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Repair of precracked RC rectangular shear beams using CFRP strip technique

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Abstract. The exploitation of fibre reinforced polymer composites, as external reinforcement is an evergreen and well-known technique for improving the structural performance of reinforced concrete structures. The demand to use FRP composites in the civil engineering industry is mainly due to its high strength, light weight, and stiffness. This paper exemplifies the shear strength of partially precracked reinforced concrete rectangular beams repaired with externally bonded Bi-Directional Carbon Fibre Reinforced Polymer (CFRP) Fabrics strips. All specimens were cast in the laboratory environment without any internal shear reinforcement. The test parameters were longitudinal tensile reinforcement, shear span to effective depth ratio, spacing of CFRP strips, and orientation of CFRP reinforcement. It mainly focuses on the shear capacity and modes of failure of the CFRP strengthened shear beams. Results have shown that the CFRP repaired beams attained a shear enhancement of 32% and 107.64% greater than the control beams. This study underscores that the CFRP strip technique significantly enhanced the shear capacity of precracked reinforced concrete rectangular beams without any internal shear reinforcement.

Keywords: shear; CFRP; repair.

1. Introduction

Most of bridges and massive structures have reached the end of service life, either due to the

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deterioration of the concrete and reinforcement or an increase in applied loads, thereby, becoming structurally deficient or functionally obsolete (El-Hacha *et al.* 2001). Strengthening of reinforced concrete structures using externally bonded Fibre Reinforced Polymer composite is a well-known technique for improving the structural performance of existing structures. It seems to be very simple but it has more difficulties than installing a new structure since it is influenced with many factors like deteriorated condition, loads during strengthening, existing material and geometry. The major demand to exploit the FRP system in civil engineering application is mainly due to its beneficial characteristics than the conventional materials. FRP composites are non-conductive, resistance to corrosion, light weight, high strength and durability (Khalifa and Nanni 2000, Raghu *et al.* 2001). The external FRP plate bonding technique has been widely attracted due to its advantages such as easy construction work, minimum change in overall cross section of the structure after the application of external plating and less interruption to traffic while the strengthening is being carried out (Adhikary *et al.* 2000).

Shear strengthening is often needed for reinforced concrete beams due to various reasons such as design and construction faults, adverse environmental attacks and functional changes. The need for shear strengthening may also arise as a result of flexural strengthening (Chen and Teng 2001). The shear enhancement of the reinforced concrete shear beams can be achieved by applying external FRP sheets around the web and soffit. Extensive works (e.g., Saadatmanesh and Ehsani (1991), Norris *et al.* (1997), Chajes *et al.* (1995a, 1995b), Khalifa and Nanni (2000, 2002), Khalifa *et al.* (2000)) have been conducted on reinforced concrete beams using continuous wrapping system to increase the shear capacity. The literature review shows that shear strengthening of reinforced concrete beams using uni-directional carbon fibre reinforced polymers sheet has been studied well. Nevertheless, the bi-directional CFRP strip technique has not been addressed yet (Jayaprakash *et al.* 2004a, 2005). Khalifa and Nanni (2000, 2002), Khalifa *et al.* (2000), Imran (2003) did some work on external FRP strip technique. However, limited work has been done on the application of FRP sheet in the form of strips (Jayaprakash *et al.* 2004b). Al-Mahaidi *et al.* (2001) and Hussain *et al.* (1995) also pointed out that little work has been done in investigating the behaviour of the partially damaged beams using FRP.

This study presents the shear strength and modes of failure of partially precracked reinforced concrete rectangular beams bonded externally with bi-directional Carbon Fibre Reinforced Polymer (CFRP) fabric strips. Ten reinforced concrete rectangular beams were cast without any internal shear reinforcement, strengthened and tested to failure. The variables were longitudinal tensile reinforcement, shear span to effective depth ratio, spacing of CFRP strips, and orientation of CFRP reinforcement.

2. Experimental program

2.1 Specimen details and material properties

A series of ten large-scale rectangular specimens with a total span of 2980 mm and a cross section of 120 mm wide and 340 mm deep were fabricated with a concrete grade of 30 MPa. These specimens were grouped into four series: BT1, BS1, BT2 and BS2. Specimens in series BT1 & BT2 and BS1 & BS2 were reinforced with high yield steel bars of two 20 mm and 16 mm diameter respectively along the longitudinal direction. No internal steel stirrups were provided in any of beams. The internal reinforcement details of the specimens are shown in Fig. 1. In each series, one beam was preserved as control or reference beam and the subsequent beams were precracked and repaired with externally bonded Bi-Directional Carbon Fibre Reinforced Polymer (CFRP) Fabric strips. Table 1 illustrates the specimen description and orientation of CFRP strip. Bi-Directional Carbon Fibre Reinforced Polymer fabrics (Sika Wrap-160C 0/90) were used as external shear strengthening reinforcement with two-component epoxy. Table 2 shows properties of carbon fibre fabrics and epoxy resin (Sikadur330).

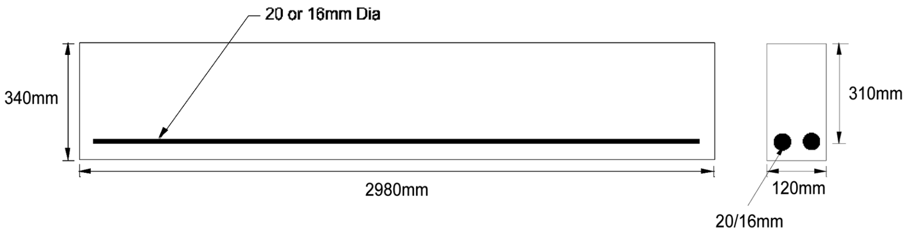


Fig. 1 Reinforcement details of series BT1/BT2/BS1/BS2

Table 1 Specimen description and orientation of CFRP strips

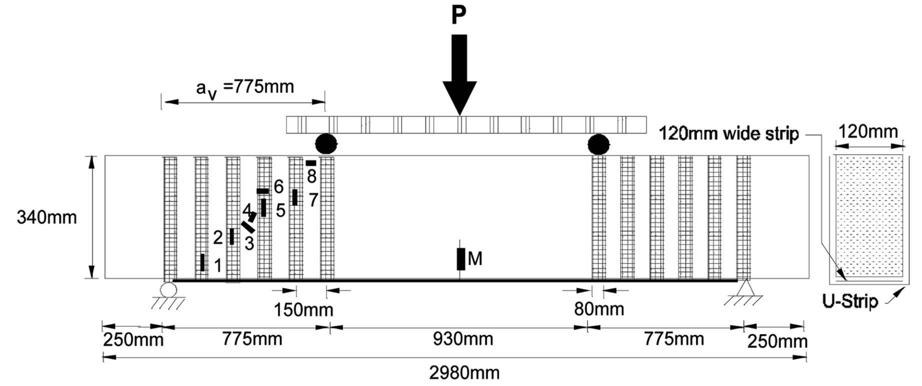
Specimen		Shear span to effective depth ratio (a_v/d)	CFRP strip specification			
			Width (mm)	Spacing (mm)	No. of plies	Orientation
BT1a	Control	2.5	---	---	---	---
BT1-1	Precracked/Repaired	2.5	80	150	1	U-strips 0/90 degree
BS1a	Control	2.5	---	---	---	---
BS1-1	Precracked/Repaired	2.5	80	150	1	U-strips 0/90 degree
BS1-2	Precracked/Repaired	2.5	80	200	1	U-strips 0/90 degree
BT2a	Control	4.0	---	---	---	---
BT2-1	Precracked/Repaired	4.0	80	150	1	U-strips 0/90 degree
BT2-2	Precracked/Repaired	4.0	80	150	1	L-strips 45/135 degree
BS2a	Control	4.0	---	---	---	---
BS2-2	Precracked/Repaired	4.0	80	150	1	L-strips 45/135 degree

Table 2 Properties of Carbon Fibre Fabrics (Based on Manufacture's Manual)

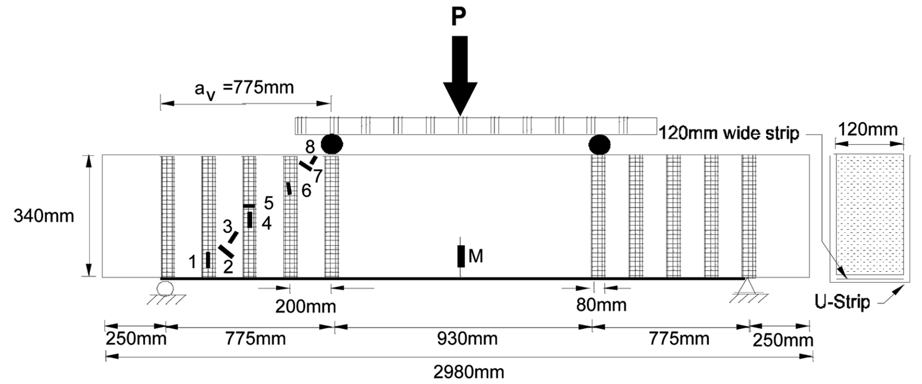
	CFRP fabrics	Epoxy resin (Sikadur330)
Fibre orientation	0/90 (Bi-Directional)	---
Thickness (mm)	0.09	---
Tensile strength (MPa)	3,800	30
Modulus of elasticity (MPa)	230,000	3,800
Tensile strain of fibres ($\mu\varepsilon$)	0.15	---
Adhesive strength (MPa)	---	4

3. Test methodology

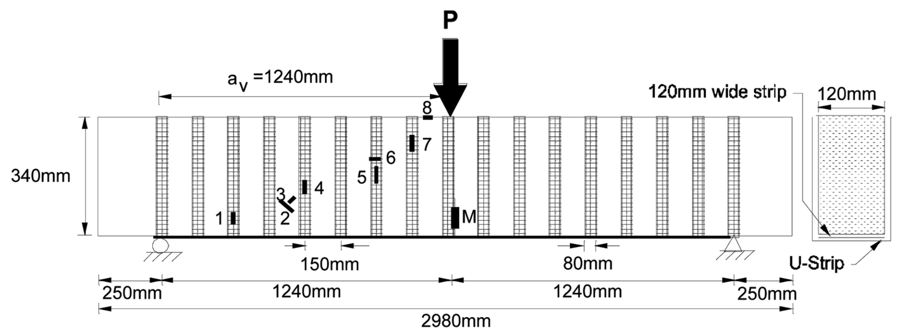
Specimens in series BT1 and BS1 were subjected to four point bending system with a shear span to effective depth ratio of 2.5. But the specimens in series BT2 and BS2 were loaded with a concentrated load at the mid span representing a shear span to effective depth of 4.0. Fig. 2 portrays the loading system of series BT1, BS1, BT2 and BS2. Specimens are categorised into two types:



(a) BT1-1 and BS1-1

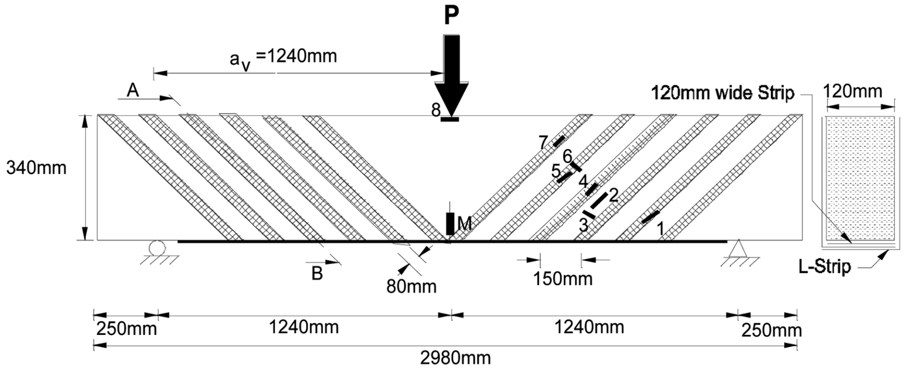


(b) BS1-2

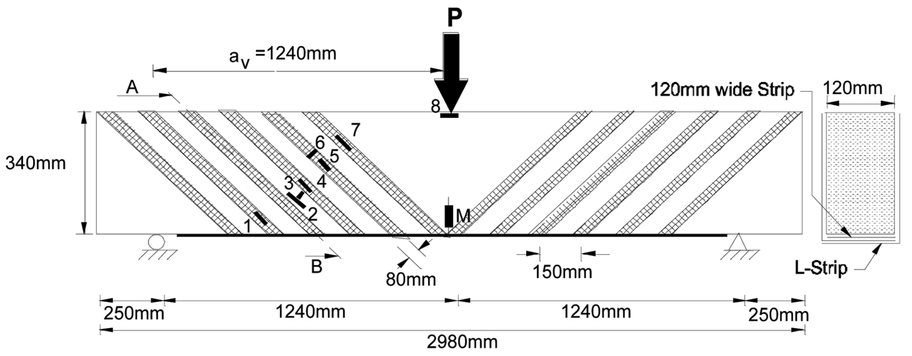


(c) BT2-1

Fig. 2(a), (b), (c), (d), and (e): Strengthening patterns and test set-up



(d) BT2-2



(e) BS2-2

Fig. 2 Continued

namely control and precracked/repaired beams. The control beam was initially loaded to develop precracks and continued by unloading to zero, then reloaded to the failure. The test procedure of the precracked/repaired specimens consisted of two phases. In the first phase, the beams were loaded for two cycles in order to develop precracks and the second phase of loading was conducted after the specimens were repaired with CFRP strips. After the application of CFRP strips, the beams were loaded in one stroke till the failure. The test set-up, strengthening patterns, position of external strain gauges and linear variable differential transformer are shown in Figs. 2(a), (b), (c), (d), and (e). During the test program, the modes of failure such as debonding or peeling of fibre fabrics/ sheets from the concrete surface or rupture of fabric strips, and crushing of concrete were observed. The crack propagation was clearly traced at each increment of load.

4. Results and discussion

4.1 Observation and failure pattern

Series BT1: The control beam BT1a was loaded with an equal increment; the first flexural crack was occurred at 28 kN. During the first cycle of loading, the flexural cracks were initially appeared along the constant moment region of the specimen. The diagonal crack was initiated near the middle of shear spans at a load of approximately 48 kN. In the second cycle, the beam was reloaded, flexural cracks were propagated and widened nevertheless the diagonal crack was extending towards the loading point. Finally, the control beam BT1a failed in the left shear span at a total load of 94.82 kN. Fig. 3(a) shows the shear failure pattern of the unstrengthened or control beam BT1a. The beam BT1-1 was loaded to 68.21 kN in the first cycle of loading then unloaded to zero and reloaded same as first cycle to widen the precracks. In the precracking phase, the flexural and shear cracks appeared similar to that of the control beam. After the application of precracking phase, the beam was repaired with 80 mm wide CFRP U-strip at a spacing of 150 mm centre to centre and a 120 mm wide CFRP strip of length 2480 mm was provided along the soffit of the beam. The bottom CFRP strip was applied prior to the application of the vertical U-strip. Again, the beam was loaded in a single stroke to the failure. The diagonal crack was observed at a load of approximately 108 kN. Failure of the beam occurred in the left shear span at a total applied load of 134.72 kN due to the rupture of CFRP strip along the shear crack. Test result shows that there was an increase of 40 kN in ultimate load capacity compared to the control specimen BT1a. The shear with CFRP fracture mode of failure of the precracked/repaired specimen BT1-1 is shown in Fig. 3(b). Fig. 4(a) depicts the load versus mid deflection profile of specimens in series BT1.

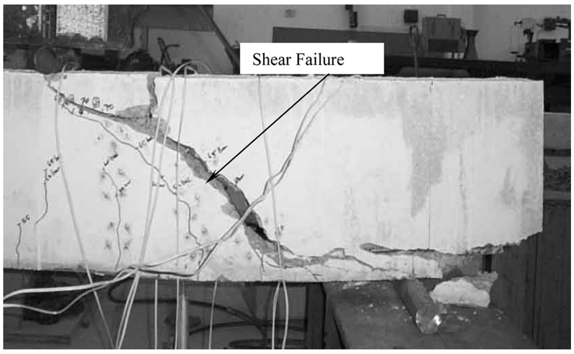


Fig. 3(a) Shear failure pattern for control specimen BT1a

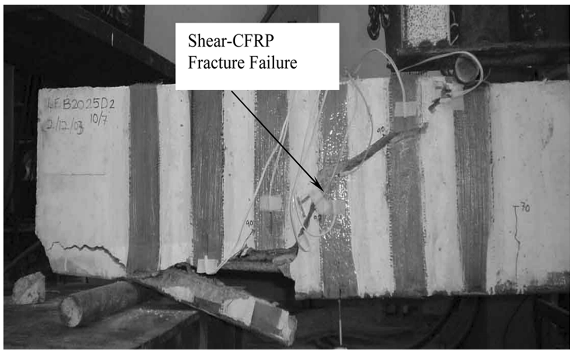


Fig. 3(b) Shear with CFRP fracture failure pattern for precracked/repaired specimen BT1-1

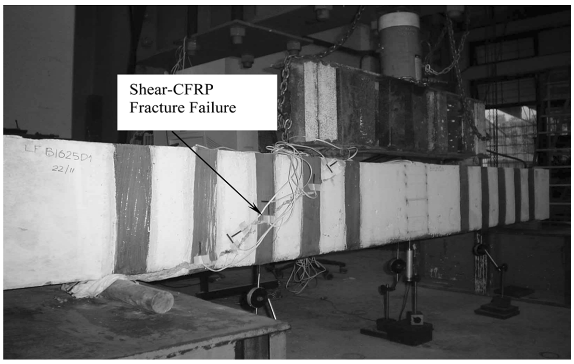


Fig. 3(c) Shear with CFRP fracture failure pattern for precracked/repaired specimen BS1-2

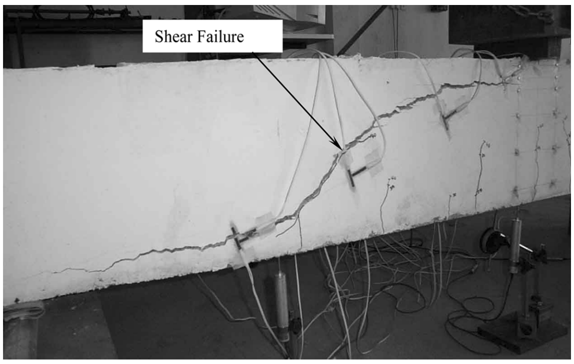


Fig. 3(d) Shear failure pattern for control specimen BT2a

Fig. 3(e) Shear with CFRP fracture failure pattern for precracked/repaired specimen BT2-1

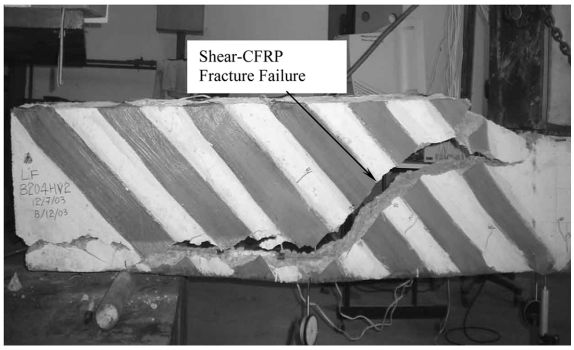


Fig. 3(f) Shear with CFRP fracture failure pattern for precracked/repaired beam BT2-2 (45/135 degree)

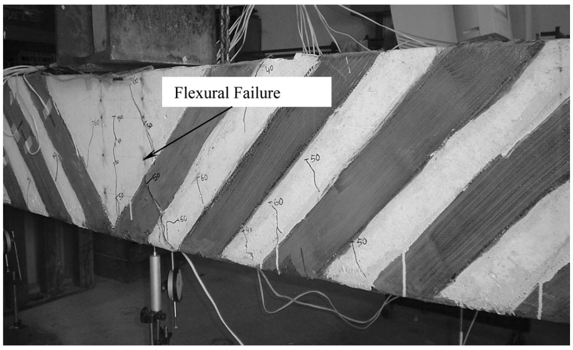


Fig. 3(g) Flexural failure pattern for precracked/repaired specimen BS2-2

Series BS1: In this series, the control specimen BS1a observed a diagonal crack at a load of 42 kN in the first cycle of loading. The critical diagonal cracks originated at the left side of the shear span. In the reloading phase, the diagonal crack in the right shear span was propagated towards the loading point and failed in shear at a peak load of 74.86 kN. The failure pattern of this beam was same as BT1a. Specimens BS1-1 and BS1-2 were precracked by the application of two cycles of loading to develop precracks along the shear span. During the precracked phase, the flexural and diagonal cracks of these specimens were similar to that of the control specimen. After the precracking phase, beams BS1-1 and BS1-2 were repaired with vertical CFRP U-strips at spacing 150 mm and 200 mm centre to centre respectively. During the application of load, there was no amplification in the diagonal cracks emerged between the CFRP strip gaps of the beam BS1-1 at a load of 82 kN. With the increase of load, the critical shear crack propagated along the concrete surface underneath the strip led to fracture or rupture at a ultimate load of 121.42 kN. This failure was initiated by shear with CFRP fracture at the right shear span. For specimen BS1-2, the diagonal crack originated approximately at 75 kN. The mode of failure of the specimen BS1-2 (see Fig. 3(c)) was observed to be the same as BS1-1 but it failed in the left shear span at an ultimate load of 101.47 kN like control beam BS1a. The shear contribution of CFRP reinforcement of the strengthened beams BS1-1 and BS1-2 were respectively 46.56 kN and 26.61 kN higher in comparison to the control specimen BS1a. It was also observed that increase in amount of internal steel reinforcement increases the load carrying capacity of the CFRP strengthened specimens.

Fig. 4(b) shows the load versus mid deflection profile of specimens in series BS1.

Series BT2: The applied load versus mid deflection of specimens in series BT2 is shown in Fig. 4(c). The control beam BT2a observed flexural and diagonal cracks approximately at 35 kN and 55 kN respectively. It was failed suddenly with an ultimate failure load of 65 kN. The failure was controlled by shear at left span similar to that of the control specimen BT1a (i.e. from series BT1). At failure, the shear crack propagated horizontally along the longitudinal reinforcement. The shear failure pattern of the control specimen BT2a is shown in Fig. 3(d). Specimens BT2-1 and BT2-2 were precracked similar to the control beam and repaired with CFRP strips at an inclination of 0/90 degree (U-strip) and 45/135 degree (L-strip) to the longitudinal axis of the beam. The width and spacing of CFRP strips was 80 mm and 150 mm centre to centre respectively. Specimen BT2-1 used CFRP U-strips along the whole effective span whereas the specimen BT2-2 was reinforced with inclined CFRP L-strips. The L-strips from front and rear side of the beam were overlapped on

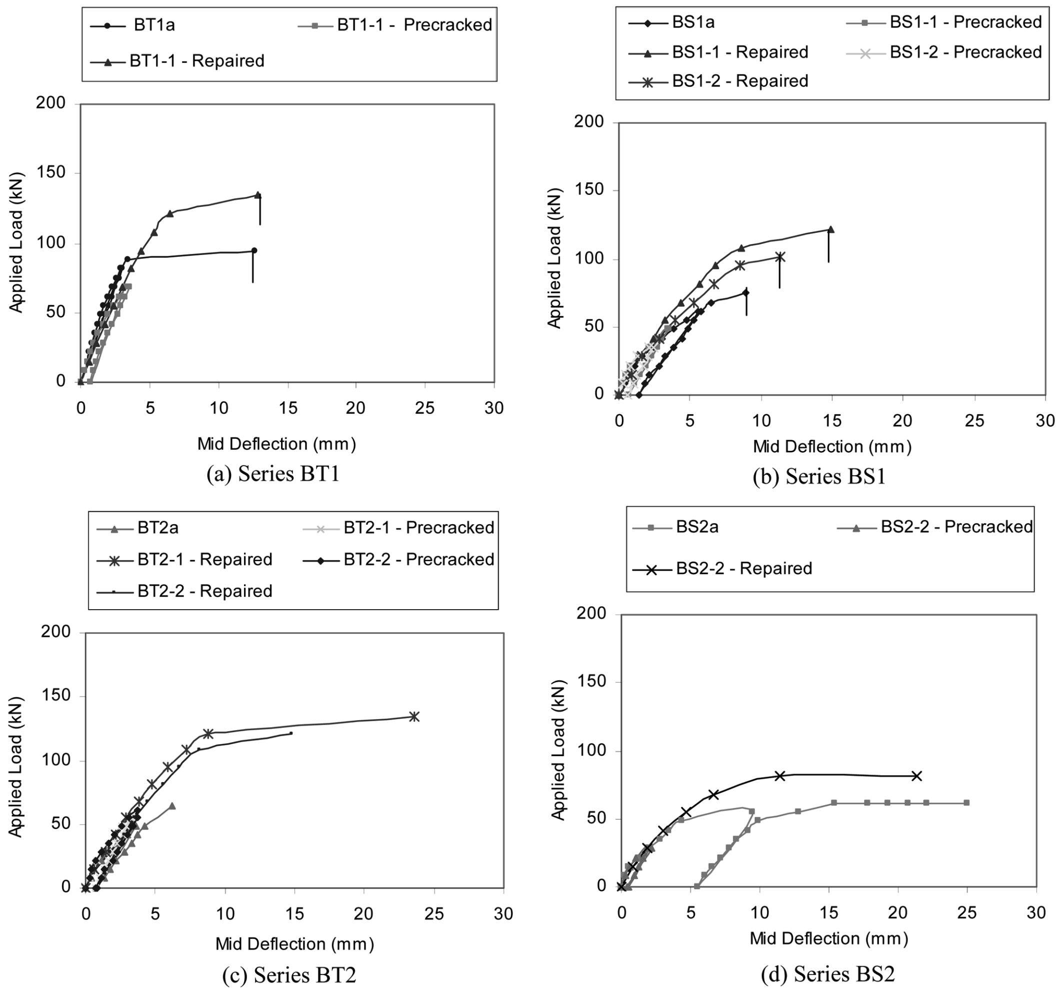


Fig. 4 (a), 4(b), 4(c), and 4(d): Load versus mid deflection curves of specimens in series BT1, BS1, BT2 and BS2 the soffit of the beam. These L or U-strips were provided after the application of 120mm wide CFRP strip along the bottom of beam. In the precracking phase the cracking pattern was similar to the control beam. After repairing, specimens BT2-1 and BT2-2 initiated diagonal cracks approximately at 95 kN and 108 kN respectively. As applied load increased, specimen BT2-1 was failed in shear with CFRP rupture or fracture at a peak load of 134.72 kN in the right shear span. Similarly the specimen BT2-2 failed in shear with CFRP rupture at a peak load of 121 kN however the failure occurred in the left shear span. The CFRP shear contribution of the specimens BT2-1 and BT2-2 were 69.84 kN and 56.54 kN respectively. Figs. 3(e) and 3(f) depict the failure pattern of specimens BT2-1 and BT2-2 respectively.

Series BS2: Fig. 4(d) portrays a typical plot of applied load versus mid deflection of specimens in series BS2. The control specimen BS2a was precracked to a load of approximately 55 kN continued by reloading to the failure. The first crack started at 21.64 kN close to the mid span of the beam. The initiation of shear crack was at 48 kN but less pronounced when compared to the flexural cracks. Eventually it failed in flexure at a failure load of 61.56 kN. The specimen BS2-2 had undergone precracking similar to the control beam BS2. This specimen was repaired with CFRP L-strips orientated at 45/135 degree to the longitudinal axis of the beam. In the second phase of loading, inclined cracks were emerged between the CFRP strip gaps (i.e., unwrapped portion) at 69 kN but the flexural cracks at the mid span were well pronounced and visible. There was no crack propagation near the middle of the shear span similar to the specimen BT2-1 (series BT2) with vertical U-strips. This might be due to the inclined orientation of CFRP strips. It was also observed that the propagation of early-developed precracks was arrested due to the orientation of inclined CFRP strips. The beam BS2-2 finally failed in flexure at a peak load of 81.51 kN (see Fig. 3(g)). The contribution of CFRP strip in the specimen BS2-2 was of approximately 20 kN greater than the control beam BS2a.

4.2 Evaluation of experimental results

Strength and Modes of Failure: The test results are summarised in Table 3. The CFRP strengthened specimen BT1-1 in series BT1 achieved a shear enhancement of 42% over the control

Table 3 Summary of experimental results

Specimen	a_v/d	CFRP strip orientation	Spacing of strip	Ultimate failure load	Contribution of CFRP strip	Shear enhancement	Modes of failure
BT1a	2.5	---	---	94.82	---	---	Shear
BT1-1	2.5	U-strip 0/90 degree	150	134.72	39.91	42.09	Shear-CFRP fracture
BS1a	2.5	---	---	74.86	---	---	Shear
BS1-1	2.5	U-strip 0/90 degree	150	121.42	46.56	62.19	Shear-CFRP fracture
BS1-2	2.5	U-strip 0/90 degree	200	101.47	26.61	35.55	Shear-CFRP fracture
BT2a	4.0	---	---	64.88	---	---	Shear
BT2-1	4.0	U-strip 0/90 degree	150	134.72	69.84	107.64	Shear-CFRP fracture
BT2-2	4.0	L-strip 45/135 degree	150	121.42	56.54	87.14	Shear-CFRP fracture
BS2a	4.0	---	---	61.55	---	---	Flexural
BS2-2	4.0	L-strip 45/135 degree	150	81.514	19.964	>32.44	Flexural

beam BT1a. Similarly, in series BS1 the percentages of shear enhancement of the CFRP strengthened specimens BS1-1 and BS1-2 were 62% and 36% higher than the control beam BS1a.

In series BT2, the percentages of shear enhancement of the CFRP strengthened specimens BT2-1 and BT2-2 were 107.66% and 87.15% over the control specimen BT2a. As in series BT2, the specimen BS2-2 in series BS2 attained a shear enhancement of 33% greater than the control beam BS2a.

Test results indicate that the RC strengthened shear beams had two types of failure at ultimate; flexural and shear with CFRP rupture. The attained flexural mode of failure increased the ductility of the CFRP strengthened specimens. It was also observed that there was no debonding of CFRP strip from concrete surface in any of the CFRP strengthened specimens.

Spacing of CFRP strips: When comparing the test results of the specimens BS1-1 and BS1-2, the shear enhancement of specimen BS1-1 was approximately 17% more than that of the specimen BS1-2 due to the increase in spacing of CFRP strips.

Longitudinal Tensile Reinforcement Ratio: Experimental result shows that the percentage of shear enhancement of the specimen BT1-1 was approximately 11% greater compared to the specimen BS1-1. It indicates that the increase of longitudinal tensile reinforcement ratio increases the shear capacity of the strengthened beam. The state of loading (four point bending system), shear span to effective depth ratio and amount and distribution of CFRP strip were similar in beams BS1-1 and BT1-1. Similarly, specimens BT2-2 and BS2-2 had similar state of loading (three point bending system), a_v/d ratio (equals to 4.0) and amount and distribution of CFRP strip. However, the shear enhancement of the specimens BT2-2 was 50% higher than the specimen BS2-2. It was apparent that the increase of longitudinal tensile reinforcement ratio affects the shear capacity of the CFRP strengthened beams.

Orientation of CFRP strips: The strengthened specimen BT2-2 was damaged by formation of cracks through its depth during the handling operation. This damage was the prime reason for the reduction in ultimate load of beam BT2-2 (45/135 degree) in comparison to BT2-1 (0/90 degree U-strip). As a result, it is not possible to conclude effect of change in orientation of CFRP strips.

Shear span to effective depth ratio: When comparing the test results of the specimens with shear span to effective depth ratio of 2.5 with that of those having 4.0, the shear contribution of the CFRP reinforcement of the specimen BT2-1 was 83% greater than specimen BT1-1. It was found that the contribution of CFRP reinforcement found to have increased with the increase of shear span to effective depth ratio.

4.3 Load strain profile

Figs. 5(a), 5(b), 5(c), 5(d), 5(e), and 5(f) illustrate the strain distribution in CFRP strips and concrete surface for beams BT1-1, BS1-1, BS1-2, BT2-1, BT2-2 and BS2-2 respectively. The strain gauges were placed along the direction of the fibres. It can be seen from figures, the strain in CFRP strengthened specimens showed elongation of CFRP strip (i.e., CFRP stressed) prior to failure, indicating the effectiveness of the CFRP strip resisting in shear. The CFRP strain values in principal fibre direction (i.e., 90/45 Degree) attained greater strain value in comparison to fibres oriented perpendicular to the principal fibres (i.e., secondary fibres). This shows that the secondary fibres in CFRP strip were not carrying any load like principal CFRP fibres. From this result, it can be concluded that the principal fibres are the carrying the loads similar to that of the internal steel

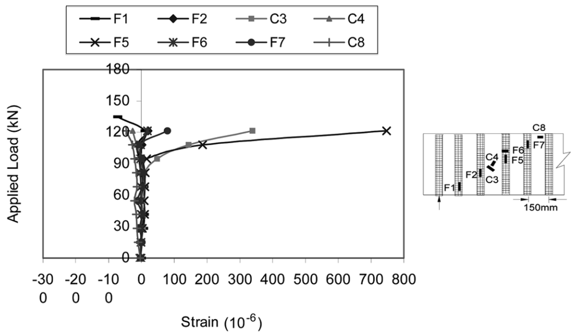


Fig. 5(a) Load versus surface strain in CFRP strip and concrete surface for precracked/repaired specimen BT1-1

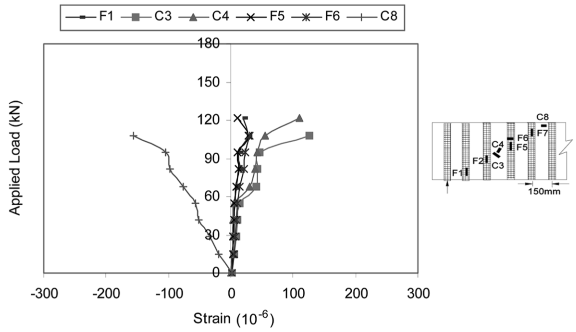


Fig. 5(b) Load versus surface strain in CFRP strip and concrete surface for precracked/repaired specimen BS1-1

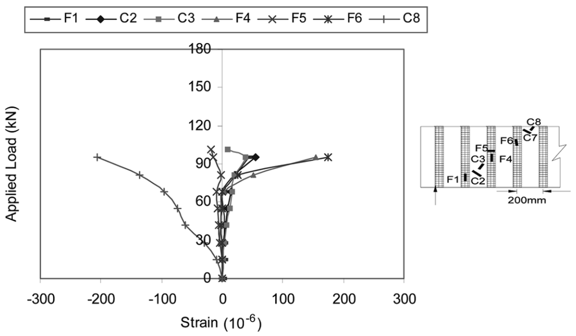


Fig. 5(c) Load versus surface strain in CFRP strip and concrete surface for precracked/repaired specimen BS1-2

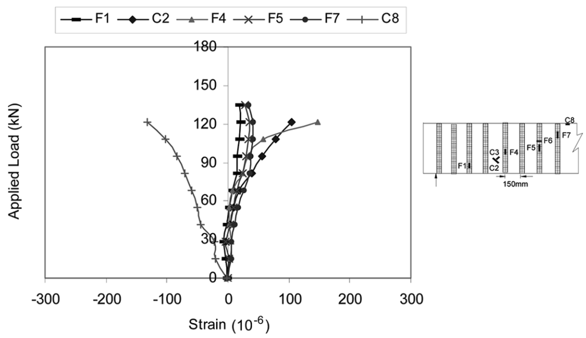


Fig. 5(d) Load versus surface strain in CFRP strip and concrete surface for precracked/repaired specimen BT2-1

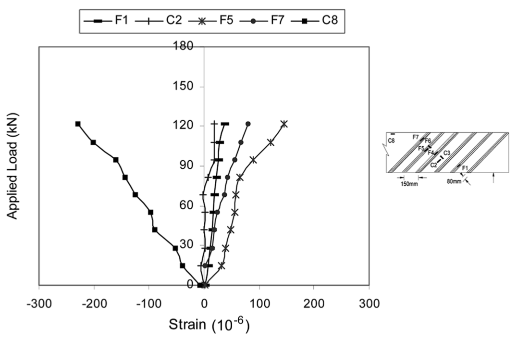


Fig. 5(e) Load versus surface strain in CFRP strip and concrete surface for precracked/repaired specimen BT2-2

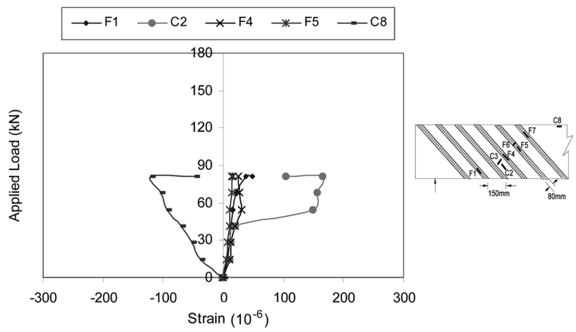


Fig. 5(f) Load versus surface strain in CFRP strip and concrete surface for precracked/repaired specimen BS2-2 stirrups however the secondary fibres are probably acting as restraint to control the debonding of CFRP strip from the concrete surface. The bi-directional CFRP strips have good bonding with concrete surface due to the presence of the horizontal fibres. Result also shows that the maximum CFRP strain values in the CFRP strengthened specimens attained less than the strain limit (0.015). Unfortunately, several strain gauges did not record reliable data because achieving bond between the gauges and impregnated surface is very difficult.

5. Conclusions

The experimental results show that the application of externally bonded bi-directional CFRP strip reinforcement has significantly enhanced the shear strength of the partially precracked reinforced concrete rectangular beams without internal shear reinforcement. The percentage of shear enhancement of the repaired specimens ranged between 32% and 107.64%. The study also revealed that the contribution of CFRP strips to the shear capacity was significantly influenced by the variables investigated. The following conclusions are drawn from the experimental investigation:

- Increasing longitudinal tensile reinforcement ratio increases the shear capacity of the CFRP strengthened beams.
- Results have shown that the contribution of CFRP reinforcement found to have increased with the increase of shear span to effective depth ratio.
- This study confirms that increasing spacing of CFRP strips affects the shear capacity of the CFRP beams.
- Test results show that the CFRP strengthened beams failed in two different modes of failure at ultimate; flexural and shear with CFRP rupture. The flexural mode of failure increases the ductility of the CFRP strengthened specimens.
- The study points out that the bi-directional CFRP strip technique is more attractive and economical for repairing or upgrading the concrete beams. The experimental investigation also demonstrates that the main fibres are the load carrying element similar to that of the steel stirrups but the fibres oriented perpendicular to the main fibres are probably acting as restraint to control the debonding of CFRP strips from the concrete surface. The bi-directional CFRP strips not only increase the shear capacity of the repaired beams but also controls the debonding of CFRP strip from the concrete surface.

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