LOAD-DEFLECTION BEHAVIOR OF REINFORCED CONCRETE BEAMS STRENGTHENED WITH CFRP SHEETS

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Abstract :

In this study experimental investigation of the deflection control of R.C. beams strengthened using continuous Carbon Fiber Reinforced Polymer (CFRP) sheets is carried out. The test results show that the strengthening with (CFRP) sheet has a significant effect on the load-deflection response by increasing beam stiffness especially beyond the precracking stage. By using (CFRP), the maximum deflection is decreased by (26.7%) in comparison with control beam. The effect of Span to depth ratio has also an important role in the control of deflection. The reduction of (Span/Depth) ratio from (20) to (15, 12.5 and 10) will reduce the maximum deflection by (21%, 30.3% and 41.6%) respectively. The test results show the load-deflection response has not been affected significantly by increasing the steel reinforcement ratio at the pre-cracking stage. However, this behavior is dramatically changed at the cracking stage, by increasing steel reinforcement ratio of ($2\times\rho_{min}$) and (ρ_{max}) as compared with (ρ_{min}), the maximum deflection is reduced by (13.5% and 29.2%) respectively. Also the load-deflection response is not affected by the grade of steel reinforcement at the cracking stage. After the cracking stage with the anticipation of large contribution of tension reinforcement, the beam reinforced with steel of yield stress equal to (460 MPa) shows a difference in deflection with the beam reinforced with steel of yield stress equal to (300 MPa), the increment in the ultimate deflection is (23.8 %).

Keywords: Strengthening, Deflection, CFRP sheet, Concrete Beam, Span to Depth ratio**.**

تصرف الهطول مع التحميل في العتبات الخرسانية المسلحة المقواة بألياف الكاربون

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الخلاصة :

في هذه الدراسة تم أجراء تحريات عملية للسيطرة على الهطول في العتبات الخرسانية المسلحة والمقواة بصفائح الكاربون. حيث بينت النتائج أن استخدام هذه الصفائح له تأثير كبير على هذا التصرف اذ أن الهطول الاقصى قد ازداد بمقدار (26,7 %) للعتبة المقواة بالكاربون مقارنة بعتبة السيطرة والتي لم يتم تقويتها. أما بالنسبة لتأثيرنسبة

(طول العتبة/سمكها) فله تأثير مهم أيضاً في السيطرة على هطول العتبة، فعند تقليل هذه النسبة من (20) الى (15و 12,5 و10) فأن الهطول الاقصى يقل بمقدار (21 %، 30,3 % و 41,6 %) على التوالي. وقد بينت النتائج أن تصرف الهطول مع الحمل المسلط للعتبات لا يتأثر بكمية الحديد المستخدم خلال مرحلة ما قبل تشقق الخرسانة ولكن هذا السلوك يتغير بصورة ملحوظة عند تشقق الخرسانة حيث كانت نسبة النقصان في الهطول الاقصى لكل من العتبتين اللتين تم تسليحهما بكمية حديد ($2\times\rho_{min}$ و ρmax) بمقدار (13,5 % و 29,2 %) عل التوالي. أما بالنسبة لصنف حديد التسليح المستخدم فأن ليس له أي تأثير على تصرف الهطول مع الحمل المسلط خلال مرحلة ما قبل تشقق الخرسانة ولكن ما بعد هذه المرحلة وعند مشاركة حديد التسليح في تحمل اجهادات الشد فأن لنوعية الحديد تأثير كبير على مقدار هطول العتبة الخرسانية وكما بينت نتائج فحص العتبة التي أحتوت على حديد تسليح ذو أجهاد خضوع بمقدار (460) نت/ملم^2 أن مقدار الهطول الأقصى يزداد بمقدار (23,8 %) مقارنة مع العتبة التي أحتوت على حديد ذو أجهاد خضوع (300) نت/ملم^2.

1. Introduction :

The initial development of the (FRP) strengthening technique with prefabricated laminates took place in Switzerland and Germany. The initial work on strengthened full-scale reinforced concrete beams by Meier and Kaiser [1] validated the strain compatibility method in the analysis of cross sections and suggested that inclined cracking (shear cracks) may lead to premature failure by peeling–off of the strengthening laminate at the crack. An analytical model for the composite plate anchoring, which agreed with the test results, was developed [1]. A comprehensive analytical and experimental study of the short-term flexural behavior of strengthened (FRP) reinforced concrete beams was carried out by Triantafillou and Plevris [2, 3]. They concluded that the flexural behavior of reinforced concrete beams strengthened with FRP laminates can be adequately described by the classical theory of plane-sectional analysis to predict the moment-curvature of the load deflection response at a specific section when premature peeling or de-bonding failure of the (FRP) is avoided. Assih et al [4] have subsequently validated these results.

Nawy and Neuwerth [5] studied the behavior of fiber glass reinforced concrete beams. This included a study of cracking, deflection, reinforcement stress, and ultimate load behavior of twenty tested beams reinforced with glass fiber rebars. They found that the beams reinforced with steel had fewer cracks than the corresponding beams reinforced with GFRP bars. At ultimate load, the deflection of the fiber glass reinforced beams was approximately three times greater than those of corresponding steel reinforced beams.

Larralde et al. [6] found that theoretical deflection predictions underestimated test results for loads above (50%) of ultimate; deflection values were fairly well predicted at load levels up to approximately (30%) of ultimate. The study suggested a procedure in which values of curvature calculated at different sections of the beam should be used to obtain a better estimate of deflection values. The present experimental work has been study the behavior of reinforced concrete rectangular beam strengthened with (CFRP).The strengthened R.C. beam with (CFRP) has been tested with three different variables, the variables are the (span/depth) ratio, the steel reinforcement ratio at tension face and the yield stress of the steel.

2. Experimental Program :

The experimental program consists of fabricating and testing eight simply supported rectangular section beams under the effect of single point load at mid-span. One concrete mix proportion (cement: sand: gravel) of (1: 2.1: 2.9) by weight, with W/C of (0.42), to produce concrete with cubic compressive strength equal to (32.5) MPa where is used to all beam specimens.

3. Materials :

3.1 Cement :

Ordinary Portland cement is used in all mixes throughout this investigation. It was stored in air-tight plastic containers to avoid exposure to atmospheric conditions. The percentage oxide composition indicated that the adopted cement conforms to the Iraqi specification No. 5/1984 [7]; **Tables (1)** and **(2)** show the physical and chemical properties of OPC.

Table (1) Chemical Composition of Cement

Compound composition (Oxides)	Chemical composition	Percentage by weight	Limits of IQS 5:1984(7)
Calcium Oxide	CaO	66.28	--
Silicon dioxide	SiO2	19.12	--
Iron oxide	Fe_2O_3	3.33	--
Aluminum oxide	Al_2O_3	6.41	--
Magnesium oxide	MgO	1.46	<5
Sulphor trioxide	SO_3	2.35	< 2.8
Lime saturation factor	L.S.F	0.92	0.66 – 1.02
Loss on Ignition	L.O.I	2.24	< 4
Insoluble residue	I.R	0.97	< 1.5
Tri-calcium silicate	C_3S	61.79	--
Di-calcium silicate	C_2S	8.53	--
Tri-calcium Aluminates	C_3A	10.39	--
Tetra-calcium aluminates ferrite	C_4AF	7.08	--

Table (2) Physical Properties of Cement

Properties	Test results	IQS 5: 1984 (7)
Fineness using Blaine air permeability apparatus (m^2/kg)	446	>230
Setting time using Vicat's Method Initial (hrs:min) Final (hrs: min)	 1:35 3:25	 >45 min <10 hrs
Soundness using Autoclave Method	0.09%	<0.80%
Compressive strength for cement 3 day 7 day	 25.7 34.9	 >15 >23

3.2 Coarse aggregate :

Rounded gravel of maximum aggregate sizes of (14) mm is used. **Table (3)** shows the grading of these aggregate, which conforms to the Iraqi specification No. 45/1984**[8]**.

Table (3) Grading of Course Aggregate

Sieve size (mm)	% passing by weight	Limits the of Iraqi specification No. 45/1984(8)
14	98	90-100
10	71	50-85
5	10	0-10
Pan	-	-

3.3 Fine aggregate :

Natural river sand is used for concrete mixes in this work. The fine aggregate has 4.75mm maximum size with rounded shape particles and smooth texture with fineness modulus of 2.75. The grading of the fine aggregate is shown in **Table (4).** The obtained results indicate that the fine aggregate grading and the sulfate content are within the limits of Iraqi Specification No.45/1984 [8].

Table (4) Grading of Fine Aggregate

Sieve size (mm)	% passing by weight	Limits of Iraqi specifications No. 45/1984 (Zone 2)(8)
10	100	100
4.75	96	90-100
2.36	83	75-100
1.18	70	55-90
0.60	55	35-59
0.30	18	8-30
0.15	4	0-10
Fineness of Modulus = 2.74		

3.4 Steel Reinforcement :

Deformed steel bars of diameters (4, 5, 6 and 8) mm have been used for the main reinforcement also deformed steel bars of diameter (4 mm) are used for stirrups.The bars are tested to determine the yield stress, ultimate stress and elongation. The test has been carried according to ASTM A615 / A615M [9]. Properties of the steel bars and results obtained from the test are present in **Table (5).**

Table (5) Properties of Steel Bars

Nominal deformed bar Diameter (mm)	Modulus of Elasticity (Es) (GPa)*	Elongation (%)	Yield Stress (fy) (MPa)	Ultimate Stress (fu) (MPa)
4	200	7.6 %	306	412
4	200	8.6 %	462	548
5	200	8.6 %	460	540
6	200	8.6 %	453	540
8	200	9.2 %	464	550

***Theoretical Value of Steel Modulus of Elasticity.**

3.5 CFRP Sheet :

Carbon fiber fabric (Sika Wrap Hex-230 C) and epoxy based impregnating resin (Sikadur-330). **Tables (6)** present the technical data of the carbon fiber fabric used in the experimental work of the resent study.

Table (6) Sika Wrap Hex-230C (Carbon Fiber Fabric)*

Fiber Type	High strength carbon fibers
Fiber Orientation	0° (unidirectional). The fabric is equipped with special weft fibers
Construction	Warp: carbon fibers (99% of total areal weight)
Areal Weight	230 g/m^2
Fiber Density	1.76 g/cm^3
Fabric Thickness	1 mm (based on total area of carbon fibers)
Tensile Strength of	4300 MPa
Tensile Modulus	238000 MPa
Elongation at Break	1.5 %
Fabric Length/Roll	≥ 50 m
Fabric Width	300/600 mm

***** *Provided by the Manufacturer***

4. Fabrication and Details of Specimens:

In the present experimental work, the detail design of the beams is according to ACI 318-08[10] code. Four wooden molds are used in the fabrication of beams. Eight simply supported beams are used with 2m span length. One of these beams is reference beam (B1), where is without (CFRP) strengthening, the others seven tested beams are strengthened with (CFRP) sheet. Total depths (h) values are (100, 133, 160 and 200 mm) have been used for the test beams.

All beams are reinforced with minimum steel ratio (ρ min) except beams (B6) and (B7), have reinforced with (2×ρmin) and (ρmax) respectively. The minimum and maximum steel reinforcement as per ACI 318-08 [10] building Code have been used in the present experimental work. The geometric configuration, element designation, dimensions and reinforcement details of the tested beams are shown in **Table (7).** For strengthened beams, (CFRP) has been placed at the tension face (bottom) for the tested beams.

Table (7) Beam Specimen Properties

Beam ID	Section (b_w× h) (mm)	Reinforcement Ratio (ρ)	Using of (CFRP)
B1	100×133	ρ_{min}	Un-strengthened
B2	100×100	ρ_{min}	Strengthened
B3	100×133	ρ_{min}	Strengthened
B4	100×160	ρ_{min}	Strengthened
B5	100×200	ρ_{min}	Strengthened
B6	100×133	2×(ρ_{min})	Strengthened
B7	100×133	ρ_{max}	Strengthened
B8	100×133	ρ_{min}	Strengthened

5. Testing Program :

5.1 Compressive Strength

Standard cubes (150 mm) were used according to BS 1881: part 2 [11] and they are demolded one day after casting. Testing is carried out at (28) days. The machine which is used in the tests is a hydraulic type of (3000) kN capacity.

5.2 Testing of the Beams

5.2.1 Beam Setup

The beams are tested under one point load at mid-span as shown in **Figure (1),** the beams are supported on roller bearing acting on similar spreader plates. The beam specimen is placed over the two steel rollers bearing leaving 100 mm from the ends of the beam. Two number of dial gauges are used for recording the deflection of the beams, the two dial gauges are placed just below the center of the beam to measure deflections, as shown in **Plate (1).**

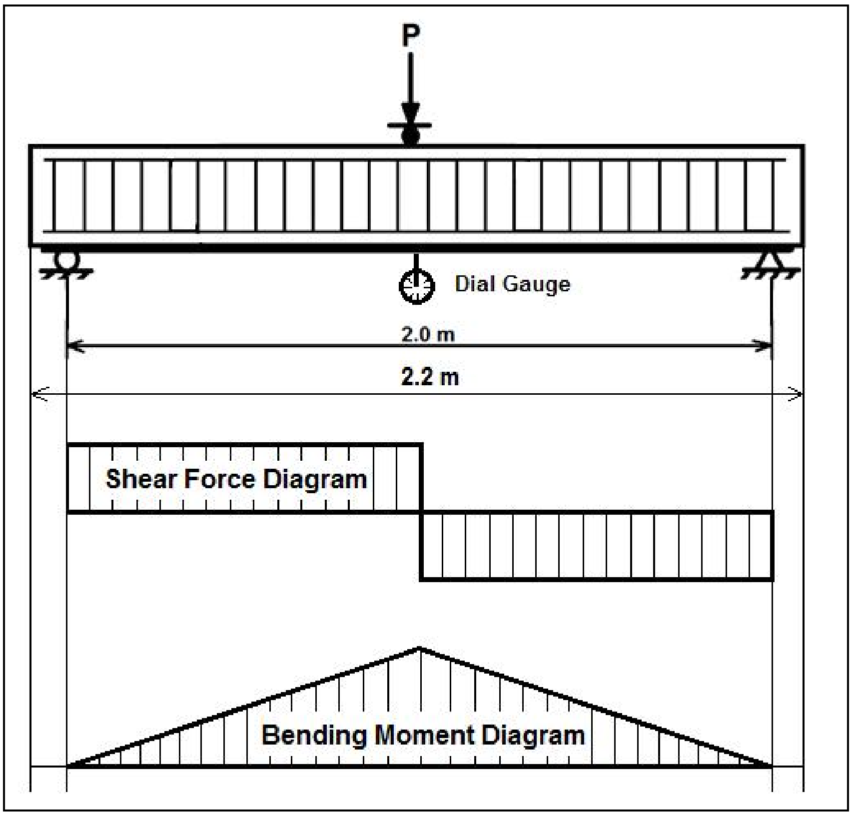

Fig. (1) Shear Force and Bending Moment Diagram of One Point Loading

Plate (1) Two Dial Gauges are Below the Center of Beams

5.2.2 Test Procedure

Before testing beams are checked dimensionally, and detailed visual inspection made with all information carefully recorded. After setting and reading dial gauges, the load is increased steadily by (2 kN) increments up to failure with loads and deflections recorded. Cracking observations are suspended as failure approaches unless special safety precautions are taken also dial gauges replacement is necessary to avoid them damage when approaching beam collapse, failure mode is also carefully observed.

6. Results and Discussions :

6.1 Compressive Strength

Table (8) shows the nominal and the measured of cubic compressive strength for concrete mixes. This strength was obtained from the average of six concrete cubes cast with every concrete mixture, and tested at the same age as the beam specimen.

Table (8) Test Results of Control Specimens

Mix	Nominal Compressive Strength (f_{cu}) (MPa)	Measured Compressive Strength (MPa)
A	30	34.6
		30.8
		33.5
B	30	28.4
		33.8
		34.1

6.2 Load-Deflection Behavior

The load-Deflection behavior for all beams is shown in **Figure (2)**. The load-deflection figures showed a different deformation and behavior under load for all beams, thus beam specimens had been made with three variables (Span/depth ratio, steel reinforcement ratio and steel grade) were tested to the ultimate load capacity in order to investigate deflection behavior in this study, **Table (9)** shows the test results of all beams.

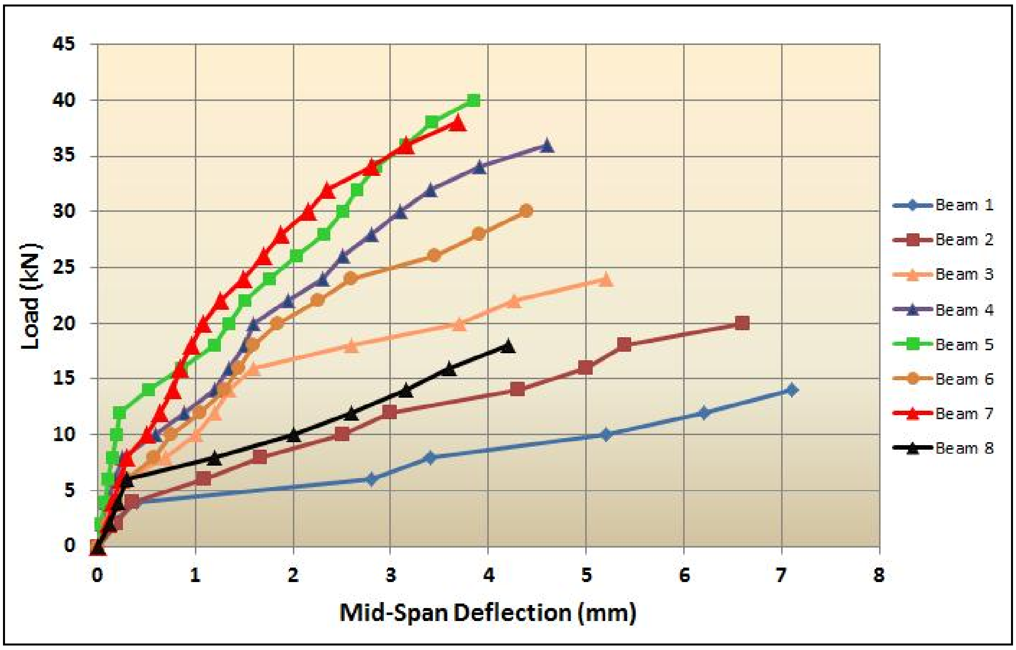

Fig. (2) Load – Deflection Curves for All Beams

Table (9) Beams Test Results

Beam ID	Load at Cracking (kN)	Ultimate Load (kN)	Deflection at Cracking (mm)	Max. Deflection (mm)
B1	3	15	0.4	7.1
B2	2	23.5	0.35	6.6
B3	4	27.5	0.3	5.2
B4	6.5	39.5	0.26	4.6
B5	8.5	43.5	0.23	3.85
B6	4.5	35.5	0.3	4.5
B7	5	42.5	0.28	3.68
B8	3.5	22.5	0.3	4.2

6.3 Effect of CFRP Strengthening on Load-Deflection Behavior

The load deflection response of unstrengthened beam (B1) and the (CFRP) strengthened beam (B3) is shown in **Figure (3).** The test results show that the using of (CFRP) is increases the tensile bending component of beam (B3) by (83 %) comparing with beam (B1) at collapse. On the other hand the ultimate deflection of beam (B3) is reduces by (26.7 %) comparing with beam (B1).

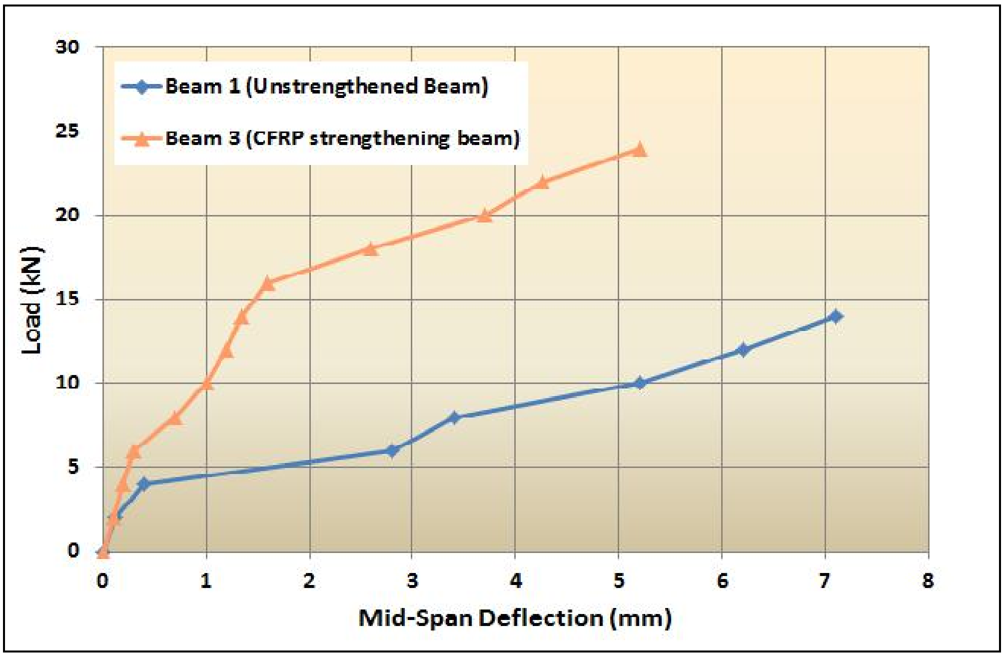

Figure (3) Effect of (CFRP) Strengthening on Load-Deflection Behavior

6.4 Effect of (Span/Depth) Ratio on the Load-Deflection Behavior

Figure (4) shows the load-deflection curves for four beams (B2, B3, B4 and B5) which have different (Span/Depth) ratios (20, 15, 12.5 and 10) respectively, in addition to the control beam (B1). According to the ACI 318-08[4] requirements for deflection, the maximum (Span/Depth) ratio of simply supported beam is (16). For beam (B2) which has a (Span/Depth) ratio more than the maximum, the test results show that this beam has the same un-cracked stiffness compared with the control beam (B1), however an reduction by (7 %) in the maximum deflection of beam (B2) comparing with beam (B1) can be observed from **Figure (4)**. This reduction is due to the effect of (CFRP) strengthening, while the comparisons of deflection for other beams with beam (B2) are as below:

- The increasing the total depth of the beams will reduce the maximum deflection by (21%, 30.3% and 41.6%) for (B3, B4, and B5) respectively.

- Also by increasing the total depth, maximum load capacity is increased by (17%, 68 % and 85%) for (B3, B4, and B5) respectively.

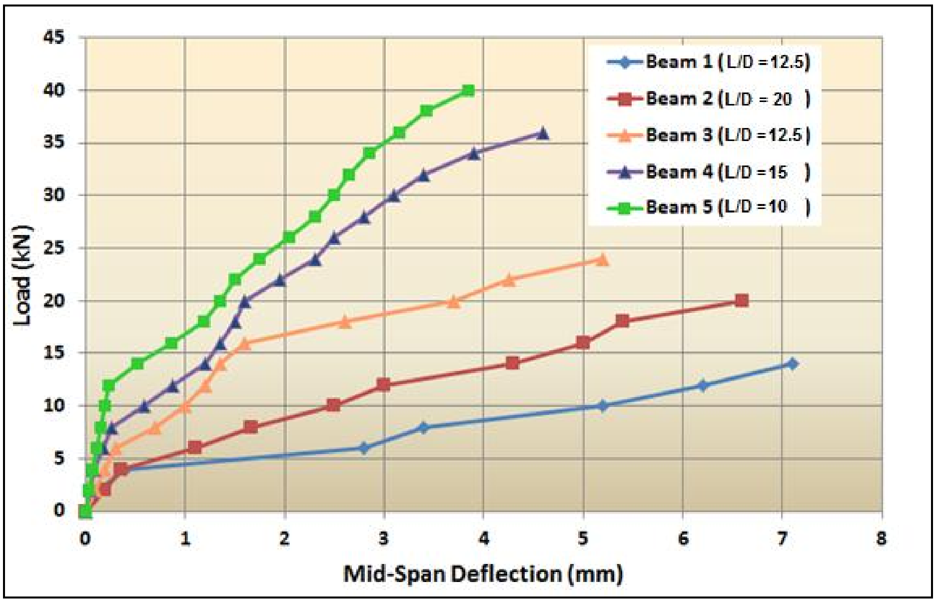

Figure (4) Effect of Beam (Span/Depth) Ratio on Load-Deflection Behavior

6.5 Effect of Steel Reinforcement Ratio on the Load-Deflection Behavior

Figure (5) shows the load-deflection curves for four beams (B3, B6 and B7) which have different tension steel ratio (ρ_{min} , 2× ρ_{min} and ρ_{max}) respectively, in addition to the control beam (B1), where reinforced with (ρ_{min}) to obtain the effect of steel reinforcement ratio on the deflection behavior. The test results show the load-deflection response is not affected by increasing the steel amount at the pre-cracking stage, however this behavior is dramatically changed at the cracking stage due to the contribution of steel reinforcement in the cracked moment of inertia (I_{cr}), so by increasing tensile steel ratio of B6 and B7 comparing with B3, the maximum deflection is reduced by (13.5% and 29.2%) for B6 and B7 respectively. Also the ultimate load capacity is increased by (29% and 54.5%) for B6 and B7 respectively.

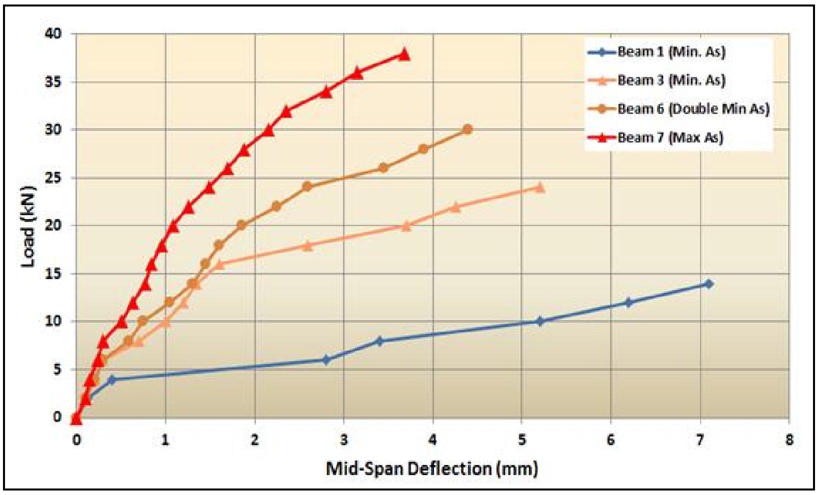

Figure (5) Effect of Tension Steel Ratio on Load-Deflection Behavior

6.6 Effect of Yield Stress of Steel on the Load-Deflection Behavior

Two beams (B3 and B8) are made to investigate this effect, where two values of yield stress of steel reinforcement are used (300 and 460) MPa for beams (B3 and B8) respectively, **Figure (6)** shows the effect of yield stress of steel on the load-deflection response.

The response of the two beams at the pre-cracking stage is identical. However at the cracking stage and with the anticipation of large contribution of tension reinforcement, beam (B3) shows a difference in deflection and strength with B8, the increment in the maximum deflection and ultimate load capacity of beam (B3) are (23.8 % and 22%) respectively. The experimental load-deflection curve of beam (B3) shows three clear stages of response (pre-cracked, cracked and post-yield up to failure), while beam (B8) shows only two stages (pre-cracked and cracked up to failure) as shown in **Figure (6).** This behavior of beam (B8) may be due to the effect of (CFRP) strengthening which have an ultimate tensile stress closes to the ultimate tensile stress of the steel reinforcement in beam (B8) and that could produce a constant stiffness up to beam failure.

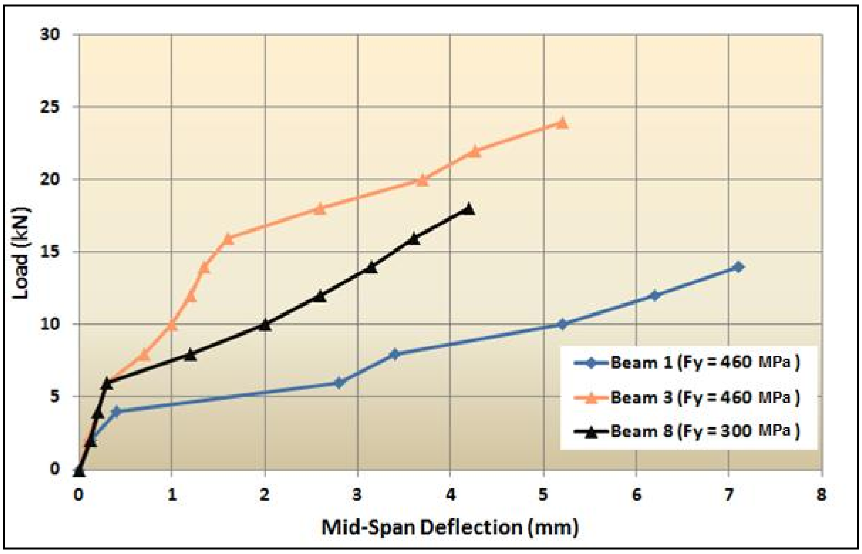

Figure (6) Effect of Yield Stress of Steel on Load-Deflection Behavior

7. Conclusions :

On the basis of eight beams described in the text, measuring load-deflection behavior of (CFRP) strengthening and some factors that affecting this behavior and the mode of all beams. The load at initial cracking and ultimate load carrying capacity is also described and the main conclusions can be summarized, as follows:

1. The strengthening with (CFRP) sheet has a significant effect on the load-deflection response by increasing beam stiffness especially beyond the precracking stage. By using (CFRP), the ultimate deflection is decreased by (26.7 %) and the ultimate load capacity is increased by (83%).

2. Span to depth ratio has also an important role in control of deflection; the comparisons of deflection for beams (B3, B4 and B5) with (B2) are as below:
   - The decreasing the (Span/Depth) ratio of the beams will reduce the maximum deflection by (21%, 30.3% and 41.6%) for (B3, B4, and B5) respectively.
   - Also by decreasing the (Span/Depth) ratio of the beams, the maximum load capacity is increased by (17%, 68 % and 85%) for (B3, B4, and B5) respectively.

3. The load-deflection response is not affected by increasing the steel amount at the pre-cracking stage, however this behavior is dramatically changed at the cracking stage, by increasing tensile steel ratio of B6 and B7 comparing with B3, the maximum deflection is reduced by (13.5% and 29.2%) for B6 and B7 respectively. Also the ultimate load capacity is increased by (29% and 54.5%) for B6 and B7 respectively.

4. The load-deflection response is not affected by the grade of steel reinforcement at the pre-cracking stage. However after the cracking stage and with the anticipation of large contribution of tension reinforcement, beam (B3) (fy = 460 MPa) shows a difference in deflection and load carrying capacity with beam B8 (fy = 300), the increment in the ultimate deflection is (23.8 %) and the reduction in ultimate load capacity is (22%) for beam (B3) comparing with beam (B8).

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