Available online at www.CivileJournal.org

Civil Engineering Journal

(E-ISSN: 2476-3055; ISSN: 2676-6957)

Vol. 9, No. 08, August, 2023

Structural Strengthening of Insufficiently Designed Reinforced Concrete T-Beams using CFRP Composites

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Received 27 March 2023; Revised 03 July 2023; Accepted 12 July 2023; Published 01 August 2023

Abstract

This study aims to compare the response of reinforced concrete (RC) T-beams strengthened with carbon fibre-reinforced polymer (CFRP) composite with that of non-strengthened control beams when subjected to monotonic two-point loading until failure for flexural once and shear again. The experimental programme tested eight RC T-beams, which included two reference beams without strengthening and six strengthened beams. The eight beams were divided into two main groups according to strengthening (flexural and shear). Experimental analysis was performed to study the effect of the CFRP laminate width in the flexural group and the spacing of CFRP U-wrap sheets in the shear group on the ultimate load capacity, load-strain relationship, and load-deflection relationship. Results show that increasing the width of the CFRP laminate in the flexural group improves the ultimate strengths to approximately 9.5%, 35%, and 41% for beams with CFRP laminate widths of 50, 100, and 150 mm, respectively, compared with the reference non-strengthened beam. The stiffness of the beams increases in direct proportion to the width of the CFRP laminate. In the meantime, decreasing the spacing of the CFRP laminate in the shear group increases the ultimate strengths to approximately 13.2%, 17.7%, and 23.5% for beams with CFRP U-wrap sheet spacings of 166, 125, and 100 mm, respectively, compared with the reference non-strengthened beam. Therefore, the spacing of the CFRP sheet is inversely proportional to the stiffness of the beam.

Keywords: T-Beams; CFRP Composites; Bending Stresses; Shear Stresses.

1. Introduction

In the last three decades of the prior century, the use of carbon fibre-reinforced polymer (CFRP) composites for strengthening reinforced concrete (RC) elements has become an intriguing tool for infrastructure rehabilitation. CFRP strengthening can be used in many different ways, including building new buildings and fixing old ones [1–4]. Along with analysing the general failure criteria of CFRP-RC beams, other researchers have focused on the local behaviour at the bond interface. Attempts have been made to define bond behaviour at the interface, where premature failures originate [5, 6].

CFRP, which has good engineering qualities, can be used to fix buildings made of RC. The benefits of CFRP boosting have become clear in terms of time and money. Considerable research has been conducted on the effectiveness of RC beams modified with CFRP laminates or sheets. CFRP composites are made of high-tensile–strength fibres that are inserted in an epoxy matrix. They have a high resistance to rust, are lightweight, have a high strength-to-weight ratio and have high mechanical strength. They can also be used to fix beams quickly with low cost. Preparing the surface is important for a good relationship between CFRP and concrete. Therefore, the strength and quality of the bond between the CFRP composites and the concrete are important for the movement of the stress from the concrete buildings to the

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http://dx.doi.org/10.28991/CEJ-2023-09-08-05

laminate or piece of CFRP that is attached externally. The quality or dependability of the bond may also depend on the material properties of the epoxy matrix of the fibres and the properties of the concrete base, such as the sharpness, strength and cleanliness of the concrete surface. Epoxy resins are most often used to join CFRP and concrete together because they stick well to both materials [7].

The contact bond is important for moving stresses from existing concrete buildings to CFRP materials that are attached externally. Effective bond length is another aspect that prevents the maximum activation of the tensile strength of CFRP materials. The concentration of shear tension is the primary cause of premature debonding. However, effective bond lengths can vary considerably due to the different definitions provided by different researchers and the dissimilar materials used in their experiments, such as 75 mm [8], 100 mm [9], 93 mm [10], and 64–135 mm [11].

Wang et al. [12] investigated the behaviour of RC T-beams retrofitted with CFRP plates using theory and tests. CFRP plates were glued to the bottom of the beams to increase the service life and load capacity. A prototype beam and six 5 m-long beams that were simply supported underwent a series of tests under repeated cyclic and constant loads until they broke. The development of the CFRP plates and the behaviour of the service and ultimate load ranges were given considerable attention. This study focuses on aspects that have not been investigated before, such as the use of plates that are not all the same size and the use of plates on beams with steel reinforcement that has been cut short. This study also examines the effect of diagonal tension cracking by incorporating a simple version of the modified compression field theory into the discrete element method. The most important conclusion of this study is that staggered CFRP plates can be used instead of full-length plates to strengthen beams against bending. The experimental programme also demonstrates that, if the plates are properly developed, then using staggered CFRP plates can be a cost-effective way to increase the service live load capacity of beams and can result in satisfactory behaviour at ultimate load. The presence of steel bar cut-off points and the effects of diagonal tension cracking in the shear span of beams should be considered when making the plates. Zaki et al. [13] investigated five full-size T-beams that were made and tested to determine the improvement rate of the bending strength of CFRP-anchored beams. Along each shear span, the second T-beam was held down by 12 clamps with a width of 14 mm. The third T-shape was held in place by nine clamps with a width of 19 mm and a distance of 203 mm per shear span. In the fourth T-sample, four 16-mm-wide CFRP supports held the sheets in place.

The test results show that the ability of RC T-beams to bend greatly improves when CFRP sheets are glued to CFRP stakes. As the number and amount of strands in the CFRP clamps increase, this improvement enhances until the full segment capacity is reached. The maximum load is also larger when the stakes are closer together. Zaki and Hayder [14] studied the effect of CFRP on the separating strains in concrete using full-scale RC T-beams. These beams were fabricated and strengthened in two stages. The first set had three concrete T-beams of standard weight. Three more T-section beams made of lightweight concrete made up the second series. The geometry, reinforcement, and length of the span were all the same across the two series. They had nearly comparable concrete qualities and the same CFRP material to analyse the difference in debonding strain between the two kinds of concrete. The debonding stresses of lightweight and regular concrete were evaluated by comparison, and the reduction factor ($\lambda = 0.90$) is good in light of the design equations in ACI-440.2R17 [15]. Ng and Lee [16] explored the bending behaviour of RC beams strengthened with CFRP laminates that were bonded externally. Different ways for these strengthened reinforced beams to break have been reported. These methods are usually called 'brittle failure' or 'ductile failure', and they involve the concrete being crushed by compression, the composite laminate debonding or breaking, and the steel reinforcement giving away. For the analysis, the stresses and strains of all the beam parts are related to the properties of the materials, such as the stress-strain curves for the concrete, steel, and CFRP laminate. The shape of the cross section of the concrete beam is believed to be a good indicator of the spread of the strain. For static balance, the forces on the cross section are equal to the loads that are applied to it. The analytical solution is based on the equilibrium equations and the fact that the strains are compatible. It can be used for single- and double-reinforced concrete beams strengthened with multiple layers of CFRP laminates. In this study, a simple and direct way of analysing the flexural capacity of concrete beams strengthened with CFRP and predicting how they will break has been proposed. The steps for computing are shown with the help of an example. For design purposes, the upper and lower limits of the CFRP cross-section areas are set to ensure that RC beams strengthened with advanced composite materials will break in a ductile way. A comparison has been made between the analytical results and the data from the literature, and they match up very well.

Mofidi & Chaallal [17] provided the results of an experimental and analytical study of shear strengthening of RC beams with externally bonded fibre-reinforced polymer (FRP) strips and sheets, especially on the effect of the strip width-to-strip spacing ratio on the contribution of FRP (V_f). Fourteen tests were performed on T-beams that were 4,520 mm long. The performance of RC beams that were strengthened in shear by CFRP strips with different width-to-spacing ratios was examined. The results were compared with those of RC beams that were made stronger by adding different numbers of layers of continuous CFRP sheets. Different formulas that have been suggested based on single or double FRP-to-concrete direct pull-out tests were checked for RC beams reinforced in shear with CFRP strips. The test results show that adding internal horizontal steel decreases the gain due to FRP in the tested cases by a large amount. The beams in series with no transverse steel reinforcement (series S_0) has higher stresses in the CFRP than the beams with transverse steel reinforcement (series S_1), but the difference in negligible. However, the contribution of FRP to shear resistance is much higher for beams of series S_0 than for beams of series S_1. Given a stronger beam and the CFRP strip width-to-strip spacing ratio, beams with wider CFRP strips have higher V_f values than beams with narrower strips.

Experiments on the shear strengthening of T-beams were conducted by Belarbi et al. [18] using full-size RC T-beams to better understand the behaviour of full-size bridge beams after being reinforced in shear with FRP. This research focused on the stirrup ratio and the effect of mechanical anchoring methods. The results show that the shear strength of the beams reinforced with FRP is approximately 23% greater than that of the control beam without any mechanical anchorages. Shear strength is improved by as much as 48% when a mechanical anchoring system is used.

Ozden et al. [19] conducted a series of tests using 10 RC T-beams that were intentionally engineered with poor shear strength. This experiment aimed to determine the effectiveness of affixing U-shaped FRP strips to the outside of the structure in enhancing shear performance. The most critical aspects of the research were the FRP material that the strips were made of and the end anchoring that they had. Several different kinds of composite materials were considered, including materials of high elasticity modulus, CFRP, and GFRP. The Hi-CFRP strips were a unique form of material that had a different elastic modulus from other materials. The surface bonding that was used relied on whether the strips were totally glued to the surface of the beam or only partly bonded. Every one of the FRP strips that were only partly connected did not have any surface bonding, but the ends of the strips that were located close to the slab-to-beam connection had epoxy-bonded FRP anchors. Either FRP anchors that are bonded together with epoxy or no anchors at all are located on the ends of the strips that have full surface bonding. The test results show that the design codes for Hi-Mod CFRP need to be modified. The reason is that the estimates of the current codes always overestimate the increase in capacity, and the design codes constantly overestimate the capability for circumstances in which FRP and Hi-Mod CFRP lack anchoring. This condition could result in the use of stress stiffening in ways that are not entirely safe.

Many studies have dealt with the effect of CFRP on the shear or flexural performance of rectangular beams, but few have dealt with T-section beams. Thus, the present study aims to determine the effect of using CFRP on the performance and behaviour of RC T-beams that are made of RC and strengthened with different laminates and U-wrap sheets of CFRP.

2. Research Significance

This research aims to evaluate the effect of CFRP composites on improving the performance of RC T-beams. A programme of experimentation was conducted to determine the response of RC T-beams strengthened for flexural or shear effects. The influence of the CFRP laminate width in the flexural group or the CFRP U-wrap sheet spacing in the shear group on the results. Figure 1 shows a flowchart indicating the methodology of this study.

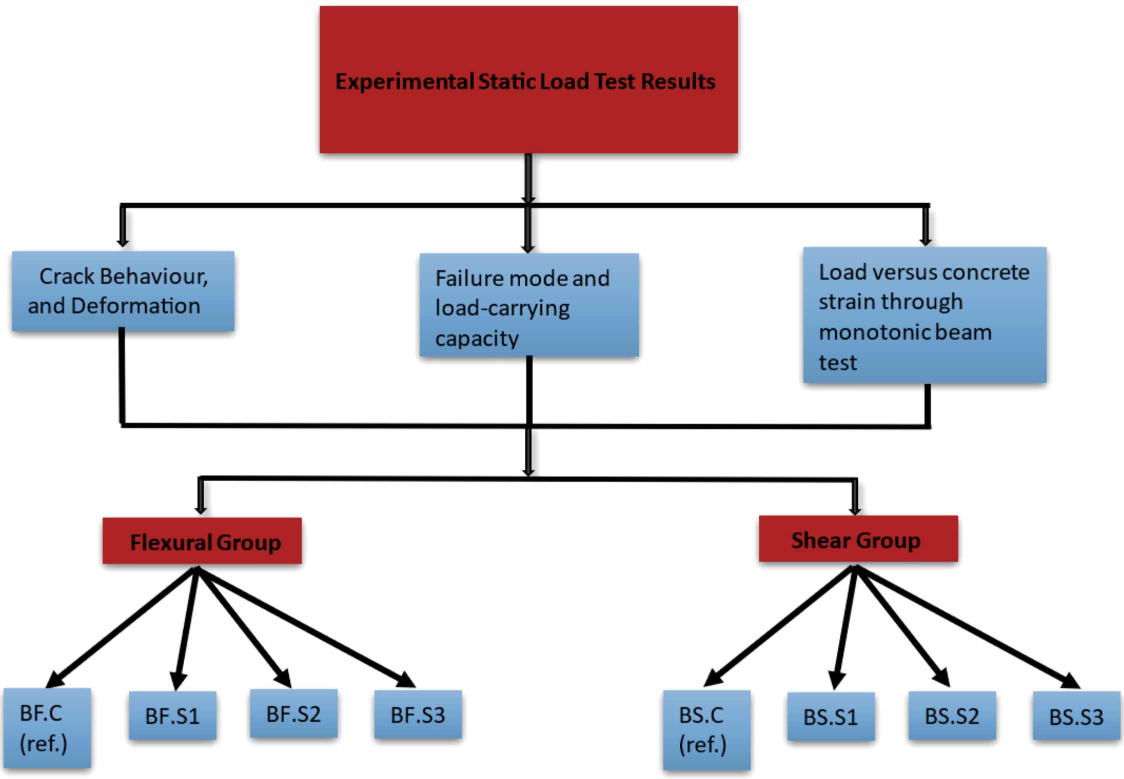


Figure 1. Flowchart of the research methodology

3. Experimental Programme and Material Properties

The experimental programme involved casting and testing eight RC T-beams, which included two reference beams without any strengthening and six strengthened beams. The eight beams were divided into two main groups: a flexural group and a shear group. The main variable chosen in the flexural group was the width of the CFRP laminates, while the spacing of the CFRP U-wrap sheets was considered in the shear group. The beams of each group had the same dimensions and reinforcement, and they were subjected to two-point loads, as shown in Figures 2 and 3. The tested beams were designed in accordance with ACI-318-19 [20] and ACI440-17 [15].

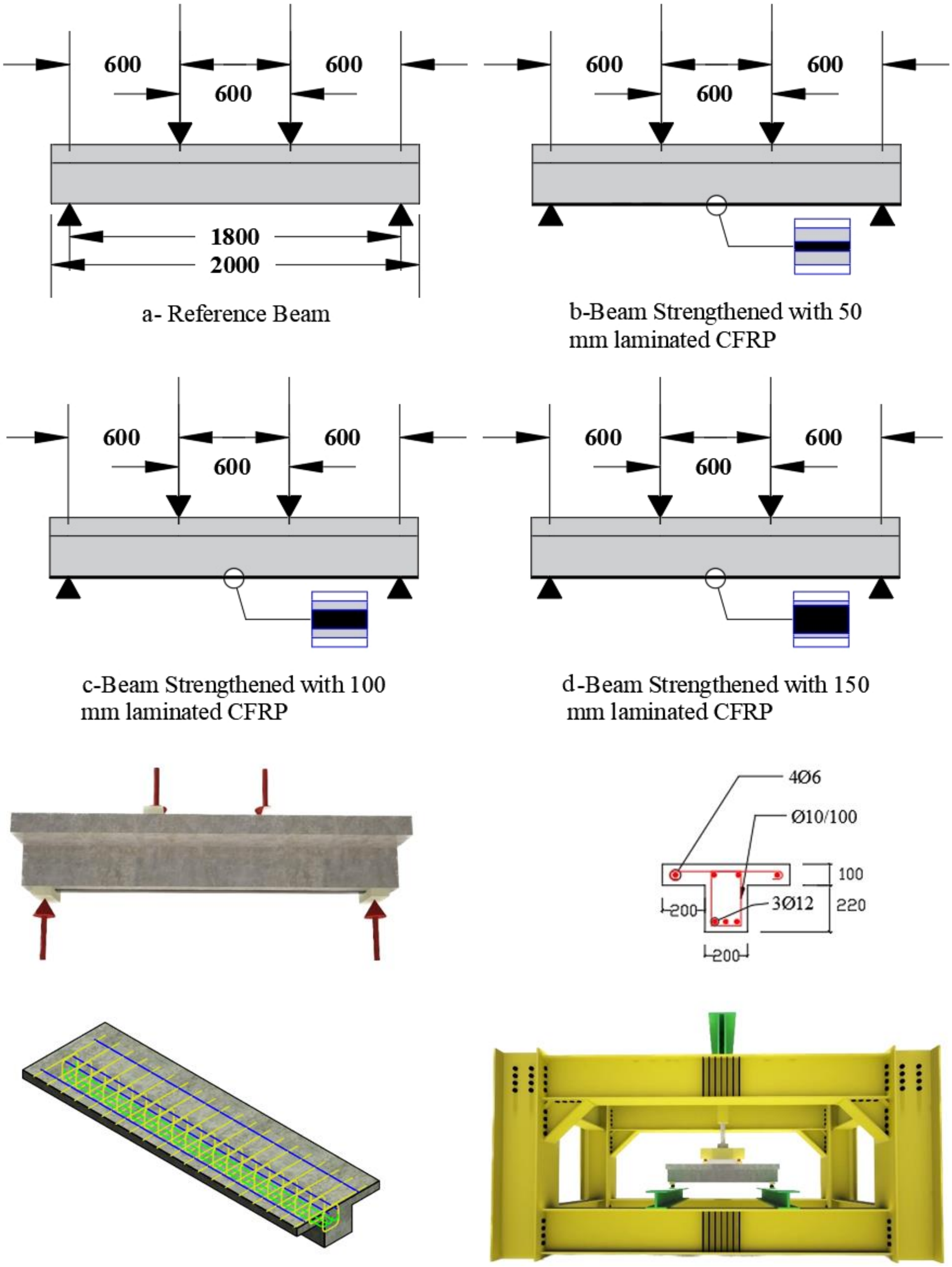


Figure 2. Details of beams in the flexural group (all dimensions are in millimeters)

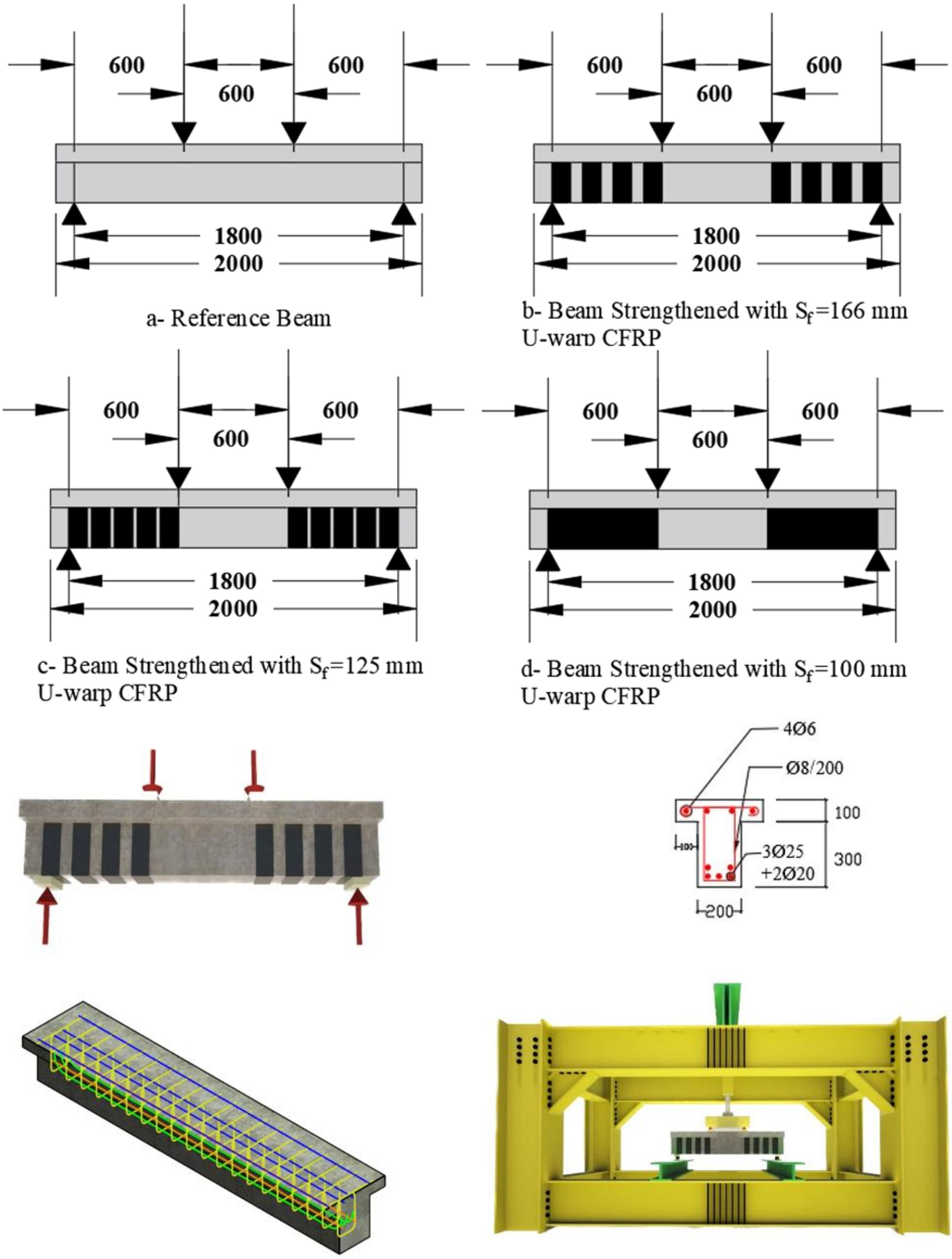


Figure 3. Details of beams in the shear group (all dimensions are in millimeters)

The three strengthened beams in the flexural group were strengthened with CFRP laminate glued to the bottom face of the beam web and to its entire full length with different widths. The three strengthened beams in the shear group were strengthened with CFRP U-wrap sheets with different spacings, as shown in Table 1.

The properties of concrete, such as modulus of elasticity, tensile strengths, and compressive strengths, were calculated using steel cylinder moulds that were 15 cm in diameter and 30 cm in height. Standard bar tests were used to assess the mean yield strength and ultimate strength of reinforcing steel bars with diameters of 8 and 10 mm. The properties of the concrete (after 28 days) and the steel reinforcements employed in this study are detailed in Table 2. Table 3 indicates the sieve analysis of the sand, while Table 4 indicates the coarse aggregate grading used in this study. The characteristics of the CFRP sheets and laminates are shown in Table 5, and the epoxy resin is shown in Table 6.

Table 1. Details of tested samples

Groups	Type of CFRP	Beam	Width of CFRP laminate or sheet (mm)	Spacing of CFRP U-wrap sheet (mm)
Flexural	Laminate	BF.C (ref.)	-	-
	Laminate	BF.S1	50	-
	Laminate	BF.S2	100	-
	Laminate	BF.S3	150	-
Shear	U-wrap sheet	BS.C (ref.)	-	-
	U-wrap sheet	BS.S1	100	166
	U-wrap sheet	BS.S2	100	125
	U-wrap sheet	BS.S3	100	100

Table 2. Properties of materials

Material	Splitting tensile strengths (MPa)	Compressive strength, fcu (MPa)	Yield stresses (MPa)	Ultimate tensile strengths (MPa)	Modulus of elasticity (GPa)
Concrete.	2.9	32.88	-	-	24.4
Steel Ø6 mm	-	-	580	650	200
Steel Ø8 mm	-	-	523	662	200
Steel Ø10 mm	-	-	508.70	647.43	200
Steel Ø12 mm	-	-	470.03	623.3	200
Steel Ø20 mm	-	-	671.61	686.32	200
Steel Ø25 mm	-	-	572.4	724.9	200

Table 3. Sieve analysis (grading) of the used fine aggregate

Sieve size (mm)	Passing % by weight	Limits of the Iraqi Specification No.45/1984 Zone 2
10.0	100	100
4.750	91	90–100
2.360	76	75–100
1.180	63	55–90
0.600	51	35–55
0.300	22.5	8–30
0.15	7.9	0–10

Table 4. Grading of coarse aggregate

Sieve size (mm)	Cumulative passing %	IQS. No.45/1984, Grade 5–20 mm
75	100	-
63	100	-
37.5	100	100
20	95	9-100
14	-	-
10	31	30-60
5	1	0-10
2.36	-	-

Table 5. Mechanical Properties of CFRP

Products name	NitoWrap CWH(300) (CFRP sheet)	Sika® CarboDur®S (CFRP laminate)
Tensile strength (MPa)	4600	3100
Modulus of elasticity (GPa)	240	170
Breaking strain (min.) %	1.4	1.8
Widths (mm)	500	50, 100 or 150
Thicknesses (mm)	0.1670	1.2

Table 6. Mechanical properties of epoxy resin

Products name	Sikadur®-330 (CFRP sheet)	Sikadur-30 Lp (CFRP laminate)
Tensile strength (MPa)	(30 MPa, 7 days)	~17 (7 days, 25 °C)
Modulus of elasticity (GPa)	(4500 MPa, 7 days)	10 (7 days, 25 °C)
Shear strength (MPa)	-	~7 (7 days, 25 °C)
Flexural strength	(60.6 MPa, 7 days)	-
Mixing ratio	1B:4A	1B:3A
Elongation at break	0.9% (7 days)	-

4. Static Load Test Results

4.1. Crack Behaviour and Deformation

Cracks were observed during tests to compare the behaviour of the stronger samples with that of the control T-beams that were not strengthened. For the two groups (flexural and shear), the behaviour of the specimens was compared based on the width of the CFRP laminate for the flexural group and the distance between the CFRP U-wrap sheets for the shear group.

This study also focused on the deformation of the sheets. The cracks that led to the deformation of the sheets are explained in the next subsections. The original loads of all the specimens and their deformations are also shown. The strain spread through the concrete, steel, and CFRP after the steady load test is shown as well.

4.1.1. First Crack Load and Crack Pattern

Table 7 shows the experimental results on cracking and ultimate loads. The initial crack occurs when the load is 40–65 kN with various first crack load (Pcr)/ultimate load (Pu) percentages of approximately 19.8%–22.9% for the beams in the flexural group; in the meantime, the initial crack occurs when the load is 112–157 kN with various first crack load (Pcr)/ultimate load (Pu) percentages of approximately 22%–24.9% for the beams in the shear group, as illustrated in Table 5. Therefore, an increase in the width of external CFRP laminates slightly improves the Pcr/Pu percentage for the flexural group. By contrast, a decrease in the spacing of CFRP sheets slightly increases the Pcr/Pu percentage for the shear group.

Table 7. Cracking loads of all samples

Specimens	Cracked Load (Pcr) (kN)	Deflection at cracked load (δ_{cr}) (mm)	% increase in cracking loads in aspect of Ref. of each group	Ultimate loads (Pu) (kN)	Pcr/Pu (%)
BF.C	40	1.87	Ref.	201.6	19.8
BF.S1	46	1.82	15	220.8	20.8
BF.S2	60	2.197	50	272.7	22
BF.S3	65	2.25	63	284.1	22.9
BS.C	112	5.1	Ref.	510.1	22
BS.S1	133	4.1	19	577.2	23
BS.S2	143	4.01	28	600.3	23.8
BS.S3	157	3.8	40	629.8	24.9

The initial flexural fracture (the maximum moment) occurs in the middle third of the beam when the tensile stresses in the bottom fibre of the concrete exceed the concrete modulus of rupture. Then, cracks begin to appear around the edges of the beam in a direction that is perpendicular to the direction that the support is facing. In some cases, flexural cracking appears and expands on either side of a fracture that has initially been oriented towards the supports. This cracking is observed in situations when the fracture is directed towards the supports. When cracks start to appear along the sides of the beam, the integrity of the compression cord is jeopardised. Except for the cracks found at the ultimate loads and the supports, all the fractures are found in the central third of the beam. Notably, no substantial shear fractures occur. Figures 4 and 5 illustrate the load and deflection of the flexural group at the cracking and final phases, respectively.

The beams strengthened with CFRP lead to a delayed appearance of the first cracks for diagonal and flexural cracks, and diagonal cracks appear before flexural cracks due to the preliminary design of beams that are deemed to fail in shear rather than flexural. Figures 6 and 7 show the load and deflection at the cracking and ultimate stages, respectively, for the shear group.

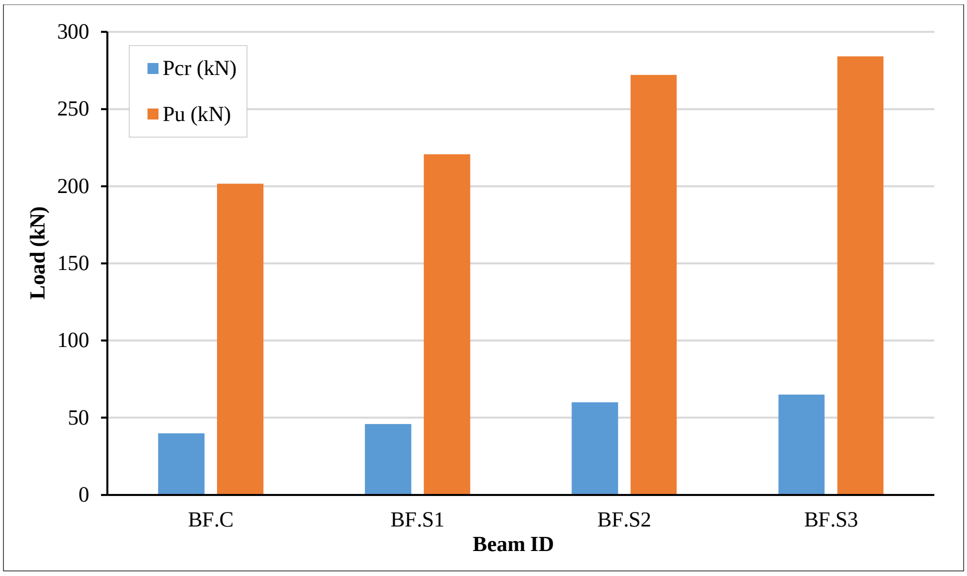


Figure 4. Load at the cracking and ultimate stages for the flexural group

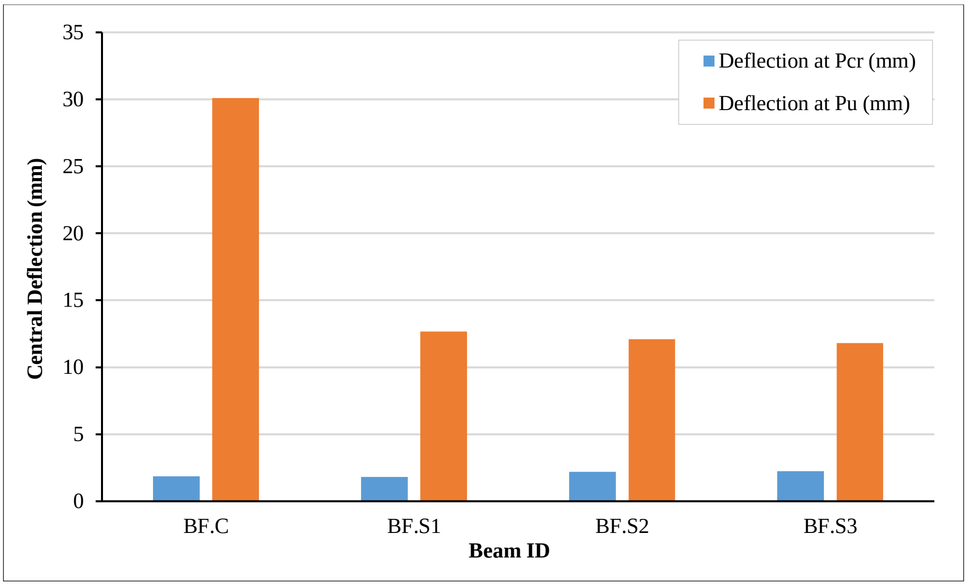


Figure 5. Deflection at the cracking and ultimate loads for the flexural group

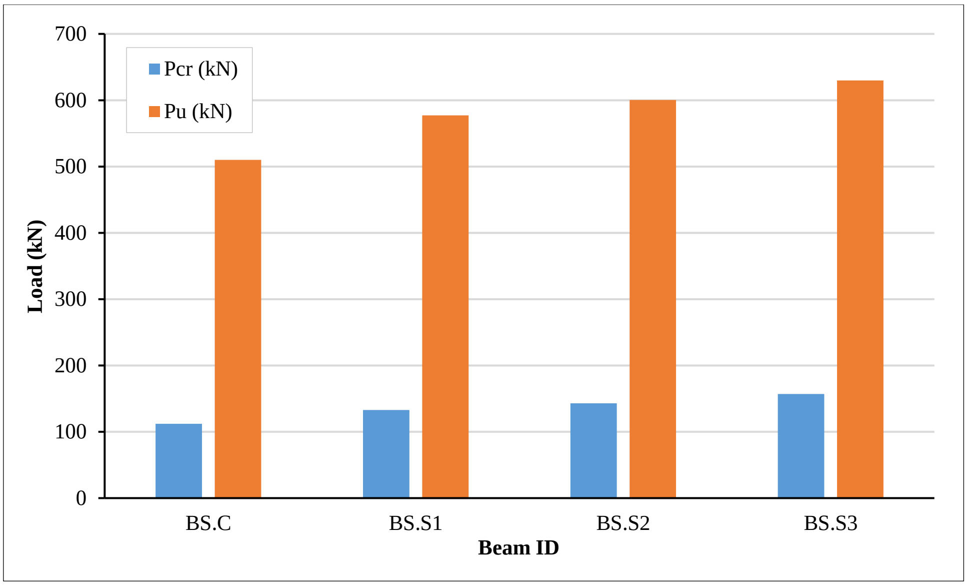


Figure 6. Load at the cracking and ultimate stages for the shear group

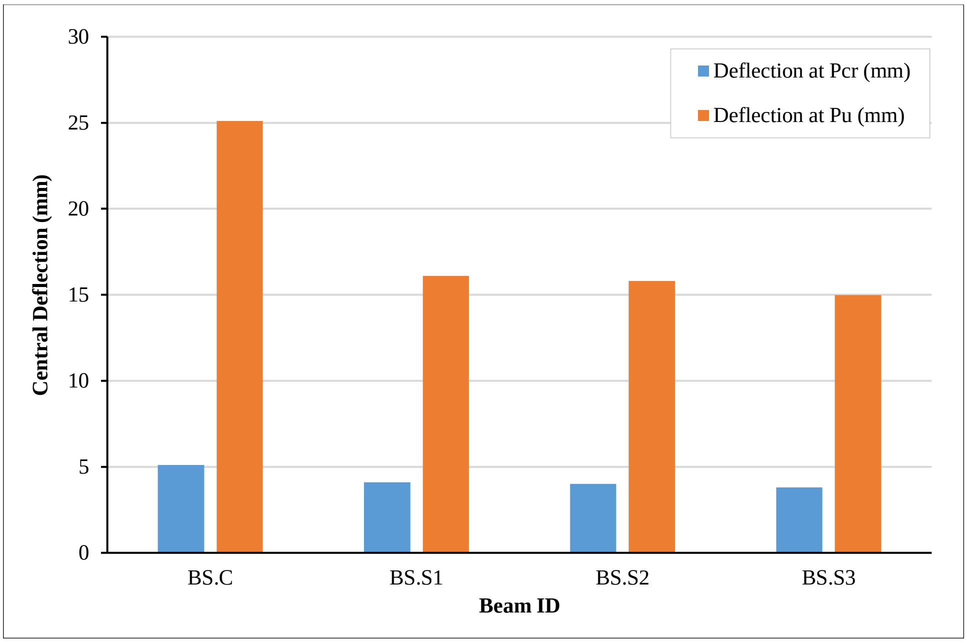


Figure 7. Deflection at the cracking and ultimate loads for the shear group

4.1.2. Deformability of the Examined Beams under Loading

Deformability can refer to the strain in a body, the rotation in a member, and the deflection in an element. Figures 8 and 9 show the relationships between the applied load and mid-span deflection from the start of loading to the failure stage for the T-beams in the flexural and shear groups, respectively. The data shown in the figures conclude at the failure load and associated deflection value given that the load behaviour after the highest point could not be controlled in all examined beams. Several researchers, including Mansur et al. [21], recommended using the experimental ultimate load divided by 1.7 as the serviceability limit due to the lack of undesired cracking or deformation at this value. As a result, Tables 8 and 9 summarise the relevant mid-span deflections of the loading stages of the service load, the ultimate load of the reference beam of the group, and the ultimate applied load for each beam in the flexural and shear groups, respectively. The chosen load of the Pu of the control beam of the group is important to compare deflections at a constant load.

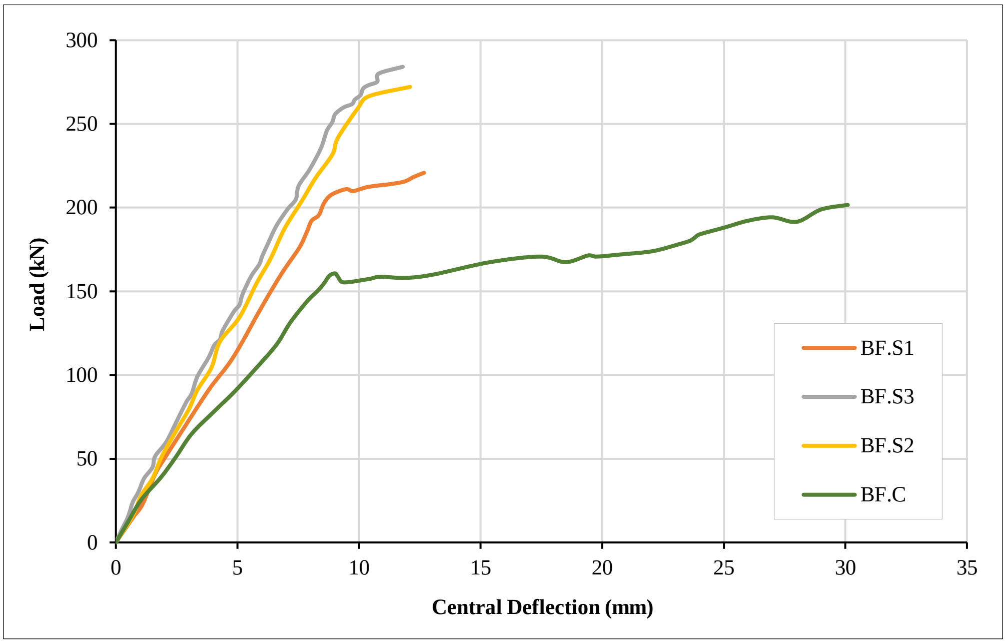


Figure 8. Load–deflection curves of the flexural group

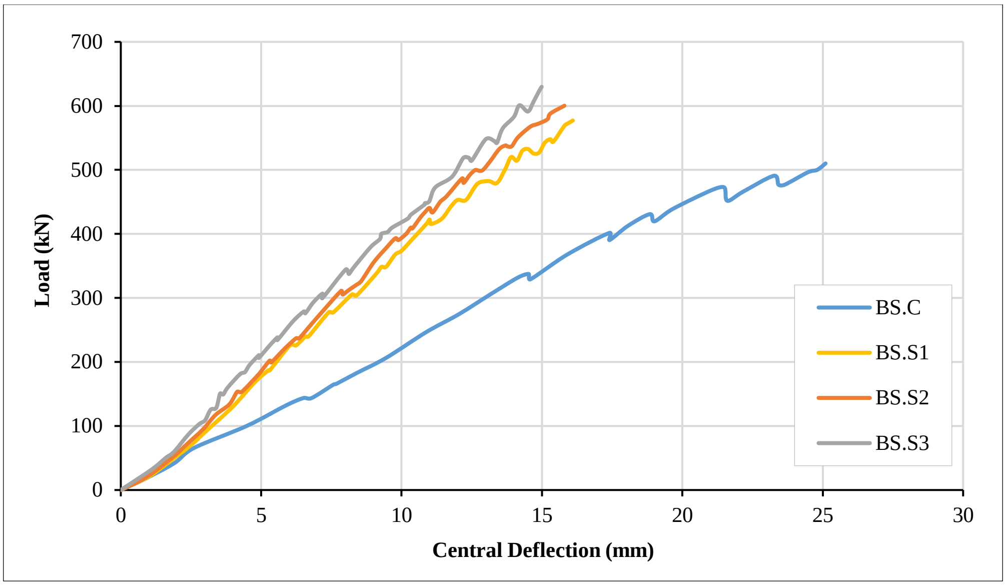


Figure 9. Load–deflection curves of the shear group

Table 8. Load and corresponding deflection for beams in the flexural group at various levels of loading

Beam ID	At service loading Ps kN		At 201.6 kN		At ultimate load		Load of failure P_{ul}, (kN)
	Deflection (mms)	% of decreasing (%)	Deflection (mm)	Percentage of decrease (%)	Deflection (mm)	Percentage of decrease (%)	
BF.C	6.6	—	30.1	—	30.1	—	201.6
BF.S1	5.5	16.7	8.54	71.6	12.67	57.9	220.8
BF.S2	6.1	7.5	7.65	74.6	12.1	59.8	272.1
BF.S3	5.9	10.6	7.1	76.4	11.8	60.8	284.1

Table 9. Load and corresponding deflection for beams in the shear group at various levels of loading

Beam ID	At service loading Ps kN		At 510.1 kN		At ultimate load		Load of failure P_{ul}, (kN)
	Deflection (mm)	Percentage of decrease (%)	Deflection (mm)	Percentage of decrease (%)	Deflection (mm)	Percentage of decrease (%)	
BS.C	13.1	----	25.1	----	25.1	----	510.1
BS.S1	9.16	30	13.8	86	16.1	35.9	577.2
BS.S2	8.98	31.5	13.1	69.5	15.8	37	600.3
BS.S3	8.82	31.7	12	71.7	14.99	40.3	629.8

The starting deflection of each flexural sample is linear. After the cracking load, the samples that are evaluated deflected in a semilinear manner with load; however, the angle at which the lines slope is considerably less steep than it was before the cracking load, and the deflection curves diverge depending on the extent of cracking and stiffness degradation. The angle at which this linear segment is tilted differs for the specimens in each group. When the loads reach the ultimate load, the tested samples deflect in a nonlinear fashion with load, which greatly departs from the deflection curve of the non-strengthened beam.

With regard to the shear group, each tested beam deflects linearly in the opposite direction. The investigated beams continue to deflect in a semilinear manner with load after the cracking load is applied; however, the incline of the lines is significantly similar to the incline before the cracking load, and the deflection curves diverge from each other depending on the level of cracking that is achieved and the degree to which the stiffness of the beam has degraded. The angle at which this linear portion is tilted is not constant across all the specimens that originate from the same group. This case is true for positive and negative angles. When loads are pushed close to the ultimate load, the tested beams begin to deflect approximately nonlinearly with load, which results in deflection curves that are significantly different from the deflection curve of the non-strengthened beam.

At the service load stage, the mid-span deflection decreases by 16.7%, 7.5%, and 10.6% for BF.S1, BF.S2, and BF.S3, respectively, for the flexural group compared with the reference. In the shear group, the mid-span deflection decreases by 30%, 31.5%, and 31.7% for BS.S1, BS.S2, and BS.S3, respectively, compared with the reference.

At the ultimate load of the reference beam (201.6 kN), the mid-span deflection decreases by 71.6%, 74.6%, and 76.4% for BF.S1, BF.S2, and BF.S3, respectively, for the flexural group compared with the reference. In the shear group (510.1 kN), the mid-span deflection decreases by 86%, 69.5%, and 71.7% for BS.S1, BS.S2, and BS.S3, respectively, compared with the reference.

The effect of the width of the CFRP laminate on the load-deflection behaviour at mid-span for the flexural group is illustrated in Figure 7. The results for the beams in the flexural group are compared with those of the reference specimen (without CFRP) in this group. The curves of load deflection show that the elastic portion of the stiffness of all four beams is the same. However, the stiffness of the beam increases in direct proportion to the width of the CFRP laminate after the yielding of the bottom bars. This result supports the findings of Dong et al. [22].

The effect of the spacing of the CFRP sheet on the load-deflection behaviour at mid-span for the shear group is illustrated in Figure 8. The results for the beams in the shear group are compared with those of the reference non-strengthened specimen in this group. The curves show that the four beams have approximately similar stiffnesses in the elastic zone; however, the increasing spacing of the CFRP sheet is inversely proportional to the beam stiffness after diagonal cracking appears. This result supports the findings of Belarbi et al. [18].

The mid-span deflection at P_{ult} decreases by 57.9%, 59.8%, and 60.8% for BF.S1, BF.S2, and BF.S3, respectively, for the flexural group compared with the reference. In the shear group, the mid-span deflection decreases by 35.9%, 37%, and 40.3% for BS.S1, BS.S2, and BS.S3 compared with the reference.

4.2. Failure Mode and Load-Carrying Capacity

The findings of this study show that the failure load is equal to the maximum static load supplied to the beam before it begins to deteriorate significantly and eventually fails.

Notably, only flexural cracks appear in the flexural frames. When the load causes major flexural stresses in the middle of the span, vertical flexural cracks nearly form in the very strong fibres at the bottom of the web section, near the section with the most bending moment. At higher amounts of pressure, the number of vertical flexural cracks grows significantly, as well as their length, the angle of their ends, and the flattening of the flexural cracks (called flexural-shear cracks). In the reference beam (BF.C), failure is caused by cracks that start on the bottom of the T-beam at its strongest point. Given that the steel gives away and then fails in compression at the load point, these cracks move up into the top zone, which is called flexural failure. The bottoms of the beams strengthened with CFRP laminate of 50, 100, and 150 mm widths (BF. S1, BF. S2, and BF. S3) fail because the concrete cover comes off and the CFRP does not stick to it anymore. Failure due to cover removal instead of other, less acceptable ways to fail shows how well the method is used. The reason is that the CFRP has effectively agglutinated to the surface of the concrete.

All tested beams of the shear group failed by shear with diagonal tensile fracture. Shear cracks distributed along the shear span were observed in control and strengthened specimens with CFRP sheets. As the load increased, the shear cracks propagated upward through the flange towards the loading point. The failure of strengthened specimens occurred directly after debonding of the CFRP laminates that intercepted the diagonal shear cracks. Therefore, the yielding of steel stirrups was delayed under higher applied loads with respect to strengthened specimens. Details are shown in Table 10 and Figures 10 to 17.

Table 10. Failure mode of T-beams

Group	Beam ID	Modes of Failure
Flexural	BF.C	Yielding in steel reinforcement preceded by compression failure.
	BF.S1	Disconnection of the concrete cover, and CFRP debonding at the bottom of the beam.
	BF.S2	Disconnection of the concrete cover, and CFRP debonding at the bottom of the beam.
	BF.S3	Disconnection of the concrete cover, and CFRP debonding at the bottom of the beam.
Shear	BS.C	Shear failure with diagonal tensile fracture.
	BS.S1	Shear failure with diagonal tensile fracture occurred directly after debonding of the CFRP laminates that intercepted the diagonal shear cracks.
	BS.S2	Shear failure with diagonal tensile fracture occurred directly after debonding of the CFRP laminates that intercepted the diagonal shear cracks.
	BS.S3	Shear failure with diagonal tensile fracture occurred directly after debonding of the CFRP laminates that intercepted the diagonal shear cracks.

Figure 10. Pattern of cracks in sample BF.C

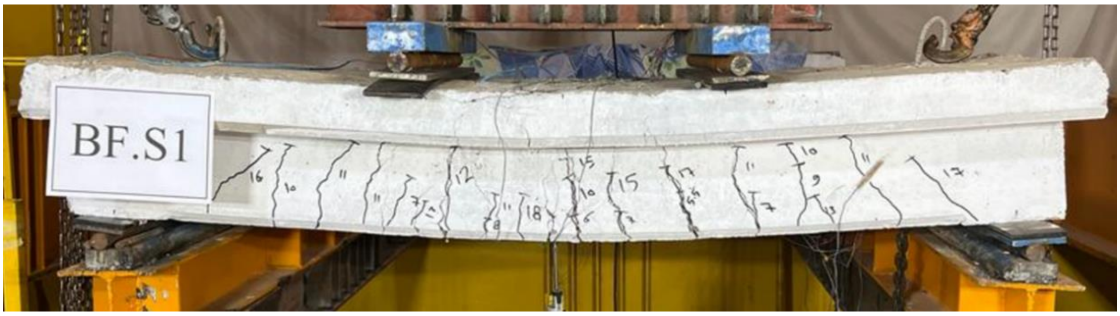


Figure 11. Pattern of cracks in sample BF.S1

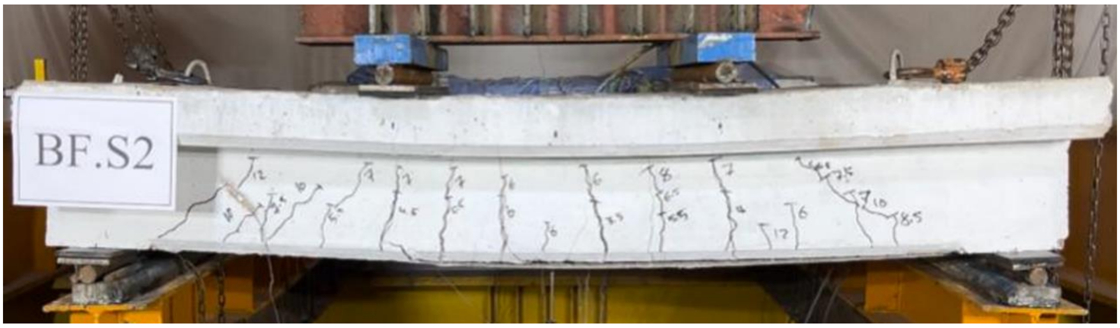


Figure 12. Pattern of cracks in sample BF.S2

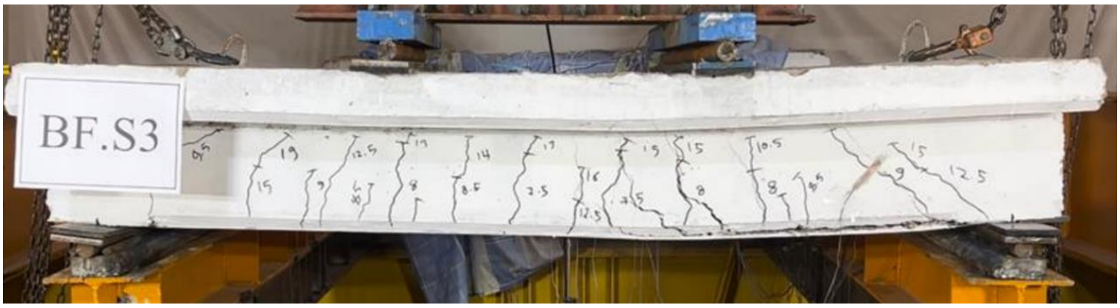


Figure 13. Pattern of cracks in sample BF.S3

Figure 14. Pattern of cracks in sample BS.C

Figure 15. Pattern of cracks in sample BS.S1

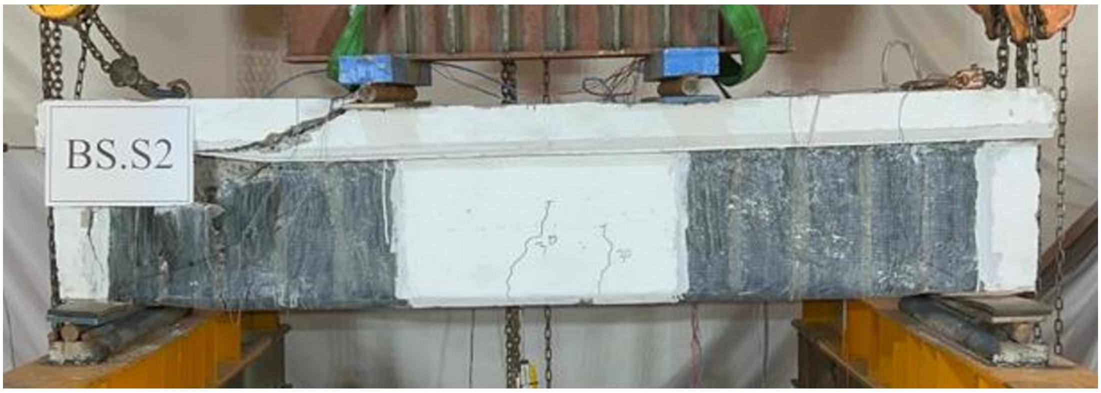


Figure 16. Pattern of cracks in sample BS.S2

Figure 17. Pattern of cracks in sample BS.S3

Table 11 (flexural group) shows that increasing the width of the CFRP laminate improves the ultimate strength by approximately 9.5% for beams with a CFRP width of 50 mm, 35% for beams with a CFRP width of 100 mm, and 41% for beams with a CFRP width of 150 mm. Therefore, the increase in the width of the CFRP laminate is directly proportional to the stiffness of the beam. This result supports the findings of Lee & Moy [23].

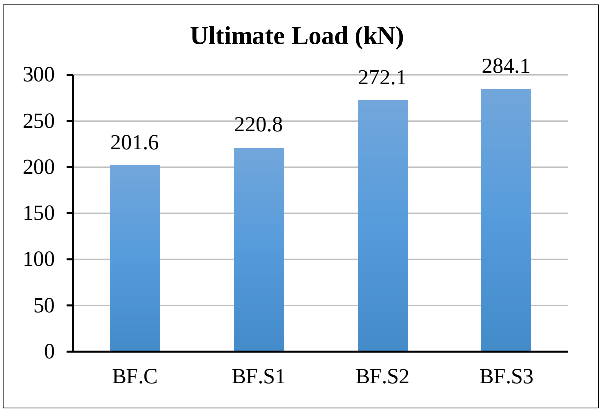
Table 11. Ultimate load for beams in the flexural group

Beam ID	Failure load P_u, (kN)	Percentage of increase in P_u (%)
BF.C	201.6	Ref.
BF.S1	220.8	9.5
BF.S	72.1	35
BF.S3	284.1	41

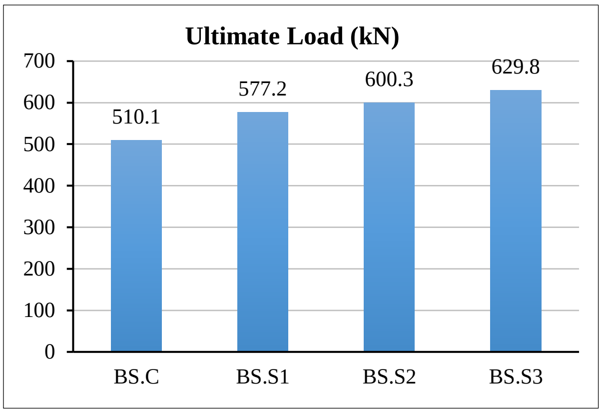
Table 12 (shear group) shows that decreasing the spacing of the CFRP laminate increases the ultimate strength by approximately 13.2% for beams with a CFRP spacing of 166 mm, 17.7% for beams with a CFRP spacing of 125 mm, and 23.5% for beams with a CFRP spacing of 100 mm. Therefore, the spacing of the CFRP sheet is inversely proportional to the stiffness of the beam. This result supports the findings of Alferjani et al. [24]. Figure 18 illustrates comparisons of the ultimate load for all samples.

Table 12. Ultimate load for beams in the shear group

Beam ID	Failure load P_u, (kN)	Percentage of increase in P_u (%)
BF.C	510.1	Ref.
BF.S1	577.2	13.2
BF.S	600.3	17.7
BF.S3	629.8	23.5



a) Flexural group.



b) Shear group.

Figure 18. Ultimate load for all beams

4.3. Load versus Concrete Strain through Monotonic Beam Tests

The surface strain in the concrete was measured along its length at the top mid-span of the T-beam. This spot was selected to study the reaction and flexural or shear behaviour of the RC T-beams comprehensively. PL-60-11-5 L strain gauges were embedded in the concrete at the chosen site to investigate the compression strain at various loading stages. The strain readings were standardised to the midpoint of the existing strain gauge.

Concrete components may crack for various reasons, including water loss, contraction, and weight application. The first kind may be narrowed down to conditions that can be cured. Thus, we ignored the longitudinal tensile stresses. Figures 19 and 20 show the flexural and shear strain groups with a significant rise in longitudinal compression stresses during the entire loading test, respectively.

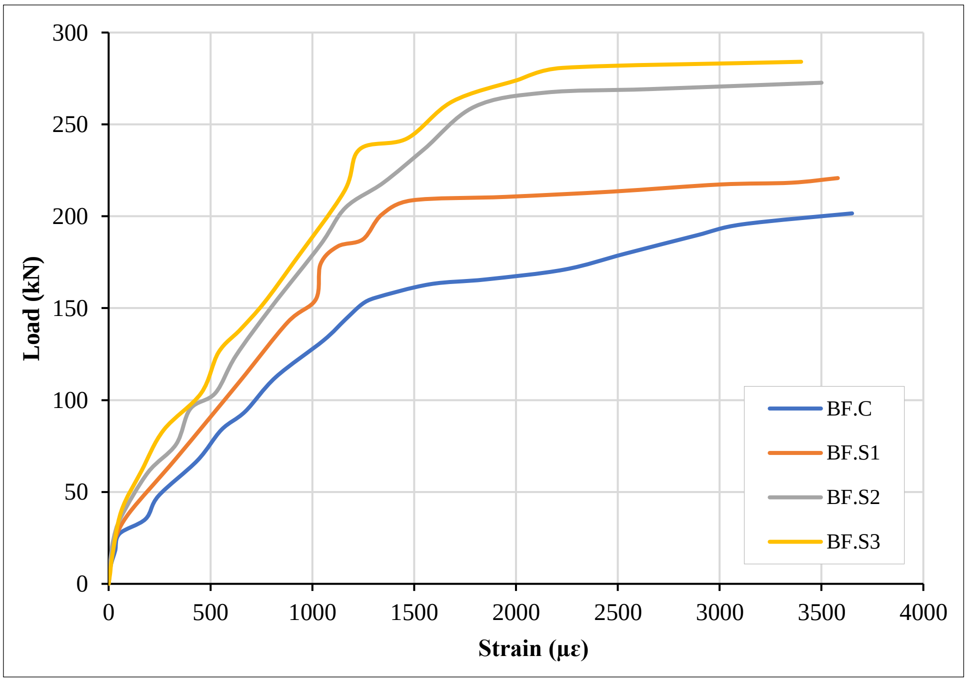


Figure 19. Load vs. compressive concrete strains at the top mid-span of beams in the flexural group

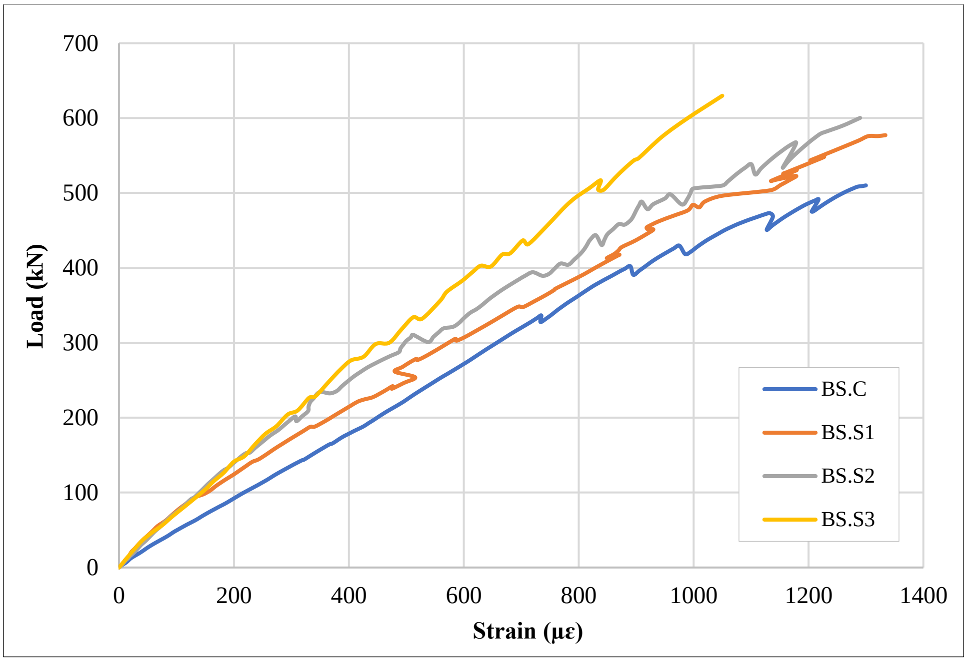


Figure 20. Load vs. compressive concrete strains at the top mid-span of beams in the shear group

At the start of loading until the stage of approximately 40 kN, all samples in the flexural group behave nearly linearly, and the resulting strains are negligible. At a higher loading stage, the control non-strengthened beam exhibits a higher increase in compression strain than the strengthened beams. Increasing the width of the CFRP laminate evidently enhances the stiffness of the beam by reducing the developed strains at the same load level. At the ultimate load, the longitudinal compressive strain in the mid-span of the control non-strengthened beam reaches 3650 με, whereas the other strengthened beams act in different ways lower than that, ranging between 3400 and 3580 με.

All the reinforced samples exhibit essentially linear behaviour for the shear group from the beginning of loading up to the stage of 100 kN, and the resultant stresses are small. The control non-strengthened beam shows a greater rise in compression strain than the strengthened beams at a higher loading stage. By minimising the generated stresses at a given load level, increasing the gap between the CFRP sheets manifests as increased beam stiffness. The mid-span longitudinal compressive strain approaches 1300 με at the maximum load for the control non-strengthened beam, whereas it remains below the range of 1050–1333 με for the reinforced beams.

Table 13 illustrates that the percentage reductions in the concrete strains at the top mid-span are 63%, 68%, and 71% for beams BF.S1, BF.S2, and BF.S3, respectively, in the flexural group compared with the beam BF.C (reference). Table 14 illustrates that the percentage reductions in the concrete strains at the top mid-span are 12%, 19%, and 35% for beams BS.S1, BS.S2, and BS.S3, respectively, in the shear group compared with beam BS.C (reference).

Table 13. Effect of the width of the CFRP laminate on the compressive concrete strains at the top mid-span for beams in the flexural group

Group	Beam ID	Longitudinal compressive concrete strains at the top mid-span- ε_c at 201.6 kN (με)	Reducing in strains in ε_c (%)
Flexural	BF.C	3650	Ref.
	BF.S1	1341	63
	BF.S2	1160	68
	BF.S3	1070	71

Table 14. Effect of the spacing of CFRP sheets on the compressive concrete strains at the top mid-span for beams in the shear group

Group	Beam ID	Longitudinal compressive concrete strains at the top mid-span- ε_c at 510.1 kN (με)	Reducing in strains in ε_c (%)
Shear	BS.C	1300	Ref.
	BS.S1	1151	12
	BS.S2	1050	18
	BS.S3	850	35

5. Conclusions

- The beams in the flexural group crack under the applied load of 40–65 kN with a first crack load (Pcr)/ultimate load (Pu) percentage of 19.8%–22.9%. The first cracks of the beams in the shear group occur at the applied load of 112–157 kN, with a first crack load (Pcr)/ultimate load (Pu) percentage of 22%–24.9%.
- The beams strengthened with CFRP led to a delayed appearance of the first cracks for diagonal and flexural cracks. In the shear group, diagonal cracks appear before flexural cracks due to the preliminary design of beams that are deemed to fail in shear rather than flexure.
- At the service load stage, the mid-span deflection decreases by 16.7%, 7.5%, and 10.6% for beams with CFRP laminate widths of 50, 100, and 150 mm, respectively, in the flexural group compared with the reference non-strengthened beam. In the shear group, the mid-span deflection decreases by 30%, 31.5%, and 31.7% for beams with CFRP U-wrap sheet spacings of 166, 125, and 100 mm, respectively, compared with the reference non-strengthened beam.
- In the flexural group, increasing the width of the CFRP laminate improves the ultimate strengths by approximately 9.5%, 35%, and 41% for beams with CFRP laminate widths of 50, 100, and 150 mm, respectively, compared with the reference non-strengthened beam. Therefore, the stiffness of the beams increases in direct proportion to the width of the CFRP laminate.
- In the shear group, decreasing the spacing of the CFRP laminate increases the ultimate strength by approximately 13.2%, 17.7%, and 23.5% for beams with CFRP U-wrap sheet spacings of 166, 125, and 100 mm, respectively, compared with the reference non-strengthened beam. Therefore, the spacing of the CFRP sheet is inversely proportional to the stiffness of the beam.
- The reference non-strengthened beam in the flexural group fails with yielding in steel reinforcement preceded by compression failure, while all the strengthened beams in this group fail with the delamination of the concrete cover and CFRP debonding at the bottom part of the beam.
- The reference non-strengthened beam in the shear group fails with shear failure of a diagonal tensile fracture. In the meantime, all the strengthened beams in this group fail with shear failure from diagonal tensile cracking that occurs directly after debonding of the CFRP laminates that intercept the diagonal shear cracks.
- On the basis of the results, the following directions are suggested for future research:
    a) The performance of RC T-beams with CFRP can be studied under dynamic and impact loads.
    b) The performance of RC T-beams with CFRP can be investigated under fire effects.
    c) The performance of RC T-beams with CFRP can be explored under repeated loads.

6. Declarations

6.1. Author Contributions

H.E.A and A.H.A. contributed to the design and implementation of the research, to the analysis of the results and to the writing of the manuscript. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

6.3. Funding

The authors received no financial support for the research, authorship and/or publication of this article.

6.4. Conflicts of Interest

The authors declare no conflict of interest.

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