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Bonding techniques for flexural strengthening of R.C. beams using CFRP laminates

Alaa Morsy [a,*], El Tony Mahmoud [b,1]

[a] College of Engineering & Technology, Arab Academy for Science, Technology, and Maritime Transport, Alexandria, Egypt
[b] Faculty of Engineering, Alexandria University, Alexandria, Egypt

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Abstract This paper presents an experimental study of an alternative method of attaching FRP laminates to reinforced concrete beams by the way of fasting steel rivets through the FRP laminate and concrete substrate. Five full scale R.C. beams were casted and strengthened in flexural using FRP laminate bonded with conventional epoxy and compared with other beams strengthened with FRP laminate and bonded with fastener "steel rivets" of 50 mm length and 10 mm diameter. Based on experimental evidence the beam strengthened with conventional bonding methods failed due to de-bonding with about 13% increase over the un-strengthened beam. On the other hand, the beams strengthened with FRP laminate and bonded by four steel fastener rivets only failed by de-bonding also but at higher flexural capacity with increase 19% over the un-strengthened beam.

1. Introduction

In the 1980s, fiber reinforced polymer (FRP) materials began being used in civil engineering applications. The external strengthening of reinforced concrete members was an ideal use for preformed FRP strips, which are lighter and easier to install than steel strips. FRP strips do not rust when exposed to moist environments as do steel strips. Currently FRP strips are bonded to the concrete surface in the same manner as the steel strips, and the concrete substrate requires similar preparation as it would for the bonding of a steel plate. The adhesive layer between the concrete and strip can present problems for the behavior of the strengthened flexural member [1–7]. Peeling stresses are induced in the ends of the strip, which tend to pull the strip away from the concrete. If these peeling stresses are larger than the strength of the adhesive, the strip will peel away from the beam suddenly [8]. This results in the beam losing the increase in strength provided by the strip, and may cause a sudden and catastrophic failure.

Flexural members with attached steel strips often have large anchor bolts on the ends of the strips. These anchor bolts are provided to keep the steel plate from falling and damaging people or property in case the adhesive layer fails. Recently end anchorages have been examined for use with FRP strips as well [9].

* Corresponding author. Tel.: +20 01001853317.
E-mail addresses: alaamorsy@gmail.com (A. Morsy), CEB2010@yahoo.com (E.T. Mahmoud).
1 Tel.: +20 01112060123.
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Many researchers have been argued that the bond is significantly affected by surface preparation and general concrete quality, the degree and type of external anchorage was found to be important in maintaining the composite behavior [10]. This motivates researches to find a more sustainable method to bond CFRP laminates with concrete substrate using mechanical techniques [9,11–13].

A method of flexural strengthening reinforced concrete members with mechanically steel bolts is developed in this research study instead of an adhesive to attach a specially designed FRP strip to the concrete. This new technique has a potentially faster installation time and a potentially more ductile failure structural response than the sudden failure of conventional bonded method with epoxy.

2. Research significance

The research aim to study the effect of mechanical bonding for the CFRP laminates with the concrete substrate to enhance the flexural beam capacity using square steel plate bonded and pressing on the CFRP laminate surface and fastened with 10 mm steel rivets to prevent laminate de-bonding. Also the research investigates the effect of bolts spacing in enhancing the flexural strengthening capacity for the beam.

3. Experimental details

Five specimens were tested in this program, a control specimen, and four specimens strengthened using two different bonding and strengthening techniques (the conventional epoxy bonding and the steel plate with steel rivets with different spacing). The following part is a description of the specimens and the materials has been used throughout the experimental program.

3.1. Description of the beams

Five reinforced concrete beams were tested in this program. The specimens had a cross section of 150 mm × 300 mm, and a total length of 2.40 m. All specimens were designed to fail in flexural. For flexure reinforcement two 16 mm deformed bars were used as top and bottom reinforcement. The shear reinforcement consisted of 8 mm stirrups spaced at 100 mm. Fig. 1 shows the reinforcement details of the beams.

3.2. Test specimens and preparation

Five identical beams constructed as mentioned in the previous section were tested in this program. The first specimen "Control B1" was a control specimen without any strengthening. The second specimen "B2" was strengthened in flexural using CFRP laminates of width 50 mm and externally bonded to the bottom of the beam using epoxy resin only. Fig. 2 shows the application of epoxy to the concrete surface for CFRP laminate bonding.

The third specimen "B3" was strengthened in flexural using CFRP laminates and bonded using epoxy in addition to two rivets on each side of the beam, the rivets was 10 mm diameter and 200 mm spacing between the two rivets. All rivets have length of 50 mm inserted through beam depth penetrating the concrete cover and going between lower reinforcement, before inserting the rivets through beam depth a square steel plate with dimension of 30 mm has been fixed between the rivet head and concrete to make bearing pressure on the FRP laminates and enhance the bonding technique. Four holes were drilled on the beam bottom and filled with epoxy, and then the rivets were fastened in concrete to fix and bond the CFRP laminate with the concrete surface. Fig. 3 shows the procedure for fixing and fastening the rivets with CFRP laminate and concrete surface.

The fourth specimen "B4" was strengthened in flexural using CFRP laminates and bonded using epoxy in addition to 10 rivets at spacing 20 cm. In consequence of the shear failure for B4, fifth specimen "B5" was strengthened in both flexural and shear. The flexural strengthening was in same technique with B4 while the shear strengthening through three CFRP laminate of 5 mm width on the beam both sides and both ends, this shear strengthening help to govern the beam for flexural failure to test the full bond capacity. Table 1 provides a summary of the details of the specimens used in this program.

3.3. Material properties

Ordinary Portland cement (ASTM type I) was used throughout the program for making concrete. The fine aggregate used was natural siliceous sand with a fineness modulus of 2.6, specific gravity of 2.63, and unit weight of 1.75 t/cm^3, while the coarse aggregate was gravel of 19 mm nominal maximum size. The grading of aggregates satisfied the requirements of the

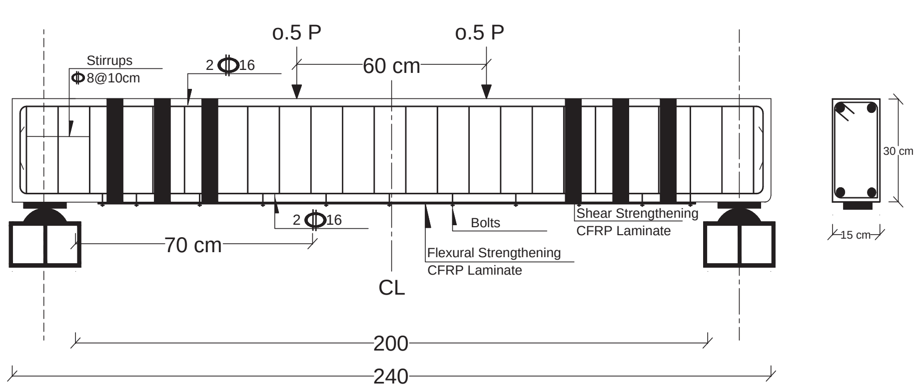

Figure 1 Longitudinal and cross section detail of the experimental beams.

Figure 2 Applying the epoxy resin on the concrete surface.

Egyptian Specification ESS 1109/71. No additives were incorporated in concrete. The cement content was 350 kg/m^3 and water-cement ratio was 0.51 based on free water. Concrete mix proportions are given in Table 2.

The concrete slump was 120 mm. The target concrete compressive strength was about 35 MPa based on testing 100 mm cubes from the same concrete mix of every tested beam and at the same day of testing the beam. The steel bars used for the flexure reinforcement and the stirrups had a nominal yield strength of 360 MPa and 240 MPa respectively. All the used strengthening laminates for all specimens have constant length of 2.0 m equivalent to the effective beam span and thickness of 1.2 mm, the MBrace CFRP laminates manufactured by BASF chemical company were used for flexural strengthening. The mechanical properties of the used CFRP laminate and its epoxy are shown in Table 3.

3.4. Test setup and instrumentation

All specimens were tested under four point bending. The span of the beams was 2.0 m and the distance between the loads was 0.6 m. Three dial gauges were used to measure the deflection at mid-span, and both loading points. A strain gauge was mounted on lower reinforcement and on the CFRP laminates. Loading was applied manually through a hydraulic pump to two hydraulic jacks at increments of 1 ton, at which time readings from the dial gauges and strains were manually recorded. Fig. 4 shows the test setup for the specimens.

4. Test results

4.1. Specimens behavior and failure modes

All specimens failed in bending except specimen B(4) failed in shear due to the extra bending strengthening. The following sections provide a description of the specimens' behavior during testing. Table 4 presents a summary of the test results.

5. Results and discussion

5.1. Crack pattern and failures modes

5.1.1. Control specimen (B1) "without strengthening"

For the control specimen the first visible crack appeared at a load of about 80 kN, the cracks extended from the beam bottom and start to spread from beam bottom to the beam top through the whole span of the beam. As loading progressed the crack widened as seen in Fig. 5. The specimen failed at a load of 160 kN. Although the failure was brittle it was less sudden than in the case of the other specimens.

5.1.2. Specimen (B2) flexural strengthened with CFRP laminate and bonded with epoxy only

The first visible crack appeared at a load of 60 kN at the mid-span of the beam. As loading progressed cracks widened then the specimen finally failed in a brittle manner at a load of 160 kN after de-bonding started immediately at the beam end then continue to the whole beam span, as seen in Fig. 6.

Figure 3 The procedure for fixing and fastening the rivets with CFRP laminate and concrete surface.

Table 1 Specimen specifications.

Specimen	Specification
B1	Control "without any strengthening"
B2	Flexural strengthened with CFRP laminate and bonded with epoxy only
B3	Flexural strengthened with CFRP laminate and bonded with epoxy + 2 bolts each side @ 20 cm
B4	Flexural strengthened with CFRP laminate and bonded with epoxy + bolts for full span @ 20 cm
B5	Flexural and shear strengthened with CFRP laminate and bonded with epoxy + bolts for full span @ 20 cm

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Table 2 Concrete mix proportions, kg/m^3.

Cement (kg/m^3)	Free water (Litre/m^3)	Coarse aggregate (kg/m^3)	Fine aggregate (kg/m^3)
350	180	1120	650

Table 3 Mechanical properties for CFRP laminate and its adhesive.

Material	Ultimate tensile strength (MPa)	Ultimate strain	Elastic modulus (MPa)	Compressive strength (MPa)
CFRP laminate	2700	1.4%	165,000	–
Adhesive	32	–	10,000	60

Figure 4 Set-up for four-point bending test in laboratory.

It was noticed that a thin layer of concrete is attached to the FRP laminate after failure, which indicate that the bonding epoxy working sufficiently till the transverse shear stress exceeds its allowable stresses.

5.1.3. Specimen (B3) flexural strengthened with CFRP laminate and bonded with epoxy + 2 bolts each side @ 20 cm

The first visible crack appeared at a load of 80 kN. The crack start at the mid-span of the beam in addition to small cracks appear at the rivets positions, while loading progressed the cracks widened then the FRP laminate start to split longitudinally all over the beam span at the rivets position, then debonding occur in the space between the right and left rivets as shown in Fig. 7.

5.1.4. Specimen (B4) flexural strengthened with CFRP laminate and bonded with epoxy + bolts for full span @ 20 cm

The main objective from this specimen is to determine the effect of increasing the number of rivets, and increasing the bonding between the FRP laminate and concrete via epoxy in addition to ten rivets covering the full span with spacing 200 mm, small flexural cracks appear at the beam mid span at load 60 kN at lower cracking load of the un-strengthened beam this may be related to the effect of drilling bolts in the bottom of the beam help in weaken this zone and accelerate cracking appearance. Also other cracks extend from beam bottom to top mainly at rivets position. Failure shear cracks appear at load 80–100 kN, those cracks extend from support to the loading position, and then the beam fails suddenly due to shear failure as shown in Fig. 8.

5.1.5. Specimen B(5) flexural and shear strengthened with CFRP laminate and bonded with epoxy + bolts for full span @ 20 cm

This specimen was strengthened in shear using three vertical CFRP laminate bonded at each beam side and on both beam ends to prevent the shear failure happen in B4. While starting loading small cracks appear in the beam mid-span and other cracks spread along the beam span initiated at rivets position at load 60–80 kN. No de-bonding occurs till failure between CFRP laminate and concrete substrate except very small areas between rivets. The beam capacity exceed the un strengthened beam by 40% and the beam cannot carry in additional load at ultimate load 220 kN and fails due to crushing in concrete at compression zone, this may be return to the sufficient bond using this fasting technique. Fig. 9 shows the compression failure zone due to crushing in concrete.

5.2. Load–deflection and load–strain relationships

The beams were tested using a load control MAGNUS testing machine. The mid span deflections were monitored using dial gauges, in addition to the deflection at the two loading points, whereas the strain in the longitudinal bars were recorded using electrical strain gages. The loads were applied continuously and recorded, along with the dial gauge and strain gages readings, using digital strain indicator. Application of the loads and the recording process continued until complete failure of the beam occurred.

The load–deflection behavior of the control beam and beam strengthened with CFRP laminates with different bonding techniques are shown in Fig. 10. It is observed from Fig. 10, that initially all the strengthened beams behave like the control beam with the internal steel reinforcing bars carrying the majority of the tensile force in the section. Before the internal steel yields, the additional tensile force is carried by the FRP

Table 4 Failure and first crack loads.

Specimen	P_{cr} (kN)	P_f (kN)	Mode of failure	Δ_f (mm)	Δ_{cr} (mm)	% Increase over un-strengthened
B1	80	160	Flexural failure	16.5	9.7	–
B2	60	180	Flexural failures after detachment of CFRP laminate	11.9	3.7	12.5%
B3	80	190	De-bonding + flex at middle	9.5	4.3	18.75%
B4	60	180	Shear failure + brittle	16.4	3.7	12.5%
B5	60	220	Ductile flexural failure, steel yield, and concrete crushing	10.3	2.2	37.5%

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Figure 5 Failure and crack pattern of control specimen B1.

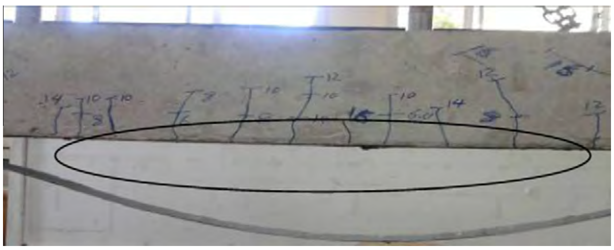

Figure 6 Failure and crack pattern of specimen (B2).

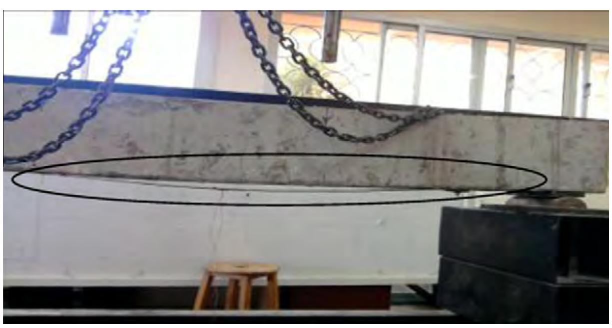

Figure 7 Failure and crack pattern of specimen (B3).

Figure 8 Shear failure and crack pattern of specimen (B4).

system and an increase of the load capacity of the member is obtained. Eventually, the FRP strengthened beams fail.

Due to the relatively low elastic modulus, linear elastic behavior and limited strain capacity of FRP's, concrete members reinforced with FRP reinforcement exhibit a brittle failure mode. Hence, lack of ductility in such members is one of the

Figure 9 Failure and crack pattern of specimen (B5).

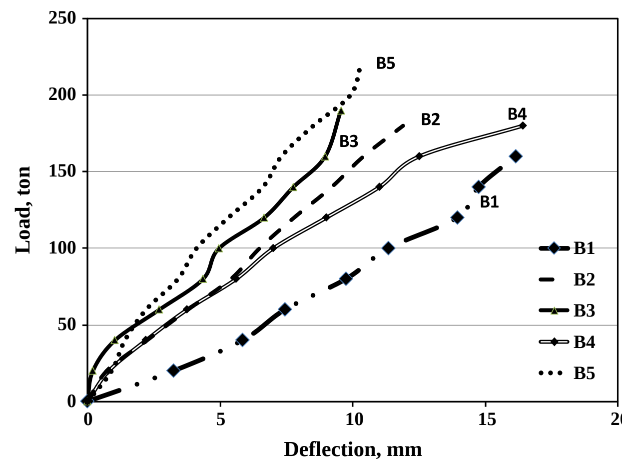

Figure 10 Mid-span deflections for all specimens.

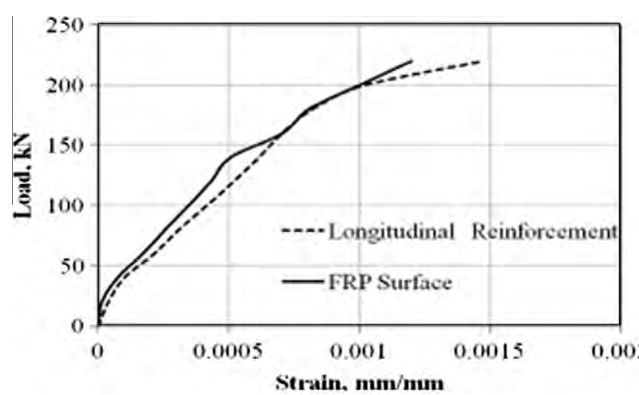

Figure 11 Stress–strain curves for specimen B5 at FRP laminate and longitudinal reinforcement.

key issues facing researchers. Ductility is commonly defined as the ability to undergo large plastic deformations prior to failure. Different approaches for achieving ductility which consists of combining a low modulus, medium strength, polymeric material with CFRP or GFRP as reinforcement are available in different studies.

However the lower reinforcement strain were measured in some specimens as the other specimens its lower reinforcement strain were damaged, it can be observed that the yield strains in steel were reached for all strengthened and un-strengthened beams. But, the measured strains in steel for strengthened beams were less than those of the un-strengthened ones under the same load level. This clearly shows the advantage of using FRP sheets in strengthening or upgrading RC beams.

FRP laminate strain and lower reinforcement strain were recorded for specimen B5 as shown in Fig. 11. It is clearly showed that both curves for FRP laminate and steel reinforcement were coincides in trend and value which indicate the full contact between FRP laminate and concrete surface, due to the effect of the rivets fastened in concrete which increase the bond effectively.

6. Conclusions

This paper has presented the results of an experimental program investigating the flexural performance of reinforced concrete beams strengthened with CFRP composites laminates and bonded with different bonding techniques. Based on the experimental results, and observations, the following conclusions can be stated:

1. The result of the experimental study indicates that externally bonded CFRP laminates is an effective method to strengthen the reinforced concrete beams and improve the structural load carrying capacity.
2. Regarding the bonding technique using rivets fastened through FRP laminate and concrete is very efficient technique for full contact for FRP laminate. Which exceed the over the strengthened specimen using epoxy by 23%.
3. Regarding the effect of rivets spacing, the specimen that fastened the FRP laminate by two rivets only on both beam ends enhance the flexural capacity by only 5% over the beam strengthened and bonded by epoxy only. Consequently it is not recommended to use partially fastening by rivets at beam end only.
4. Beams strengthened with CFRP laminate and bonded by epoxy only have not reached their ultimate flexural capacity due to the effect of peeling and premature de-bonding failure of the laminates. On the other hand beams were strengthened with CFRP laminate and bonded by epoxy in addition to fastened by rivets the mode of failure changed from flexural sudden failure due to de-bonding of CFRP laminate and delay the failure till the laminates carry most of its tensile strength followed by compression failure in concrete. The use of the fastener rivets is more prominent since the full flexural capacity for the strengthened beams can be achieved in terms of full span fastening by rivets.

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Alaa Morsy Dr. Alaa Morsy works as an Assistant Professor, Construction, and Building Depart., college of Engineering & Technology. He has tweleve years of experience in Structural engineering, practice and research. His fields of interest in usage Advanced Composite Materials (FRP) in Repair and Strengthening of R.C., Heat Transfer and fire Protection, and Use Finite Elements Soft wares in Modelling, he is curentrly posted as head of research and development department, at Port Training Institute, AASTMT.

El Tony Mahmoud El Tony Mahmoud, born 1966, received his civil engineering degree from the Alexandria University 1990 and his Ph.D also from Alexandria University at 2001. His fields of interest include the effect of strengthening and behaviour of Reinforced concrete elements using the CFRP, GFRP laminates and punching of Flat-Slab Column Connection.

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