Ductility and Toughness of Unsymmetrical CFRP Strengthening of Reinforced Concrete Beams

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(Received 16 /7 /2017; accepted 22 /1 / 2018)

Abstract

The use of externally bonded composite materials such as carbon fiber reinforced polymers (CFRP) sheets is a modern and convenient way for strengthening and repairing reinforced concrete (RC) beams. This study presents experimental investigations on the flexural behavior of reinforced concrete beams strengthened by unsymmetrical CFRP sheets with various configurations. Effects of number of which strengthened faces of strengthening and fiber direction on the flexural strength of RC beams are examined. Six RC beams with dimensions of 100 mm * 220 mm were casted and tested under two points loading. One beam considered as a reference (unstrengthened) beam. Five residual beams were strengthened using CFRP sheets with various configurations. From the results, it was observed that all strengthened beams showed higher ultimate load capacity than that of the control beam. On the other hand, it was found that a progressive reduction in flexural ductility and toughness of beams with strengthening in one face and two faces with horizontal fiber direction. The highest decrease in flexural ductility and toughness for strengthened beams with horizontal fiber direction in comparison to control beam were 63% and 54%, respectively. On the contrary, the flexural ductility and toughness of strengthened beams increased with strengthening by vertical fiber direction. Additionally, the maximum percentage of increase in flexural ductility and toughness were 41% and 54%, respectively in comparison with control beam.

Keywords: Fiber Reinforced Polymers, CFRP sheets, Unsymmetrical strengthening, ductility, RC Beams, Toughness

المطيلية والمتانة للعتبات الخرسانية المسلحة والمقواة بألياف الكاربون البوليميرية الغير متناظرة

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الخلاصة

استخدام المواد المركبة الملتصقة خارجيا مثل الياف الكاربون البوليميرية تعتبر طريقة مناسبة ومتطورة لتقوية واصلاح العتبات الخرسانية المسلحة. قدمت في هذه الدراسة تحريات عملية لدراسة تصرف الانثناء للعتبات الخرسانية المسلحة والمقواه بألياف الكاربون بطريقه غير متناظرة. تأثير عدد الوجوه التي تم تقويتها واتجاه الالياف على مقاومة الانثناء تم التحقق منها. ستة عتبات مسلحة بأبعاد ١٠٠مم × ٢٠٠مم قد صبت وفحصت تحت نقطتي تحميل. عتبه واحده اعتبرت عتبة مرجعيه (غير مقواه بألياف الكاربون). العتبات الخمس المتبقية قد قوت باستخدام الياف الكاربون بترتيبات مختلفة. من خلال نتائج الفحص تم ملاحظة أن كل العتبات التي تمت تقويتها بطريقة غير متناظرة كانت ذات سعة تحمل اعلى بالمقارنة مع العتبة المرجعية الغير مقواه. ومن ناحية اخرى فقد وجد ان هنالك انخفاض تدريجي في مطيلية الانثناء والمتانة للعتبات بالتقوية بوجه واحد وبوجهين وباتجاه الياف افقي. اعلى انخفاض في المطيلية والمتانة للعتبات المقواة باتجاه الياف افقي بالمقارنة مع عتبة السيطرة كانت ٦٣٪ و ٥٤٪ عل التوالي. على العكس، مطيلية الانثناء والمتانة للعتبات المقواة ازدادت بالتقوية باتجاه الياف عموديه. بالإضافة، نسبة الزيادة القصوى في المطيلية والمتانة كانت ٤١٪ و ٥٤٪ على التوالي بالمقارنة مع العتبة المرجعية.

1. Introduction

There are many materials and construction techniques, which can be used for strengthening and retrofitting concrete structures. Strengthening enhance the ultimate load carrying capacity and repair deterioration damages. Composites are increasingly used as strengthening materials of reinforced

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concrete members such as beams, columns and slabs. The conventional strengthening methods such as section expand, steel plate that bonded to the external surface, and jacketing members with reinforced concrete have ability to maintain the adequacy of concrete structure with high loading and increasing ductility of different structural members **ACI Committee 440.2R (2008).** But these strengthening methods are not widely use because of steel plate more sensitive to corrosion which needs coating and painting, strengthening structures with steel plate increases dead load of structures, because of steel plate possess heavy weight and limitation in available plate lengths. Also section enlargement unsuitable for strengthening purposes because it reduces the usable living area. The disadvantage of the methods described above promoted many researchers to seek alternative strengthening techniques to revive the deteriorations. FRP composite is found to be suitable alternative to conventional techniques due to its superior properties. It has very high tensile strength, high modulus of elasticity, very good resistance to corrosion, low density and good resistance to chemicals. Likewise, CFRP sheets are comparatively expensive compared to another types of FRP composite, possess high electric conductivity and due to its linear behavior until failure its fail in a brittle manner **ACI Committee 440.2R (2008).**

Beam strengthening using FRP composite sheets have been studied widely in the last two decades. **Aboutaha et al (2003)** tested a nine reinforced concrete beams strengthened with CFRP sheet to evaluate the flexural ductility of strengthened RC beams. From the results, it was concluded that the flexural ductility of strengthened beams with CFRP sheets increased, with increasing the steel reinforcement. In addition, flexural ductility of reinforced concrete beams strengthened with CFRP sheet increased by providing anchors in the strengthening system because this anchors prevent delamination of CFRP sheet. **Maghsodi and Bengar (2009)** tested nine high strength reinforced concrete beams (HSRC) to evaluate ductility of reinforced concrete continuous beams externally bonded with CFRP sheets. It was concluded that strength increased with increasing the number of CFRP sheet layers, but the ductility and ultimate strain on CFRP reduced with increasing number of CFRP sheet layers. The ductility of strengthened beams above is reduced by 72.7%, 76.6%, 82.4% and 84.1%, respectively. **Bsisu et al (2015)** investigate the effect of number of layers, width and strength of fiber reinforced polymers (FRP) sheets on flexural ductility and strength of reinforced concrete beams. It was concluded that, using of single layer of FRP sheet would increase strength with a little reduction in ductility. On the other hand, using multiple layers of wide FRP sheet leads to more increase in strength, but reduce ductility of reinforced concrete beams. Strengthening beams with FRP sheets increased the flexural capacity of beams by 23.6% to 66% over the strength of the control beams, depending on number layer and width of CFRP sheets.

Many researches have investigated the use of CFRP to enhance the flexural strength of concrete beams. However, the flexural ductility of RC beams strengthened by unsymmetrical CFRP sheets with respect to the amount and direction of fiber has not been investigated. This study aims to illustrate the ductility behavior of the reinforced concrete beams strengthened by unsymmetrical CFRP sheets failing in flexural modes, because the full wrapping strengthening by CFRP configurations have decreased the ductility of RC beams.

2. Experimental work

2.1. Material used in this study

2.1.1. Cement

Ordinary Portland cement is used in the experimental work of this study. It is kept in dried place and away from harsh environmental conditions. The physical and chemical properties of this type of cement are listed in Tables (2) and (3), respectively. It is conformed to the Iraqi standard specifications (No.5-1984).

Table (2): The chemical properties of cement

Oxides	Percentage by weight	Iraqi specification limit IQS 5/1984
CaO	66.26	--
Fe2O3	3.73	--
SiO2	19.11	--
Al2O3	6.42	--
MgO	1.45	Not more than 5%
SO3	1.85	Not more than 2.5%
Lime saturation factor	0.91	0.66 - 1.02
Loss on ignition	2.2	Not more than 4%
Insoluble residue	0.96	Not more than 1.5%
Main compounds		
C3A	3.0	Less or equal 3.5%
C2S	8.52	--
C3C	2.9	--
C4AF	7.07	--

Table (3): Physical properties of cement

Type of test	Property	Iraqi specification limit IQS 5/1984
Initial setting time (minutes)	194min.	Not less than 45 min
Final setting time (minutes)	245min	Not more than 600 min
Fineness (cm2 / gm) by blain method	2600	Not less than 2500
Compressive strength at 3 days (MPa)	16	Not less than 15 (MPa)
Compressive strength at 7 days (MPa)	28	Not less than 23 (MPa)

2.1.2. Fine aggregate

Natural sand is used in this study from Al-Akhaider region. It has smooth texture and rounded shape with 4.75 mm maximum size. Tables (4) and (5) show grading and chemicals properties of fine aggregate. The test result show that the grading and sulphate content of fine aggregate in the range of the **Iraqi specifications (No.45-1984).**

Table (4): Grading of fine aggregate

NO.	Sieve size (mm)	Cumulative passing %	Limit of Iraqi specification NO.45-1984 , (zone1)
1	**10**	100	100
2	**4.75**	93	100 – 90
3	**2.36**	71	95 – 60
4	**1.18**	52	70 – 30
5	**0.6**	30	34 – 15
6	**0.3**	13	20 – 5
7	**0.15**	3	10 – 0

Table (5): Chemical test of fine aggregate

Type of test	Test result	Limit of Iraqi specification NO.45-1984
Sulfate content	0.3%	Not more than 0.5%
Specific gravity	2.7	--
Absorption	0.8	--
% Passing 0.075mm sieve	1.5%	Not more than 5%

2.1.3. Coarse aggregate

Crushed gravel from samara city in Iraq was used in this study with maximum particle size 14 mm. The results obtained from the test indicated that the grading of coarse aggregate conform to requirement of **Iraqi specifications (No.45-1984).** Tables (6) and (7) show the grading and chemical properties of coarse aggregate respectively.

Table (6): Grading of coarse aggregate

NO	Sieve size (mm)	Cumulative passing	Limit of Iraqi specification NO.45-1984
1	20	100	100
2	14	97	90 – 100
3	10	54	50 – 85
4	5	8	0 – 10

Table (7): Chemical properties of coarse aggregate

Type of test	Test result	Limit of Iraqi specification NO.45-1984
SO3	0.03%	Not more than 1%
Specific gravity	2.67	--
Absorption	0.68%	--

2.1.4. Steel reinforcement

Deformed reinforcing bars were used as tension reinforcement with diameter 10 mm. Smooth reinforcing bars were used for stirrups with diameter 6 mm. The test was done in the materials lab of civil engineering department in university of Anbar according to **ASTM A615 (2015).** Table (8) shows the properties of deformed and smooth reinforcing bars.

Table (8): Properties of steel reinforcement

Type of bars	Samples	Diameter (mm)	Yield stress (MPa)	Average Yield stress(MPa)	Ultimate stress (MPa)	Average ultimate stress(MPa)
Deformed bars	Sample1	10	617	597	857	801.5
	Sample2	10	577		746	
Smooth bars	Sample 1	6	300	337	390	424
	Sample 2	6	374		458	

2.1.5. CFRP (carbon fiber reinforced polymers) sheets and epoxy resign

In this study, SikaWrap-300C is used. It is unidirectional woven carbon fiber. It is used for strengthening and repairing purposes in flexural and shear for concrete members, brickwork, and timber. The suitable epoxy resin was used to attach CFRP sheet on the concrete structures this type of resign solvent polymer called Sikadure-330. The Sikadure-330 has superior properties such as high strength, low shrinkage, good resistance to chemicals and good adhesive properties. The service temperature of this type of epoxy is varying from -40°C to +50°C and required 7 days curing period to ensure good adhesion.

To determine mechanical properties of CFRP sheets two samples were tested using universal testing machine with capacity 100 kN, as shown in Figure (2). The test was performed according to **ASTM D3039 (2014)** to determine ultimate tensile strength, elastic modulus and ultimate strain. The test samples had width and length of 17 mm and 150 mm, respectively as shown in Figure (3). Table (9) presents the CFRP sheets test results

Figure (2): CFRP machine testing Figure (3): Test samples of CFRP sheets

Table (9): CFRP sheets test results

Samples	Width (mm)	Length (mm)	Thickness (mm)	Tensile strength (MPa)	Average Tensile strength (MPa)	Elastic modulus (MPa)	Average Elastic modulus (MPa)	Strain %	Average strain %
S_1	17	150	1.2	244.1	263.55	56000	55500	0.49	0.53
S_2	17	150	1.2	283		55000		0.58	

2.2. Test specimens

The experimental program in this study was conducted to investigate the flexural ductility of unsymmetrical CFRP rectangular strengthened beams with various strengthening schemes. The experimental work included of testing a six reinforced concrete rectangular beams under static 2-points loading. A total of six reinforced concrete rectangular beams with dimensions 100mm width, 220mm height and span length 1200mm. One beam was used as a reference (unstrengthened) beam. The remaining beams were strengthened with various strengthening schemes. Two deformed steel bars with 10 mm diameter were used as main reinforcement and placed at effective depth of 190 mm and two smooth bar with 6 mm diameter were used as compression steel reinforcement at a depth of

30 mm, as shown in Figure (1) b. Stirrups with 6 mm diameter were used along span to resist shear failure with spacing 80 mm except above support at 40 mm from center to center, as shown in Figure (1) a.

The strengthened specimens were divided into two groups. The first group included two beams. The CFRP sheets were externally bonded at one side of beam with different fiber direction (0° and 90°). The second group included three specimens. The CFRP sheets were externally bonded at tension face and one side of beam. for one specimen, CFRP sheets were atached at 0° with beam axis and for two specimen, CFRP sheets were attached at 90° with beam axis. One of these two beams, 50mm CFRP strips were attached with net spacing of 50mm. All specimens were fully wraped at the ends with distance of 150 mm to avoid supports failur. The sumirized discriptions of beams were listed in Table (1).

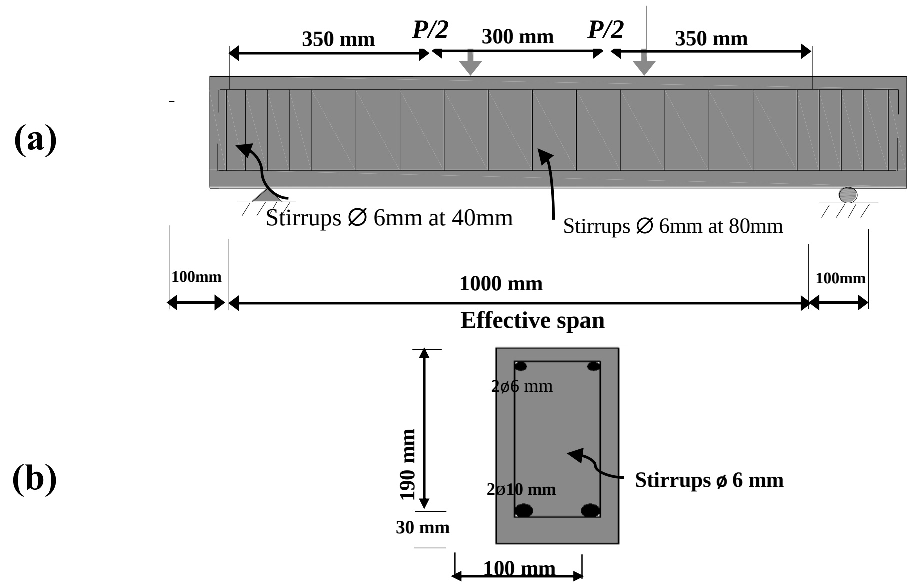

Figure (1) Beam dimensions and steel reinforcement details: (a) longitudinal section; (b) beam cross section

Table (1): Beams description

Specimens sympol	Detailes of specimens
RR	Control beam (un-strngthened with CFRP sheets)
R.1F-0°	Strengthened beam in one side of concrete beam with horizontal fiber direction
R.2F-0°	Strengthened beam in tension face and one side of concrete beam with horizontal fiber direction
R.1F-90°	Strengthened beam in one side of concrete beam with vertical fiber direction
R.2F-90°	Strengthened beam in tension face and one side of concrete beam with vertical fiber direction
R.ST.2F-90°	Strengthened beam with strips of CFRP in tension face and one side of concrete beam with vertical fiber direction

The mix proportions were used to achieve compressive strength 30 MPa at 28 days (normal strength) are presented in Table (10). The concrete cylinders (150 mm * 300 mm) were casted with each beam. The concrete compressive strength was determined by taking the average of six cylinders.

Prior to applying CFRP sheet on the concrete surfaces the required region of concrete was cleaned and made rough by using wire wheel brush to remove fragile layer from the surface. The edges at the region of warping were made rounded because the sharp edges may have effect on the CFRP sheet during loading. Then the beams were cleaned by air jet to remove dust from the surfaces. The CFRP sheet is cut to the required dimensions before applied to concrete surface. The epoxy resin is mixed according to manufactured instruction. The mixing performed in plastic container for several minute until the mixture color became uniform. After cleaning operation is done a thin layer of Sikadure-330 is applied on the required concrete surface. Then the CFRP sheets are placed above the resign and pressed by roller to remove the entrapped bubbles and to ensure good contact between concrete surface and the fabric, as shown in Figure (4). This process was performed at room temperature, where it was (13°C). The concrete beams were strengthened with CFRP sheet left 7 days at room temperature and humidity for curing to ensure good hardening for resin before testing, where the temperature and humidity were 13°C and 43%, respectively. Figure (5) shows the strengthened beams.

Table (10): Mix proportions and average compressive strength of concrete

Mix	(W/C) Ratio	Mix proportions (Kg/m^3)				Slump (mm)	Average compressive strength for Cylinders (150mm*300mm) (MPa)
		W	C	G	S		
1	0.48	210	430	1100	700	25	31

(c) (d)

Figure (4): Strengthening process by CFRP sheets: (a) CFRP cutting; (b) Thin layer of epoxy resign; (c) CFRP sheets installation; (d) Remove entrapped air bubbles

Figure (5): Strengthened beams

2.3. Test of beam specimens

The concrete beams were tested under two points load until failure. The beams were tested by hydraulic machine with capacity 200 kN, as shown in figure. The beams were placed over to steel roller with effective span of 1000mm, as shown in Figure (6). An electronic gage was placed below the center of beam for measuring the deflection.

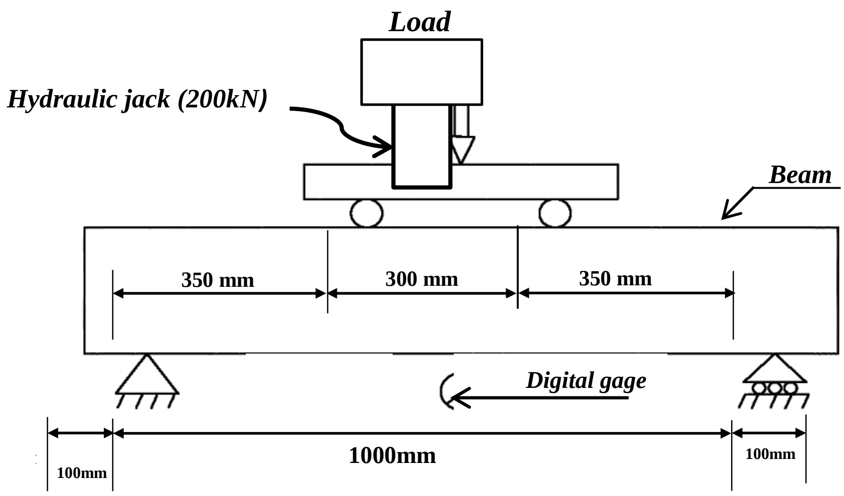

Figure (6): Flexural test set-up

3. Test results and discussion

3.1 Load deflection response

All control and strengthened beams were tested monotonically from pre-cracked stage. The experimental results are presented in Table (12) including first crack deflection (Δi), yield deflection (Δy), failure deflection (Δu), load at first crack (Pi), ultimate load (Pu). In addition to that, including the change in maximum deflection for strengthened beams with respect control beams and increasing in load bearing capacity for CFRP strengthened beams. The ultimate carrying capacity (Pu) means the maximum applied load which the RC beam can carry before failure occurrence and deflection corresponding to that load called ultimate deflection (Δu).

Table (11): Summary of deflection and load values

Specimens	Δi (mm)	Δy (mm)	Δf (mm)	Pi (kN)	Pu (kN)	Increasing percentage Δf	Decreasing percentage Δf	Increasing percentage Pu
RR	0.93	4.47	15.7	30	104.34	--	--	--
R.1F-0°	1.47	4.66	9.82	39	128.96	--	- 37%	+ 24%
R.1F-90°	1.05	4.9	23.17	32	106	+ 48%	--	+ 2%
R.2F-0°	1.51	5.59	7.29	44	149.19	--	- 54%	+ 43%
R.2F-90°	1.34	4.91	23.83	36	107	+ 52%	--	+ 3%
R.ST.2F-90°	1.01	4.9	20.29	30	106.28	+ 29%	--	+ 2%

3.1.1. Effect of faces of strengthening

3.1.1.1. Beams strengthened by 0° fiber direction (horizontal fiber direction)

Figure (7) show the effect of faces of strengthening on load-mid span deflection curves for rectangular beams strengthened with vertical fiber direction in one face and two faces. The test result show that the load-mid span deflection curves for beams (RR), (R.1F-0°) and (R.2F-0°) were almost identical until yielding point of control beams (RR). This is expected the load deflection response not affected significantly by faces of strengthening at post-cracking stage, due to failure was flexural. However, this behavior dramatically changed after yielding point of control beam due to contribution of CFRP sheets. It is noticed that the maximum deflection of the strengthened beam in one side (R.1F-0°) is reduced by 37% and the maximum deflection of strengthened beam in one side and tension face (R.2F-0°) is reduced by 54% comparing with control (un-strengthened) beam (RL). As a result of that the effect of faces of strengthening on the deflection of beam is decreasing deflection of (R.1F-0°) about 16% when strengthened in two faces. Generally the use of externally bonded CFRP sheets can affect the deflection of the beams strengthened in tension face. Where the externally CFRP sheets in tension face reduce the mid span deflection because it is considered as an additional external tensile reinforcement and this reduction in deflection is attributed to the enhancement of beam stiffness and rigidity which results in significant reduction in deflection of beam. Finally, the percent increase in load carrying capacity for the beams (R.1F-0°) and (R.2F-0°) was equal to 24% and 43%, respectively.

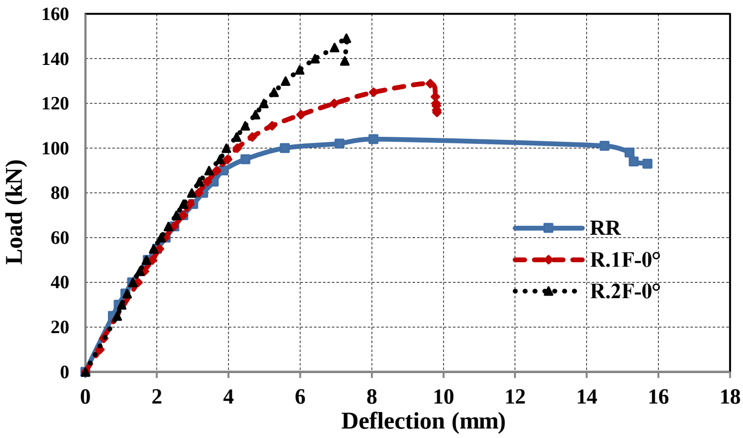

Figure (7): Effect of faces of strengthening on load-deflection behavior for rectangular beams strengthened with horizontal fiber direction

3.1.1.2. Beams strengthened with 90° fiber direction (vertical fiber direction)

Figure (8) shows the effect of faces of strengthening on load-mid span deflection curves for rectangular beams strengthened by CFRP sheets with vertical fiber direction in one face and two faces. It was noticed that close relationships for beams (RR), (R.1F-90°) and (R.2F-90°) until yielding point of control beams (RR). However, this behavior not changed significantly after yielding point due to contribution of CFRP sheets with vertical fiber direction not increase the effective section area to resisting compression. The maximum deflection of the strengthened beams in one face and two faces with vertical fiber direction (R.1F-90°) and (R.2F-90°) is increased by 48% and 52% respectively, comparing with control beam (RL). On the other hand, the beam (R.2F-90°) had an increase in maximum deflection of 3% compared to beam (R.1F-90°). This increasing in deflection may be attributed to the presence of the vertical CFRP sheets along beam span eliminated the development of diagonal tension cracks. Therefore, it was noticed that wide bending cracks in the middle third span length. Finally, the percent increase in load carrying capacity for the beams (R.1F-90°) and (R.2F-90°) was equal to 2% and 3%, respectively.

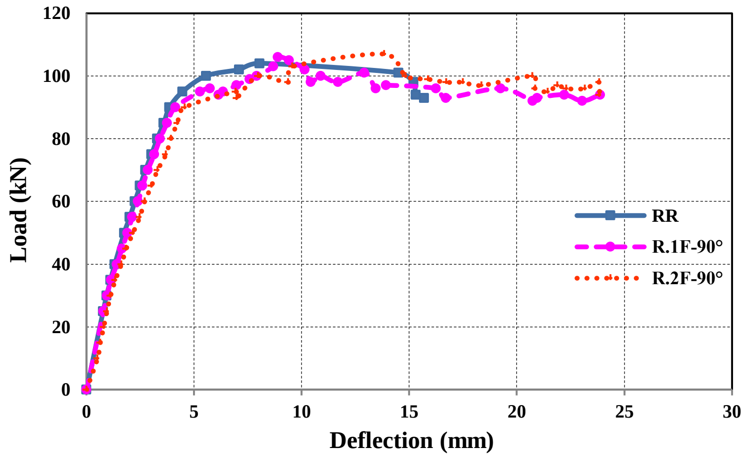

Figure (8): Effect of faces of strengthening on load-deflection behavior for rectangular beams strengthened by CFRP with vertical fiber direction

3.1.1.3. Beam strengthened by strips of CFRP sheets in two faces with vertical fiber direction:

Figure (9) shows the effect of strengthening by strips in two faces on load-mid span deflection curves for rectangular beams. The test results show that the load-deflection curves for beams (RR) and (R.ST.2F-90°) were approximately identical and had small different with (R.2F-90°). However, this behavior not changed significantly after yielding point due to contribution of CFRP sheets with vertical fiber direction not effected significantly on behavior of beam. It is observed that the deflection at failure of the beams (R.2F-90°) and (R.ST.2F-90°) is increased by 52% and 29% comparing with control beam (RR). Finally, the percent increase in load carrying capacity for the beams (R.2F-90°) and (R.ST.2F-90°) was equal to 3% and 2%, respectively.

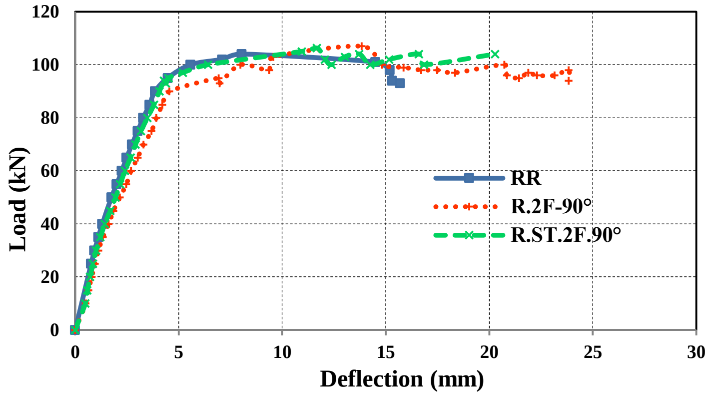

Figure (9): Effect of faces of strengthening on load-deflection behavior for rectangular beam strengthened by stirrups of CFRP with vertical fiber direction

3.1.2. Effect of fiber direction on load deflection behavior

3.1.2.1. Beams strengthened in one face with different fiber direction:

Figure (10) shows the effect of fiber direction on load-mid span deflection curves for rectangular beams strengthened in one side. The test results show that the load-deflection response at pre-yielding stage for beams (RR), (R.1F-0°) and (R.1F-90°) were almost identical until yielding point of control beams (RR). However, at yielding stage with anticipation of large contribution of CFRP sheets with horizontal fiber direction, beam (R.1F-0°) show differences in deflection behavior and strength with beam (R.1F-90°). It is noticed that the maximum deflection of beam (R.1F-0°) is reduced by 37%, while the maximum deflection of beam (R.1F-90°) is increased by 48% comparing with control (un-strengthened) beam (RR). Finally, the percent increase in load carrying capacity for the beams (R.1F-0°) and (R.1F-90°) was equal to 22% and 2%, respectively.

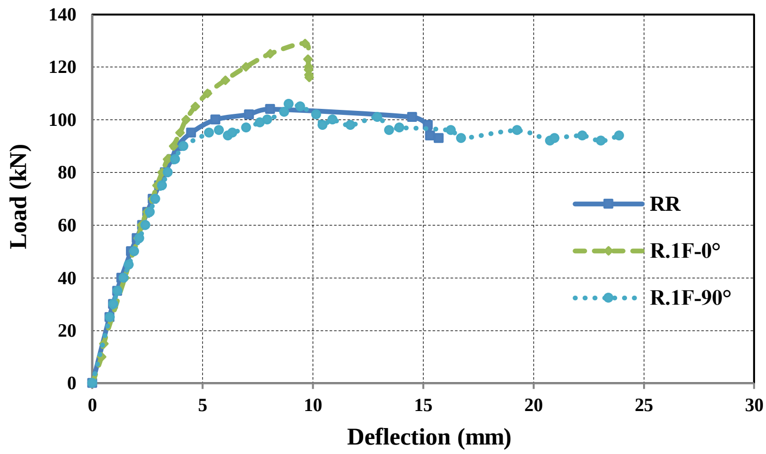

Figure (10): Effect of fiber direction on load-deflection behavior for rectangular beams strengthened by CFRP in one face

3.1.2.2. Beams strengthened in two faces with different fiber direction:

Figure (11) show the effect of fiber direction on load-mid span deflection curves for rectangular beams strengthened in two faces. The test results show that the load-deflection curves for beams (RR), (R.2F.0°) and (R.2F.90°) was approximately close from beginning with small different in deflection until yielding point of control beams (RR). However, this behavior dramatically changed for beam (R.2F.0°) after yielding point of control beam (post yielding stage) due to contribution of CFRP sheets. The behavior of beam (R.2F.90°) not changed significantly and continue align to control beam due to fiber direction that which is not effect significantly on behavior of RC beams. The maximum deflection of beam (R.2F-0°) is reduced by 54%, while the maximum deflection of beam (R.2F-90°) is increased by 52% comparing with control (un-strengthened) beam (RR). The percent increase in the load carrying capacity of beams (R.2F-0°) and (R.2F-90°) was equal to 43% and 3%, respectively.

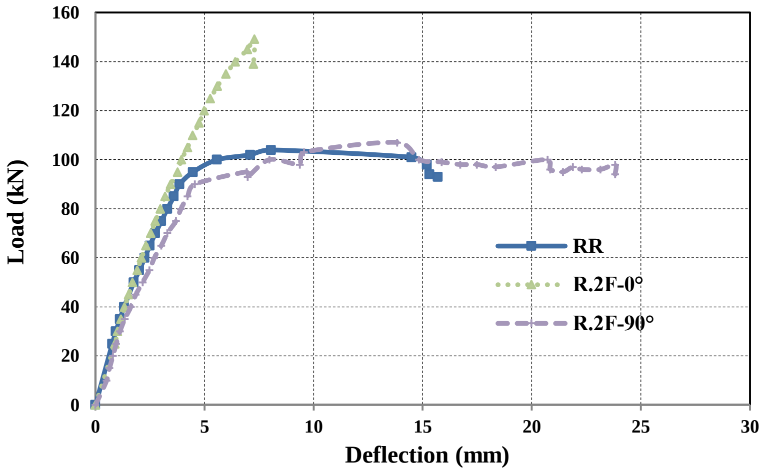

Figure (11): Effect of fiber direction on load-deflection behavior for rectangular beams strengthened by CFRP in two faces

4. Flexural ductility

Ductility can be defined is the ability of concrete members to sustain inelastic deformation before reach failure without significant loss in flexural strength. Ductility is important property added to strength and serviceability of concrete structures. It is important to avoid sudden failure and ensure concrete not fail in brittle manner without warning. The conventional method for measurement of ductility called a ductility index or (μ). The ductility index is calculated by dividing rotation (θ), curvature (ϕ) and deflection (Δ) at failure to the corresponding property at yield point of steel reinforcement **Grace et al (1999)**. To determine the ductility of RC beam in this study the yield point of steel reinforcement was represented as a reference point to determine the increase in the ductility. The ratio of deflection at failure to deflection at yield (Δfailure) / (Δyield) was used to calculate the ductility of beams. Table (12) presents the ductility index values of strengthened.

Table (12): Summary of ductility index values

Specimens	$\mu\Delta = \Delta u / \Delta y$	Difference*
RR	3.51	--
R.1F-0°	2.1	- 40 %
R.1F-90°	4.72	+34 %
R.2F-0°	1.3	- 63 %
R.2F-90°	4.85	+38 %
R.ST.2F-90°	4.14	+18 %

*Compared with beam RR

4.1. Effect of faces of strengthening on flexural ductility of (UnCSB)

4.1.1. Strengthened beams with horizontal fiber direction in each faces:

It can be noticed from Figure (12) that the strengthened beams in one face and two faces with horizontal fiber direction (R.1F-0°) and (R.2F-0°) exhibited 40% and 63%, respectively lower flexural ductility at failure than that of the control beam (RR). Moreover, the beam (R.2F-0°) had decrease in flexural ductility of 38% compared to (R.1F-0°).

4.1.2. Strengthened beams with vertical fiber direction in each faces:

Figure (12) shows that the strengthened beams in one face and two faces with vertical fiber direction (R.1F-90°) and (R.2F-90°) exhibited 34% and 38% respectively, higher flexural ductility at failure than that of the control beam (RR). Moreover, the strengthened beam (R.2F-90°) had an increase in flexural ductility of 3% compared to (R.1F-90°).

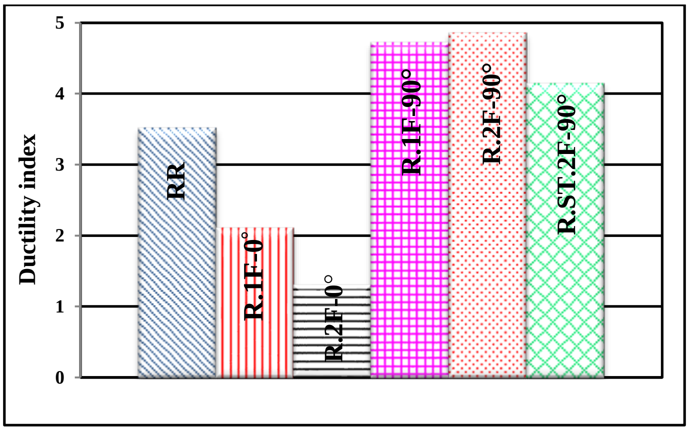

Figure (12): Effect of faces of strengthening on flexural ductility of strengthened beams with different fiber direction

4.2. Effect of fiber direction on flexural ductility of (UnCSB)

4.2.1. Strengthened beams in one face with different fiber direction:

It can be noticed from Figure (13) that the strengthened beams with vertical fiber direction exhibited higher flexural ductility at failure than that of the beams strengthened with horizontal fiber direction. The strengthened beam in one face with horizontal fiber direction (R.1F-0°) had decrease in flexural ductility of 56% compared to beam strengthened in one face, but with vertical fiber direction (R.1F-90°).

4.2.2. Strengthened beams in two faces with different fiber direction:

Figure (13) shows that the strengthened beam in two faces with horizontal fiber direction (R.2F-0°) had decrease in flexural ductility of 73% compared to beam strengthened in two faces, but with vertical fiber direction (R.2F-90°) and 69% compared to strengthened beam by stirrups of CFRP sheets in two faces with vertical fiber direction (R.ST.2F-90°).

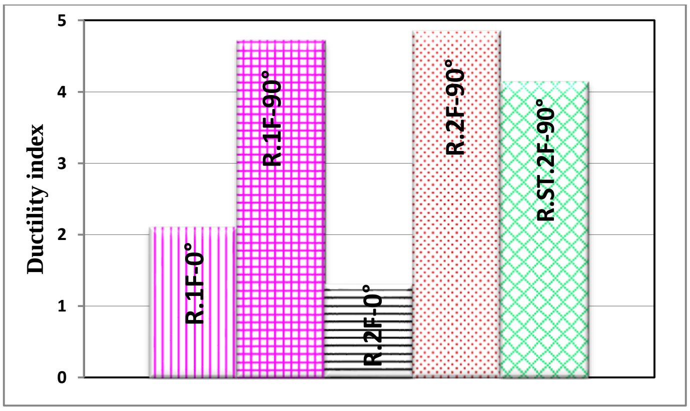

Figure (13): Effect of fiber direction on flexural ductility of strengthened beams with different faces

5. Flexural toughness

Toughness of reinforced concrete beams, representing the ability of beam to absorb energy. The flexural toughness is calculated as the area under load-deflection curve from the origin to the failure. Table (13) represents the values of flexural toughness for strengthened beams with various configurations.

Table (13): Flexural toughness values of beams

Specimens	Flexural toughness (N.mm)
RR	1389100
R.1F-0°	883540
R.1F-90°	2058230
R.2F-0°	637050
R.2F-90°	2133330
R.ST.2F-90°	1849410

It can be observed from Table (13) that the strengthened beams with horizontal fiber direction exhibited lower flexural toughness than that of the control beam. On the other hand, the strengthened beams with vertical fiber direction exhibited higher flexural toughness than that of control beam. The strengthened beams R.1F-0° and R.2F-0° had decrease in toughness of 36% and 54%, respectively compared to control beam. The strengthened beams R.1F-90°, R.2F-90° and R.ST.2F-90° had an increase in flexural toughness of 48%, 54% and 33%, respectively compared to control beam.

6. Crack pattern and failure modes

In all RC beams when the load is applied the first cracks noticed in the middle third of the span length. When the load was increased more the current cracks get widened, while new cracks started to form. The control beams (RR) is failed by yielding of main reinforcement followed by concrete crushing at the beam mid-span, as shown in Figure (14). The strengthened beams (R.1F-0°) and (R.2F-0°) failed by yielding of main steel reinforcement followed by debonding between the concrete substrate and CFRP composite sheets, as shown in Figure (15) and (16). The failure mode and crack pattern for the beams (R.1F.90°), (R.2F.90°) and (R.ST.2F.90°) are similar to the control beam except that the load at collapse in the strengthened beams was more than the reference beam. Where, the failure occurs by yielding of main steel reinforcement followed by concrete crushing at mid span. The cracks were observed to be wide in the middle third of the span length, distributed non-uniformly and quickly propagated compared with beams that strengthened with horizontal fiber direction, due to presence of CFRP sheets transverse to beam axis and it has not restraining effect, as shown in Figures from (17) to (19).

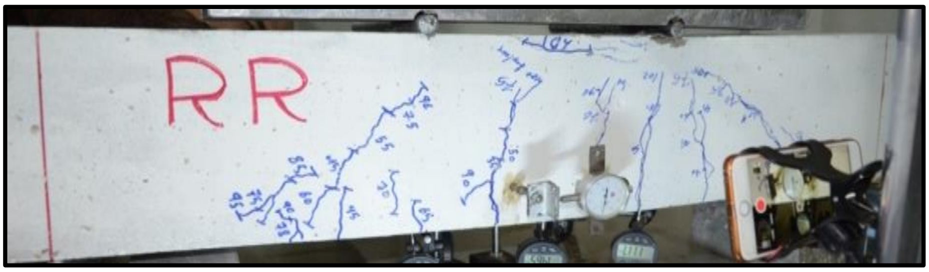

Figure (14): Crack pattern of beam (RR)

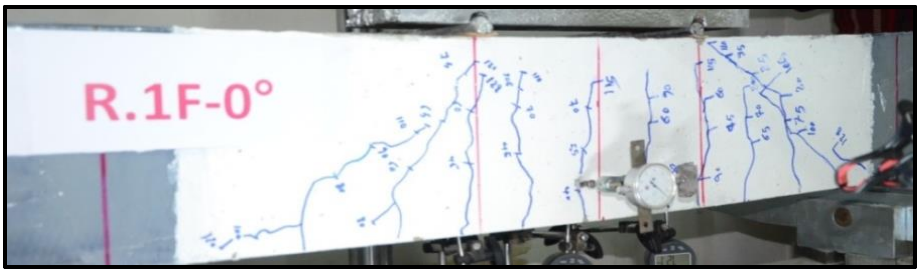

Figure (15): Crack pattern of beam (R.1F-0°)

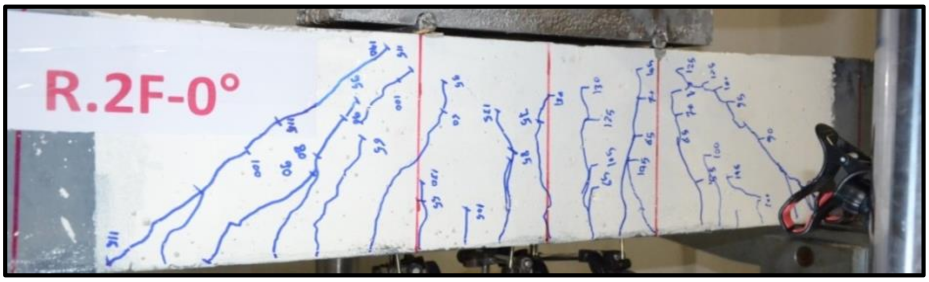

Figure (16): Crack pattern of beam (R.2F-0°)

Figure (17): Crack pattern of beam (R.1F-90°)

Figure (18): Crack pattern of beam (R.2F-90°)

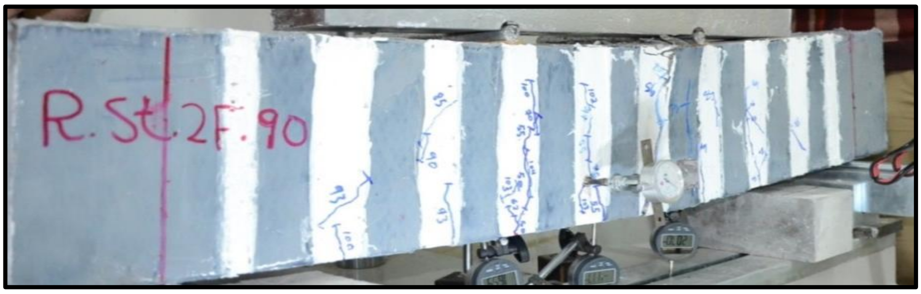

Figure (19): Crack pattern of beam (R.ST.2F-90°)

7. Conclusions

1) All beams exhibited a higher load carrying capacity compared with their respective control beams, due to restraining effect of CFRP sheets. The load capacity was increased in the range of 2 - 43%.
2) The strengthening of beams using CFRP sheets with 0° fiber direction is found to be more effective in increasing the load bearing capacity, but the flexural ductility was reduced significantly. The maximum decrease in flexural ductility was 63%.
3) The test results showed that strengthening beams with 90° fiber direction not effect significantly on load bearing capacity, but increased beams ductility. The maximum increase in flexural ductility was 38%.
4) The load deflection response was not affected by faces of strengthening at pre-yielding stage for all beams, but this behavior changed at post yielding stage for beam strengthened with horizontal fiber direction.
5) It can be noticed from the experimental test results that the strengthened RC beams with horizontal fiber direction exhibited lower flexural toughness than that of the control beam. In contrast, the strengthened beams with vertical fiber direction exhibited higher flexural toughness. The higher increase and decrease in flexural toughness was 54%.
6) The flexural ductility improved with un-symmetrical strengthening if compared with full wrapping or U-jacket.

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