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STRENGTHENING OF REINFORCED CONCRETE BEAMS WITH TEXTILE-REINFORCED CONCRETE

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Abstract

Numerous problems that can occur during regular building use may necessitate the need for reinforced concrete RC members to be strengthened. An increase in live loads or structural damage is two examples. Various techniques can be used to increase load-carrying capability. Concrete reinforcement with textile-carbon fiber (TCF) is a more recent option. For almost all active forces, this strengthening procedure is appropriate. For bending, shear, torsion, or axial forces, strengthening is an option. The experimental work for this study examined the impact of textile carbon mesh in reinforced concrete with various numbers of layers and sikadure-330 as the bonding material with different damage ratio (0%, 45%, 55% and 70%). As well as the flexural behavior of reinforced concrete beams strengthened with TCF, by casting and testing 13 beams under the monotonic load, one of them represented the control beam, they designed according to ACI 318-14 to ensure flexural failure. From the results obtained in this study it was shown that the flexural capacity of all strengthened beams increased as a consequence of TCF strengthening. Therefore, TCF jacketing is a very promising technique for increasing reinforced concrete flexural capability, which is necessary for retrofitting and strengthening.

Keywords:

Reinforced concrete beams;
Strengthening of R.C. beams;
Flexural behavior;
Textile-carbon fiber TCF;
Sikadure-330 bond material.

1 Introduction

Depending on the demand for strengthening, many strengthening methods are available on the market. A structural member can be strengthened with textile-carbon fiber by utilizing various reinforcement materials, in various amounts, and with various matrix materials. Textile-reinforced concrete is a material with increased mechanical properties that can allow the production of lighter structural elements [1]. Textile-Reinforced Concrete (TRC) can produce novel structural techniques in civil engineering fields [2]. A cost-effective option depends on the materials' availability on the market and the simplicity of the strengthening technique's application. Additionally, the repair is required in the event of a visible crack to continue transporting loads and transferring them to the ground [3]. The mechanical and durability features can be improved by adding different types of fibers in the right amounts [4].

Textile-carbon fiber (TCF) is a relatively innovative and complex composite material. Carbon fiber reinforcement and a bonding matrix make up the majority of it, while other fiber materials, such as Alkali-resistant (AR) glass fiber textiles, may also be used as strengthening [5].

TCF is characterized by (non-corrosive textile concrete fiber reinforcing, TCF constructions are lightweight, creating thin structures, it uses less material than traditional concrete structures, TCF results in a significant reduction in both material use and expense and cracking behavior with very small crack widths) [6].

The objectives of the research:

- Examining experimentally the viability of enhancing the service flexural performance and the ultimate capacity of reinforced concrete beams using TCF systems.
- Comparing the effectiveness of reinforced concrete beams strengthened by TCF with non-strengthened beams.
- Investigate the effectiveness of repairing damaged reinforced concrete with TCF.

Flexural strengthening beams bonded with TCF have received a lot of interest from most researchers through experimental tests.

Si Larbi Amir et al. 2011 [6] studied the behavior of five beams having 2 m lengths that were all tested under four-point bending. The results appear that TCF by itself has a sizable impact and that the load at fracture is significantly higher than for the reference specimen. It is conceivable and encouraging, in terms of final behavior, to reinforce beams that are susceptible to bending with connected TRC sheets.

Triantafillou. 2011 [7] focused on the efficiency of TCF as externally applied bending-enhancing reinforcement in reinforced concrete (RC) beams. Under four-point bending, 3 down-reinforced beams (150 x 250 x 2000 mm). As a control sample, one out of three specimens were utilized for the test (un-strengthened). Whereas the 2nd specimen had 4 layers of textile fabric strengthened with cement-based mortar, the 3rd specimen had 4 layers of reinforcement but was bound with an epoxy resin-based matrix. The specimens were monotonically tested. In summary, TCF-based strengthening has 30 percent high ductile efficiency but 30 percent less efficiency in terms of flexural strength.

Al-Salloum et al. 2012 [8] studied experimentally and numerically, it examined if textile-reinforced concrete is effective at boosting reinforced concrete beams' shear resistance. Eight beams that had their exterior shear capacity increased by TCF layers are tested as part of the experimental program, and two control beams were purposefully created to have inadequate shear capacity. The results show increasing in shear resistance. The greatest rise in shear force is achieved with more layers of cloth with a 45° orientation and cementitious mortar treated with polymers.

Elsanadedy et al. 2013 [9] studied experimental and numerical research to determine the effectiveness of textile-reinforced concrete, as a means of increasing the flexural capacity of reinforced concrete (RC) beams. Basalt-based textile, a new form of fabric, was utilized as a reinforcing material. Their analysis takes into account the number of TRC layers, the type of reinforcing material, and the type of mortar. Four-point loads were used to evaluate six small-scale beams (150 x 200 x 2000 mm) with straightforward supports. By using basalt textile-reinforced mortar, the flexural capacity of RC beams was enhanced from 39 percentage points to 91 percentage points.

Verbruggen, et al. 2014 [10] focused on the RC beams' tendency to break that have been enhanced using carbon fiber reinforced polymer (CFRP) or textile-reinforced concrete (TRC). Out of a total of 17 beam specimens having various types, 3 beam kinds (control, TRC strengthening, or CFRP reinforcement) were used to assess the effect of external reinforcement on the behavior of interior reinforced concrete beams. All of the beams were evaluated with small-scale third-point stress and four-point bending (100 x 100 x 650 mm). According to experimental findings, a significant increase in the ultimate load at failure.

Escrig et al. 2015 [11] studied four various kinds of TRC on RC beams, which are employed as a tensile strengthening system, and are examined till failure. An analysis of their mechanical behavior in comparison to one another reveals that the various TRC configurations used were able to improve their load-bearing capability and alter their method of failure. 9 beams were created and constructed for the experimental campaign without tensile reinforcement in two specific places. Beams had a cross-sectional area of 300 mm and a length of 1.70 m. According to the results, all TRC-enhanced specimens achieved better flexural toughness levels than the control beam. These results also point to the importance of adhesion between the concrete and TRC in determining the rupture mechanism and bending toughness of TRC-enhanced specimens.

Shah et al. 2017 [12] Experimental research is done to determine how well Textile Reinforced Concrete (TRC) works in terms of improving the Flexural and Shear Capability of (RC) Beams. Instead of using epoxy resin as the bonding agent for the textile fabric, a new type of (AR) glass textile fabric was employed as reinforcement since it has advantages related to fire safety and is reasonably priced. One, three, and five strengthening layers as well as the reinforcing arrangement, which consists of bottom- and U-shaped casing — are among the factors that were evaluated in this research. In total,18 (RC) beams (150 × 250 × 1500 mm) were cast and tested under three-point bending till failure as simply supported. The findings show that the maximum load-carrying capacities of strengthened layers had increased.

Jayakrishnan and Shaji. 2018 [13] This study involved using textile reinforcement to strengthen concrete constructions. The beam sections employed in this study have dimensions of 150 x 250 mm and a length of 1500 mm. The beam is retrofitted with basalt cloth mesh to fix it after a failure. Before applying weight, some beams are retrofitted, and the resistance of the specimen is tested before and after the basalt net. Crack pattern analyses and the determination of flexural strength were both completed. As a result, the flexural toughness of the reinforced specimens increased noticeably.

Koutas et al. 2019 [14] An up-to-date review of TRC's use in concrete structure strengthening is provided in this publication. Bonding TRC layers to the tensile surface, which is commonly the bottom face of a slab or the soffit of a beam. The experiments used AR glass, basalt, aramid, carbon, and PBO fiber fabrics, textiles made of PBO and carbon are the most frequently studied. According to the authors, the use of textile-based composites for earthquake-resistant design and reinforcement of concrete structures has a great promise approach that is gaining more and more attention from the scientific community throughout the world.

Jie Zhu et al. 2020 [15] To strengthen RC beams at the soffit, this study created a textile-reinforced cementitious composite (TRCC) based on MKPC (magnesium potassium phosphate cement). Two reference beams without reinforcement and two reinforced beams underwent three-point bending experiments. The TRCC system shows good adhesion with substrate concrete, according to research TRC composite layer observations. Elevated textile rates reduced the ductility of reinforced beams while increasing load resistance.

Koutas and Papakonstantinou. 2021 [16] Explained the result of slurry type on the effectiveness of TRC reinforcement by changing the kind of fabric and the number of layers of fabric. Nine medium-sized RC beams in total are produced, tested, and found to be under 4-point bending, simply supported. A single beam was used as a control sample and was tested as compact without reinforcing. As a result, the flexural capacity caused by TRC strengthening increased and ranged from 7.4% to 37.4% for all strengthened beams.

Giese et al. 2021 [17] This research aims to investigate the possibility of bending enhancing reinforced concrete beams using a locally made AR fiberglass textile. The specimens underwent a four-point flexure experiment and had dimensions (1500 mm long, 200 mm deep, and 120 mm broad). The experimental investigation examines the effects of different textile layers (2, 3, and 4), TRM age (3, 7, and 28 days), and specimen pre-cracking level (no precracking, 50% and 100% of the yielding load) on the bending performance of reinforced RC specimens. The findings showed an increase in load-carrying capacity and it rises with the number of textile layers.

Ponniah and Chidambaram. 2022 [18] To prevent growth in cross-section in the tension area of this investigation, the TRC layers were used there. Five beam specimens. Four various arrangements of RC beams are tested, also with one control sample for comparison. The tensile face of the beam and the reinforcing layer was from outside joined. The proper connection between the old concrete surface and cementitious materials is achieved using a thin coating of epoxy covering. The study's reinforcing method was successful in improving the bending behavior of the RC beams.

2 Experimental work

The experimental work for this study examined the impact of textile carbon mesh in reinforced concrete with various numbers of layers and sikadure-330 as the bonding material as well as the flexural behavior of reinforced concrete beams strengthened with TCF. The flexural behavior of the reinforced concrete beams which strengthened with TRC investigated by casting and testing 13 beams under the monotonic load designed according to ACI 318-14 to ensure flexural failure. One of the beams represented the control beam and the other beams strengthened with a different number of TRC layers with a thin layer of sikadure-330 as bonding material and different damage ratios (0%,45%, 55%, and 70%).

2.1 Materials

• Materials utilized for this study.

• Maas (Ordinary Portland cement) that complies with Iraqi standard specifications I.Q.S No, 5/1984 [19].

• Fine aggregate (sand) obtained from the Al-Ukhaidher region which complies with Iraq's specifications (I.Q.S No. 45, 1984) [20].

• Samarra coarse aggregate conforming to the Iraqi specifications (I.Q.S No. 45, 1984) [20]. The coarse aggregate's largest particle size was (10 mm).

• Tap water for aggregate washing, concrete mixing, and curing of specimens.

• Steel reinforcement: Ø 10 mm (deformed) with a yield strength of 587 MPa for all the stirrups, top bars, and bottom longitudinal bars according to (ASTM A615 2016) [21], and ASTM A(496M-07) specification [22].

• Textile carbon fiber mesh grid (TCF) was used for external strengthening of the tested beams as shown in Fig. 1, Table 1. Showed the properties of (TCF).

• The adhesive material used with (TCF) sheets is Sikadur-330. This type of adhesive consists of two parts, part A (Resin) which is white, and part B (Hardener) which is grey. as indicated in Table 2 and Fig. 1. shows the technical properties of the used Sikadur-330.

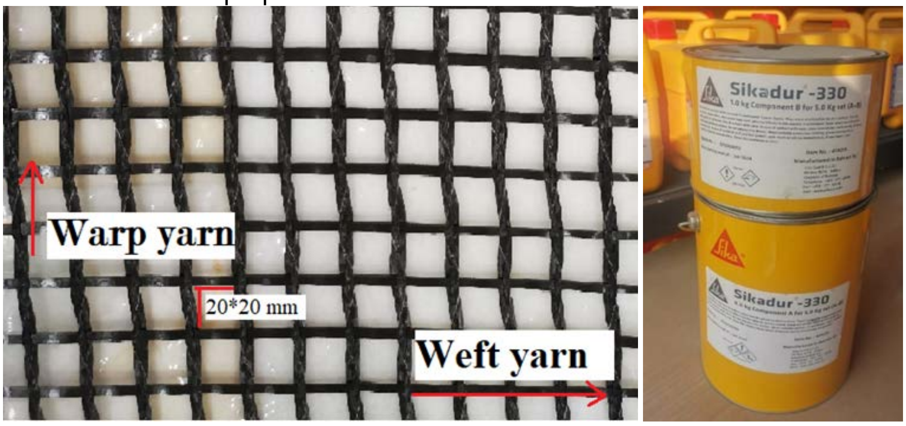


Fig. 1: Shape of Textile carbon fiber mesh grid and Sikadur-330.

Table 1: The technical properties of TRC.

Properties	Carbon fiber mesh grid
width (mm)	1000
Density (g/m²)	160 ± 10
Thickness (mm)	0.008 for every filament
Tensile Strength (MPa)	≥ 3000
Modulus of Elasticity (MPa)	≥ 2.4 * 10^5

Properties are provided according to the manufacturer datasheet.

Table 2: The technical properties of Sikadure-330.

Properties	Sikadur - 330
Density (kg/L) at +23°C	1.30 + 0.1 (parts A+B mixed)
Tensile Strength (MPa) 7 days at +23°C	30
Modulus of Elasticity (GPa) 7 days at +23°C	Flexural: 3.8 Tensile: 4.5
Elongation at Break (%) 7 days at +23°C	0.9
Mixing	Part A : part B = 4 : 1 by weight

Properties are provided according to the manufacturer datasheet.

2.2 Concrete mixes

The mixture is designed to get the perfect compressive strength and good workability (ASTM C496-011) [23]. The compressive strength of the mixture was tested at 7 days and 28 days. The results represented the average of three cubes. Table 3. Illustrated the detailing of the mix design.

Table 3: Proportion of Mix Design.

Cement Kg/m³	Sand Kg/m³	Gravel Kg/m³	Water Kg/m³	W/C	f_{cu}/ 7 days MPa	f_{cu}/ 28 days MPa
400	800	750	140	0.35	38	45

2.3 Mixing and casting

Step 1: Using a lubricating brush, the molds are cleaned and oiled before the steel reinforcement is inserted.

Step 2: Install the spacers with bars to verify the cover (25mm) complies with the (ACI 318M-2019) specification, and then place the reinforcement inside the molds that were made in step one.

Step 3: With the digital balance near the mixer, weigh each component of the mixture.

Step 4: The coarse aggregate, a portion of water, cement, and sand were all added to the mixer. After that, the remaining water was added, and everything was mixed for four minutes.

Step 5: The mixture was put into the molds once step 4 was finished. Using a vibrator for 15 seconds to achieve full compaction. Samples are preserved in the field.

Six cubes 150×150×150 mm, six cylinders 150×300 mm, and two prisms 100x100x400 mm were cast with the mix to determine Compressive, and splitting tensile strengths, elastic modulus, and flexural strength respectively. All steps are indicated in Fig. 2; after 24 hours, all specimens were removed from their molds and cured in water until they were 28 days old.

Fig. 2: Casting, curing method, and beam specimens.

2.4 Designation and details of beams

To explore the flexural behavior of normal Reinforced concrete beams, a total of thirteen simply supported beam specimens were divided into one beam as a control beam and four groups (A, B, C, D). Each group included three samples of the RC beam with three different numbers of layers (1, 2, 3), where group (A) with (0%) damage ratio, group (B) with (45%) damage ratio, group (C) with (55%) damage ratio and group (D) with (70%) damage ratio. A monotonic load has been placed on all beams. The tested beams were designed to ensure flexural failure following ACI 318-19. The length, width, and height of the tested beams were (1600x150x200) mm, respectively. Fig. 3 and Table 4 show all the details of the beam specimens.

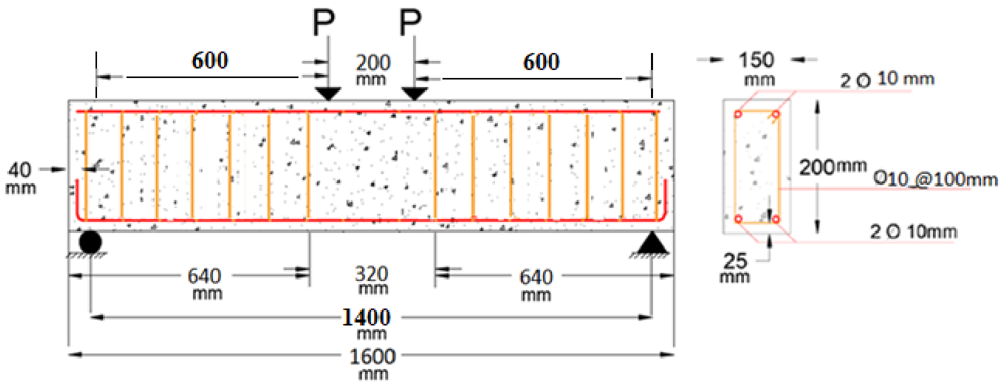
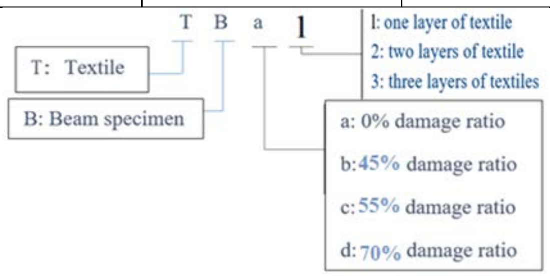


Fig. 3: Reinforcement Details of Beams Specimens.

Table 4: Details of Beam Specimens.

Group No.	Specimen symbols	Damage ratio	Strengthening details
Control beam	BC	Without Damage	None
A	TBa1	0%	One layer of textile at the bottom of the beam
	TBa2	0%	Two layers of textile at the bottom of the beam
	TBa3	0%	Three layers of textile at the bottom of the beam
B	TBb1	45%	One layer of textile at the bottom of the beam
	TBb2	45%	Two layers of textile at the bottom of the beam
	TBb3	45%	Three layers of textile at the bottom of the beam
C	TBc1	55%	One layer of textile at the bottom of the beam
	TBc2	55%	Two layers of textile at the bottom of the beam
	TBc3	55%	Three layers of textile at the bottom of the beam
D	TBd1	70%	One layer of textile at the bottom of the beam
	TBd2	70%	Two layers of textile at the bottom of the beam
	TBd3	70%	Three layers of textile at the bottom of the beam



2.5 Preparing beams for TCF application

2.5.1 Concrete surface roughening

The concrete surface was prepared so that the coatings should make a strong bond with the underlying concrete. The technique used to roughen the surface was done by the concrete grinder as shown in Fig. 4.

Fig. 4: Concrete grinder.

2.5.2 Cut the Textile grid according to the required dimensions

The grid with dimensions (1×5.7) m was cut by scissors into twenty-four parts, according to the dimensions of the beams as in Fig. 5.

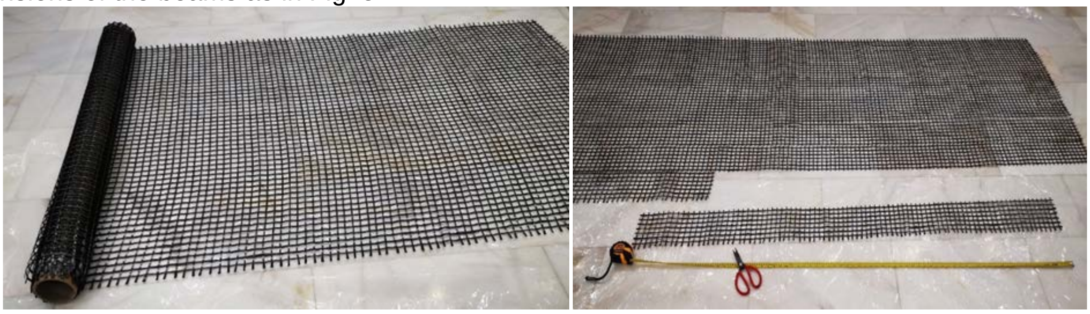


Fig. 5: The Textile grid.

2.5.3 Mixing of bonding material

Type A and type B epoxy impregnation resin had been mixed to the recommended ratio (4:1) as specified by the manufacturer by using the mixer until the color was uniformly gray. Resin mixing was in quantities sufficiently small to ensure that all mixed resins can be used within the resin's pot life. As in Fig. 6.

Fig. 6: Mixing of Sikadure-330.

2.5.4 Laying of Sikadure-300 and Textile layers

The textile was placed so that it should be sandwiched between the layers of epoxy. A thin layer of mixed epoxy was applied and the first layer of textile was then placed, a pressing roller was used in the longitudinal direction of the grid to remove any air bubbles trapped behind the textile grid and by exerting sufficient pressure to properly seat the grid so that it was dipped inside the epoxy. For multi-layer TCF specimens, the above steps were repeated. At last, the textile grid was coated with a thin layer of epoxy and left to dry. The beams were tested after seven days of TCF installation according to the product data sheet. Fig. 7 presents the TCF application and the details strengthening of beams present in Fig. 8.

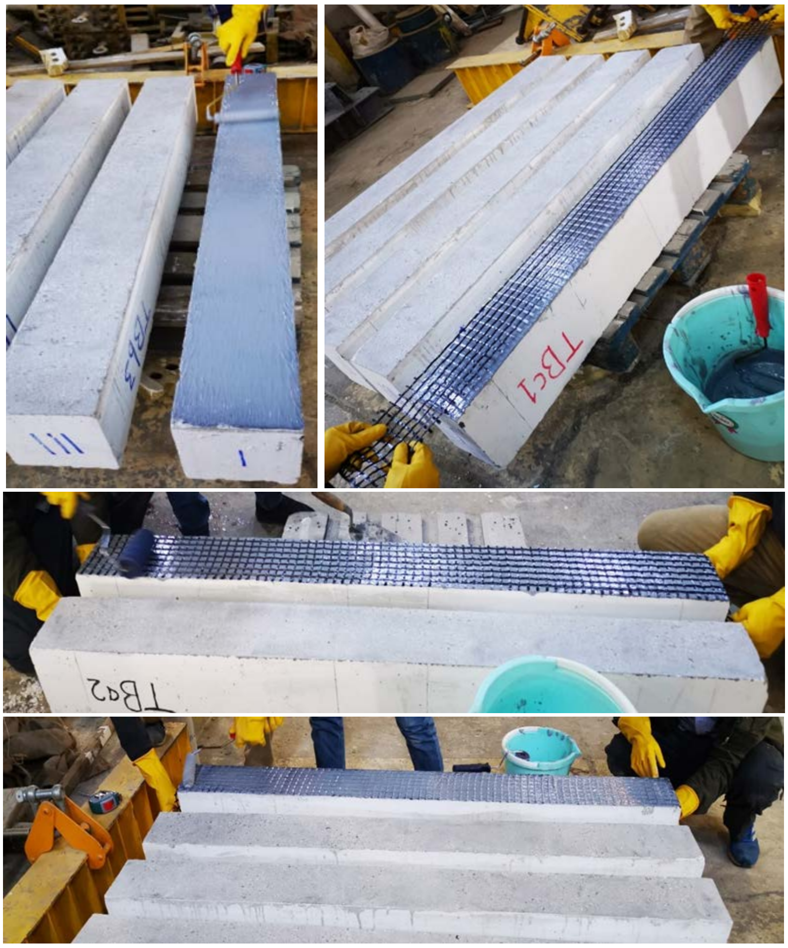


Fig. 7: TCF application.

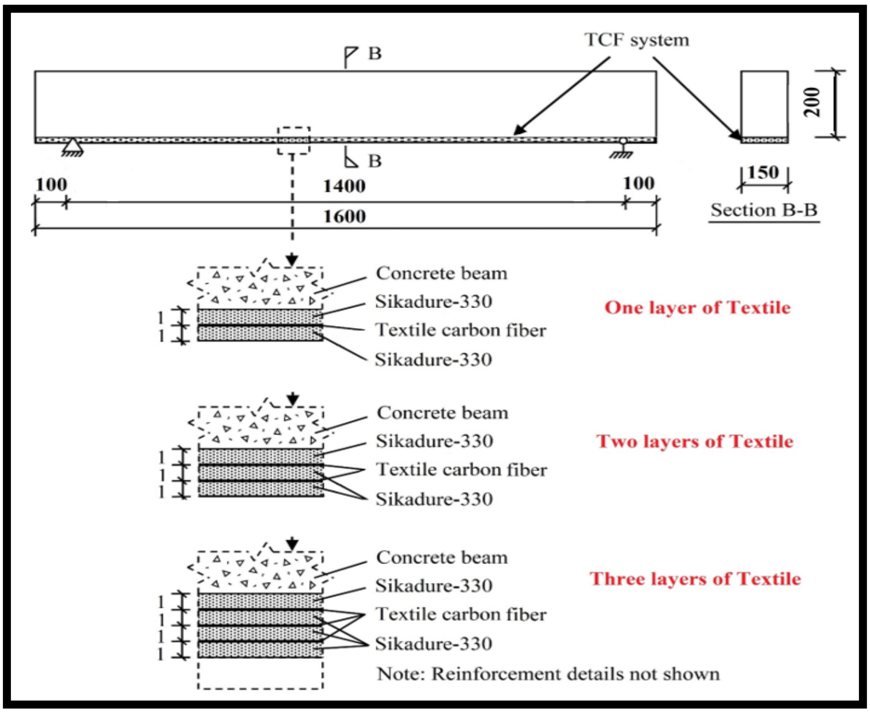


Fig. 8: Details of strengthening of beams.

2.6 Testing setup

Tested in a hydraulic device with a 2000 kN maximum load capability. It was used to test all beams, as can be observed in Fig. 9. All beams were loaded under monotonic loading. The weight is applied from one upper point, and by two arms connected from the bridge to the girders, the load is then split equitably into two points. The control beam was tested until failure, all the other beams in each group—except for the control beam—were tested (before strengthening) using various damaged ratios from the ultimate load, as shown earlier in Table 4 for control beams under two-point loads. Following the strengthening procedure, the load was applied in regular increments as it grew steadily. Each beam's load-deflection behavior was recorded. Moreover, the load corresponding to the first crack was recorded while the position and extent of other consequent cracks were marked on the surface of the beam. The loading increments were applied until the beam fails.

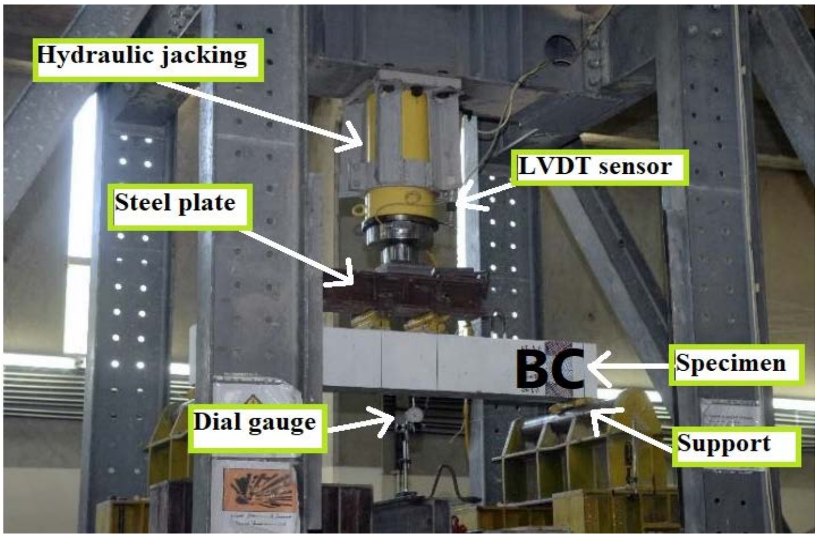


Fig. 9: Test setup for beam.

3 Test results

3.1 Mechanical properties

Cubes 150×150×150 mm were tested according to BS EN 12390-3:2019 [24] and cylinders 150×150 mm were tested according to ASTM C496/C496M-11 [25] to determine compressive strengths, splitting tensile strengths, elastic modulus of concrete, and modulus of rupture at 28 days. These tests were done in the University of Al-Nahrain concrete lab. The results are shown in Table 5.

Table 5: Mechanical Properties of Results.

Specimens	$fcu\ (MPa)$	$f_c'(MPa)$	$f_t\ (MPa)$		$E_C\ (GPa)$		$f_r\ (MPa)$	
			Exp.	code	Exp.	code	Exp.	code
cubes	45.3	-	-	-	-	-	-	-
cylinders	-	32.1	3.4	3.1	28	26.6	-	-
prisms	-	-	-	-	-	-	4.6	3.5

3.2 Testing and results beams

The following is a description of the basic behaviors of the beam specimens that were being tested. All of the examined beams exhibited elastic behavior, and no cracks developed under light loads. The mid-span deflections were minimal and corresponded to the applied force. The first crack in the beam was a flexure crack, and it spread vertically between the loading positions (tension zone) in the lower portion of the beam (Perpendicular to the tensile stress direction). All beams are generally observed to have this crack at the same loading stage, between (20 and 24 KN). All of the R.C. beams' findings are displayed in Table 6.

Table 6: Experimental Result of the Beams.

Group No.	Specimen symbols	Damage ratio	Before retrofitting		After retrofitting		Pcr / Pu (%)	Increase in Pu (%)*	Increase in Deflection (%)*
			Load at first crack Pcr (KN)	Deflection at first crack Δcr (mm)	Ultimate load Pu (KN)	Ultimate deflection Δu (mm)			
Control	BC	Without	20.3	2	45.27	12	44.84	-	-
A	TBa1	0%	18.52	1.85	62.87	15.65	29.45	38.87	30.42
	TBa2	0%	19.25	1.98	67.98	19.5	28.32	50.16	62.5
	TBa3	0%	19.85	1.5	68.55	18.52	28.95	51.42	54.33
Group No.	**Specimen symbols**	**Damage ratio**	**Before retrofitting**		**After retrofitting**		**Pcr / Pu (%)**	**Increase in Pu (%)***	**Increase in Deflection (%)***
			Load at first crack Pcr (KN)	**Deflection at first crack Δcr (mm)**	**Ultimate load Pu (KN)**	**Ultimate deflection Δu (mm)**			
B	TBb1	45%	20.23	1.51	60.1	14.8	33.66	32.76	23.33
	TBb2	45%	20.85	2.52	65.71	15.9	31.73	45.15	32.5
	TBb3	45%	20.25	1.3	73.1	19	27.7	61.47	58.33
C	TBc1	55%	23.24	2.2	62.31	15.8	37.29	37.64	31.66
	TBc2	55%	20.84	1.7	70.82	17	29.42	56.43	41.66
	TBc3	55%	22.68	2.6	71.39	18.2	31.76	57.69	51.66
D	TBd1	70%	23.41	3.1	49.25	13.5	47.53	8.79	12.5
	TBd2	70%	22.57	3.1	58.9	16	38.32	30.1	33.33
	TBd3	70%	23.13	3	65.14	20.8	35.51	43.89	73.33

* Increase in Pu (%)= [(Pu new – 45.27) / 45.27] × 100%, Increase in Δu (%)= [(Δu new – 12) / 12] × 100%.

3.3 Structural behavior, cracking pattern, and failure mode

The control beam BC was tested for failure without retrofitting. The first flexure cracks were observed at (20.3) kN with a corresponding mid-span deflection of (2) mm. These cracks began to spread and expand, causing failure with the increased load. In the middle zone to the bottom part of the beam, new flexural cracks were also formed. This reached an ultimate load of (45.27) kN which created an ultimate deflection at mid-span of (12) mm.

Except for the control beam and group (A), all the other beams for groups (B, C, and D) were loaded (before strengthening) with a different damaged ratio (45, 55, and 70) % of the ultimate load as mentioned earlier in Table 6. The beams' maximum load is expected to be between (18 and 24) kN when the first crack first appears. After strengthening the beams were loaded until failure with an ultimate load between (49 and 73) kN. The beams retrofitted by TCF failed by debonding or rupturing TCF or crushing concrete. All the beams showed the same pattern of failure and failure appeared unexpectedly through small cracks as shown in Fig. 10.

Fig. 10: Crack patterns and failure mode.

3.4 Ultimate load capacity

Fig. 11 Shows the final failure of all beams. Based on the results, the increase in the number of layers of TCF sheets as a strengthening material for beams in group A (0% damage ratio) has an ultimate load between (62.8 – 68.5) kN and the increasing percentage in ultimate load between (38.87-51.42) %. While the increase in the number of layers of TCF sheets as a repairing material for beams in groups B, C, and D (45%, 55%, and 70% damage ratio) have an ultimate load (60.1- 73.1), (62.31-71.39), and (49.25-65.14) kN and the increasing percentage in ultimate load ranging between (8-61) %. It can conclude from the above that the use of TCF was useful as a repair and strengthening material by reducing crack widths and giving an increase in the ultimate load capacity by about (8-61) % compared to the control beam. The use of two layers of strengthening can be considered sufficient in terms of improving the flexural capacity and more economical in terms of cost.

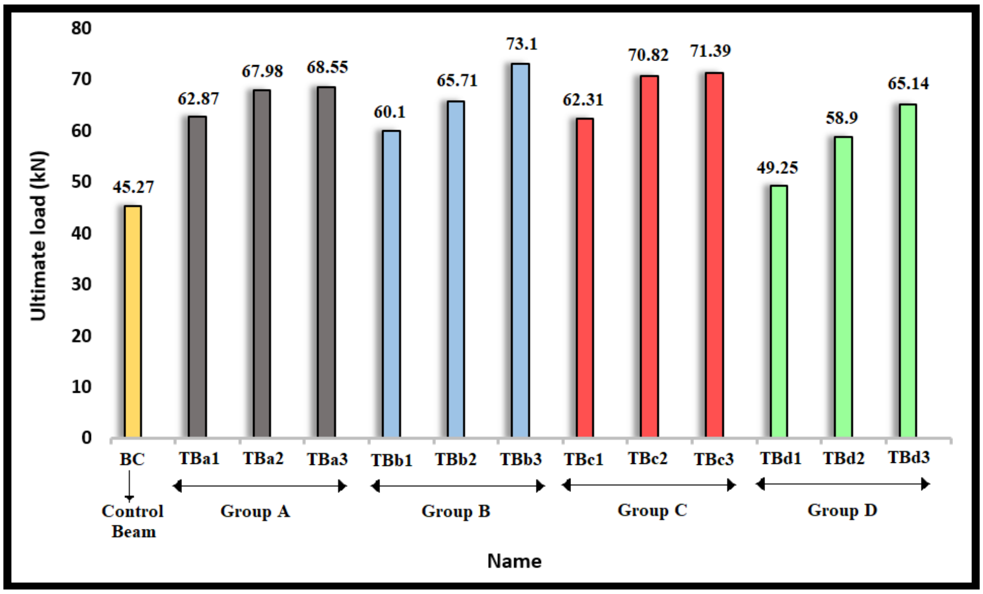


Fig. 11: Ultimate load for all groups.

3.5 Load-deflection behavior

The load-deflection relationship is an essential variable in explaining how the structural components behave in their entirety. In Fig. 12 the load-displacement reactions for the specimens are displayed. Testing was stopped when the specimen failed, and it could either be determined by the damage that resulted from the failure or by the fact that the load could no longer be increased or started to decrease as a result of the continuous rise in deflection.

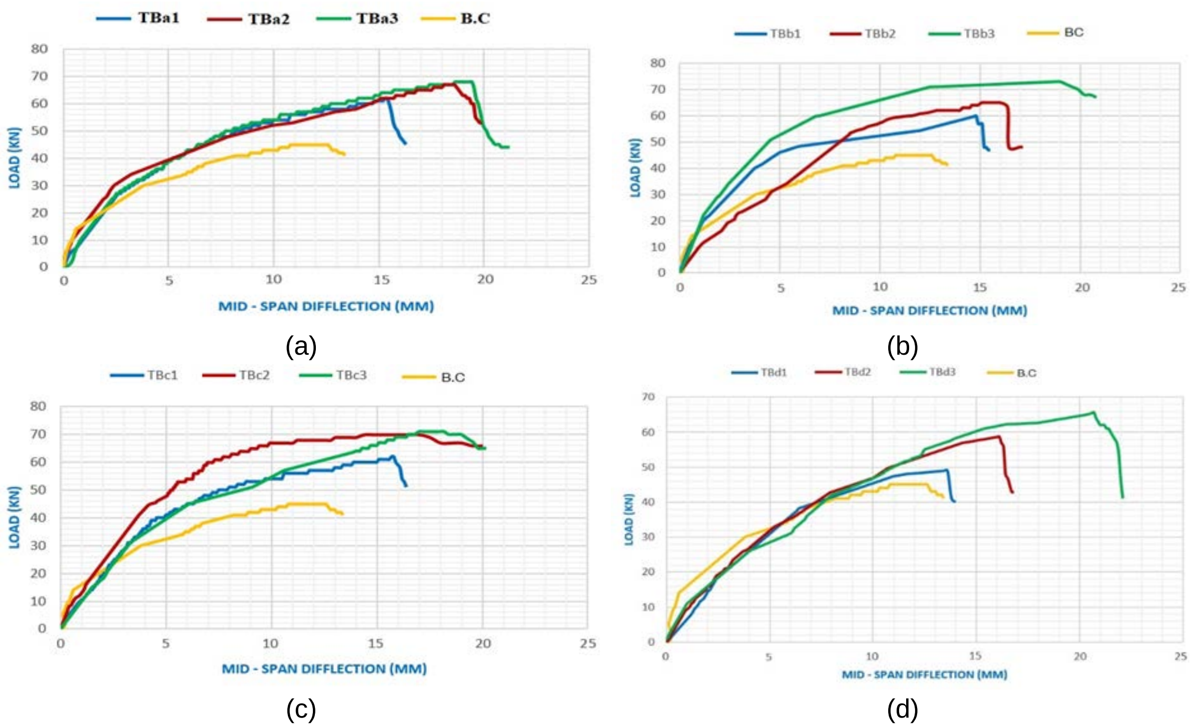


Fig. 12: Curve of load-deflection for all groups with control beam: (a) group A, (b) group B, (c) group C, and (d) group D.

4 Conclusion

The previous study's major objective is to look at the flexural behavior of reinforced concrete beams strengthened by textile carbon mesh with different damage ratios and a different number of layers by using thirteen supported beams that were simply tested under two-point loads in the experimental program. From the results of the experimental specimens, certain conclusions can be derived as follows:

1) Concrete mix is designed to have a compressive strength of more than 35 MPa in this study. All tests were performed according to (ASTM C496-04). This mixed design gave excellent workability.

2) This study describes a new strengthening method (TCF) for RC members as well as flexural strengthening. Where the authors believe increasing the flexural strength of reinforced concrete members through the use of TCF wrapping is a very hopeful option.

3) The flexural effectiveness of damaged R.C. beams is improved by the employment of the TCF system for strengthening. The improvement in ultimate load capacity of (8 to 62) % when compared to control specimens without strengthening, as well as a rise in the ultimate mid-span deflection proportion ranging from (12 to 74) %, corresponded to an improvement in the ultimate load capacity of beams.

4) The deformation and crack width of strengthening beams were less than the control beam.

5) Deflection increased linearly with the load when all R.C. beams strengthened with TCF. This linear relationship indicates that deflection remains within the elastic range.

6) The results showed that the preloading of the beams with different damage percentages (45, 55, 70) % affects the concrete in the compression zone as a result of the degradation resulting from an increase in loading, and this effect appears clearly in the beam TBd1 with a damage ratio (70%), which gave a slight increase in the percentage of the ultimate load about (8%) compared with other strengthening beams.

7) The failure mode of control beams was a flexural failure and beams strengthened by TCF failed by rupture of the grid and by brittle fracture, that is, the concrete is crushed in beams with (one and two TCF layers), while debonding was the failure mode in beams with (three TCF layers) because the increase in the number of layers led to an increase in the strength of the grid.

8) The first crack was a flexure crack and was observed in the lower part of the beam at the middle region. This crack is to be formed at around (18 - 24) kN. This crack is to be formed at around (8 - 15) % of the ultimate load for the beams.

9) The best strengthening technique is the two-layer TCF beam because it greatly improves the flexural capacity as it gives an increase in the ultimate load of up to 56%. It can be considered sufficient in terms of improving the flexural capacity and more economical in terms of cost.

10) Overall, the type of bonding material had a strong influence on the flexural performance of TCF-strengthened RC beams. According to the previous study, the use of epoxy as a bonding material gives an increased strength (by about 50%).

11) Textile carbon fiber is one of the strongest types where according to one of the previous studies, the flexural capacity of the specimen was raised by 50% by three layers of glass textile, which is similar to 3/7 = 0.46 of one layer of carbon textile in terms of axial stiffness and 0.43 times the increase for one layer of carbon textile.

12) When comparing the results of previous research when using CFRP and the results of this study when using TCF, it was shown that the TCF-based strengthening system is slightly less effective in terms of enhancing the flexural strength of RC beams but more effective in terms of deflection ductility.

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