Journal of Babylon University/Engineering Sciences/ No.(5)/ Vol.(21): 2013

Experimental and Theoretical Analysis for Behavior of R.C. Continuous Beams Strengthened by CFRP Laminates

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Abstract

This research presents an experimental program conducted to study the flexural behavior of reinforced concrete continuous beams strengthened by carbon fiber reinforced polymer (CFRP) sheets. The test program consists of nine RC continuous (two-span) beams each span has length 1500mm with cross section 150x250 mm divided into two groups. The first group has six continuous RC beams with roller support in the ends. The second group has three continuous RC beams with rigid joint ends supports (jointed to columns in the ends). All the reinforced concrete beam specimens were designed of the same steel reinforced identically to fail in flexure under static load .The main parameters including type of end support, location of the CFRP sheets and type of end anchorage for CFRP. The experimental results showed that the externally strengthened reinforced concrete beams with bonded CFRP sheets showed significant increases in their ultimate loads. An increase in ultimate load reached up to (42.1 % for group 1 and 35.18 % for group 2). The CFRP anchor is very effective more than the U-warp in increasing ultimate load and reduced beams deflection.

Three-dimensional nonlinear finite element analysis is used to investigate the performance of reinforced concrete continuous beams strengthened with CFRP sheets. The results obtained from the finite element analysis show very good agreement with the results obtained from the experimental study with maximum difference in ultimate loads is about (10 %).

الخلاصة

قدم هذا البحث دراسة عملية لدراسة سلوك الانحناء للاعتاب الخرسانية المسلحة المستمرة المقواة بالياف الكاربون البوليمرية (CFRP). الدراسة العملية تشمل تسعة اعتاب خرسانية مسلحة مستمرة (من فضائين) كل فضاء له طول 1500 مليمتر بالمقطع العرضي 150x 250 مليمتر قسم إلى مجموعتين. المجموعة الأولى لها ستة أعتاب خرسانية مسلحة مستمرة مسندة في النهايات بالدحروجة (roller support).المجموعة الثانية لها ثلاثة اعتاب خرسانية مسلحة مستمرة بمساند ثابتة في النهايات (مربوط الى اعمدة في النهايات).جميع نماذج الاعتاب الخرسانية المسلحة كانت مصممة لحديد التسليح بشكل مماثل للفشل في الانحناء، المتغيرات الرئيسية تتضمن حالة الاسناد في النهايات، موقع شرائح الياف الكاربون البوليمرية ونوع الارساء في النهايات لالياف الكاربون. اظهرت النتائج العملية بان الاعتاب الخرسانية المقواة خارجيا بشرائح الياف الكاربون البولمرية ابدت زيادات هامة في الاحمال القصوى. الزيادة في الحملِ الاقصى وصلت إلى (42.1 % للمجموعة الاولى و35.18 % للمجموعة الثانية). ان الارساء بالياف الكاربون البولمرية (CFRP anchor) فعال جداً أكثر من التثبيت العرضي (U–warp) في زيادة الحمل النهائي وتقليل هطول الاعتاب.

استخدم التحليل اللاخطي الثلاثي الابعاد بطريقة العنصر المحدد لتحري أداء الاعتاب الخرسانية المسلحة المستمرة بشرائح الياف الكاربون البولمرية . النتائج التي حصل عليها من التحليل بطريقة العنصر المحدد بينت توافق جيد مع النتائج التي حصل عليها من الدراسة العملية . الاختلاف الاقصى في الاحمال القصوى يساوي تقريبا (10%).

1. Introduction

Although many in-situ RC beams are continuous construction, there has been very limited research into the behavior of such beams with external reinforcement. In addition, most design guidelines were developed for simply supported beams with external FRP laminates. Ductility is even more important for statically indeterminate structures, such as continuous beams, as it allows for moment redistribution through the rotations of plastic hinges. Moment redistribution permits the utilization of the full capacity of more segments of the beam (1).

Many researchers reported that the use of carbon fiber reinforced polymer (CFRP) has very significant in upgrading the weakness structure. The effects of concrete compressive strength, anchorage depth, size of anchor hole, and width of CFRP sheet per anchor on the tensile capacity of anchors are studies **(2, 3)**. Peeling failure was the dominant mode of failure for all the strengthened beams tested. The beam strengthened with both top and bottom CFRP plates produced the highest load capacity. The load and moment capacities were increased by up to 55% and 57% respectively **(4)**. The ductility of all strengthened beams was reduced compared with that of the respective unstrengthened control beam and found out that increasing the CFRP sheet length to cover the entire negative or positive moment zones did not prevent peeling failure of the CFRP laminate**(5)**. The continuity tests found that beams without continuous reinforcement can reach catenary action (depending on design details) and a CFRP retrofit, if designed correctly (placed in locations that do not cause rebar fracture before catenary), may be able to reduce vulnerability to progressive collapse**(6)**. FRP application at positive and negative moment's zones generally reduces the redistribution ratio by approximately 20% (one sheet) up to 50% (four sheets) **(7)**. The test results showed that the use of GFRP sheet in strengthening of continuous beam reduced loss in ductility and moment redistribution but did not significantly increase the ultimate strength of them. The use of end anchorage in strengthened continuous beams increased the ultimate strength and moment redistribution. The moment enhancement ratio of the strengthened continuous beams was significantly higher than the ultimate load enhancement ratio in the same beam **(8)**. **Resheq (9)** studied sixteen RC continuous beams, which were strengthened at some locations with CFRP laminates and carefully designed to fail in flexure, the results show that the use of CFRP laminate as external strengthening has a significant increases in their ultimate loads.

2. Experimental program

2.1 Description of Specimens

Nine beams divided into two groups. The first group has six continuous RC beams with roller support in the ends consist of two span with length 1500mm for each span and rectangular cross sectional dimensions of 250 mm overall depth and 150 mm width . The flexural reinforcement of the beams consisted of 2Ø12 mm bars at the top and 2Ø10 mm bars at the bottom and Ø10mm diameter closed stirrups spaced at 100mm along the beam length and the steel bar had a 90º hook of length (12xØ=120mm) at each ends to provide sufficient anchorage. Concrete cover of 25 mm was adopted. The second group has Three RC continuous beams with rigid joint ends supports consist of two spans have length 1500mm for each span with rectangular cross sectional dimensions of 250 mm height by150 mm width and two columns in the ends have length of 750mm with square cross section dimensions of (300 x 300) mm). To provide rigid joint ends used six bolts in each column for tightening it to the steel column. The flexural reinforcement of the beams consisted of 2Ø12 mm bars at the top and 2Ø10 mm bars at the bottom and Ø10mm diameter closed stirrups spaced at 100mm along the beam length and the steel bar had a 90º hook of length 250mm at each ends to provide sufficient anchorage. The steel reinforcement of the columns consisted of 6Ø16mm bars for each column and Ø10mm diameter ties spaced at 100mm along the column length. Concrete cover of 25 mm was adopted.

2.2 CFRP Strengthening System

Strengthening system chosen carefully according to some considerations, mainly, crack pattern around moment's regions, practical applied in the actual and economic. The six continuous reinforced concrete beams of first group including, the first (**P**) serve as a pilot to ensuring flexural failure, the second (**B1**) was kept without strengthening as a control beam for comparison and four beams are strengthened with externally bonded CFRP sheets and all the external anchorages (**B2**, **B3**, **B4**, **B5**) used in this study were made from CFRP sheets at the end of longitudinal CFRP sheet as described in ***tabel 1*** and shown in ***Figure 1***. The three continuous reinforced concrete beams of second group including, the first one was kept without strengthening as a control beam for comparison (**BF1**) and two beams (**BF2**, **BF3**) are strengthening with externally bonded CFRP sheets and all the external anchorages used in this study were made from CFRP U-shape the end of longitudinal CFRP sheet as described in ***tabel 1*** and shown in ***Figure 1***.

Table 1 Description of the tested beams

Beam's Symbol	CFRP Locations	Type of Anchorage
B1	Nil	Nil
B2	At top face of beam at the negative zone and bottom face of beam at the positive zones.	U-warp
B3	At side face of beam at the negative zone and bottom face of beam at the positive zones.	U-warp
B4	At top face of beam at the negative zone and bottom face of beam at the positive zones.	CFRP anchor
B5	At side face of beam at the negative zone and bottom face of beam at the positive zones.	CFRP anchor
BF1	Nil	Nil
BF2	On top face of beam at the negative zones and bottom face of beam at the positive zones.	U-warp
BF3	On side face of beam at the negative zones and bottom face of beam at the positive zones.	U-warp

Two CFRP anchors in each end of longitudinal CFRP sheet have 250mm length of the anchor with 100mm of the anchor inserted into a 10mm.-diameter-hole drilled into concrete and the rest of the anchor was spread out in a fan shape on the CFRP sheet, 100mm width and 0.131mm thickness.

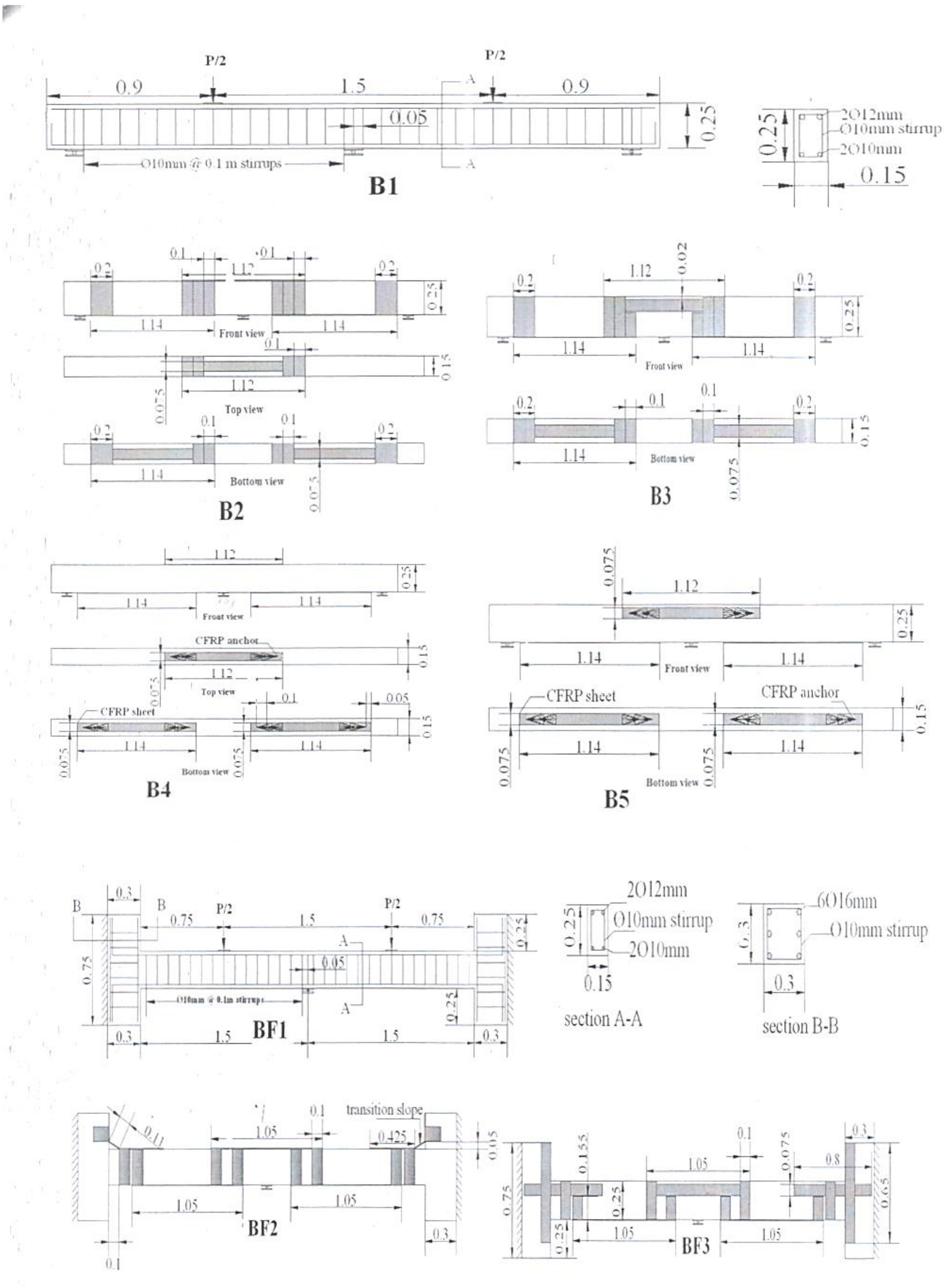


Figure 1 Detail and Geometry of Specimens (All Dimensions in meter)

2.3 Material Properties

Normal weight concrete was used to cast the specimens. The 28-day concrete compressive strength was 28 MPa and the splitting (tensile) strength was 2.5 MPa. The longitudinal steel reinforcement deformed has a 520 and 580 MPa yield stresses for Ø10mm and Ø12mm respectively. A CFRP sheet has a tensile strength of 4.3 GPa, an modulus of elasticity of 238 GPa, the elongation at break of 1.8% and the thickness of 0.131 mm **[Sika, 2005] (10)**.

2.4 Test Setup

Tests were carried out using (1500 kN) hydraulic testing machine as shown in ***Figure 2***. A convenient test frame was available in the structures laboratory at the University of Babylon. The main characteristics of the structural behavior of the beam specimens were detected at every stage of loading during testing. At each test, the first crack and the failure load were recorded. A dial gauge of 0.01 mm accuracy was used at the mid – span in order to calculate the deflection for each stage of loading. Demec point's arrangements for 200 mm mechanical extensometer were fixed at the center of mid span, at the middle support of beam and CFRP strain was measured at critical location in order to measure the strains through the beam section. The specimens were placed on the supports of the testing machine, at the first the specimens loaded by 5 kN to seat the support and the load system, then reduce to zero. The load increment was 5 kN along the test.

Figure 2 Test Setup

3. Experimental results

All specimens were used to investigate the enhancement in flexural behavior of strengthened beams that was designed to fail by flexural mode.

In specimen (**Pilot**) the test of this beam is conducted for proof testing system and to ensure it for smooth running and testing as well as to check that shear failure will not occur.

The flexural failure was the final failure mod at load 185 kN. In specimen (**B1**) the first observed crack occurred at load about (35 kN) in mid support region. As the load is increased, flexural cracks increased in number, width and depth. When the load was increased further, flexural failure in tension was the mode failure by yielding of main steel reinforcement. The failure load was recorded when a rapid increasing in the deflection readings occurred obviously which means yielding the main reinforcement in the beam specimens. The beam reached an ultimate load of (190 kN) at center of left span as shown in ***Figure3a***. In specimen (**B2**) is strengthened with one strips of CFRP sheet of 75mm at center of bottom and top faces along the positive and negative moments respectively with U-warp CFRP anchor in the end of each strip. In this beam, the first observed crack occurred at load about 45 kN in mid support region. As the load was increased, flexural cracks increased in number and width, further flexure-shear cracks appeared at load about 150kN. The failure was rupture of CFRP sheet at top layer in negative moment when the load reach about 235 kN with an increase in ultimate load of about (23.68%) with respect to control beam (**B1**) as shown in ***Figure 3b***. In specimen (**B3**) is strengthened with one strips of CFRP sheet of 75mm width at center of bottom face for each positive moment and two strips of CFRP sheet of 75mm width glued on the side faces at level of reinforcement negative moment with U-warp CFRP anchor in the end of each strip. In this beam, the first observed crack at load about 50 kN in center of left span. As the load was increased, flexural cracks increased in number and width, further flexure-shear cracks appeared at load about 120kN.The failure was rupture in CFRP sheet at the center of left span when the load reach about 250 kN with an increase in ultimate load of about (31.57%) with respect to control beam specimen (**B1**) as shown in ***Figure 3c***. In specimen (**B4**) is strengthened with one strips of CFRP sheet of 75mm at center of bottom and top faces along the positive and negative moments respectively with CFRP fan anchor in the end of each layer. In this beam, the first observed crack at load about 60 kN in mid support region. As the load was increased flexural cracks increased in number and width, further flexure-shear cracks appeared at load about 165kN. The failure was rupture in CFRP sheet at top layer in negative moment when load reach about 255kN with an increase in ultimate load of about (34.21%) with respect to control beam (**B1**) as shown in ***Figure 3d***. In specimen (**B5**) is strengthened with one strips of CFRP sheet of 75mm width at center of bottom face for each positive moment and two strips of CFRP sheet of 75mm width glued on the side faces at level of reinforcement negative moment with CFRP fan anchor in the end of each strip. In this beam, the first observed crack occurred at load about 60 kN in mid support region. As the load was increased, flexural cracks increased in number and width, further flexure-shear cracks appeared at load about 135kN. The failure was rupture in CFRP sheet at center of left span in positive moment when the load reach about 270kN with an increase in ultimate load of about (42.1%) with respect to control beam specimen (**B1**) as shown in ***Figure 3e***. In specimen (**BF1**) the first observed crack occurred at load about 55 kN in mid support region. As the load developed the cracks were propagate at the positive moment zones. The flexural tensile failure flowed by concrete crash was occurred at load about 270 kN at mid-support section as shown in ***Figure 3f***. In specimen (**BF2**) is strengthened with one strips of CFRP sheet of 75mm at center of bottom and top faces along the positive and negative moments respectively with U-warp CFRP anchor in the end of each layer.In this beam, the first observed crack at load about 70 kN in mid support region. As the load was increased, flexural cracks increased in number and width, further flexure-shear cracks appeared at load about 160kN. The failure was rupture in CFRP sheet at top layer for mid-support in negative moment when load reach about 330 kN with an increase in ultimate load about (22.22%) with respect to control beam (**BF1**) as shown in ***Figure 3g***. In specimen (**BF3**) is strengthened with one strips of CFRP sheet of 75mm width at center of bottom face for each positive moment and two strips of CFRP sheet of 75mm width glued on the side faces at level of reinforcement for each negative moment with U-warp CFRP anchor in the end of each strip. In this beam, the first observed crack at load about 60 kN in mid support region. As the load was increased, flexural cracks increased in number and width, further flexure-shear cracks appeared at load about 200kN. The failure was rupture in CFRP sheet at side strip for mid-support in negative moment when load reach about 365 kN with an increase in ultimate load about (35.18%) with respect to control beam (**BF1**) as shown in ***Figure 3h***. ***Figure 4*** shows summary and comparison of load-deflection curves.

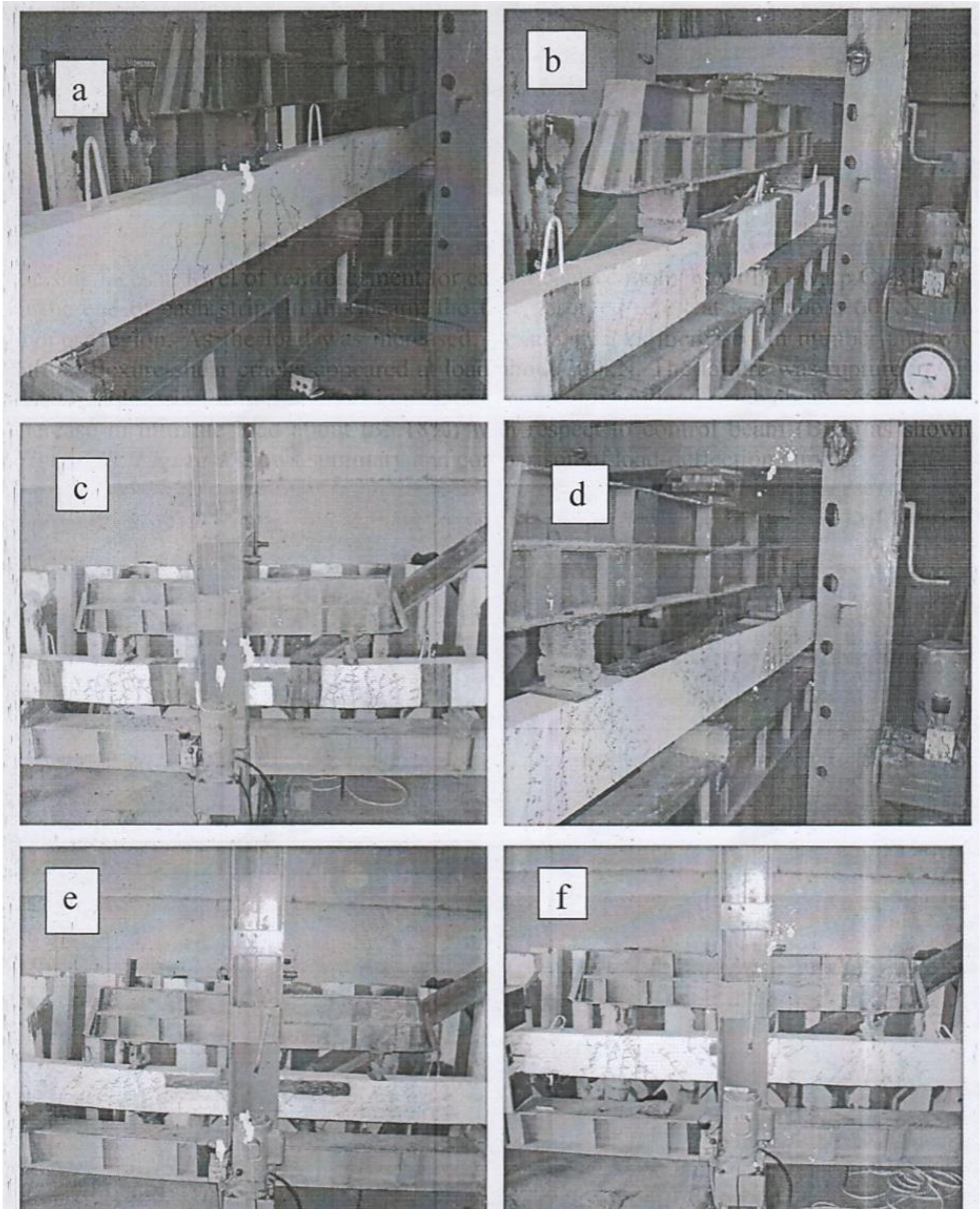


Figure 3 Mode of Failure

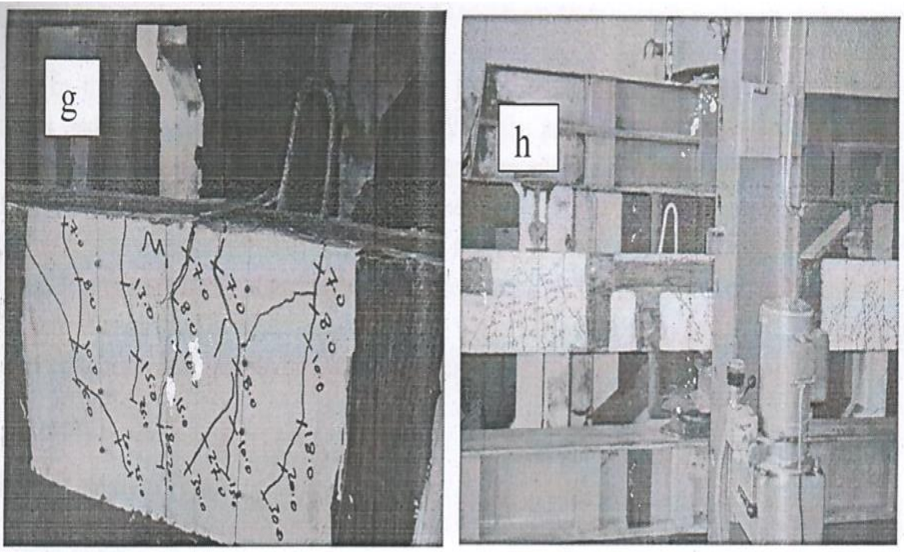
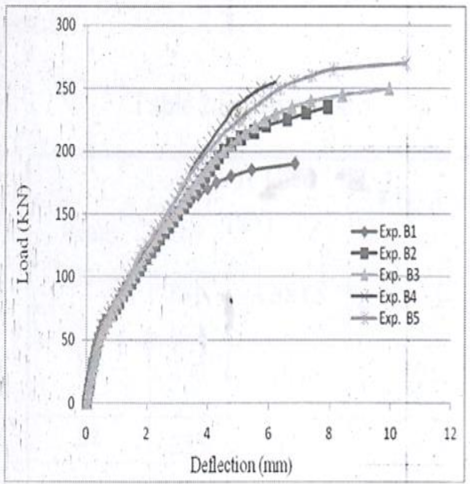
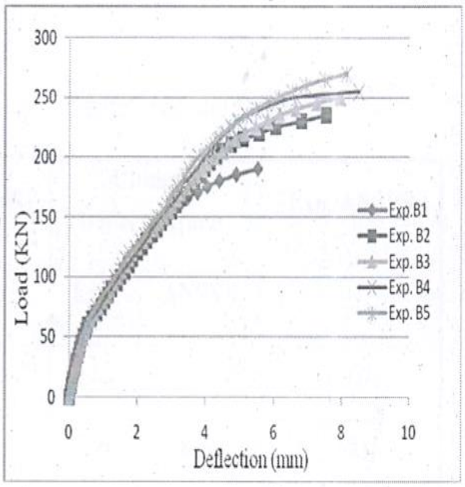
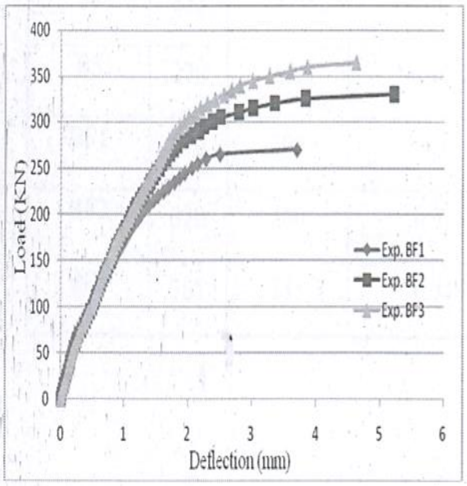


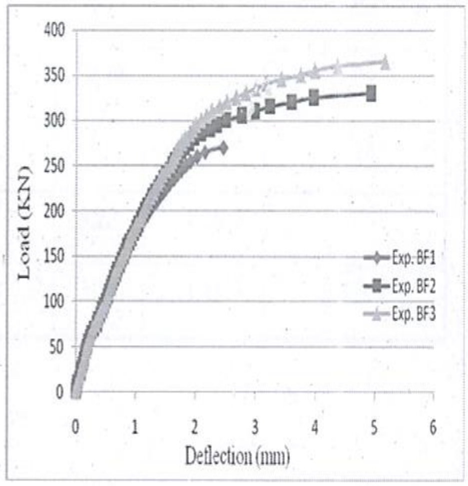
Figure 3 Continued





first span in group one *second span in group one*





first span in group two *second span in group two*

Figure 4 Load-Deflection Curve For All Tested Beams

4. Analytical Results

In this section, comparisons between the results from the ANSYS finite element analysis and the experimental results that explore the adequacy of elements type, material modeling, real constants and convergence criteria are adequate to model the response of the reinforced concrete continuous beams strengthening by CFRP. Package software [ANSYS, 2004] ***(11)*** was adopted in analysis the tested model. A three dimension SOLID65 element was used to represent the concrete element because it has the capability of crack and crash also, cure the situation of material nonlinearity while LINK8 element and SHELL41 element were used to represent longitudinal reinforcement and carbon fiber respectively ***(11)***.

4.3 Finite element results

A comparison between the ultimate loads and ultimate deflections of the tested beams with numerical ultimate loads and ultimate deflections from finite element analysis is shown in ***Table 2***. The table shows, a good agreement between the theoretical and experimental results.

Table 2 Experimental and Theoretical Ultimate Load and Deflection

Beam Symbol	Failure Load (kN)		Exp./ANSYS	Ultimate Deflection(mm)		Exp./ANSYS
	Exp.	ANSYS		Exp.	ANSYS	
B1	190	205	0.927	6.85	7.38	0.928
B2	235	247.5	0.95	7.91	8.04	0.98
B3	250	262.5	0.952	9.95	9.63	1.03
B4	255	247.5	1.03	8.5	8.04	1.06
B5	270	262.5	1.028	10.49	9.63	1.09
BF1	270	300	0.9	3.7	2.34	1.58
BF2	330	360	0.916	5.22	4.26	1.23
BF3	365	385	0.948	5.16	3.45	1.5

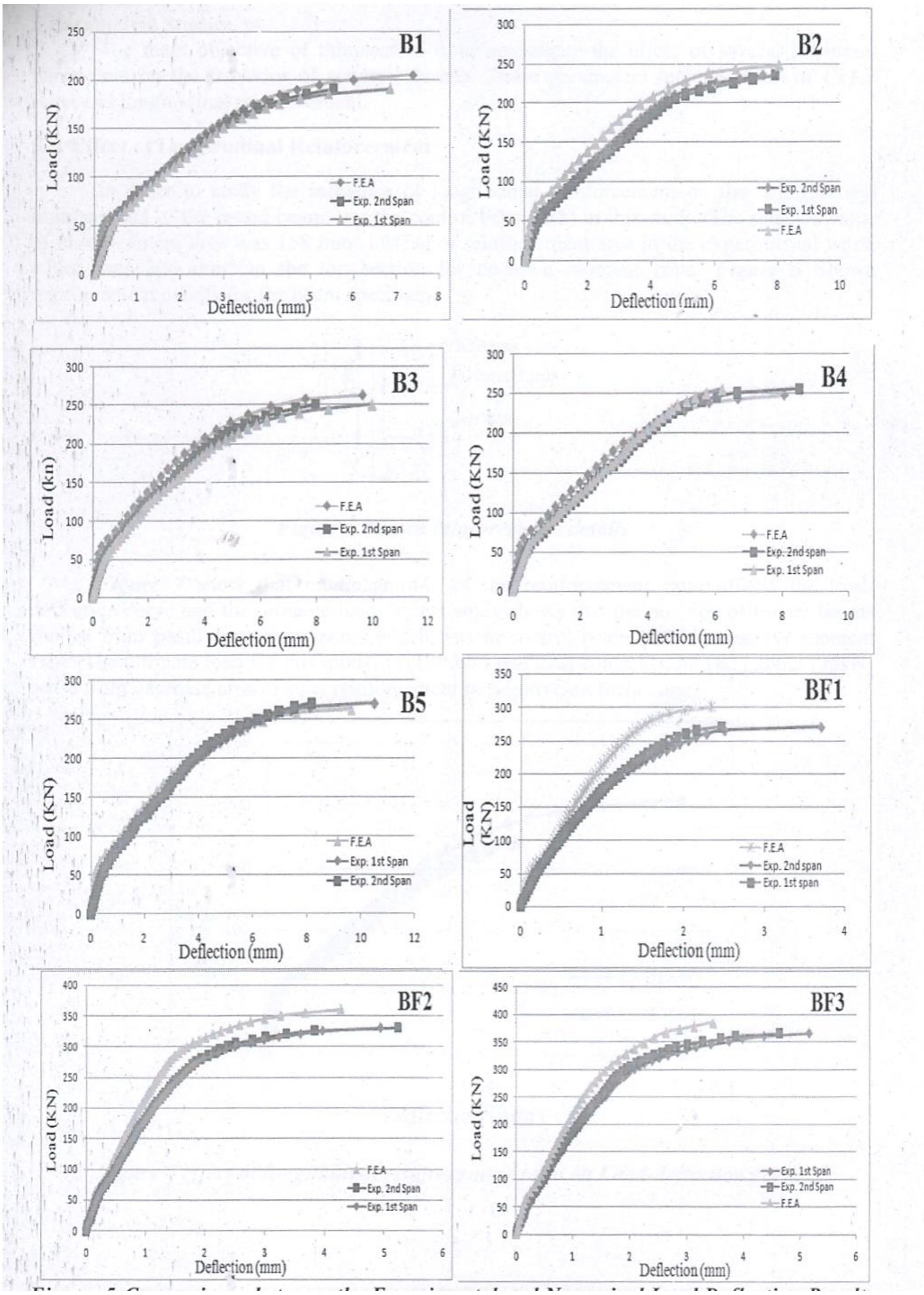


Figure 5 Comparisons between the Experimental and Numerical Load Deflection Results

5 Parametric Studies

The main objective of this section is to investigate the effect of several important parameters on the behavior of concrete beams. These parameters include width of CFRP sheet and longitudinal reinforcement.

5. 1 Effect of Longitudinal Reinforcement

In order to study the influence of longitudinal reinforcement on the behavior and ultimate load of the tested beam, use the control beam (**B1**) in this study. The selected value of reinforcement area was 158 mm^2 instead of reinforcement area in the experimental work, which was 226 mm^2 in the top section for negative moment zone. ***Figure 6*** Shown reinforcement details for the beam specimen.

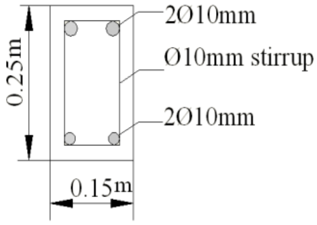


Figure 6 Shown reinforcement details

Figure 7 show that the magnitude of the reinforcement ratio affects the load-deflection curve and the ultimate load. In this study shows that the position of failure beams change from positive moment zone, which was in control beam (**B1**) to negative moment zone. The ultimate load for this model is (170 kN) less than control beam (**B1**) about (35kN) cause from decrease area of steel reinforcement in negative moment zone.

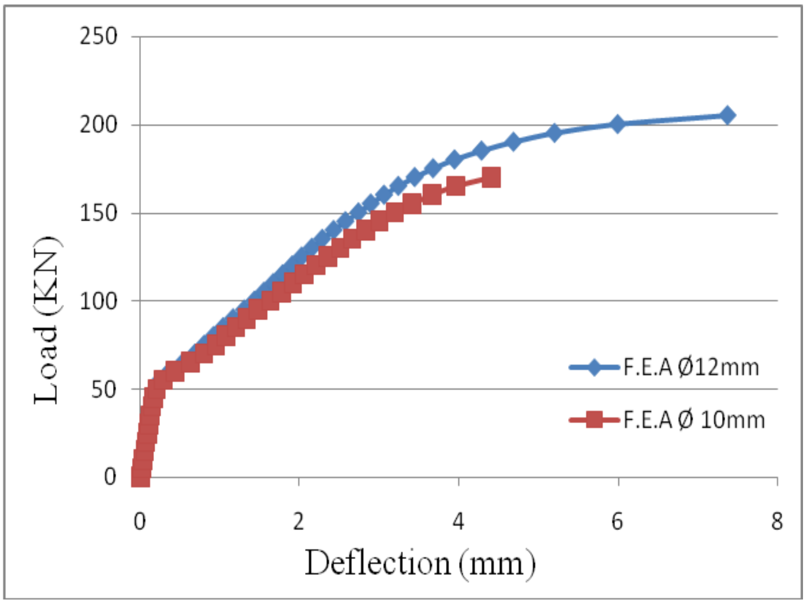


Figure 7 effect of longitudinal reinforcement ratio on Load-deflection curve

5. 2 Effect of CFRP Sheet Width

In order to investigate the effect of the CFRP sheet width on the behavior of strengthened beam, used model of beam with side strengthened (**B3**, **B5**). The selected value of CFRP width was (37.5 mm) instead of (75 mm) in the each side of the beam in negative moment zone.

Figure 8 shows the effect of CFRP sheet width on the load-deflection curve of strengthened beam. In this study shows that reduced the CERP width in the side to half (which equivalent to quantity of CFRP in top face for negative moment) change the position of failure beams from positive moment zone to negative moment zone. The ultimate load for this model is (227.5 kN) less than side strengthened beam and top strengthened beam about (35 kN) and (20 kN) respectively.

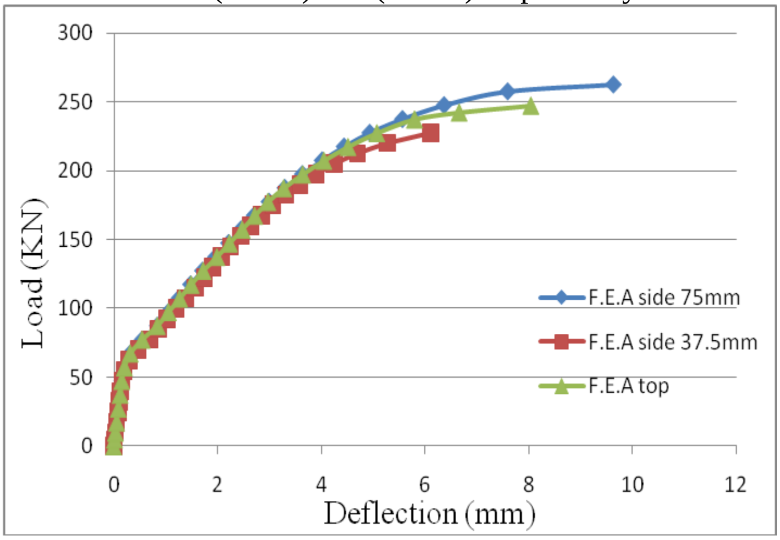


Figure 8 Effect of CFRP sheet width on the Load-Deflection curve

6. Conclusions

1. The externally strengthened reinforced concrete beams with bonded CFRP sheets showed significant increases in their ultimate loads. An increase in ultimate load reached up to (42.1 % for group 1 and 35.18 % for group 2).
2. An increase in cracking load was observed when using CFRP sheets. This increase is about to 71.42 % for group 1 and 40 % for groups 2 for reinforced concrete beam externally strengthened with CFRP sheets.
3. The reinforced concrete beams strengthened with CFRP sheets showed a lower deflection at corresponding loads than those of unstrengthened beam about (38% - 53%) due to the presence of CFRP sheets.
4. The external anchorages (CFRP anchors) are very effective in increasing the interaction between the CFRP and the concrete section and improving the structural behavior of the strengthened beams (increasing stiffness of the beam).The CFRP anchors better than the U-warp because the CFRP anchors spread in the same direction of main longitudinal CFRP sheet in spite of The quantity of CFRP anchors less than quantity of U-warp shape (increased 8.5% in ultimate loads).
5. The side strengthened of negative moment in the ends of the beam is very effective (increase the ultimate load and reduced beam deflection) more than the top strengthened of negative moment in the ends of the beam because the side strengthened in the same direction of longitudinal reinforcement steel (increased 10.6% in ultimate loads).
6. Rigid joint end support was more capacity in ultimate loads and more stiffness than roller end support.
7. The general behavior of the finite element models represented by the load-deflection curve plots at mid-span show good agreement with the experimental tested beams, the maximum difference in ultimate loads is about (10 %).
8. The parametric study with respect to decreasing the diameter of main steel reinforcement in the top for control beam (B1) shows that this effect has a

significant effect on the load–deflection behavior of reinforced concrete beam(reduced ultimate load).

9. The width of the CFRP sheet affects the overall load-deflection behavior of the strengthened concrete beams. A 50% decrease in the CFRP sheet width caused a decrease of (35KN) in the ultimate load capacity of the strengthened concrete by using F.E.M.
10. From parametric study with respect to decreasing width of the CFRP sheet shows that the top strengthened better than side strengthened (increased 8.8% in ultimate loads).

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