Eng. & Tech. Journal, Vol.28, No.9, 2010

Influence of Anchorage on the Behavior of CFRP RC Beams in Flexure

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Received on: 24/6/2008
Accepted on: 3/9/2009

Abstract

This research study involves experimental and theoretical investigations of the behavior of flexural debonding of carbon fiber reinforced polymer (CFRP) laminates with steel anchorages. A total of nine reinforced concrete beam specimens with cross section of (150mm width by 250mm height and 2000mm length) were investigated in this study to observe the flexural strength of each one. Eight beam specimens were strengthened with CFRP laminates and one beam specimen was tested without strengthening. The experimental results showed that the use of CFRP strips as external strengthening has significant positive effect on ultimate loads, crack patterns and deflections. The percent of increasing of the ultimate load capacity can be increased by about 65% when using two layers of CFRP strips instead of one layer. The ultimate load is increased by about 118% for the beams strengthened with bonded CFRP and external anchorage with respect to the reference beam. Three-dimensional nonlinear finite element analysis (i.e. ANSYS - version 9.0 computer program) is used to investigate the performance of reinforced concrete beams strengthened with CFRP. The comparison between the numerical and the experimental results asserted that good validity of the numerical analysis and the methodology developed in this study.

Keywords: CFRP, anchorage, flexure, RC Beams

تأثير الإرساء على سلوك العتبات الخرسانية المسلحة و المقواة بألياف الكاربون البوليميرية في الإنحناء

الخلاصـــــة

ان هذا البحث يتضمن دراسة عملية و نظرية لسلوك العتبات الخرسانية المسلحة و المدعمة بأشرطة الياف الكاربون البوليمرية على طول الوجه السفلي للعتبة و المقواة بالإرساء الحديــدي نيــة لمنع الإنفصال بتأثير الانحناء. تم فحص تسع نماذج لعتبات خرسانية مسلحة مختبرياً ذات مقطع ثابت بأبعاد (150 ملم عرض، 250 ملم ارتفاع، 2000 ملم طول العتبــة) لتحــري أجهــادات الإنحنــاء المتولدة. تم تدعيم ثمان عتبات بشرائح الياف الكاربون البوليميرية و ترك عتبة بدون تدعيم كمصــدر لمقارنة النتائج معها. أن النتائج العملية أظهرت ان استخدام شرائح الالياف الكاربونية ذو تأثير ايجابي و كبير على سلوك العتبات الخرسانية المسلحة و المعرضة لعزوم الانحناء. أظهرت هذه الدراسة بأن سعة التحمل الاقصى للعتبات قد عززت بشكل متزايد و ملحوظ الى حــوالي 65% عنــد اســتخدام طبقتين من الالياف الكاربونية بدلاً من طبقة واحدة. مقاومة الانحناء للعتبات أظهرت زيادة ملموســة أيضاً و بشكل متميز يصل الى حد 118% للعتبات المدعمة بألياف الكاربون البوليميريــة و المقــواة أيضاً بالارساء الخارجي مقارنة بالعتبة الغير مدعمة او مقواة. تم أستعمال التحليل اللاخطي بواسطة العناصر الثلاثية الابعاد لتحري اداء العتبات الخرســانية المســلحة و المدعمــة بأليــاف الكــاربون

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https://doi.org/10.30684/etj.28.9.12
2412-0758/University of Technology-Iraq, Baghdad, Iraq

البوليميرية و المقواة بإرساء الحديد الخارجي. أستعمل البرنامج الحاسوبي ANSYS V9.0 . المقارنة ما بين النتائج النظرية و العملية المستحصلة أكدت صـــلاحية التحليـــل العـــددي بشـــكل واضـــح.

1. Introduction:

Due to a deteriorating infrastructure many buildings and bridges are in need of rehabilitation. Strengthening of existing structures using lightweight composite materials is becoming widespread due to their ease of installation and competitive pricing compared to traditional methods. Fiber Reinforced Polymer (FRP) strengthened reinforced or prestressed concrete beams often fail in flexure, due to concrete crushing or FRP rupture. This type of failure can be well predicted using a cracked section analysis of the strengthened section using the specified FRP material properties from the manufacturer. The behavior under fatigue loading of FRP strengthened beams is often controlled by the stress range of the internal steel reinforcement, which should be kept within prescribed limits [1].

It is well known that concrete is a building material with high compressive strength and poor tensile strength. A concrete beam without any form of reinforcement will crack and fail when subjected to a relatively small load. The failure occurs suddenly in most cases, and in a brittle manner. The most common way to reinforce a concrete structure is to use steel reinforcing bars that are placed in the structure before the concrete is cast. It is unusual for the designing demands on any concrete structure to change with time. But the long life concrete structures requirements get the attention for finding a solution for this demand. The structure may have to carry larger loads at a later date, or fulfill new standards. In extreme cases a structure will have to be repaired due to an accident. A further reason can be that errors have been made during the design or construction phase resulting in need for strengthening the structure before usage. If any of these situations should arise it needs to be determined whether it is more economic to strengthen the existing structure or to replace it. In comparison to build a new structure, strengthening an existing one is often more complicated, since the conditions are already set.

2. FRP Composites:

An FRP is a specific type of two-component composite material consisting of high strength fibers embedded in a polymer matrix as indicated in Fig. (1) [2]. A scanning electron micrograph showing microscopic carbon fiber used in FRP fabrication is also shown in Fig. (2) [2]. The study of FRPs is complicated by the innumerable combinations of materials that can be used to create an FRP composite. This is both an advantage and a disadvantage for FRPs as engineering material. For instance, FRPs can be tailored to suit virtually any application; however, this versatility leads to a wide range in possible properties, making it difficult in many cases to arrive at generalizations with respect to FRP behavior. Because FRPs are composed of two distinct materials, overall FRP material properties depend primarily on those of the individual constituents.

3. Characteristics of CFRP Materials:

The introduction of carbon fiber reinforced polymer (CFRP) materials to the civil engineering arena gave the engineers a material that does not corrode, that is strong, stiff and lightweight. However, these materials are still almost unknown to engineers in the civil engineering industry, although the knowledge seems to be increasing. Glass, carbon and aramid fibers are the most commonly used fibers in civil engineering while carbon is the dominating one [2].

CFRP systems for strengthening concrete structures have emerged as an alternative to traditional strengthening techniques, such as steel plate bonding, section enlargement, and external post-tensioning [2].

FRP strengthening systems used CFRP composite materials as supplement to externally bonded reinforcement. This system offers advantages over traditional strengthening techniques such as lightness, relatively easiness to install, and are noncorrosivity. Carbon fibers are the stiffest, more durable, and most expensive fibers. Glass fibers have lower strengths and stiffness, compared to carbon fibers but with a reduced cost. Strength, stiffness and durability of carbon fibers makes it very suitable for withstanding sustained stress conditions arising from flexural and shear strengthening applications. The stress-strain properties of typical various fibers are shown in Fig. (3) [2].

4. Experimental Program:

4.1 Scope:

Nine reinforced concrete beam specimens were investigated in this research. One specimen without CFRP as control beam, two specimens with CFRP but without steel strengthening, while the other six specimen beams were strengthened with different types of steel strengthening techniques in addition to the CFRP. Most of the variables included in this study are focused essentially on using different strengthening techniques to avoid the debonding at the ends of the beams. The other variable involved is the number of CFRP layers used (i.e. one layer centered at the bottom fiber of the beam or two layers).

4.2 Details of Test Beams:

All of the RC beams are 150×250 mm in cross section and 2000 mm long. The beams are reinforced with 2-Ø12 mm deformed bars at the tension and compression faces, and they are provided with closed stirrups of Ø10 mm at 100 mm center-to-center spacing for the shear span only in the transverse direction. The basic concrete beam without external reinforcement was designed to have sufficient shear strength so as to fail in flexure. The ratio of longitudinal reinforcement to the area of concrete (As/bd) was taken as 1.41%. Fig. (4) shows geometrical details of beams and steel reinforcement provided with a clear cover to the reinforcement of 30 mm.

4.3 Specimens Notation:

The identification for each test specimen is carried out according to the CFRP strengthening schemes as illustrated in Fig. (5) and Table (1) The same concrete mix is used for the all specimens since it is required to study the strengthening and debonding extensively without internal variation in concrete consistency which may affect the conclusion of this study.

Strengthening with CFRP and the techniques for controlling the debonding were chosen in a way which controls and investigates the flexural behavior of the specimens and the debonding of the CFRP strips at the end of the specimens in this study.

Specimen S1 is not strengthened with CFRP and considered as a control or reference beam in this investigation as shown in Fig. (5-a). Specimens S2 and S3 are strengthened with one layer and wo layers of CFRP strips respectively as shown in Figs. (5-b, 5-c).

Specimens S4 and S5 are strengthened with CFRP strips with one and two layers of CFRP stripes respectively. Two steel closed anchorages to control the debonding at each side of the end of the CFRP strips are also used for those beams as shown in Figs. (5-d, 5-e).

Specimen S6 is strengthened with two layers of CFRP strips. One steel anchorage at each side of the beam is used to prevent the debonding of the CFRP strips at the end of the strips as shown in Fig. (5-f).

Specimens S7 and S8 are strengthened with CFRP strips with one and two layers of CFRP strips respectively extended to the end of the beams. Two steel anchorages are used at the both supports of the beam to control the debonding at each side of the ends of CFRP strips as shown in Figs. (5-g, 5-h).

Specimen S9 is strengthened with two layers of CFRP strips. A continuous steel plate system is used as retrofitting layer along the shear spans of the beam which the debonding is expected to be active there as shown in Fig. (5-i). All the steel anchorages used in this research are st 37 type (i.e. f_y=248MPa).

4.4 Materials:

4.4.1 Cement:

Ordinary Portland cement (Iraqi Manufacturing) named Kubaisa [ASTM C150-TypeI] was used throughout this investigation for casting all the specimens. The cement was kept in air-tight plastic containers to avoid under exposure to the atmosphere. The test results show that the cement conforms to the provisions of Iraqi specification No.(5)-1984 for ordinary Portland cement. This test has been carried out at the NCCL (National Center for Constructional Labs).

4.4.2 Fine Aggregate (Sand):

Natural sand of maximum size 4.75 mm was used in this investigation. It was brought from Al-Akhaider region. It is sieved at sieve size (4.75 mm) to get the coarse aggregate separately from the sand. Before being ready to use, the sand was washed and cleaned by water several times, later it was spread out and left to dry in air to avoid the humidity saturation which may affect the water content extensively. The grading test results conform to Iraqi specification No.45/1984 and ASTM C33 specifications (2002). This test has been carried out at the construction laboratory of the Building and Construction Engineering Department, University of Technology.

4.2.3 Coarse Aggregate (Gravel):

A maximum size of 19 mm of crushed gravel from Al-Nibaey region was used in the current study. The gravel was washed and cleaned by water several times and left to dry in air.

4.2.4 Mixing Water:

Potable water of Al-Risafa, Baghdad, was used throughout this investigation for mixing and curing.

4.2.5 Steel Reinforcing Bars:

Two sizes of deformed steel reinforcement bars were used for all specimens. Ø12 mm bar size used as longitudinal reinforcement and Ø10 mm bar size used as transverse reinforcement (closed stirrups).

4.2.6 CFRP Strip Properties:

Since this study is specialized on the flexural behavior of the beams strengthened with CFRP sheets, the ost tensile strength was chosen (Sika CarboDur S) to get the highest benefit of the CFRP sheets in addition to get the debonding extensively as a phenomenon which was studied and handled widely in this research. Sika CarboDur S512 was chosen in this study due to its suitable width with the specimens. Its width is 50 mm while its thickness is only 1.2 mm.

The CFRP sheet had a linear stress-strain behavior without any plastic behavior up to failure at the tension load. The mechanical properties of CFRP sheets which are shown in Table (2) may explain the sudden failure for this type of fibers. All these properties of CFRP strips are taken from the manufacturing specification of Sika [3].

4.2.7 Epoxy Adhesives Properties:

The adhesive used for bonding the plates was a two-component epoxy resin suitable for CFRP strips according to Sika's instructions. The most suitable adhesive material with CFRP sheet (Sika CarboDur S512) is Sikadur-30. This adhesive type consists of two compounds, compound A (white colour) and compound B (black colour). The mixed creamy pasty compound is light grey colour with a mix ratio compound 3:1 as A:B. Its main properties as supplied by the manufacturer, are shown in Table (3).

4.5 Mixing, Casting and Curing of the Specimens:

Two wooden moulds were manufactured at the laboratory. For each concrete batch, two specimens were cast. Prior to casting the interior face of moulds were greased to prevent natural bond between them and the concrete. Six steel cube moulds in dimensions of (150 × 150 ×150 mm) were also cast from the same concrete used for beams. Three cubes were cured under the same conditions as the test specimens and tested at the same time to provide information of the concrete strength. While the other three cubes were cured in the laboratory conditions and tested after 28 days to provide information of cube strength under ideal condition.

Table (4) shows the test summery of the five concrete batches for the cube specimens used in this study.

4.6 Surface Preparation and CFRP Installation:

Before installation of CFRP strip at the bottom fiber of the specimens, it was cleaned very well from any oil or grease which may bond at the concrete bottom fiber surface due to the residual of such materials between the specimen and the mould. The loose particles or laitance were avoided also by using an automatically smoothing machine, as a preparation for the bottom fiber surface. The surface to be coated (bottom fiber) was leveled, with steps and form work marks not greater than 0.5 mm. All the dust was removed from the surface with an industrial vacuum cleaner to ensure proper bonding of concrete and CFRP strips.

Component B was added to component A by using a scale and stirred with a mixing spindle fitted to an electrical low speed mixer (max. 500 rpm) to avoid entrapping of air. The Sika CarboDur plates were placed on a table and the ground side of the concrete specimen was cleaned before applying the Sikadur-30 adhesive with a roof shaped spatula onto the CarboDur strip. Within the open time of the adhesive, depending on temperature, the coated Sika CarboDur plates were placed gently onto the prepared concrete surface. These CFRP plates were ressed into the epoxy adhesive by using a rubber roller until the material is forced out on both sides of the strip. The consumption use of epoxy is 0.35 kg/m^2 [(58)].A uniform light loading along the specimen was placed to ensure the good bond between the concrete surface and the CFRP strip for at least 24 hrs. Two days before testing date, all the specimens were painted white so that the crack propagation can be easily detected.

4.7 Loading Condition, Instrumentation and Test Procedure:

A convenient test frame was available in the heavy structure laboratory at the University of Technology. The test were done by a (500 kN) capacity hydraulic jack. All of the specimen beams were tested under third point loading, over an effective span of 1,800 mm, with the loads applied at 300 mm on either side of the midspan.

Tests were carried out using an 'AVERY' (500 kN) hydraulic testing machine. A convenient test frame was available in the heavy structures laboratory at the University of Technology.

5. Test Results:

Load - deflection curve and the strain distribution along the cross section of the beam respectively for different load stages of the nine tested beams have been obtained and studied extensively.

Table (5) shows the cracking and failure loads for all the tested beams as a summary of the results obtained. Table (6) shows the increase in the cracking and failure loads percentages for these beams studied in the current research.

6. Finite Element Formulation and Non-Linear Solution Technique:

ANSYS V. 9.0 software (ANSYS Multiphysics FLEX1m v9.2), a powerful finite element method package is used for the model analysis.

SOLID65 is used for the 3-D modeling of concrete solids with or without reinforcing bars (rebar). LINK8 is a spar (or truss) element which has been used for reinforcement idealization. The layered version of the 8-node structural SHEL46 has been used also for CFRP idealization. While the steel anchorage system idealized as SHELL63. Nonlinear solution technique has been used for theoretical analysis through this study [4,5,6,7,8,9,10,11,12].

7. Theoretical Output Results:

Figs. (6 to 14) show a comparison between the load-deflection curves by the experimental and the numerical results. The variation of mid-span deflection with the applied step-loads for the all beams (S1 to S9) is recorded through the all these curves.

The comparison between the theoretical (FEM by ANSYS) cracking loads [Pcr)theo] and experimental cracking loads [Pcr)exp] shown in Table (7). While Table (8) shows the comparison between the theoretical (FEM by ANSYS) ultimate loads [Pu)theo] and experimental ultimate loads [Pu)exp].

8. Conclusions and Discussions:

8.1 Conclusions from Experimental Work:

The use of CFRP laminates only as external strengthening has significant effects on ultimate loads capacity. 26% increase of ultimate load when using one layer of CFRP at the bottom face. 44% increasing of ultimate load when using two layers f CFRP at the bottom face. The use of steel anchorages decreases the debonding of CFRP strips at the ended bottom face of the reinforced concrete beams of each side. And hence, the cracking and ultimate loads increased about 80% and 118% respectively. A significant and tangible decrease of the obtained mid-span deflections and increasing the ductility of all reinforced concrete strengthened beams was obtained when compared with the control or reference beam at all stages of loading. This behavior was much noted when the steel anchorages have been used.

Less deflection is produced by increasing the area of CFRP strips. When the area of CFRP strips doubled, the stiffness of the beam increased, and consequently the deflection at corresponding loads is reduced. But the difference in deflection is only about 15% in spite of the doubled area of CFRP. Extending the layers of CFRP behind the supports and along the beam of the bottom face gives very interesting increasing results especially for the two layers of CFRP along the beams. Such increase in the ultimate load reaches about 7.5% and 18% for one and two layers of CFRP respectively and with respect to the not extended one layer CFRP specimens.

The external steel anchorages have very significant effect for increasing the bond strength between the CFRP laminates and the concrete face. And consequently, enhancing the structural behavior positively (i.e. increasing first cracking, ultimate loads and reducing the deflection). The steel closed anchorages at the support points have the large effect of improving the structural behavior and especially the continuous steel anchorage plates along the shear spans which gives about 30% increase of ultimate load and 46% drop of deflection from the anchorage which was not continuous.

8.2 Conclusions from Finite Element Model

The three-dimensional finite element model used in the present work is able to simulate the flexural behavior of externally strengthened reinforced concrete beams by CFRP strips. The comparison between the numerical and experimental results asserted the validity of the numerical analysis and the methodology developed where the maximum difference ratio in ultimate load was less than 6.15 % for all the tested and analyzed beams.

The results from testing and finite element analysis show that the prediction of the deflection at mid-span by the proposed analytical method was sufficiently accurate but showed slightly smaller stiffness than the experimental results. The crack patterns from the finite element models corresponded well with the observed failure modes of the tested beams.

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Table (1) Specimens Identification of Strengthened Beams with CFRP Strip and Anchorage Distribution

Beam No.	Strengthened Layers	CFRP Plate Length	Type of Anchorage
S1	-	-	-
S2	1	1600 mm	-
S3	2	1600 mm	-
S4	1	1600 mm	2SE
S5	2	1600 mm	2SE
S6	2	1600 mm	1SE
S7	1	2000 mm	1SS
S8	2	2000 mm	1SS
S9	2	2000 mm	CS

SE: steel anchorage at the end of the plate SS: steel anchorage at the support
CS: continuous steel anchorage

Table (2) Mechanical Properties of CFRP Strips

Sika Fiber	Tensile Strength, (MPa)	Tensile-E-Modulus, (MPa)	Elongation at Failure, (%)	Major Poisson's Ratio
Sika CarboDur S512	2,800	165,000	1.7	0.184

Table (3) Properties of Sikadur-30 Adhesive

Characteristics	Guide Values
Pot Life	Min. 30 minutes (at +35°)
Density	1.77 kg/l
Shrinkage	0.04%
Modulus of Elasticity	12800 MPa
Tensile Bending Strength	Concrete failure (4 MPa)
Shear Strength	Concrete failure (15 MPa)

Table (4) Compressive Strength of Each Concrete Batch

Batch	Compressive Strength, ($f`_c{}^{\dagger}$)	Compressive Strength, ($f_{cu}{}^{\dagger}$)
A	27.60 MPa	34.5 MPa
B	26.45 MPa	33.0 MPa
C	30.30 MPa	38.0 MPa
D	35.70 MPa	44.5 MPa
E	37.40 MPa	46.5 MPa

† $f`_c = 0.80\ f_{cu}$

Table (5) Cracking and Failure Loads for the All Tested Beams

Beam Symbol	Cracking Load (kN)	Failure Load (kN)
S1	36	87
S2	40	110
S3	56	125
S4	60	135
S5	62	140
S6	46	115
S7	40	145
S8	55	165
S9	65	190

Table (6) The Increasing of the Cracking and Failure Loads Percentages for the Beams with Respect to the Control Beam (S1)

Beam Symbol	Cracking Load Increase (1st Crack Load) Percentage	Failure Load Increase Percentage
S2	11%	26%
S3	55%	44%
S4	67%	55%
S5	72%	61%
S6	27%	32%
S7	11%	67%
S8	53%	90%
S9	80%	118%

Table (7) Theoretical and Experimental Cracking Loads Comparison

Beam Symbol	Cracking Load (kN)		$\frac{P_{cr)theo}}{P_{cr)exp}}$
	$P_{cr)exp}$	$P_{cr)theo}$	
S1	36	29.8	0.827
S2	40	36.5	0.9125
S3	56	51.23	0.915
S4	60	53.15	0.886
S5	62	58.42	0.942
S6	46	42.16	0.917
S7	40	37.64	0.941
S8	55	51.56	0.937
S9	65	59.17	0.910

Table (8) Theoretical and Experimental Ultimate Loads Comparison

Beam Symbol	Ultimate Load (kN)		$\frac{P_{u)theo}}{P_{u)exp}}$
	$P_{u)exp}$	$P_{u)theo}$	
S1	87	81.65	0.9385
S2	110	109.64	0.9967
S3	125	122.45	0.9796
S4	135	137	1.0148
S5	140	134.5	0.960
S6	115	111.82	0.9723
S7	145	142.52	0.9829
S8	165	167.65	1.0161
S9	190	179.84	0.9465

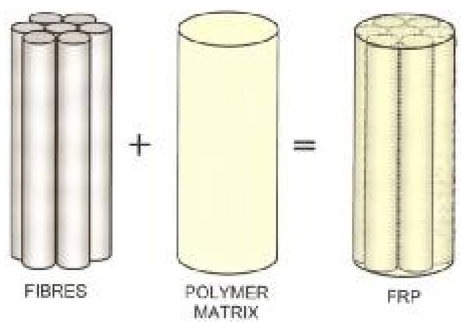


Figure (1) Basic Material Components that are Combined to Create an FRP Composit

Figure (2) Scanning Electron Micrograph Showing Microscopic Carbon Fibers Used in FRP Fabrication

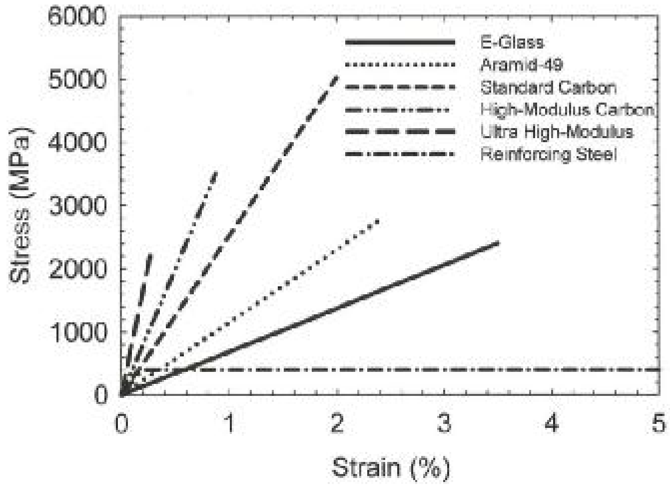


Figure (3) Stress – Strain Properties of Typical Fibers

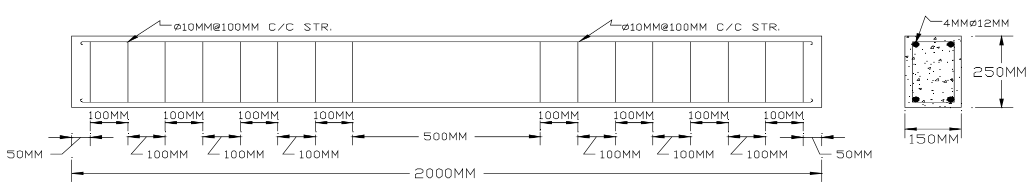
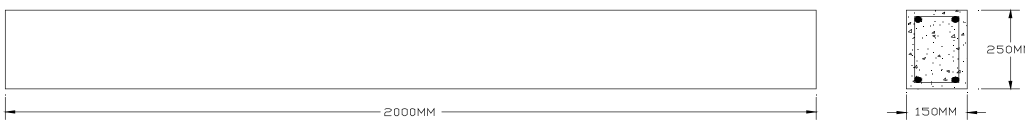
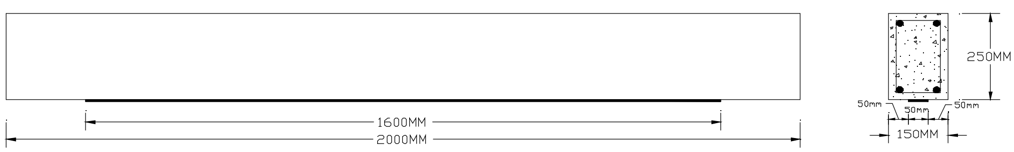


Figure (4) Reinforcement Details of Tested Beam

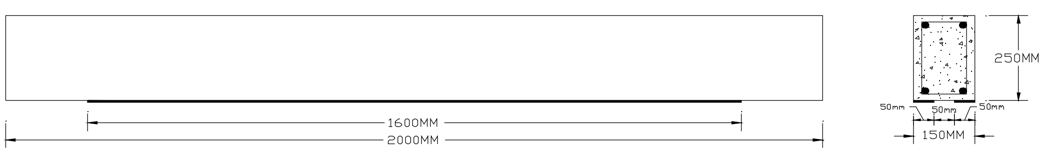
FRP Fabrication



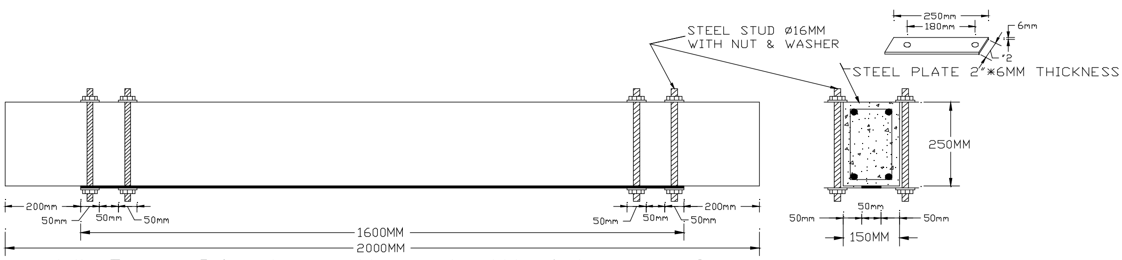
(a) Beam S1 as control beam



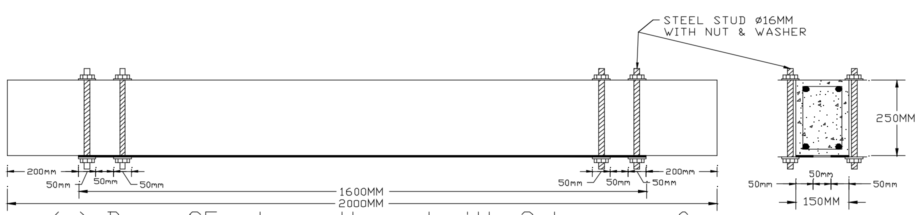
(b) Beam S2 strengthened with 1 layer of CFRP



(c) Beam S3 strengthened with 2 layers of CFRP



(d) Beam S4 strengthened with 1 layer of CFRP & 2 steel anchorages of each side of the end



(e) Beam S5 strengthened with 2 layers of CFRP & 2 steel anchorages of each side of the end

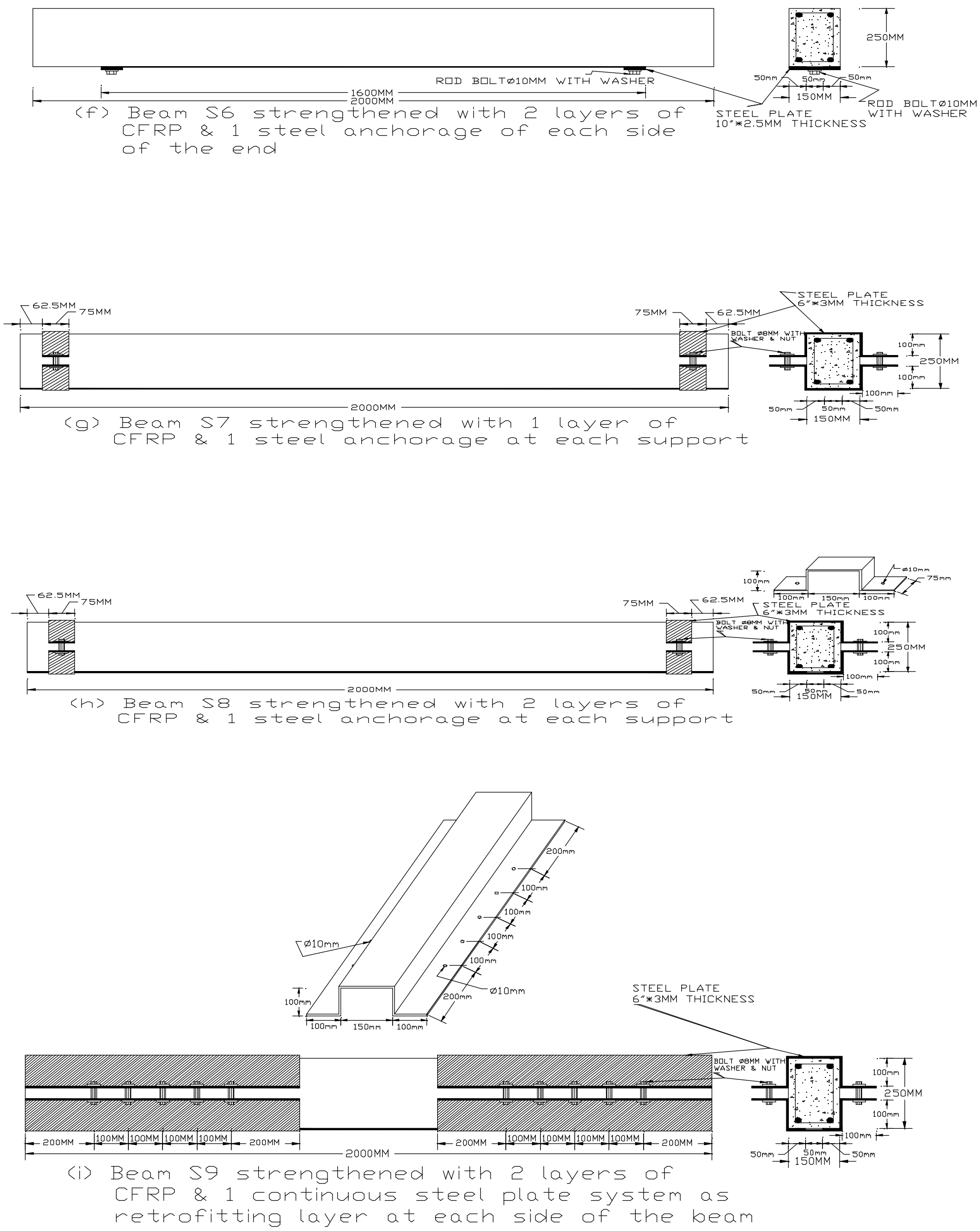


Figure (5) Arrangement and Location of CFRP Strips and Beam Anchorages

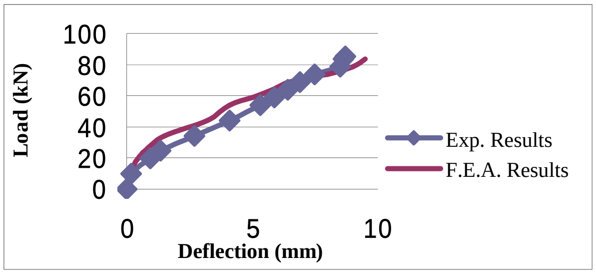


Figure (6) Load – Deflection Curves for the Control Beam (S1)

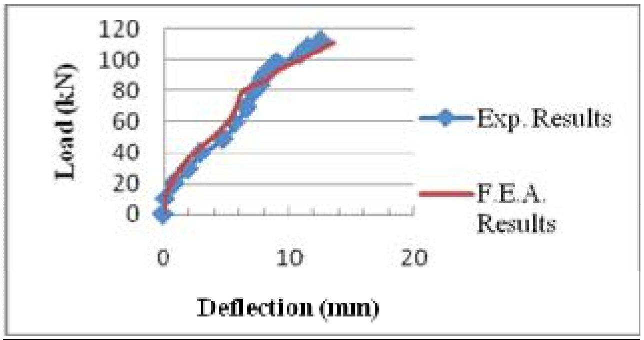


Figure (7) Load – Deflection Curves for the Control Beam (S2)

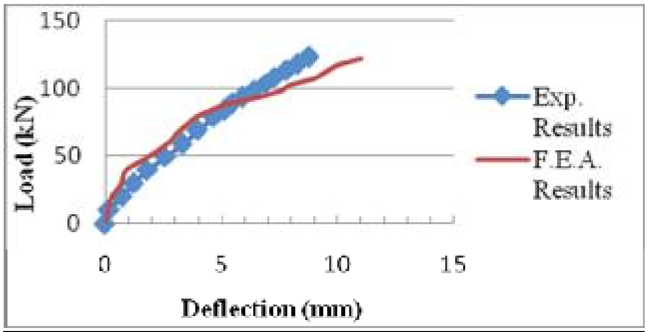


Figure (8) Load – Deflection Curves for the Control Beam (S3)

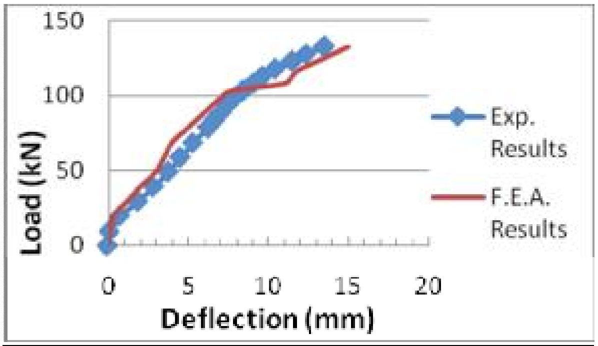


Figure (9) Load – Deflection Curves for the Control Beam (S4)

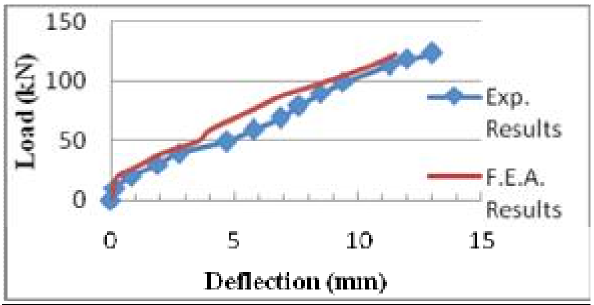


Figure (10) Load – Deflection Curves for the Control Beam (S5)

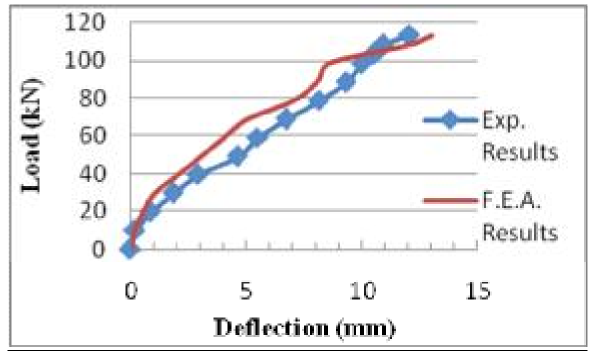


Figure (11) Load – Deflection Curves for the Control Beam (S6)

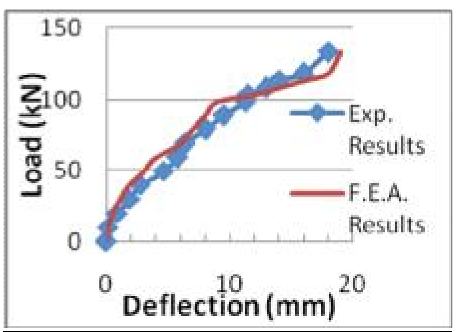


Figure (12) Load – Deflection Curve for the Control Beam (S7)

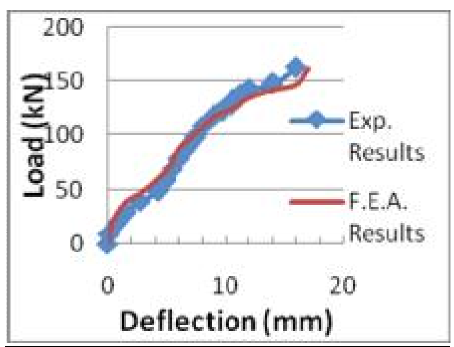


Figure (13) Load – Deflection Curves for The Control Beam (S8)

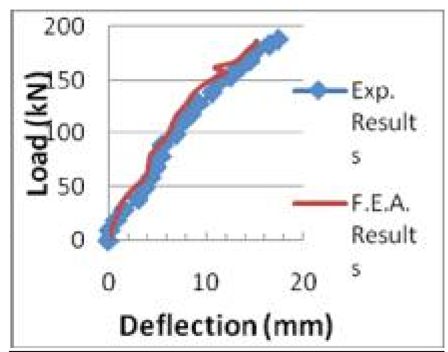


Figure (14) Load – Deflection Curves for the Control Beam (S9)