	33.8
		Flexural strength [MPa]	60.6
		Elongation at break [%]	1.2
SikaWrap Fx-50C	Unidirectional CFRP cord	Dry diameter [mm]	6.0
		Impregnated diameter [mm]	10.0
		Dry tensile strength [MPa]	4000
		Impregnated tensile strength [MPa]	2000
		Dry modulus of elasticity [MPa]	240×10^3
		Impregnated modulus of elasticity [MPa]	230×10^3
Sikadur-52 LP @7 days, 30 °C	Low-viscosity resin	Compressive strength [MPa]	≥ 70.0
		Tensile strength [MPa]	27.0

¹Data of all products are provided by the manufacturer.

2.3. Design of the Specimens

A total of nine geometrically identical RC beams were designed, fabricated and tested up to failure under four-points-bending scheme. All beams, including the strengthened ones, have been designed to fail in flexure considering to

potential increase in the flexural capacity due to the strengthening process. Each beam was fabricated in dimensions of $B \times H \times L$ equals to $120 \times 170 \times 1200\text{mm}$ with a clear span of 1000mm and a shear span-to-depth ratio (a/d) of 2.20 . Flexural reinforcements consisted of $2D8$ mm lower and $1D8$ upper steel bars. The beams were strengthened against shear stresses by $D8@60\text{mm}$ bars to avoid shear failure especially in strengthened beams as stated earlier. Figure 3 shows the geometry and reinforcement details of the tested beams.

In addition to the control beams (CB) of no strengthening or anchoring techniques incorporated, three groups of strengthened beams were tested. The first group (G1) comprised of three beams: one with only EBR along the bottom span of the beam, which also serves as a reference beam for strengthening benefits, a beam with EBR and additionally anchored through a single 100mm wide CFRP u-wrap at each end and a beam with EBR and additionally anchored by using an 80mm deep single vertical bottom spike anchor. This group was designed to investigate the potential strength gain, or behaviour improvement, when additionally anchoring the EBR layer through a single technique. Group G2, on the other hand, investigated EBR with a single end u-wrap combined with either a double lateral or single vertical bottom SA.

In an attempt to improve the end-anchors contribution through midspan strengthening, Group 3 adopted a configuration of double end u-wraps supplemented by a 100mm wide intermediate u-wrap, with anchorage provided by either single or double lateral spike anchors per sheet. Therefore, the term “double u-wraps” or “double end u-wrap” in this study denotes a configuration comprising three u-wraps: two applied at the beam ends and one positioned at midspan. Figure 4 and Table 3 show the strengthening and anchoring configurations details of all groups.

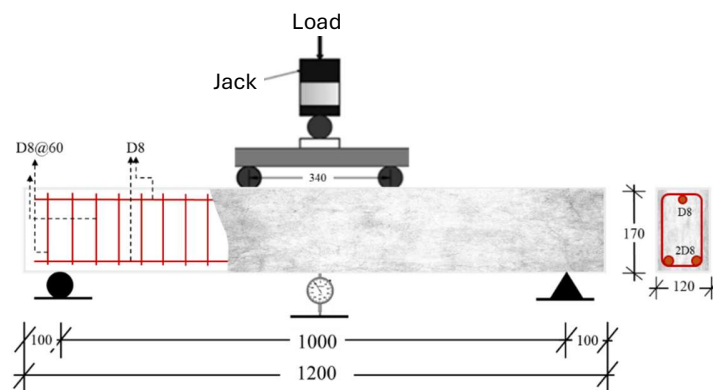


Figure 3: Geometry and reinforcement details of the tested beams [Dimensions are in mm]

2.4. Installation of CF Sheets and Anchors

At the end of concrete curing period, the beams have been removed from water and allowed to dry out before the CF sheets installation process begins. In accordance with the CFRP manufacturer's guidelines and prior research recommendations, the concrete surface should be thoroughly prepared by removing any residue, debris, or contaminants such as grease, and ensuring it is as rough as possible before CFRP installation. Therefore, after marking and drilling the locations of spike anchors, bottom and side surfaces of the beams had been thoroughly cleansed by a steel grinder, roughened by mechanical steel brush, and thoroughly cleaned prior to the application of CFRP sheets and anchors as shown in Fig. 5 (a) and (b). It should also be noted that the sharp edges of the beams with u-wrapping have been smoothed (rounded) using a steel grinder as per prior research recommendations.

For the beams to be additionally anchored by using CF spike anchors, holes of 12 mm diameter (2 mm larger than the diameter of impregnated spike anchor to be used) and have been predrilled, cleaned by using air pump and special brush, as shown in Figure 5 (c) and then by water jetting to ensure best quality of bonding with epoxy resin to be used. The

depth of the bottom and side holes was kept as 90mm, which is 10mm deeper than the spike anchors to be inserted for better connectivity with epoxy resin.

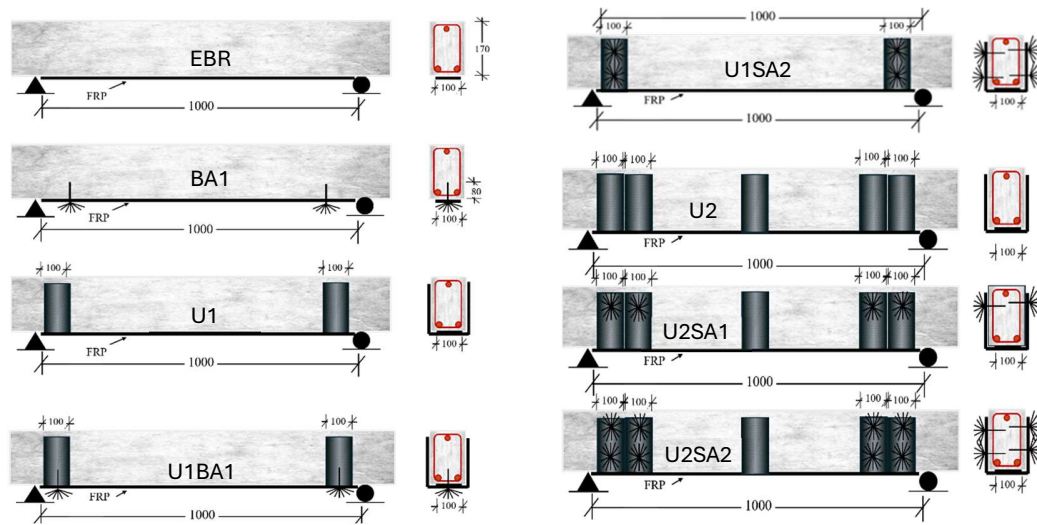


Figure 4: Strengthening and anchoring configurations of beams in all groups

Table 3: Strengthening and anchoring configurations of beam specimens

Beam Description	Group	Beam	No. of U-wraps	No. of spike anchors	Intermediate U-wrap?	Orientation of spike anchors
Control beam (non-strengthened)		CB	-	-	No	-
Externally Bonded Reinforcement.	G1	EBR	-	-	No	-
EBR with single bottom spike anchor at each end		BA1	-	2	No	Vertical
EBR with single end u-wrap at each end		U1	2	-	No	-
EBR with single end u-wrap and double side spike anchors at each end	G2	U1SA2	2	8	No	Lateral
EBR with single end u-wrap and single bottom spike anchor at each end		U1BA1	2	2	No	Vertical
EBR with double end u-wraps plus single intermediate u-wrap at each end	G3	U2	4	-	Yes	-
EBR with double end u-wraps plus single intermediate u-wrap and single side spike anchor for each wrap at each end		U2SA1	4	8	Yes	Lateral
EBR with double end u-wraps plus single intermediate u-wrap and double side spike anchors for each wrap at each end		U2SA2	4	16	Yes	Lateral

With respect to the CFRP sheets application, the epoxy material has been mixed by a percentage of 4:1 by weight and applied evenly to the surface of concrete by a suitable brush. After that, the pre-cut SikaWrap-230C sheets have been applied to the bottom surface of the beam (dry layup) and a special roller tube was used to increase the quality of glueing and to avoid any entrapped air underneath the CFRP sheets. Vertical u-wrapping installation was performed by following the same process and was done immediately after the bottom CFRP installation.

To prepare the anchors, a 6 mm dry diameter SikaWrap-Fx50 was used for this purpose. Each anchor was precut to length of 130 mm. From that length, 80 mm was impregnated first by Sikadur-52 LP, which is already prepared by mixing the two parts by the recommended percentages and then tightened from its end by using plastic ties to make it easy inserted inside prepared holes. The anchors were left in the room temperature for approximately 10 minutes before inserting them inside the predrilled holes. The diameter of the impregnated anchors was approximately 10 mm; which is 2 mm less than

the diameter of the predrilled holes as per manufacturer recommendations. Details of spike anchors preparation and dimensions are shown in Figure 6.

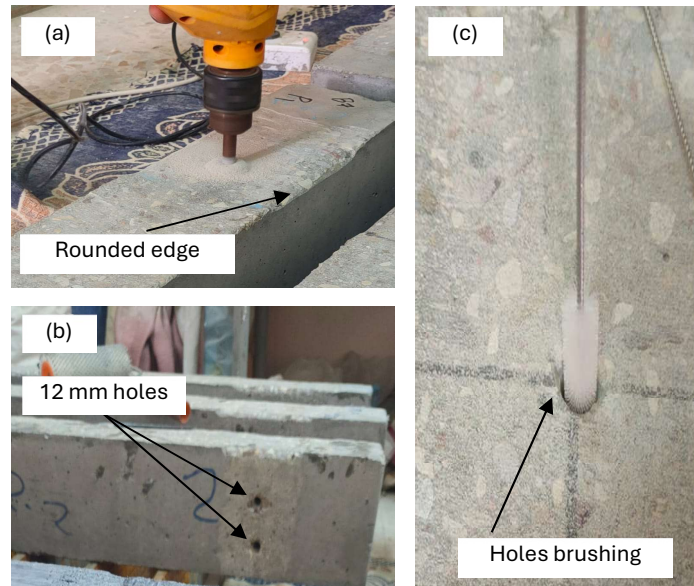


Figure 5: (a) Holes drilling, (b) Surface preparation and (c) Holes brushing of the test specimens

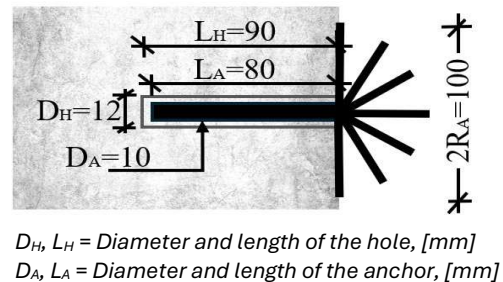


Figure 6: Details of drilled holes and spike anchors used

After the applications of both bottom CF and u-wrapping sheets, the predrilled holes were filled by Sikadur 330 epoxy resin and then the prepared spike anchors were individually inserted up to the desired depth at each hole. The remaining 50 mm length of each spike anchor was then sprayed out to form a 100 mm diameter fan shape and glued over the preinstalled CF sheets by using Sikadur 330 and the same tools used in the installation of CF sheets. Same technique has been used previously by (Alhelal et al., 2026; del Rey Castillo, Dizhur, et al., 2019; Sun et al., 2020) and has been recommended by the most recent version of (ACI PRC 440.2, 2023). After the successful application of the hybrid anchoring system is done, the beam specimens have been left 7 days for curing at the room temperature. Fig. 7 shows the most important steps of the whole strengthening process.

2.5. Test Configuration

All beam specimens were simply supported with 1000mm clear span and tested under four-points flexural testing using a 200 kN machine. A stiff steel spreader beam was utilized to divide the applied load into two equal point loads with a clear spacing of 340 mm (shear span equals to 330 mm from each support) as shown in Figure 3. To determine the load-deflection relationships and the associated structural performance indices such as stiffness and ductility, a high-resolution electronic dial gauge of 0.01mm accuracy was installed underneath the central point of the beam to measure the deflection.

The load was applied gradually with a constant rate of approximately 0.5 kN/s until the failure of beams. Prior to testing, the sides of the beam samples have been white painted to better monitor the initiation and propagation of developed cracks.



Figure 7: Strengthening and anchoring test specimens using CF sheets, u-wrapping and spike anchors

3. Results

This section reports on the recorded and calculated results including cracking load, steel yielding load, ultimate load, and the corresponding deflections of each phase. In addition, the structural performance indices such as ductility, stiffness and toughness will also be calculated for each tested beam. The modes of failure for the tested beams will also be reported and discussed in this section.

3.1. Critical Loads and Deflections

The cracking, flexural steel yielding, and ultimate loads during test, and the related deflections have been carefully recorded. Table 8 shows the reported loads and deflections for all tested beams. On the hand, the percentage increase/decrease in loads and deflections have been calculated as compared to the control beam and listed inside parenthesis in Table 8 as well.

Since different materials such as steel, concrete and carbon fibre are incorporated in the tension side of the beam, no clearly defined yield point had resulted in almost all load-deflection curves produced. Therefore, the most realistic definition of yield point reported by (R. Park, 1988) has been implemented to calculate the yield load and the corresponding yield deflection of steel bars. The implemented definition considers the equivalent elasto-plastic behaviour with 75% secant stiffness (reduced stiffness) compared to the ultimate load. The same definition has been later adopted by many researchers such as (Mirmiran et al., 1999) and (Pam et al., 2001). Figure 8 shows the definition of the yield point, as well as cracking and ultimate loading states for the control (CB) beam. The same process has been followed to determine the yield load and deflection of each tested beam in this research.

3.2. Structural Indices

The behaviour of structural elements such as beams can be quantified by using some structural indices such as ductility, stiffness and toughness. These indices can define the overall behaviour of the tested element since they utilize realistic data driven from the tested objects. In this section, these indices will be defined and then calculated for each tested beam.

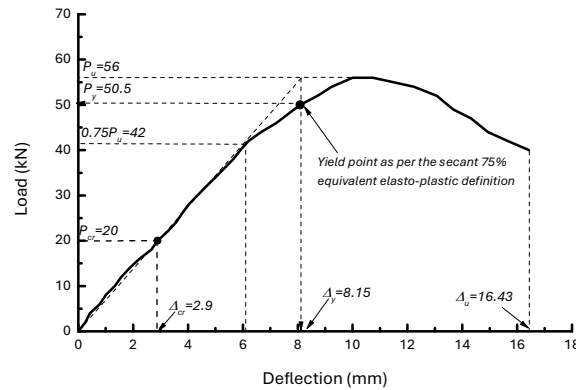


Figure 8: Elasto-plastic definition of yielding, cracking and ultimate points of the CB sample

Ductility is defined as the ability of a structural member to absorb energy before sudden failure. This index utilizes the maximum and the yield displacements and can be calculated as the ratio of the maximum-to-yield displacement (Hussein et al., 2012; Pam et al., 2001). Stiffness index, on the other hand, can be defined as the amount of elastic deformation the element can undergo under the applied loads (Hajighasemali et al., 2014). This definition is like the slope of the elastic part of the load-deflection curve and therefore, can be directly calculated from the load-deflection data. Toughness is another important performance index which defines the amount of load it can be absorbed by the member before failure. This index can therefore be defined as the area under the load-deflection curves (Hajighasemali et al., 2014).

The calculated structural indices and the percentages of increase/decrease of such indices compared to the control beam are summarized in Table 9. For better readability, Figure 9 can also be used to show the load carrying capacity of all tested beams as well as the percentages of increase (or decrease) of the structural indices discussed. As will be discussed later, careful reviewing of Table 9 and Figure 9, the reader can clearly see that although the critical loads have increased, the ductility of all tested beams decreased due to the decrease in the ultimate deflection due to the application of CFRP strengthening.

Table 8: Critical loads and the corresponding deflections, and the percentages of increase / decrease

Beam	Cracking load [kN] [%]	Cracking deflection [mm] [%]	Yielding load [kN] [%]	Yielding deflection [mm] [%]	Ultimate load [kN] [%]	Ultimate deflection [mm] [%]	Failure mode
CB	20 [0.00]	2.9 [0.00]	50.5 [0.00]	8.2 [0.00]	56 [0.00]	16.43 [0.00]	Flexural
EBR	30 [50]	3.5 [20.69]	63 [24.75]	9.1 [10.98]	68 [21.43]	10.86 [-33.90]	Debonding of CFRP
BA1	30 [50]	3.66 [26.21]	90 [78.22]	10 [21.95]	101.5 [81.25]	13.6 [-17.22]	Rupture of CFRP
U1	36 [80]	4 [37.93]	69.5 [37.62]	9.8 [19.51]	78 [39.29]	11.04 [-32.81]	Rupture of CFRP
U1SA2	54 [170]	5.4 [86.21]	92 [82.18]	10.8 [31.71]	103 [83.93]	14.3 [-12.96]	Rupture of CFRP
U1BA1	36 [80]	3.73 [28.62]	92 [82.18]	11.2 [36.59]	104 [85.71]	13.25 [-19.35]	Rupture of CFRP
U2	42 [110]	3.67 [26.55]	79 [56.44]	8.4 [2.44]	91 [62.50]	11.56 [-29.64]	Rupture of CFRP
U2SA1	33 [65]	3.7 [27.59]	82 [62.38]	11.8 [43.90]	88 [57.14]	13.04 [-20.63]	Rupture of CFRP
U2SA2	42 [110]	3.8 [31.03]	94 [86.14]	10.2 [24.39]	110 [96.43]	12.65 [-23.01]	Rupture of CFRP

3.3. Load-Deflection Curves

The load-deflection curves have been constructed for all tested beams. As stated earlier, the load was applied gradually from zero up to the failure load with constant rate of 0.5 kN/s. In all beams, the data of load, and the corresponding

deflection, were collected for each 2 kN increment for better construction of the curves. Figures 10-12 illustrates the load-deflection curves of the three tested groups, where the reader can clearly notice the strength gain due to the implementation of either a single (as in Figure 10) or the hybrid (Figure 11 and 12) anchoring system for the EBR strengthening. Nevertheless, the results of all tested beams will be individually discussed. Please notice is that the samples CB and EBR were included in all of these three figures since both can serve as reference specimen in the discussion that will be provided in the next sections.

Table 9: Percentage increase/decrease of structural indices

Beam	Ductility	[%]	Stiffness	[%]	Toughness	[%]
CB	2.00	0.00	5.75	0.00	642	0.00
EBR	1.19	-40.45	5.89	2.40	432	-32.71
BA1	1.36	-32.14	9.46	64.45	865	34.74
U1	1.13	-43.79	5.78	0.37	490	-23.68
U1SA2	1.32	-33.93	7.04	22.28	1047	63.08
U1BA1	1.18	-40.97	7.50	30.27	792	23.36
U2	1.38	-31.33	7.82	35.93	653	1.71
U2SA1	1.11	-44.86	6.05	5.12	670	4.36
U2SA2	1.24	-38.11	8.13	41.19	817	27.26

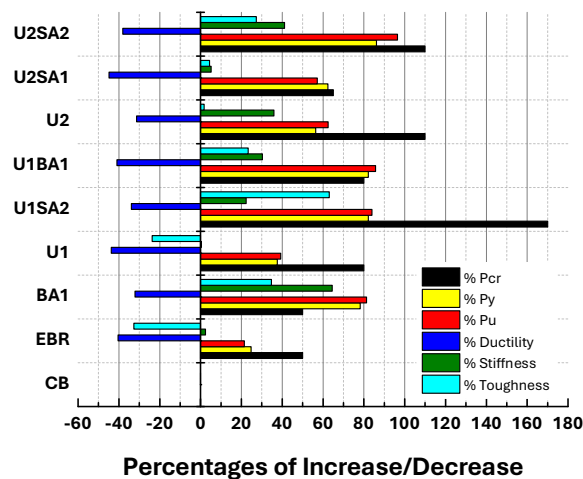


Figure 9: Percentages increase/decrease of the critical loads and structural indices

3.4. Modes of Failure

The failure mode represents a critical indicator of how a beam ultimately behaves under applied loads. Despite its qualitative nature, failure mode carries greater significance than other structural indices previously discussed. Therefore, the authors aim to qualitatively describe the observed failure mechanisms of each tested beam. A review of Figure 13, which illustrates the failure modes of all tested beams, reveals that the incorporation of anchorage techniques such as u-wrapping or spike anchors effectively altered the failure mechanism. Whereas the externally bonded reinforcement (EBR) beam failed by premature end debonding, the anchored beams exhibited a more favourable mode of failure, namely CFRP rupture/tearing. Alongside the notable increase in load-carrying capacity, this shift in failure mode indicates a more efficient utilization of the CFRP material, ensuring that it performs closer to its intended structural purpose.

The rupture load of the CFRP can be directly related to its tensile properties. For the CFRP sheet used in this study (thickness = 0.13 mm, width = 100 mm, tensile strength = 4300 MPa), the theoretical tensile capacity is approximately 56 kN. This value represents the maximum axial force the CFRP can sustain before rupture. All tested beams exhibited ultimate loads exceeding this theoretical CFRP capacity, especially with the further implementation of spike anchors and u-wraps. The final failure mode was CFRP rupture, confirming that the CFRP material properties governed the ultimate load. This demonstrates that the reported rupture loads are physically justified by the intrinsic tensile strength and modulus of the CFRP.

4. Discussion

Given the data presented above regarding the critical loads, and corresponding deflection of each loading stage, structural indices of each tested beam, percentage of increase (or decrease) of the loads and the performance indices, and the modes of failure, this section will be dedicated to discuss these results in a group-by-group form to achieve the objectives of the research:

4.1. Control Beam

The non-strengthened RC control beams, CB, has been designed to fail in flexure. As per the most current ACI 318 Code (ACI Committee 318, 2025), the theoretical design load it can carry is about 49 kN. Test results showed a normal load-deflection behaviour where the deflection has increased gradually as the applied load was increased from zero up to the failure load of 56 kN. The failure mode of this beam sample was a pure flexural failure due to the propagation of flexural cracks near the midspan of the beam. The ductility index of this beam was 2.0, which is larger than other tested beams in this experimental work.

4.2. Group G1

This group, as discussed previously, consisted of three beams (EBR, BA1 and U1) and has been designed to investigate the effects of individual anchorage system that can be additionally implemented to overcome the debonding failure of EBR strengthened beams. All the beams in this group showed linear load-deflection relationships up to the failure loadings are reached. Beam EBR has showed a greater load-carrying capacity ($\approx 22\%$) than the control beam. However, it failed suddenly by CFRP debonding from one end of the beam when the ultimate load reached 68 kN. Flexural cracks began to appear at the beam's midspan once the applied load reached the cracking threshold of approximately 30 kN. With further loading, these cracks propagated deeper into the section and widened progressively, accompanied by the initiation of additional flexural and shear cracks as the applied load increased. The ultimate deflection of the beam sample was lower than the control beam by 6mm, which has resulted in a significant reduction of the ductility as shown in both Figure 9 and Table 9.

On the other hand, BA1 and U1 which are additionally anchored by using either a bottom spike anchor or a single u-wrap at each end, respectively, have supported greater load as compared to EBR sample and both samples have failed by CFRP rupture roughly at midspan of the beam. The failure mode of BA1 and U1 emphasizes the role of anchors in providing extra capacity for the anchored beams and therefore altering the mode of failure from debonding to rupture. As can be seen in Figure 9 and Table 9, that although the ductility of both samples has been reduced compared to the CB sample, the overall performance of BA1 was much better than U1 sample in terms of stiffness and toughness. For example, BA1 showed percentages increase in ultimate load, stiffness and toughness by 81, 42 and 35%, respectively, compared to the control beam.

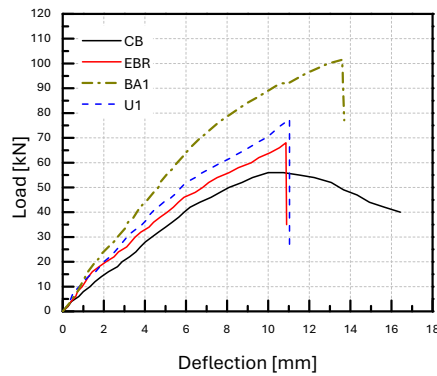


Figure 10: Load-deflection curve of group G1 and CB

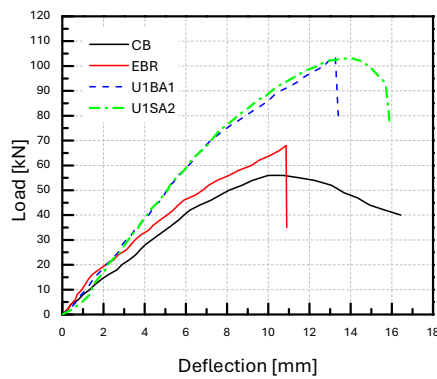


Figure 11: Load-deflection curve of group G2, EBR and CB

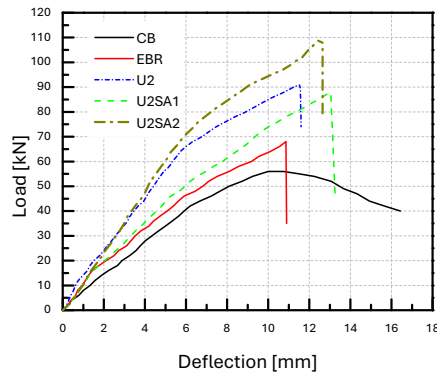


Figure 12: Load-deflection curves of group G3, EBR and CB

4.1. Group G2

To investigate the hybrid contribution of both u-wrapping and spike anchors, Group G2, which consisted of two beam sample was designed. Both samples were anchored by using a single u-wrap at each end, however, sample U1SA2 was additionally anchored by two side spike anchors while sample U1BA1 was anchored by a single bottom vertical spike anchor. As shown in Table 8, comparing the ultimate load capacity of both beams to CB specimen, both beams have provided superior ultimate load capacity by more than 84% increase. Stiffness and toughness of both beams, as shown in Fig. 9, have also been respectively increased by more than 22 and 63% for beam U1SA2, and by more than 30 and 23% for beam U1BA1. Compared to each other, on the other hand, the performance of both samples was relatively similar in terms of the determined structural performance indicators and mode of failure. Although both samples surpassed either CB or

EBR, the performance of these two beams was almost indistinguishable from beam BA1 tested in group G1. The mode of failure of both samples in this group, was CFRP rupture at midspan triggered by the development of wide and extensive intermediate cracks (IC). In fact, such mode of failure can be encountered due to the higher flexural stresses at midspan compared to the stresses at ends of the beams. Consequently, the anchorage modifications applied at the ends in Group G2 did not yield significant improvements over Group G1. To address this limitation, all beams in Group G3 were additionally anchored at midspan using an extra u-wrap, aiming to reinforce the region of maximum stress and redistribute the demand toward the beam ends for potentially enhanced anchorage efficiency.

4.2. Group G3

In addition to the double u-wraps incorporated at each end of the beams of this group, they have been additionally anchored at midspan by an extra 10mm wide u-wrap. Beam U2 was tested to assess potential improvements in structural behaviour relative to sample U1. Beams U2SA1 and U2SA2 have been additionally anchored by single and double side spike anchors, respectively. The results of this group, in general, have not resulted in any significant improvements compared to the beams of Group G2, except sample U2SA2 which provided percentage increase in ultimate load, stiffness and toughness by 97, 41 and 27%, respectively compared to CB beam. On the other hands, the mode of failure of this group was CFRP rupture at the unanchored area between beams midspan and one of its ends as shown in Figure 13.

5. Conclusions

This research investigated the potential effect of combining two anchoring techniques to improve the bonding strength of the externally bonded CFRP material (EBR) to the concrete surface, and therefore, to maximize the flexural capacity of the strengthened members. Based on the results obtained, the following results can be stated:

- Strengthening of RC beams solely by EBR can result in a noticeable increase in the load carrying capacity of the strengthened beams. Although this improvement of load capacity is advantageous for the strength limit state, the ductility of the member, can be decreased sharply due to this strengthening which is undesired from the serviceability limit state viewpoint.
- Anchoring the EBR strengthened beams by double u-wraps at end of the CFRP layer provided better flexural performance than single u-wrap in all the structural indices investigated. This can be seen by comparing the results of U2 compared to U1 sample.
- Anchoring of EBR strengthened beams by means of bottom spike anchors at ends of CFRP layer outperformed the beams anchored by either a single or double u-wrapping. For example, almost all structural indices of BA1 are better than the corresponding indices of U1 or U2 beams.
- In terms of cracking load, yielding load, ultimate load, ductility and toughness, the incorporation of double side spike anchors as in beam U1SA2 showed better results compared to the single bottom spike anchor as in beam U1BA1.
- Incorporating of a single u-wrap with double side spike anchors as in beam U1SA2 provided better load carrying capacity and structural indices compared to beam U2SA1, which has been anchored by double u-wraps and single side spike anchor.
- A comparison between specimens BA1 and U1BA1 indicates that the addition of u-wrapping to the bottom spike anchor system produced only a negligible enhancement in load-carrying capacity. The ultimate load increased marginally from 101.5 to 104 kN, a gain too minor to justify the additional time, effort, and cost associated with incorporating u-wraps alongside bottom spike anchors.

- Anchoring the EBR-strengthened beams with any of the configurations examined in this study has altered the failure mode from CFRP debonding to CFRP rupture, thereby enabling greater utilization of the CFRP's tensile capacity for its intended strengthening function.

However, given the limitations of time and resources, the authors recommend that future studies should further investigate spike anchor configurations, including parameters such as embedment depth, anchor diameter, spacing, and alternative arrangements.

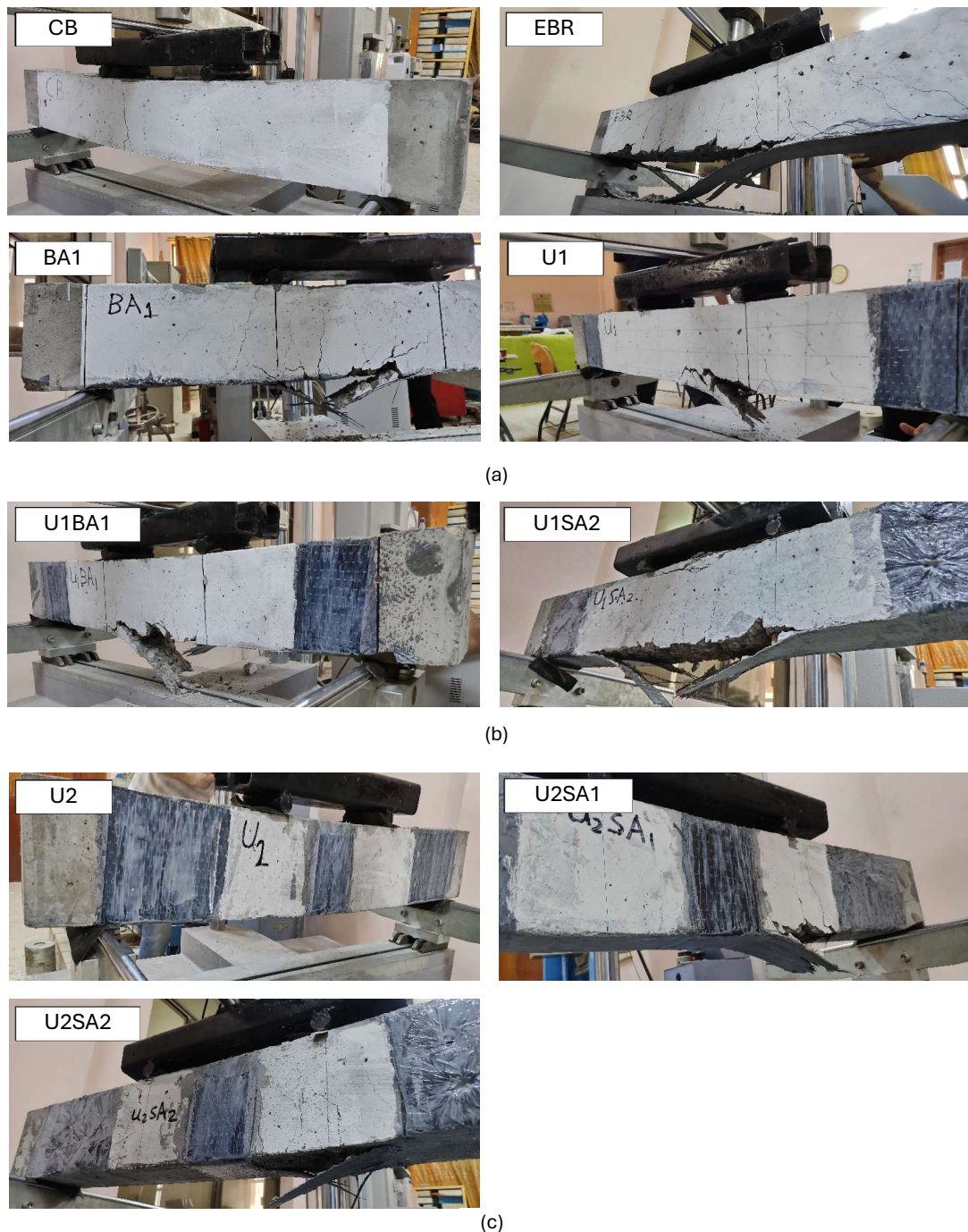


Figure 13: Modes of failure: (a) Beams of group G1, plus CB, (b) Beams of group G2 and (c) Beams of group G3.

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Author Contributions

A.A.S. & M.A.M. conceived and designed the study, conducted the experiments, collected the data and contributed to manuscript writing. **Sh.N.A.H.** performed the statistical analysis. **R.A.H.A.** contributed to data interpretation and manuscript drafting. All authors critically reviewed and approved the final version of the manuscript and agreed to be accountable for all aspects of the work.

Disclosure of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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