

Research Article

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Flexural behavior of RC beams externally reinforced with CFRP composites using various strategies

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Abstract: The external composite material bonding is an effective and practical method for flexural strengthening of reinforced concrete (RC) beams, providing a large opportunity to develop high-performance and cost-effective structures. Numerous uses exist for carbon fiber-reinforced polymer (CFRP) materials as RC-member strengthening methods. However, issues with bonding and de-bonding continue to be a barrier to this technique's accomplishment. In this research, the CFRP sheets were integrated as an external strengthening material to evaluate their contribution to the flexural performance and so determine how well the CFRP sheets are being used. The experimental work includes one control beam and ten RC beams with CFRP sheets as external strengthening. All beams have the same dimensions: a length of 1.7 m and a sectional area of 20 cm × 25 cm. Experimental tests were carried out with varying CFRP types, lengths, numbers, and arrangements. Each beam's performance was evaluated in terms of failure mode, ultimate load capacity, ultimate deflection, and a load–deflection curve. The findings demonstrate the effectiveness of CFRP strengthening by demonstrating a considerable improvement in the majority of the study variables. Furthermore, the CFRP strengthening offered an exterior crack-arresting mechanism.

Keywords: flexural behavior, reinforced concrete, composite material, carbon fiber-reinforced polymer

1 Introduction

Many degraded reinforced concrete (RC) structures around the world require reinforcement for a variety of reasons, including their expired design life, probable damage from environmental effects and mechanical activities, extra stringent design requirements, changes in functionality, and initial design and construction mistakes. Several approaches for strengthening concrete members were created based on previous research and design practice, including the use of external bonding of plates, which is helpful for flexural components of the structure. Externally fiber-reinforced polymer (FRP) sheets are becoming more popular in strengthening structures due to their numerous advantages, such as the high ultimate strength of FRP, high elastic modulus, corrosion resistance, a low mass-to-inertia ratio, and a high strength/weight ratio, and a shorter installation time. This is especially true when utilized for complicated-shaped structural elements.

Aramid, glass, and carbon fibers are the most commonly used. Aramid fiber-reinforced polymer (AFRP) and glass fiber-reinforced polymer (GFRP) members are significantly more ductile than carbon fiber-reinforced polymer (CFRP) members. Numerous studies have been made to increase the strength, durability, and stiffness of RC beams reinforced with GFRP and CFRP. In a typical flexural strengthening procedure to increase flexural capacity, FRP is applied longitudinally along the beam axis [1,2].

2 Background

CFRP sheets are now widely used as a strengthening technique for RC members such as columns, beams, beam–column connections, and slabs [3].

Numerous studies have been conducted on the feasibility of using FRP materials to strengthen various structural members; where Attari et al. [4] examined the efficiency of using the external FRP composite as a strengthening

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technique for RC beams. Seven RC beams strengthened with CFRP or GFRP were applied to two-point loads until failure is analyzed. Beams' failure modes, strength, ductility, and stiffness are discussed for many strengthening parameters. In addition, a finite element model for predicting the flexural failure of the beams is used; it accurately predicts the beams' behavior under the applied loads. The study also indicated that the use of two layers of GFRP is cost-effective as a strengthening arrangement for RC structures.

Górski *et al.* [5] discussed the results of mechanical testing on the strengthening of structures. Utilizing the conductivity of carbon fibers, smart textiles may measure strains while monitoring changes in electrical resistance as a result of increasing loads. Also, the primary experiments were conducted on a natural-scale RC beam with carbon fiber-reinforced fabric. The effectiveness of smart textiles was demonstrated in both strengthening and strain monitoring as the load increased.

Kuntal *et al.* [6] revealed that the beams' ductility and stiffness can be significantly increased by applying the right arrangement for the near-surface mounted (NSM) strips. Jadooe *et al.* [7] investigated the flexural behavior of eight RC beams with sheets of CFRP after heating. The study showed that repairing with the CFRP laminate by using NSM systems with cement-or-epoxy-based notches created into the surface of concrete increased the beams' stiffness and load capacity. The finite-element method was used in this study, and they were capable of predicting the experimental behavior reasonably well.

Obaidat *et al.* [8] extended the CFRP composites to concrete columns using fillets and chamfers placed at the beam-column intersection to study the structural behavior of cantilever beams. Fourteen beam-column intersections were tested after bonding CFRP sheets only along the beam's tension zone or extending the CFRP elements to the column surface by making fillets and chamfers at the intersection of the beam-column. The length, width, and layer number of CFRP sheets, and the use of concrete fillets and chamfers all influenced the mechanical behavior of the studied beams. End anchorage with U-shape CFRP composites helped delay the de-bonding of the CFRP sheets and subsequently improved mechanical behavior, particularly for cantilever beams repaired with CFRP extended to the columns' surfaces.

Amaireh *et al.* [9] demonstrated the efficacy of CFRP strips as primary or secondary shear reinforcement for RC beams. The CFRP strips perform the same function as the steel stirrups in conjunction with the concrete and steel reinforcement. The studied variables consist of layer number and the area of CFRP strips. The findings demonstrate that

CFRP elements can be successfully used in RC beams as internal shear reinforcement. By adding just one 5 cm CFRP strip to the beam sides, the maximum shear strength was increased by 30%; when the shear span was completely reinforced with CFRP strips, the shear capacity was roughly doubled.

Zaki and Rasheed [10] investigated the efficiency of reinforcing six RC beams with four layers of flexural CFRP plus longitudinal GFRP sidebars or side patches to anchor the flexural CFRP sheets used to strengthen RC beams. Three of the six beams have rectangular cross-sections, while the other has a T-cross-section. All beams were applied to two-point loads till failure, and the findings demonstrated that employing CFRP sheets increased the beams' flexural capacity. The same conclusions were reached when compared to the results of U-wrap anchored samples from other research. Shomali *et al.* [11] used the NSM method to examine the RC beams' behavior; the beams designed with and without stirrups strengthened in shear. The beams were under two-point loads, and the failure modes, as well as the load-deflection curves, were discussed. The study indicates that the use of CFRP composites leads to improvement of beams' shear capacity, and the failure occurs because of the rupture of CFRP. Furthermore, when NSM-strengthened beams were compared to reference beams, the ductility decreased for all strengthened beams. Moreover, the stiffness of the strengthened beams with a stirrup was higher than those without a stirrup. The finite element method revealed that the possibility of de-bonding decreases as the concrete strength decreases, and the ultimate strain in CFRP composite reduces when the amount of shear reinforcement increases.

Hassan *et al.* [12] examined the flexural effectiveness of beams with GFRP reinforcement and CFRP strengthening. Ten GFRP-RC beams have been outfitted and applied to two concentrated loads. The parameters studied were the GFRP reinforcement ratio and the CFRP sheet numbers. The mid-deflection, concrete strains, and size of the beam cracks were measured and compared. The results showed that the mid-deflection and size of cracks were decreased by raising the ratio of GFRP reinforcement and CFRP layer number. Al-Rousan *et al.* [13] used the CFRP sheet as a longitudinal reinforcement for concrete elements. The objective was to evaluate the CFRP sheet's contribution to flexural performance in order to determine whether utilizing it as primary or supplementary longitudinal reinforcement is effective. The studied parameters are the CFRP sheet length, CFRP layer number, and strengthening type. The beams' performance was checked for the maximum load capacity, stiffness, maximum deflection, load-deflection curve, failure mode, ductility index, energy absorption,

CFRP strain, and performance factor. The results demonstrate the effectiveness of internal strengthening by demonstrating considerable incensement in the majority of the tested parameters. Internal strengthening creates an external crack-arresting technique, even after having reached the maximum load capacity. Sukanto et al. [14] reviewed different kinds of epoxy and curing methods that are frequently used as composite matrices. The results show that these materials nowadays play a significant role in research, design, production, and recycling.

This research aims to assess the usefulness and impact of CFRP strengthening on the flexural behavior of RC beams. Eleven RC beams with various variables, such as the type, length, and arrangement of CFRP, were constructed and examined under four-point loads.

3 Experimental program

3.1 Description of materials

3.1.1 Concrete

All of the specimens were built with the same concrete mix (1:1.8:2.7 by weight) for cement, fine, and coarse aggregate, with a water-to-cement ratio of 0.47. The maximum size of aggregate used was 20 mm; also, a superplasticizer material has been used as a percentage of the weight of cement in order to enhance the concrete workability. The compressive

strength of concrete was 36 MPa; it was measured based on the BS EN 12390-3:2019 by using 100 mm × 200 mm cylinders. The slump of the concrete mixture was 80 mm [15]. The average splitting tensile strength of concrete at 28 days was 2.6 MPa measured by 100 mm × 200 mm cylinders based on ASTM C496/C496M-17 [16]. The average concrete modulus of rupture was 4.1 MPa. According to ACI 318-14 [17], the reinforcement steel bars were N10 and N16 for strips and longitudinal reinforcement, respectively, and their properties are shown in Table 1.

3.1.2 Strengthening materials

The use of FRP as an externally bonded systems have received a great deal of attention in recent decades. It can be used to strengthen and repair existing RC structures. Full bonding is typically assumed between the FRP materials and the attached surface of the beams during the design and analysis processes. In contrast, the ideal bond is based on the adhesive shear stiffness [18]. Most structural resin adhesives can achieve excellent bond characteristics. Some epoxy resins, in contrast, have low shear stiffness, which leads to bond slip between the concrete substrate and the FRP material, reducing composite action [1,2]. When the beam was 28 days old, the process of strengthening began, with two types of strengthening used.

- As shown in Figure 1, a CFRP composite consists of woven carbon fabric (SikaWrap®-300 C) and an epoxy agent (Sikadur®-330 LP). SikaWrap®-300 C is a mid-range

Table 1: Reinforcement properties

Steel bar diameter(mm)	Modulus of elasticity (GPa)	Ultimate strength (MPa)	Yield strength (MPa)
10	199.7	635	490
16	199.9	680	510



a unidirectional woven carbon fiber



Sikadur®-30 LP

Figure 1: Strengthening material.

Table 2: Properties of SikaWrap®-300C

Density (g/cm ³)	Thickness (mm)	Width (mm)	Elongation at break (%)	Tensile strength (MPa)	Modulus of elasticity (MPa)
1.82	0.167	500	1.7	4,000	230,000

Table 3: Properties of epoxy resin (Sikadur®-330LP)

Density (kg/l)	Tensile strength (N/mm ²)	Modulus of elasticity (MPa)	Elongation at break (%)
1.3	30	3,800	0.9



Carbon fiber plate



Sikadur 30 LP

Figure 2: Strengthening material.**Table 4:** Properties of carbon fiber (Sika CarboDur, Type S 1012)

Density (g/cm ³)	Thickness (mm)	Width (mm)	Modulus of elasticity (MPa)	Tensile strength (MPa)	Elongation at break (%)
1.60	1.2	100	160,000	2,800	1.69

strength unidirectional woven carbon fabric that can be installed using either a wet or dry application process. Strengthens RC, masonry, brickwork, and timber elements to improve shear and flexural capacity. The CFRP and epoxy properties, which are provided by the manufacturer, are shown in Tables 2 and 3.

- Figure 2 shows a CFRP composite consisting of a carbon fabric plate (Sika CarboDur) and an epoxy agent (Sikadur®-30 LP). A pultruded CFRP laminate (Sika CarboDur) is

intended to strengthen concrete, masonry, and wood structures. The CFRP plate was attached to the structure using epoxy resin (Sikadur 30 LP) as the adhesive. The CFRP and the epoxy properties are listed in Tables 4 and 5.

3.2 Specimen details

Eleven simply supported RC beams under four-point loads were used in the experimental work to find the efficacy of CFRP elements as a strengthening member. Plywood sheets were created and produced for the beams so as to utilize the precision of the specifications and a high-quality concrete surface finish. The experimental beams measured (250 × 200) mm in cross-section and 1,700 mm in length. Longitudinal reinforcement was included for all beams in

Table 5: Properties of epoxy resin (Sikadur®-30LP)

Density (kg/l)	Tensile strength (MPa)	Modulus of elasticity (MPa)
1.65	25	10,000

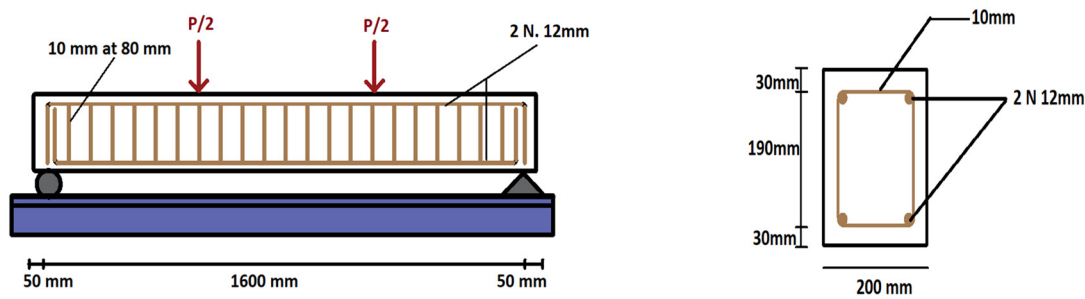


Figure 3: Specimen details and concrete beam preparation.

the form of two N12 bars at the compression and tension surfaces of the beams. Shear-reinforced N10 stirrups were designed to be spaced 80 mm apart along the length of the beams to work in conjunction with CFRP strengthening to resist flexural failure. For all concrete beams, steel reinforcement was embedded into the formwork and supported by the bottom and web concrete cover spacers to achieve the desired cover. Figure 3 depicts the beam dimensions and reinforcing details. The parameters examined were the CFRP layer number of one, two, and three, the CFRP length of 750, 1,000, and 1,500 mm, the CFRP plate width of 100 and 200 mm, the CFRP type of woven and plate, and finally, the arrangement of CFRP as shown in Figures 6–10.

3.3 Application and layout of CFRP to beams

Ten of the simply supported beams were cast and strengthened with two types of CFRPs; they were classified into five groups (A, B, C, D, and E) depending on the CFRP arrangement as summarized in Table 6 and Figure 4. One of the beams was used as a control member (T), and the others

with CFRP were strengthened in flexure by using various anchorage arrangements as discussed in Sections 3.3.1–3.3.5. Depending on the studied case, the CFRP was trimmed to the appropriate width and length. For each beam, first, the beams were cast and left for 28 days. The bonding region of the beams was cleaned by an air vacuum cleaner in order to eliminate any undesired particles. Finally, a uniform epoxy layer was put over the contact zone, and the CFRP was set on top of the epoxy. The strengthened beams were left at room temperature for 7 days, based on the manufacturer's instructions for curing and hardening the epoxy before use. Figure 5 shows the beam through the surface preparation.

3.3.1 Specimens T-W-1L-75, T-W-1L-100, and T-W-1L-100

Beams (T-W-1L-75), (T-W-1L-100), and (T-W-1L-150) were strengthened with a single layer of unidirectional CFRP (SikaWrap®-300 C). Table 6 shows that the CFRP woven was cut into sheets that were 200 mm wide and varied in lengths by 750, 1,000, and 1,500 mm, and they were attached to the tension face of the beam only (Figure 6).

Table 6: Dimension details of the specimens

Beam designation	Group	No. of CFRP layers	Type of CFRP	Length of CFRP (cm)	Width of CFRP (mm)	Side no. of strengthening
Control (T)		—	—	—	—	—
T-W-1L-75	A	1	W	75	200	Bottom side
T-W-1L-100		1	W	100	200	Bottom side
T-W-1L-150		1	W	150	200	Bottom side
T-W-1L-150	B	1	W	150	200	Bottom side
T-W-2L		2	W	150	200	Bottom side
T-W-3L		3	W	150	200	Bottom side
T-W-1L-150	C	1	W	150	200	Bottom side
T-W-U-150		1	W	150	700	Three sides (U-shape)
T-P-1L	D	1	Plate	150	100	Bottom side
T-P-2L		1	Plate	150	200	Bottom side
T-W-R	E	1	Woven			At the bottom and around the ends of the beam

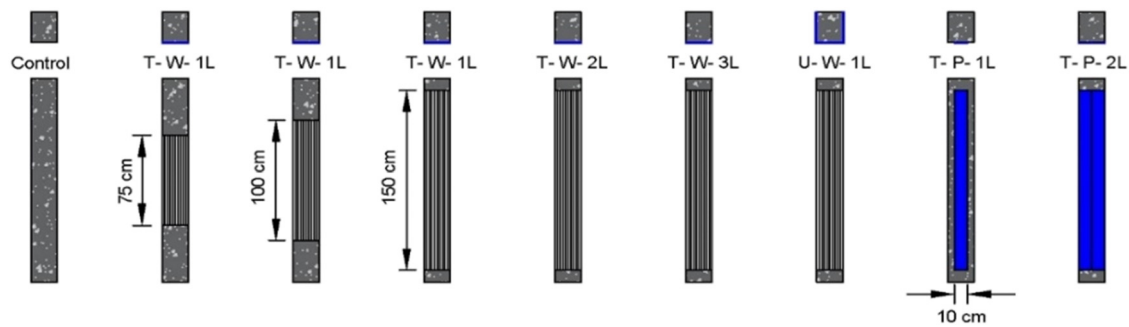


Figure 4: Beams' details.



Figure 5: Surface preparation for the tested beams.

3.3.2 Specimens T-W-1L-150, T-W-2L, and T-W-3L

Beams T-W-1L-150, T-W-2L, and T-W-3L were fortified in flexure with different CFRP wrap layers. However, the design for those three beams involved using one, two,

and three CFRP wrap layers, respectively. Table 6 shows that the CFRP woven was cut into sections with dimensions of 200 mm × 1,500 mm. After roughening and cleaning the concrete-bonded region with an air vacuum cleaner, the initial epoxy layer was uniformly settled over the contact zone, and the CFRP woven was laid on top of the epoxy. For beams T-W-2L and T-W-3L, the second epoxy layer was put over the first layer of CFRP woven with a uniform distribution before applying the other CFRP woven layers (Figure 7). The CFRP wraps of these beams were placed at the bottom face only.

3.3.3 Specimen T-W-U-150

The T-W-U-150 beam was strengthened with a single layer of unidirectional CFRP wrap with a length of 1,500 mm attached to the bottom and to the two side faces of the beam as a U-shape (Figure 8).

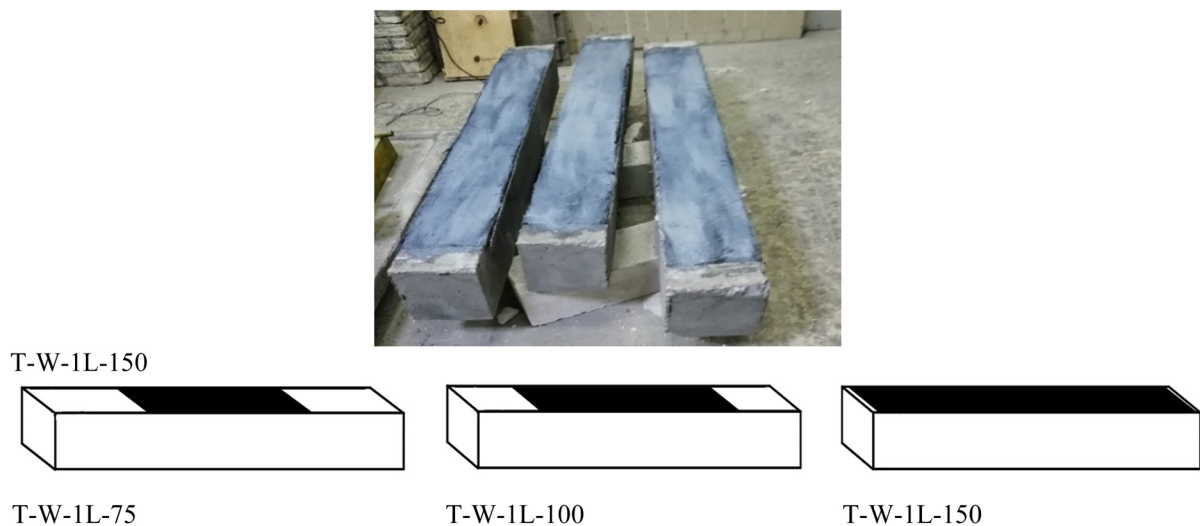


Figure 6: Beams with various CFRP lengths.

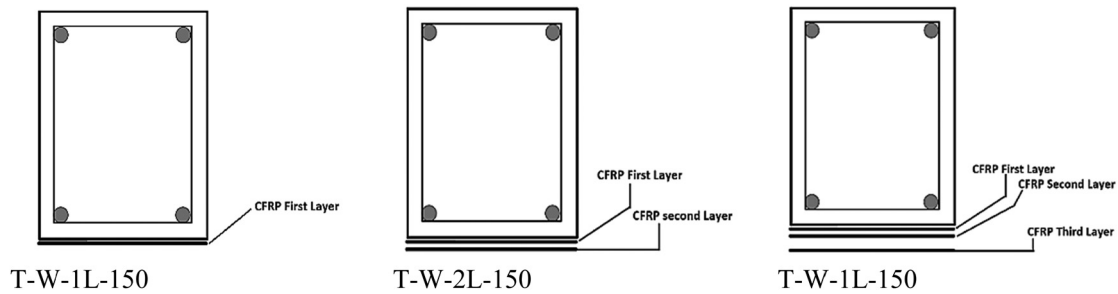


Figure 7: Beams with different numbers of CFRP layers.

3.3.4 Specimens T-P-1L and T-P-2L

Beams T-P-1L and T-P-2L were strengthened with CFRP plates in the flexure area. The design for beam T-P-1L consisted of using one standard CFRP plate with a 100 mm width and 1.5 m length, while the T-P-2L beam involved using two standard CFRP plates (Figure 9).



Figure 8: Beam with U-shape of CFRP woven.



Figure 9: Beam with CFRP plates for group D.

3.3.5 Specimen T-W-R

Beam T-W-R was strengthened with CFRP wrap in the flexure area. The design for beam T-W-R consisted of a CFRP woven wrap around the beam ends with a width of 300 mm (Figure 10).

4 Results and discussion

The experimental results were discussed with respect to load–deflection behavior, improvement of performance, and failure mode. All beams were subjected to two concentrated loads by a testing machine with a load capacity of 500 kN, as shown in Figure 11. The load was put on with a



Figure 10: Beam with CFRP composites at the bottom and the ends.



Figure 11: Testing machine of the simply supported beam.

Table 7: Summary of the beam results

Specimen designation	Max. load (kN)	Increase of max. load (Ti – T0)/T0 (%)	Max. def. (mm)	Increase of max Def. (Ti – T0)/T0 (%)	Failure mode
Control (T)	110	—	14	—	Concrete crashing
T-W-1L-75	127.5	15.9	10.69	23.6	Delaminating of CFRP
T-W-1L-100	135	22.7	9.04	35.4	Delaminating of CFRP
T-W-1L-150	139	26.4	10.62	24.1	Delaminating of CFRP
T-W-2L	150	36.4	9.27	33.8	Delaminating of CFRP
T-W-3L	160	45.5	8.2	41.4	Delaminating of CFRP
T-W-U-150	155	40.9	10.79	22.9	CFRP rupture
T-P-1L	143	30	8.88	36.57	Delaminating of CFRP
T-P-2L	157	42.7	9.6	31.4	Delaminating of CFRP
T-W-R	160	45.5	11.06	21	Delaminating of CFRP

constant increment of 5 kN per minute until the beam failed, at which point the ultimate load was measured. The ultimate deflections were also measured using a least count located in the beams' mid-span. Table 7 shows an overview of the experimental data.

4.1 Load–deflection

Table 7 summarizes the beams' flexural behavior in relation to the ultimate loading capacity and related mid-deflection. Where the increase in ultimate loads ranged from 15.9 to 26.4% and 26.4 to 45.5%, respectively, based on the various strengthening lengths and layer numbers of CFRP sheets. CFRP woven in a U-shape raises the ultimate load by 40.9%. Furthermore, the use of CFRP plates increases the ultimate load from 30 to 42.7%, and finally, the use of CFRP at the beam ends, in addition to the bottom CFRP plate, improves the ultimate load capacity by 45.5% in compression with the control member. Figure 12 depicts load vs. deflection at mid-span of all beams. The load–deflection curves of the beams with a single layer of CFRP of three different lengths are presented to demonstrate the influence of CFRP woven length (Figure 12(a)), the effect of the number of CFRP sheets for beams strengthened with 150 mm length of CFRP (Figure 12(b)), the effect of beam strengthened with U-shaped CFRP woven (Figure 12(c)), and the effect of CFRP plate width for specimens with one layer of CFRP plate (Figure 12(d)). There is a slight change in the mechanical behavior of all beams, as illustrated in Figure 12. There are two stages to the relationship of the load–deflection: The first step is to go from zero loadings to pre-cracking, which is when the load is drastically increased with only a minor rise in deflection. Following the formation of the initial flexural crack, the load

is gradually raised as deflection instantly increases. The flexural crack formation reduced beam stiffness, so the CFRP sheets withstand the applied load. When compared to the control beam, the slope of both stages of the curve raised significantly and marginally for beams with CFRP sheets. The findings show that an increment in length, layer number, and width of the CFRP sheet enhances load and deflection capacity once the primary flexural fracture is formed. Also, the results cleared that the adding of CFRP sheets improved the ultimate strength and ultimate deflection.

4.2 Ultimate load capacity and deflection

The maximum load and deflection of the examined beams were standardized in relation to the control beam (Figure 13(a and b)). According to Figure 13, the load improvement for beams with one CFRP layer and lengths of 75 cm, 100 cm, and 150 cm was 15.9, 22.7, and 26.4%, respectively. Whereas the increase in maximum load for beams with one, two, and three CFRP layers is 26.4, 36.4, and 45.5%, respectively. The load improvement for beams with 100 and 200 mm width of FRP plate was 30 and 42.7%, respectively. In contrast, the increase in the maximum load for one layer of CFRP woven is 40.9% for beams with CFRP at three sides. Finally, improvement at ultimate load and corresponding deflection are 45.5 and 21% for beams with tension CFRP plate and ends CFRP woven. According to the findings, the use of the CFRP sheets was an effective method for strengthening. The best experience was when using three layers of CFRP woven (T-W-3L-150), as it gave the highest load capacity and the lowest deflection. The beam with a CFRP plate at the bottom and CFRP woven at the ends (T-W-1L-R) has the same ultimate load as beam T-W-3L-150 but has a greater deflection.

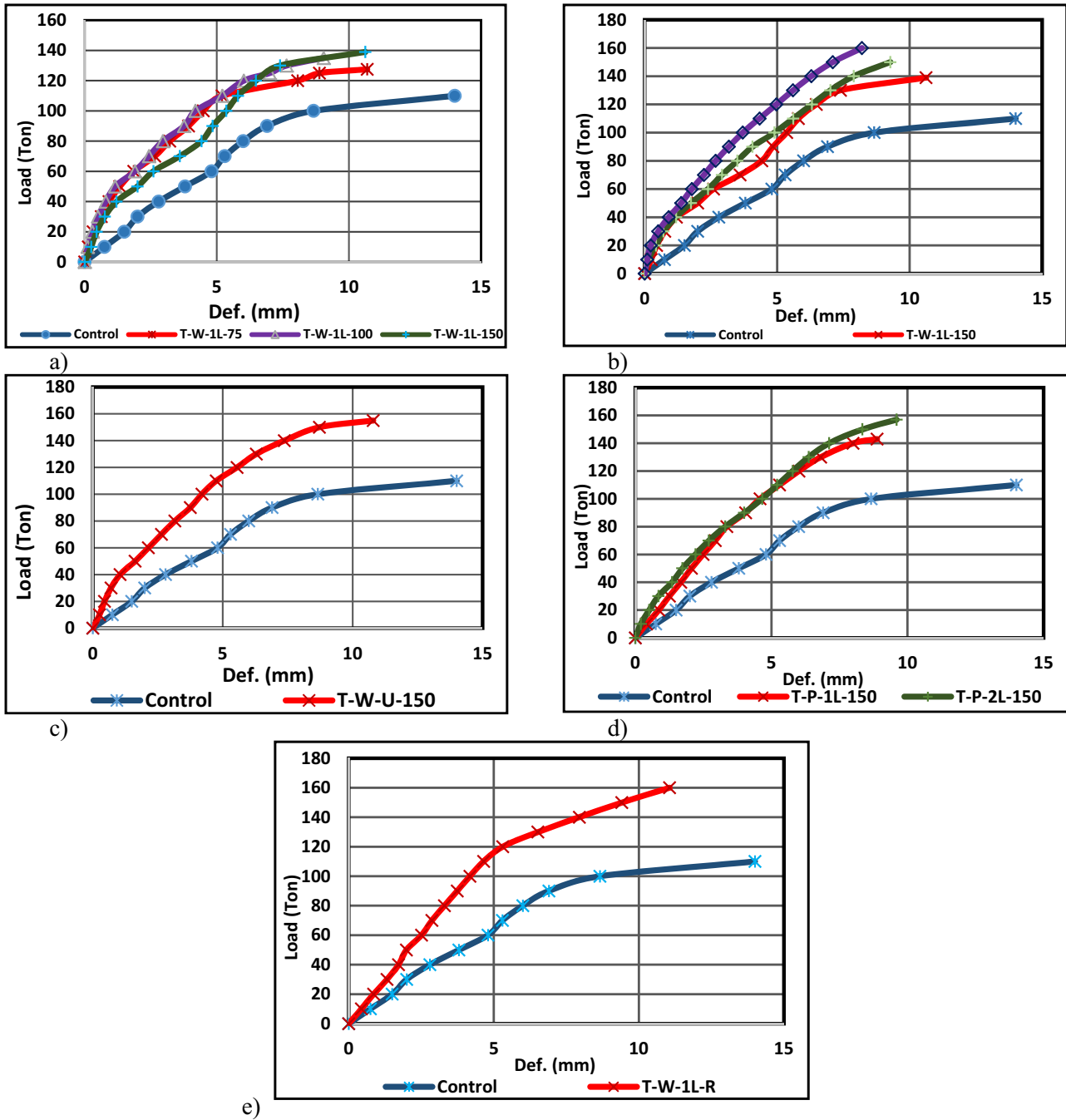


Figure 12: Load-deflection curves of all tested beams. (a) Group A. (b) Group B. (c) Group C. (d) Group D. (e) Group E.

4.3 Cracking and failure mode

Figure 14 displays the control beam's failure modes and cracking patterns, as well as the beams with CFRP sheets. The initial flexural crack created at the mid-span on the tension zone of the beams was followed by de-bonding of the CFRP sheet. The following is a description of the de-bonding failure: Because flexural cracks occurred in the

region with a pure moment as the load grew, the bond between the concrete and FRP began to break at a specified loading level, and the failure then spread to the shear span, causing the majority of the CFRP sheets to separate from the RC beam. As is evident, the bond between the CFRP and the surface of the concrete is insufficient to prevent the composites with CFRP sheets from rupturing. As a result, the bond strength of the CFRP-concrete determines the

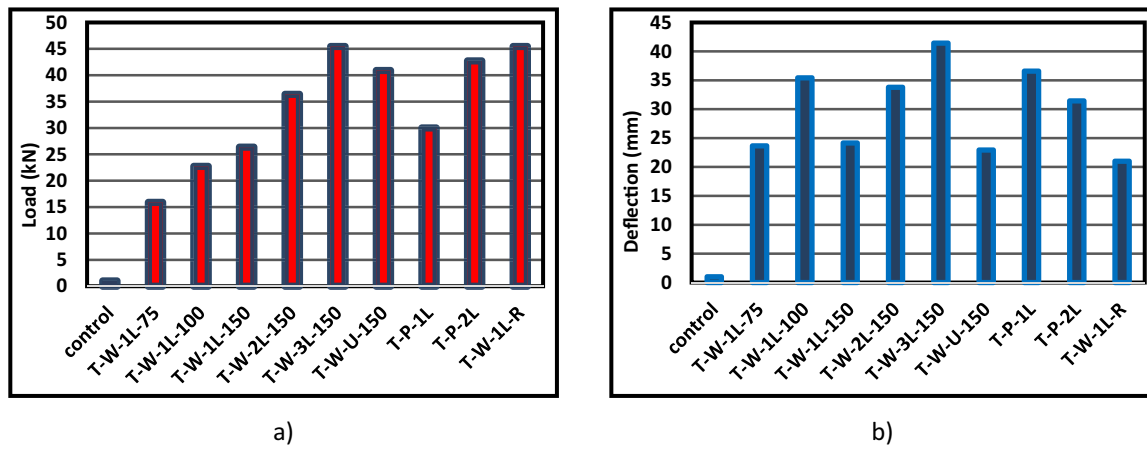


Figure 13: Ultimate load and deflection relative to the control beam. (a) Maximum load. (b) Maximum deflection.

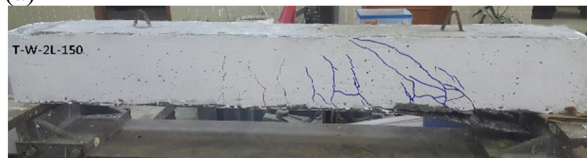


T (Control beam)



T-W-1L-100

(a)



T-W-2L-150

(b)



T-1P-150

(c)



T-W-U-150

(d)



T-W-1L-75



T-W-1L-150



T-W-3L-150



T-2P-150



T-W-R

(e)

Figure 14: Failure mode of the tested beams. (a) Group A, (b) Group B, (c) Group C, (d) Group D, and (e) Group E.

mode of failure. It was recognized that the length, type, and arrangement of CFRP sheets had a noticeable effect on the cracks' numbers, length, and distribution. Figure 14(a) shows that the distribution and number of cracks increased as the length of CFRP material increased, but the length of the cracks (from the bottom to the top side of the neutral axis of the cracking part) lowered. Figure 14(b) shows that as the number of strengthened layers increased, the distribution, length, and number of cracks also decreased. This is due to the CFRP sheet's capacity to provide enough development length to bridge flexural cracks. Additionally, the increasing CFRP layers had a significant impact on reducing the length and number of cracks. This may be explained by the external CFRP sheet's ability to prevent beams from delaminating, which results in exceptional behavior in the flexural crack-arresting process. Figure 14(c) shows that as the CFRP plate width is decreased, the number of cracks and damages increase, and the damage is also greater than if a CFRP weave is used as the beam (T-W-1L-150). In the case of the application of CFRP sheets on three sides of the beam T-W-U-150, the beam failure mode transferred from FRP delamination from the concrete substrate to FRP rupture in the constant moment area. Figure 14 depicts two common modes of failure. Finally, the failure of the reinforced beam in Figure 14(e) was caused by the de-bonding of the CFRP plate coupled with horizontal cracking in the tension zone at the beam mid-span. This type of failure occurs due to the sudden propagation of horizontal cracks in the region of the concrete-steel bond. This kind of crack occurs along the concrete steel interface, which is the weakest surface, which leads to the beam failure as soon as the cracks open and separate the cover of concrete from the whole beam.

5 Conclusion

One reference and 10 beams strengthened with CFRP elements bonded with an epoxy were examined under a four-point load, and the results of the failure of those 11 RC beams have been discussed. This study investigates the efficiency of RC beams strengthened with CFRP elements of various lengths, types, and configurations. Table 1 contains a summary of the tested results.

The following are the key conclusions of this study:

1. The use of CFRP woven along the beam tension region halts flexural cracks and enhances the serviceability and performance of the studed beams. The efficacy of CFRP woven into the flexural crack bridging improved as the CFRP length increased.

2. According to the test results, the load-carrying capability of the RC beams improved with the layer number of the CFRP woven.
3. Comparing the results of the beams strengthened by CFRP plates with the control beam showed that the CFRP plates increased the beam's load-carrying capacity, especially for beams with two plates.
4. The CFRP sheets had a significant impact on the length and width of cracks.
5. All the test beams failed because of de-bonding of CFRP sheets, with the exception of the U-shaped CFRP beam, which failed due to carbon fiber woven rupture.
6. The maximum increments in the maximum load of the beams were 45.5% when flexural CFRP strengthening was anchored with three CFRP woven (T-W-3L-150) and with a plate in addition to the CFRP woven at the ends (T-w-R).
7. Lastly, the use of CFRP woven at the ends of the beam causes failure only at the mid-span but is ineffective in delaying premature de-bonding.

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Data availability statement: Most datasets generated and analyzed in this study are comprised in this submitted manuscript. The other datasets are available on reasonable request from the corresponding author with the attached information.

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