Strengthening of Continuous Reinforced Concrete Beams by Cfrp Laminates

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ABSTRACT

Experimental investigations of the behavior of reinforced concrete three-span continuous beams with 1200 mm length for each span, with cross-section 120 mm width and 180 mm depth strengthened by CFRP in flexure case of beams have been presented. The experimental program consisted of nine RC beams, which were strengthened at some locations with CFRP laminates and carefully designed to fail in flexure. The results show that the use of external CFRP laminate connected to the beams could enhance the ultimate flexural load capacity up to 102.88%.

Keywords: Carbon Fiber, CFRP, CFRP laminates, RC beam

تقوية العتبات الخرسانية المسلحة المستمرة باستعمال الياف الكاربون

الخلاصة

في هذه الدراسة، أجريت تحريات عملية لسلوك العتبات الخرسانية المسلحة ذات 3 فضاءات مستمرة بطول 1200 مليمتر للفضاء الواحد بابعاد (120 مليمتر عرض ، 180 مليمتر) ، المقواة باستخدام CFRP لحالة عتبات الانثناء. البرنامج العملي تألف من صب وفحص 9 عتبات تم تقويتها بالياف الكاربون في اماكن مختلفة من طول العتبة لنتائج بينت أن استخدام الـCFRP كمقوي خارجي له تأثير مهم على الحمل الأقصى، شكل التشقق و الانحراف. تم الاستنتاج أن استعمال شريحة CFRP الخارجية مربوطة إلى أوجه شد العتبة يعزز سعة التحمل الأقصى إلى حد (102.88%).

INTRODUCTION

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There is a large need for strengthening of concrete structures all around the world and there can be many reasons for strengthening, increased loads, design and construction faults, change of structural system, and so on. The need exists for strengthening in flexure as well as in shear. Epoxy Figure bonding with Carbon Fiber Reinforced Polymers, CFRPs has been shown to be a

competitive method for strengthening of existing structures and increasing the load carrying capacity [1].

Carbon fibers have received considerable attention in recent years because of their high efficiency in producing ductile concrete. CFRP is a combination of carbon fibers and an epoxy resin matrix. CFRP laminates have unidirectional structural properties as they have very high strength and rigidity in the fiber direction and outstanding fatigue characteristics [2].

The main objectives of the present study are doing Experimental investigation of the flexural behavior of three-span continuous RC beams, strengthened with CFRP laminates in the negative and/or positive moment zones and wrapped by external CFRP sheets acting as anchorages.

MATERIAL PROPERTIES

The properties of materials used in any structure are of considerable importance [3, 4]. For the strengthening of the structural member (Concrete strengthening or repairing by CFRP), the analysis and investigation of the behavior, depend on many parameters, including the strength properties of concrete, steel reinforcement and CFRP. The properties of materials used in the current study are presented. Standard tests according to the American Society for Testing and Materials (ASTM) and Iraqi specifications were conducted to determine the properties of materials. Some of these tests were conducted with the help of the National Center for Constructional Laboratories and Researches in Baghdad.

Ordinary Portland cement from Iraq plant named Kubaisa was used throughout this investigation. The cement was stored in air-tight plastic containers to avoid undue exposure to the atmosphere. Chemical and physical composition and properties for the used cement conform to the Iraqi Specifications limits (I.O.S. 5/1984) [5] for ordinary Portland cement.

Natural sand from Al-Akhaidher region in Iraq was used for concrete mixes in this study. The obtained grading results indicated that the fine aggregate grading and the sulfate content were within the limits of Iraqi specification No. 45/1984 and ASTM Standard C33-2002 Limitations [6, 7].

Crushed gravel passing sieve 14mm used throughout the tests. The crushed river coarse aggregate was washed, then spread then stored in a saturated dry surface condition before using. The specific gravity and absorption were (2.66) and (0.66%) respectively. The obtained grading results indicated that the coarse aggregate grading were within the requirements of Iraqi specification No. 45/1984 and ASTM Standard C33-2002 Limitations [6, 7]. Clean tap water was used for casting and curing all the specimens.

For all beams, one size of steel reinforcing deformed bars was used. Bars of size Φ10 mm were used as longitudinal reinforcement as well as transverse reinforcement (closed stirrups). The steel used in this study was assumed to have a modulus of elasticity equal to 200000 MPa. The tensile tests were performed using the testing machine available at the Constructional Laboratory of

University of Technology. Table (1) shows the properties of the reinforcement steel bars.

The uniaxial tension behavior of the Carbon Fiber Reinforced Polymer (CFRP) laminate (Mbrace CFK 150/2000) and sheet (Mbrace CF240) used in this study has been reported by the manufacturers to be linear up to failure. Properties for the Carbon Fiber Reinforced Polymer laminate and sheet were not determined in the laboratory. However, the properties published by the manufactures (BASF The Chemical Company). Mbrace Laminate Adhesive 220 , is a two component less viscous epoxy paste, used for bonding the carbon fiber reinforced polymers laminate to the surface of reinforced concrete beam specimens. Mbrace Saturant is an epoxy resin used in conjunction with (Mbrace CF240) sheets, for bonding the carbon fiber reinforced polymers sheets to the surface of reinforced concrete beam specimens. Properties of both adhesives were not determined in the laboratory. However, the properties as published by the manufactures (BASF The Chemical Company).

SAMPLE PREPARATION

The primary objective of this study is to investigate the actual effect of CFRP in enhancing the flexural behavior of continuous and simplify reinforced concrete beams.

The experimental program included testing of sixteen CFRP strengthened RC. Beams, which were designed to fail by flexure under the action of concentrated loads. These beams were tested in the Heavy Structures Laboratory, University of Technology, using an "AVERY" testing machine with maximum load capacity of 250 tons.

The variables considered in this experimental investigation are:

1. Type of the RC beam: three-span continuous RC beams.
2. Location of the CFRP laminates: This includes locating CFRP on the tension face of the RC beam at either the negative moment regions only or at the positive moment regions only or at both the negative as well as the positive moment regions.
3. Length of the CFRP laminates: This includes using different lengths of CFRP laminates at any moment zone as well as studying the effect of using CFRP to cover the total length of the beam.

The nine tested RC beams were devoted to study the flexural behavior of CFRP strengthened continuous RC beams. each of which was a three-equal span continuous RC beam having an effective span of 1200mm and tested under the action of three equal concentrated line loads with each load applied at the middle of a span, see figure (1). Four heavy duty pin rollers were used to support the beam and to furnish the desired three equal spans. The three equal concentrated line loads were applied to the top surface of the RC beam in successive increments up to failure using steel pins. The individual beams of this group differ in the location and length of the CFRP laminates used for strengthening.

Nine RC beams were cast, each of length 4000 mm and having a rectangular cross section of dimensions of 120 mm width by 180 mm height. The flexural reinforcement of the beams consisted of 2Φ10 mm bottom bars and 2Φ10 mm top bars, both of which are placed over the total length of the beam. To avoid shear failure, the beams were over reinforced for shear with Φ 10 mm closed stirrups spaced at 50 mm on center. Figure (2) shows the specimen dimensions and reinforcement details.

Strengthening schemes were chosen carefully based on the practical needs and the field conditions. The nine continuous reinforced concrete beams of this group consisted of one beam (B1) left unstrengthened as control beam and eight beams (B2 to B9) strengthened with externally bonded CFRP laminates as described below, and all the external anchorages used in this research were made from CFRP sheets tied around the end of CFRP laminates.

The first concrete beam specimen (B1) was kept without retrofitting and was considered as a control beam for comparison as shown in Figure (3). The second concrete beam specimen (B2) was provided with two CFRP strips having (2 × 750 mm) length, 100 mm width and 1.4 mm thickness installed at top face on the center of the middle supports as shown in Figure (4).

The third concrete beam specimen (B3) was provided with one CFRP strip having 1950 mm length, 100 mm width and 1.4 mm thickness installed at top face on the middle supports and the length between them, as shown in Figure (5). The fourth concrete beam specimen (B4) was provided with three CFRP strips having (2 × 1050 mm, 500mm) length, 100 mm width and 1.4 mm thickness installed at bottom face on the positive moments zones, as shown in Figure (6). The fifth concrete beam specimen (B5) was provided with one CFRP strip having 4000 mm length, 100 mm width and 1.4 mm thickness installed at bottom face on the whole beam length, as shown in Figure (7).

The sixth concrete beam specimen (B6) was provided with two CFRP strips having (2 × 750 mm) length, 100 mm width and 1.4 mm thickness installed at top face on the center of the middle supports and three CFRP strips having (2 × 1050 mm, and 1 × 500mm) length, 100 mm width and 1.4 mm thickness installed at bottom face on the positive moments zones, as shown in Figure (8).

The seven concrete beam specimen (B7) was provided with two CFRP strips having (2 × 750 mm) length, 100 mm width and 1.4 mm thickness installed at top face on the center of the middle support and one CFRP strip having 4000 mm length, 100 mm width and 1.4 mm thickness installed at bottom face on the whole beam length, as shown in Figure (9).

The eighth concrete beam specimen (B8) was provided with one CFRP strip having 1950 mm length, 100 mm width and 1.4 mm thickness installed at top face on the middle supports included the area between them and three CFRP strips having (2 × 1050 mm, and 1 × 500 mm) length, 100 mm width and 1.4 mm thickness installed at bottom face on the positive moments zones, as shown in Figure (10).

The ninth concrete beam specimen (B9) was provided with one CFRP strip having 1950 mm length, 100 mm width and 1.4 mm thickness installed at top face on the middle supports included the length between them and one CFRP strip having 4000 mm length, 100 mm width and 1.4 mm thickness installed at bottom face on the whole beam length using external anchorage by tying the CFRP sheet strip around beam within 100 mm from the end of laminates, as shown in Figure (11).

For all beams, CFRP sheet strip was using external anchorage by tying the around beam within 100 mm from the end of laminates.

Deflections of beams were measured at every single load level using dial gauges of the type (ELE) having 0.01mm sensitivity and 30 mm travel. These dial gauges were placed underneath the bottom face of the test beam at specified locations depending on the type of the test beam. Longitudinal strains were measured at each load increment by the use of demec points fixed at one side of the beam in different depth levels and acted as seats for the demec gauge. A series of 4 demec points of 150mm gauge length were fixed at depth levels of (10, 60,120 and 170mm) from the top face of the RC beam. Extensometer of 0.002 mm accuracy was used to measure the changes in displacement resulting between each pair of demec points lying on the same horizontal level, and from which the longitudinal strain was calculated at each load increment. Such longitudinal strain profiles were measured at specified locations depending on the type of the test beam.

It can be seen from figure (12) the deflections were measured at the middle of each of the three spans of the beam directly under the applied concentrated loads and the longitudinal strains were measured at the middle of the exterior span (i.e. section of maximum positive bending moment) and at the interior support (i.e. section of maximum negative bending moment).

EXPERIMENTAL RESULTS AND DISCUSSIONS

The full details of the experimental tests carried out in the present investigation In the present work, all beams had a flexural reinforcement ratio of 0.73%, which is higher than the minimum reinforcement ratio required by the ACI code to avoid sudden failure at cracking load. All beams were under-reinforced characterized by tensile failure type according to the ACI code. Clear covers of 30mm to the main reinforcement were provided for all tested beams. The structural behavior and failure load of each tested R.C beam were recorded and plots were made for its load-deflection response as well as the strain distribution across the depth of the critical sections.

The cracks pattern of the unstrengthened reinforced concrete beam (control beam) B1 is shown in Figure (13). First crack was observed at an applied load of (25 kN) at center of left span. As the load was increased, the flexural cracks increased in number, width and depth. After the formation of first crack, a loss of stiffness occurred and the beam reached an ultimate load of (57.67 kN) at center of left span and exhibited a ductile behavior. Ductility of the beam was mainly due to the amount of reinforcement provided, which was larger than the minimum reinforcement.

The load-deflection curve for the beam specimen (B1) is shown in Figure (14). The beam failed due to yielding of the tension steel reinforcement and flexural cracks were observed in the beam throughout the left span length.

For second concrete beam specimen (B2), first crack load was (30 kN) at center of left span with as vertical flexural crack at the center of left span. As the load was increased, new cracks observed at the supports then inclined cracks throughout the beam spans. The beam failed at an ultimate load of (73.33 kN) with an increase in strength of about (27.15 %) with respect to unstrengthened beam specimen (B1) (control beam).

The beam failed due to yielding of the tension steel reinforcement and flexural cracks were observed in the beam throughout the left span length. Also debonding of the CFRP laminates was shown at the right span as shown in Figure (15).

The load-deflection curve for the beam specimen (B2) is shown in Figure (16).

For third concrete beam specimen (B3), first crack load was (28 kN) at center of right span. With increased the load , new cracks were observed and the beam failed at an ultimate load of (78.33 kN) with an increase in strength of about (35.82 %) with respect to unstrengthened beam specimen (B1) (control beam).

The beam failed due to yielding of the tension steel reinforcement and flexural cracks were observed in the beam throughout the right span length. Also debonding of CFRP laminates was shown at the right interior support as shown in Figure (17). The load-deflection curve for the beam specimen (B3) is shown in Figure (18).

For fourth concrete beam specimen (B4), first crack load was (40 kN) at center of right span as vertical flexural crack and with increasing of load, new cracks appeared and started from center of span as flexural cracks then going to flexural-shear cracks and the beam failed at an ultimate load of (95 kN) with an increase in strength of about (64.74 %) with respect to unstrengthened beam specimen (B1) (control beam).

The beam failed due to debonding of concrete cover from the end of CFRP laminates at the left span as shown in Figure (19). The load-deflection curve for the beam specimen (B4) is shown in Figure (20).

For fifth concrete beam specimen (B5), first crack load was (40 kN) at the center of left and right spans. As the load was increased, new flexural and flexural-shear cracks appeared and the beam failed at an ultimate load of (105 kN) with an increase in strength of about (82.01 %) with respect to unstrengthened beam specimen (B1) (control beam). This beam had the best results for load and deflection comparison with the last three strengthened beams ago.

The beam failed due to debonding of CFRP laminates from the flexure-shear cracks zone with crashing in concrete under the applied load at center of left span as shown in Figure (21). The load-deflection curve for the beam specimen (B5) is shown in Figure (22).

For sixth concrete beam specimen (B6), first crack occurred at a slightly higher load than of the unstrengthened beam specimen (B1), which was observed at an applied load of (45 kN) at center of right span. As the load was increased, the cracks increased and flexure-shear cracks appeared on the lest span and the beam failed at an ultimate load of (94 kN) with an increase in strength of about (63.00 %) with respect to unstrengthened beam specimen (B1) (control beam).

The beam failed due to concrete cover debonding plus CFRP laminates debonding from flexure-shear cracks zone at the left span as shown in Figure (23). The load-deflection curve for the beam specimen (B6) is shown in Figure (24).

For seventh concrete beam specimen (B7), first crack occurred at a slightly higher load than of the unstrengthened beam specimen (B1), which was observed at an applied load of (50 kN) at right interior support. As the load was increased, flexure-shear cracks appeared on the beam spans and the beam failed at an ultimate load of (110 kN) with an increase in strength of about (90.75 %) with respect to unstrengthened beam specimen (B1) (control beam).

The beam failed due to debonding of top concrete over in the end of CFRP laminates near the support plus CFRP laminates debonding from flexure cracks zone as shown in Figure (25). The load-deflection curve for the beam specimen (B7) is shown in Figure (26).

For eighth concrete beam specimen (B8), first crack occurred at a slightly higher load than of the unstrengthened beam specimen (B1), which was observed at an applied load of (50 kN) at right interior support. As the load was increased, cracks was increased and the beam failed at an ultimate load of (98.67 kN) with an increase in strength of about (71.09 %) with respect to unstrengthened beam specimen (B1) (control beam).

The beam failed due to debonding of bottom concrete cover plus CFRP laminates debonding from flexure-shear cracks zone of left span as shown in Figure (27).

The load-deflection curve for the beam specimen (B8) is shown in Figure (28).

For ninth concrete beam specimen (B9), first crack occurred at a slightly higher load than of the unstrengthened beam specimen (B1), which was observed at an applied load of (50 kN) at right interior support. As the load was increased, cracks was increased in number and width and flexure-shear cracks was appeared and the beam failed at an ultimate load of (117 kN) with an increase in strength of about (102.88 %) with respect to unstrengthened beam specimen (B1) (control beam).

The beam failed due to debonding of top concrete over near to right interior support plus CFRP laminates debonding from flexure-shear cracks on the same zone as shown in Figure (29). The load-deflection curve for the beam specimen (B9) is shown in Figure (30).

The comparison between the load - deflection curves for all the nine tested beams (unstrengthened and strengthened beams) are shown in Figures (31), (32) and (33). For left, right and center spans respectively

Comparison of the percentage increase in cracking and ultimate load of the strengthened beams with respect to unstrengthened beam (control beam) are shown in Table (2).

CONCLUSIONS

1.The externally strengthened reinforced concrete beams with bonded CFRP laminates showed significant increases in their ultimate loads. The enhancements in ultimate load reached up to (102.88 %).

2.An increase in cracking load was observed when using CFRP laminates. This increase is about to 100 % for reinforced concrete beam externally strengthened with CFRP laminates.

3.The reinforced concrete beams strengthened with CFRP laminates showed a lower deflection at corresponding loads than those of unstrengthened beam due to the presence of CFRP laminates.

4. Extending the CFRP laminates up to supports is effective in increasing the ultimate load carrying capacity of the strengthened beam. As the CFRP laminate extends up to supports, an increase in ultimate load reached up to 31.79 % with respect to those CFRP laminates which stopped before the supports.

5. In all beams with external CFRP strengthening, the crack pattern for flexural failure was similar. The failure cracks appear in the tension face and they initiate

from tension side and move to the other side of beams. The crack width continues to increase until the beam failure.

7. Failure in the strengthened beams is caused by either steel yielding flexural or by Concrete cover debonding followed by CFRP laminates depending.

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Table (1) Properties of steel reinforcement

Reinf. bar diameter (mm)	Yield Stress (MPa)	Yield Strain	Ultimate Strength (MPa)	Ultimate Strain	Modulus of Elasticity (MPa)*
10	465	0.0028	603	0.0295	200000

* assumed value, ACI 318M-08

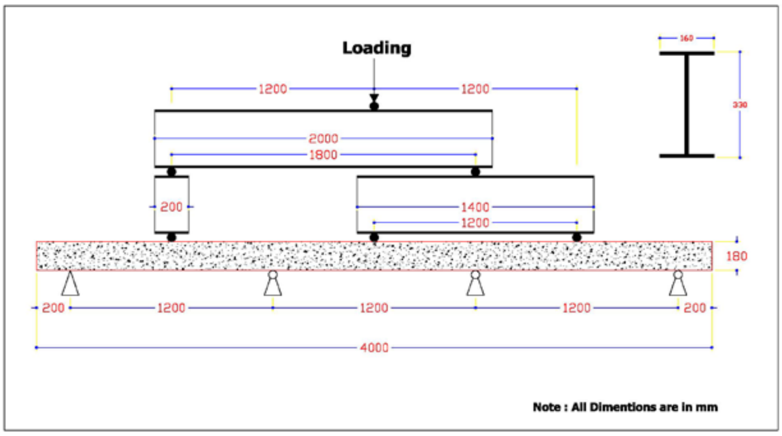


Figure (1)) Schematic representation of tested beams.

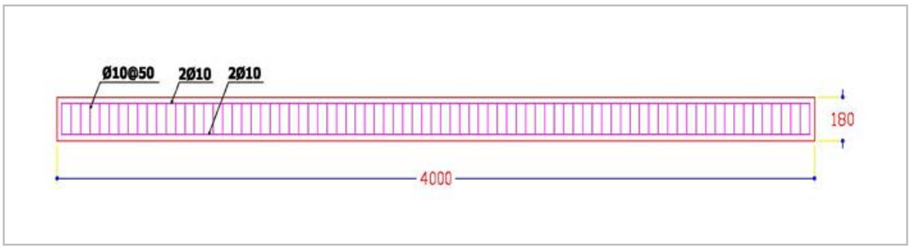


Figure (2) Geometry and reinforcement of the tested RC specimens.

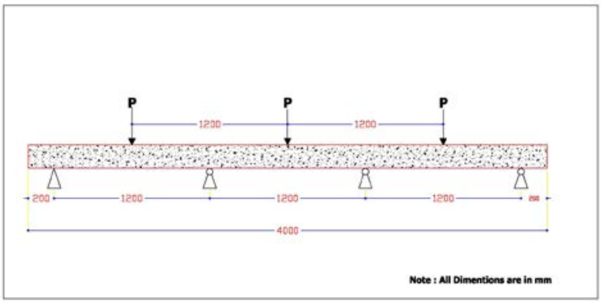


Figure (3) Schematic of specimen B1 without bonded CFRP strip.

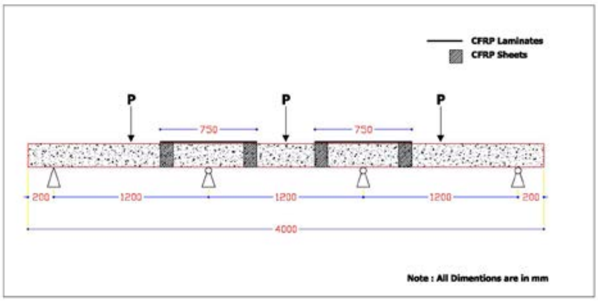


Figure (4) Schematic of specimen B2 with bonded CFRP strips

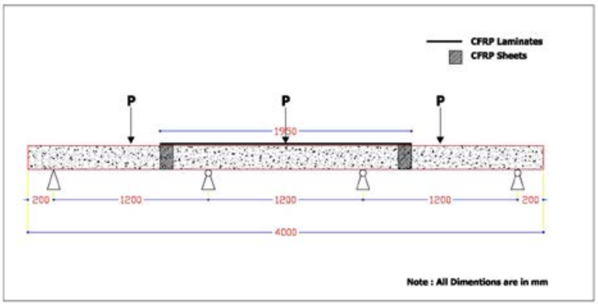


Figure (5) Schematic of specimen B3 with bonded CFRP strip.

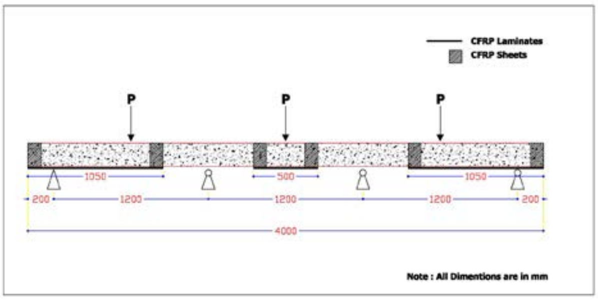


Figure (6) Schematic of specimen B4 with bonded CFRP strips.

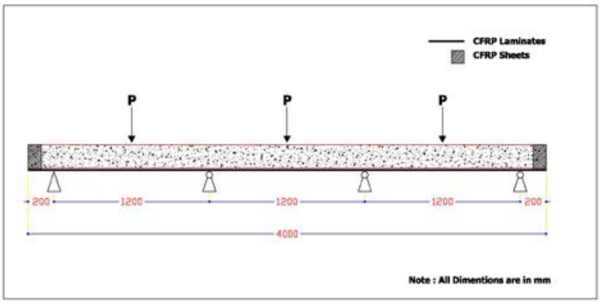


Figure (7) Schematic of specimen B5 with bonded CFRP strip.

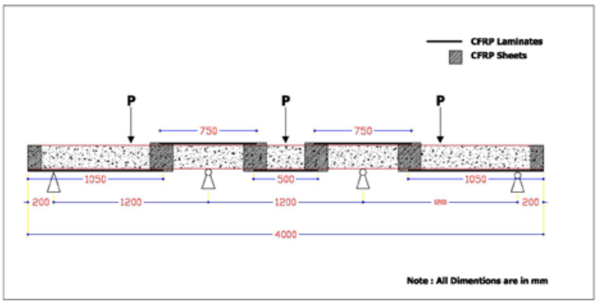


Figure (8) Schematic of specimen B6 with bonded CFRP strips.

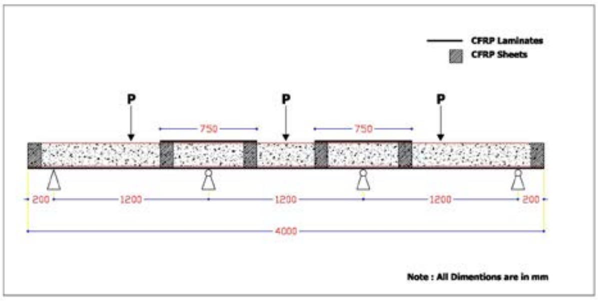


Figure (9) Schematic of specimen B7 with bonded CFRP strips.

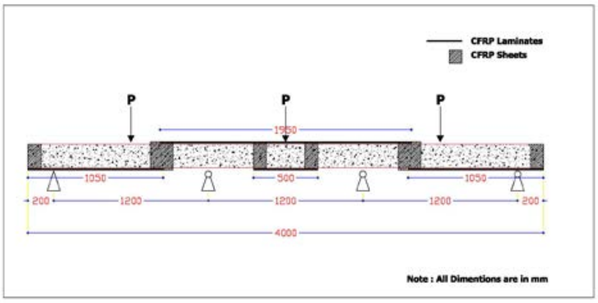


Figure (10) Schematic of specimen B8 with bonded CFRP strips.

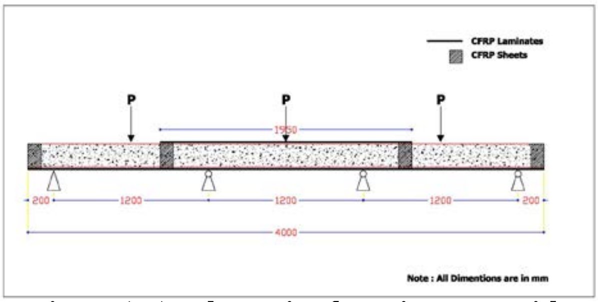


Figure (11) Schematic of specimen B9 with bonded CFRP strips.

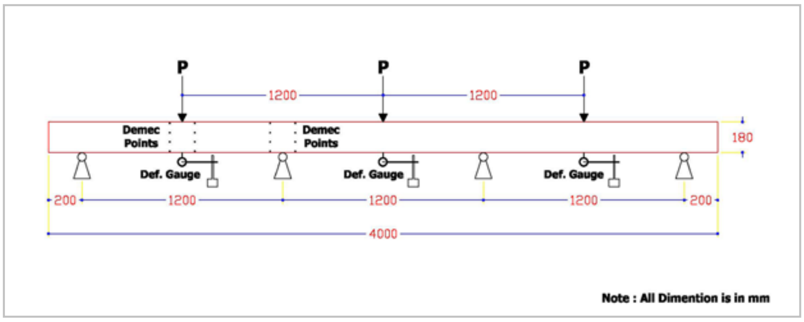


Figure (12) The locations adopted for measuring deflections and longitudinal strains

Figure (13) cracks pattern of beam (B1).

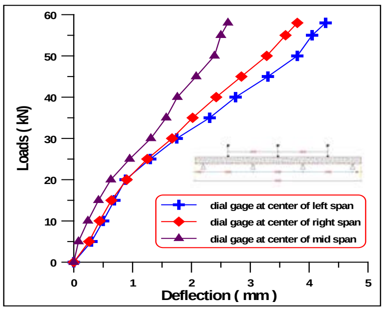


Figure (14) Load – Deflection curve for beam (B1).

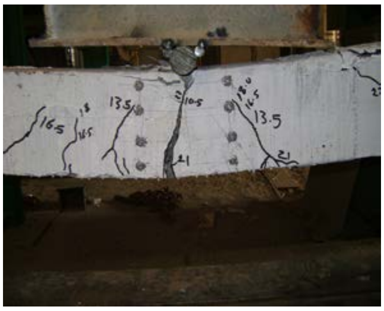


Figure (15) cracks pattern of beam (B2).

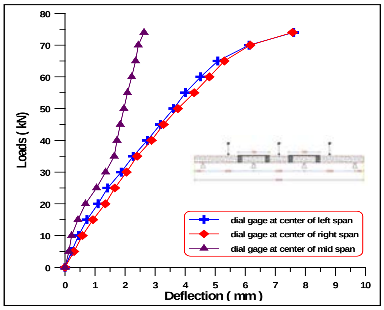


Figure (16) Load – Deflection curve for beam (B2).

Figure (17) cracks pattern of beam (B3).

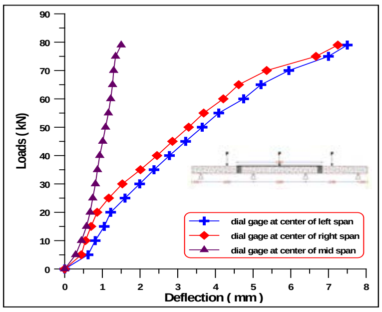


Figure (18) Load – Deflection curve for beam (B3).

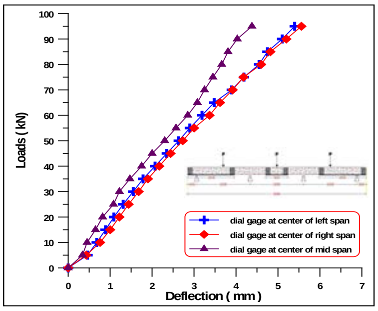


Figure (19) cracks pattern of beam (B4).

Figure (20) Load – Deflection curve for beam (B4).

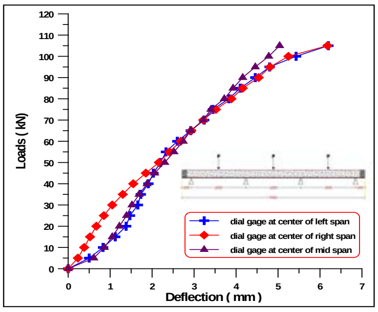


Figure (21) cracks pattern of beam (B5).

Figure (22) Load – Deflection curve for beam (B5).

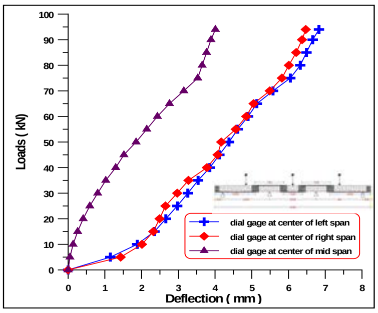


Figure (23) cracks pattern of beam (B6).

Figure (24) Load – Deflection curve for beam (B6).

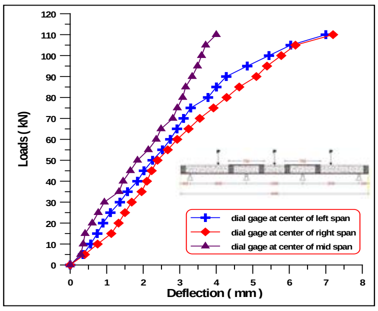
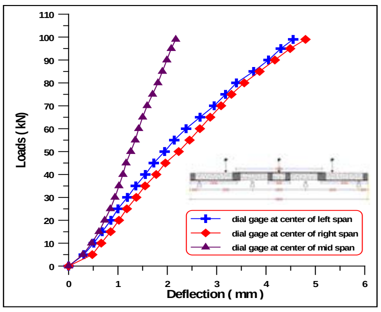


Figure (25) cracks pattern of beam (B7).

Figure (26) Load – Deflection curve for beam (B7).



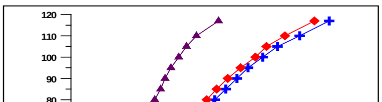


Figure (27) cracks pattern of beam (B8).

Figure (28) Load – Deflection curve for beam (B8).

Figure (29) cracks pattern of beam (B9)

Figure (30) Load – Deflection curve for beam (B9)

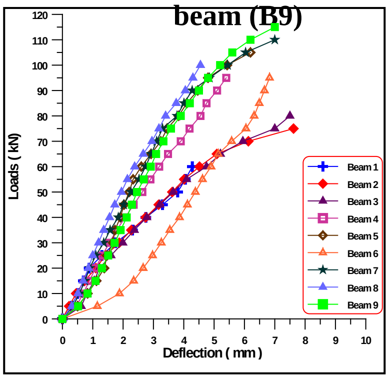


Figure (31) Load Versus Deflection at center of left span for the beams.

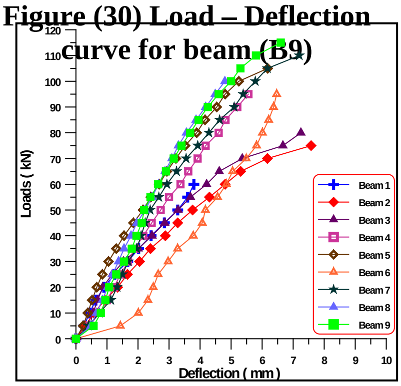


Figure (32) Load Versus Deflection at center of right span for the beams.

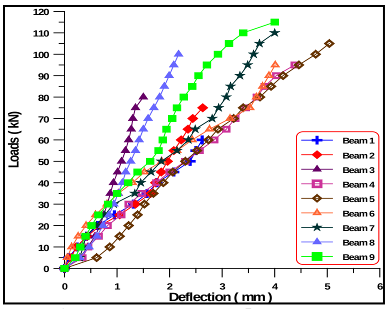
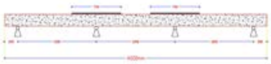
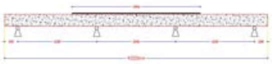
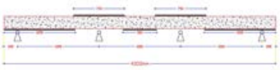
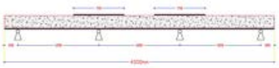
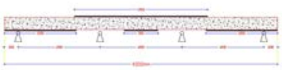
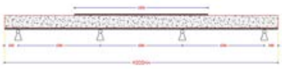


Figure (33) Load Versus Deflection at center of middle span for the beams.

Table (2) Percentage increase in load for the beams.

Beam's Symbol	CFRP Locations	Cracking Load (kN)	Percentage of increase %	Ultimate Load (kN)	Percentage of increase %
B1		25	---	57.67	---
B2		30	20	73.33	27.15
B3		28	12	78.33	35.82
B4		40	60	95	64.73
B5		40	60	105	82.07
B6		45	80	94	63.00
B7		50	100	110	90.74
B8		50	100	98.67	71.09
B9		50	100	117	102.88