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Optimal Shear Strengthening of Severely Deficient RC Beam Using JFRP Laminate with Anchor

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ABSTRACT

High-strength jute fibre-reinforced polymer (JFRP) laminates have recently been introduced to strengthen RC beams against shear. In contrast to synthetic-based composites, JFRP laminates would be more ductile, compatible with steel shear rebar and effective in reducing debonding due to their lower modulus of elasticity. The prime objective of this research was providing an optimal solution to strengthen a severely deficient RC beam against shear using an externally bonded JFRP laminate with anchor. Fabrication of the JFRP laminate was carried out with the maximum fibre content of 37.5% to obtain high tensile strength. Five full-scale RC beam specimens were cast. Shear strengthening was done by an externally bonded JFRP laminate with double connector, multiple connector and embedded-bar anchor systems. The dimensions of JFRP laminate were obtained based on proposed guidelines. Based on the experimental test, the average tensile strength of the fabricated JFRP laminate was found to be 162 MPa. Results also showed that the JFRP laminate with multi-connector anchor increased the maximum shear capacity of deficient RC beams by 89% and the beams had failed by the fracture of laminate. Beams strengthened with embedded-bar anchor had shown flexural ductile failure. Both beams failed after yielding of flexural bar. The proposed guidelines could be used for shear strengthening of severely deficient beams to enhance the maximum shear capacity using full strength of JFRP laminate with anchor.

KEYWORDS: RC beam, Shear strengthening, JFRP laminate, Anchor, Optimal design.

INTRODUCTION

Synthetic carbon fiber-reinforced polymer (CFRP) laminates have been widely used for shear strengthening of reinforced concrete (RC) beams in recent years because of their high strength to weight ratio and non-corrosive properties (Mhanna et al., 2019, Shekarchi and Khaloo, 2021; Nawaz et al., 2022; Arcine et al., 2023; Al-Karkhi and Aziz, 2018; Fayyadh and Razak, 2021; Bhuvaneshwari and Mohan, 2015). However, the laminate tends to debond from concrete-adhesive interface before reaching full strength of strengthened beam due to weaker bond strength of concrete. The CFRP laminate would also debond after yielding of internal shear reinforcement due to separation of concrete cover (Alam and Ali, 2021). After yielding of steel shear reinforcement, the elastic CFRP laminate could not maintain compatibility with plastic deformation of steel, which caused debonding of laminate with separation of concrete cover. As the cover of concrete has been separated after yielding of shear re-bar, the debonding strain of CFRP laminate would be the yield strain of steel shear reinforcement (approximately 0.002), which is extremely low as compared to tensile strain of the laminate (0.012) (Alam and Ali, 2021). The debonding of CFRP laminate at concrete-adhesive interface could be delayed using proper anchor systems; however, concrete-cover separation could not be prevented through mechanical anchor systems (Abdalla et al., 2022; Arslan et al., 2022). Since CFRP laminate debonds at low strain (0.002) as compared to its tensile strain (0.012), the strength of laminate could not be

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effectively utilized for shear strengthening of RC beams. Moreover, debonding due to separation of concrete cover causes catastrophic brittle failure. The shortcomings of the CFRP laminate could be overcome using relatively soft material with low modulus of elasticity as an externally bonded laminate. Because of being soft in nature, the laminate could be compatible with internal steel shear reinforcement at both elastic and plastic stages of the steel shear reinforcement and thus, the debonding of laminate due to separation of concrete cover could be eliminated. In this regard, natural fibre-based composite laminates would have huge potentiality for shear strengthening of RC beams. Recently, composite laminates using natural fibres have been fabricated and investigated for structural applications (Akid et al., 2021; Ananthi and Sakthieswaran, 2015; Ed-Dariy, 2021; Nwankwo et al., 2023; Jirawattanasomkul et al., 2020; Omar et al., 2022; Pradeep et al., 2015; Salih et al., 2019, Sen and Reddy, 2013). Alam et al. (2018, 2021) had investigated the potentiality of jute fibre-reinforced polymer (JFRP) and kenaf fibre-reinforced polymer (KFRP) laminates for shear strengthening of reinforced concrete beams. The JFRP laminate was fabricated with low modulus of elasticity, which was found to be better in delaying of premature debonding of laminate. As compared to CFRP laminate, JFRP laminate showed better shear contribution, as it delays the debonding of laminate (Alam and Riyami, 2018). Moreover, jute fibre is a pure green agricultural product, extracted from the stems of the plants. The fibre is a locally available and relatively cheap as compared to CFRP laminate. The beams with JFRP laminate, in most of the cases, had shown flexural failure rather than premature debonding or concrete-cover separation even without mechanical anchors (Alam and Riyami, 2018). Since the JFRP laminate could prevent concrete-cover separation, the debonding of laminate at the interface of concrete to adhesive could be eliminated using mechanical anchors. Once the debonding is eliminated, the full strength of laminate may be utilized to improve shear resistance of deficient beam. Although investigation on the maximum shear contribution of JFRP laminate for optimal shear strengthening of RC beam is novel, research in that area is limited. The primary objective of this study was to investigate the maximum contribution of JFRP laminate for optimal shear strengthening of severely deficient RC beam with various anchor systems. Structural performances of those anchor systems were experimentally investigated. Properties of fabricated JFRP laminate were also experimentally investigated for shear strengthening of RC beam.

Proposed Design Guidelines of JFRP Laminates for Shear Strengthening of Severely Deficient Reinforced Concrete Beams

Comprehensive design guidelines for shear strengthening of severely shear-deficient RC beams using full strength of JFRP laminates had been proposed in this research. The ultimate tensile strength of JFRP laminate had been used in design for the maximum contribution of the laminate. The beam was designed for the maximum shear capacity, which would be obtained based on the flexural capacity of the beam in accordance to EC2 (2004).

Maximum Design Shear Force for Strengthening of RC Beam

The shear capacity of existing beam can be enhanced up to its maximum flexural strength. In accordance to EC2 (2004), the ultimate flexural capacity of the beam is:

$$M = Tz = A_s f_{tk}\left[d - \frac{0.588 A_s f_{tk}}{f_{ck} b}\right] \tag{1}$$

where,

$$x = \frac{A_s f_{tk}}{0.85 f_{ck}(0.8)b} = \frac{A_s f_{tk}}{0.68 f_{ck} b} \tag{2}$$

$$z = d - 0.4x = \left[d - \frac{0.588 A_s f_{tk}}{f_{ck} b}\right] \tag{3}$$

Thus, the maximum design shear for the beam is:

$$V_{ds} = \frac{M}{L_s} = \frac{A_s f_{tk}}{L_s}\left[d - \frac{0.588 A_s f_{tk}}{f_{ck} b}\right]. \tag{4}$$

Shear Contribution of Concrete

According to EC2 (2004), concrete is disregarded to resist the shear force at the stage of failure (after shear crack). Only shear reinforcements resist the shear force. Since the deficient span of the beam has no shear reinforcement, the shear contribution of concrete could be considered as zero after shear crack. As recommended by EC2, the shear contribution of concrete before shear crack could be the capacity of severely deficient control beam, as shown in Equation 5.

$$V_{Rd,c} = \left[0.12k(100p_1 f_{ck})^{1/3}\right] b_w d \quad (5)$$

Required Optimal JFRP Laminate Cross-sectional Area to Shear Strengthen Severely Shear-deficient RC Beam

Since deficient shear span has no shear reinforcement, shear contribution of concrete and shear link could be disregarded for resisting shear force. The crack inclination of strengthened beam could be considered as 45 degrees for conservative design of externally bonded JFRP laminate. A two-sided JFRP laminate will resist shear force, as given by Equation 6.

$$V_{JFRP} = 2A_{JFRP}\sigma_{JFRP}N_{JFRP} = 2A_{JFRP}\sigma_{JFRP}\frac{(d-d')cot\theta}{s_{JFRP}}. \quad (6)$$

The shear-strengthened beam could fail by flexure; thus, the maximum design shear could be obtained by Equation 4. The required optimal shear design of the strengthened beam for the maximum capacity (up to flexural failure of beam) can be achieved as follows:

$$V_{JFRP} = V_{ds} = \frac{A_s f_{tk}}{L_s}\left[d - \frac{0.588A_s f_{tk}}{f_{ck}b}\right]\frac{A_{JFRP}}{s_{JFRP}} = \frac{V_{ds}}{2\sigma_{JFRP}(d-d')cot\theta} = \left\{\frac{A_s f_{tk}}{L_s}\left[d - \frac{0.588A_s f_{tk}}{f_{ck}b}\right]\right\}/\left[2\sigma_{JFRP}(d-d')cot\theta\right]. \quad (7)$$

EXPERIMENTAL PROGRAM

Fabrication of JFRP Laminate

Jute fibre-reinforced polymer laminate had been fabricated in the lab using the thermoset cold pressed hand lay-up method, as shown in Figure 1. Epoxy diospyros discolor was used as binder of jute fibre. All fibres were dried properly and cleaned from dust. Short fibres and those having dark black spots were removed. The casting mould was cleaned using a lubricant and a thin plastic sheet was placed on the mould. Resin and hardener of the epoxy were mixed properly. The fibres were laid on the casting mould by layers. Well-mixed epoxy was placed on the layer of fibre. All fibres were required to be soaked with epoxy properly. When the epoxy was found in a semi-solid state, the epoxy-soaked fibres were then pressed and compacted using a hydraulic jack for 24 hours. Figure 1 shows the fabrication process of JFRP laminate. Table 1 shows the details of all mixes for casting of JFRP laminates. The average fibre content of the JFRP laminate was 37.5%.

Jute Fibre

Applying epoxy on fibre

Compaction of epoxy-soaked fibre

Figure (1): Fabrication of JFRP laminate

Table 1. Mixes of JFRP laminate

Specimens	Raw Materials			Materials in JFRP laminate				
	Length of Fibre (mm)	*Weight of Fibre (gm)*	*Weight of Epoxy (gm)*	*Length of Plate (mm)*	*Weight of Plate (mm)*	*Weight of Fibre (mm)*	*Fibre Conten t (%)*	*Avg. Fibre Content (%)*
JP-1	400	160	355	370	380	148	38.95	37.5
JP-2	400	160	350	310	338.8	124	36.60	
JP-3	400	160	352	370	404.9	148	36.55	
JP-4	400	160	356	315	330.6	126	38.11	

JP-5	400	160	400	325	345.7	130	37.60	
JP-6	400	160	375	328	327.9	131.2	40.01	
JP-7	400	160	352	312	317.5	124.8	39.31	
JP-8	400	160	395	310	322.2	124	38.49	

Beam Specimens

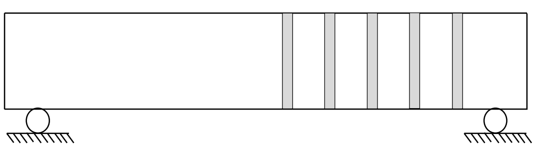
In this research, five reinforced concrete beam specimens were prepared. The length, depth and width of the beams were 1300 mm, 250 mm and 150 mm, respectively. The beams were shear-reinforced with 8-mm steel bar having 55-mm centre-to-centre (c/c) spacing. Only one side of the shear span was reinforced with shear reinforcement, so that another side of the beam remained in a severely shear-deficient condition. One beam was prepared as an un-strengthened control specimen, while the rest of the beams were shear-strengthened using fabricated JFRP laminates. In order to prevent premature debonding failure of JFRP laminate at concrete-adhesive interface, the beams were further strengthened using double-connector, multiple-connector and embedded-bar anchors. The strengthened beams were designed for maximum contribution of shear in accordance to proposed design guidelines, as shown in Equation 7. The maximum tensile strength of JFRP laminate was used to design the beams. The details of beam specimens are presented in Table 2 and shown in Figure 2.

Tab le 2. Details of beam specimens

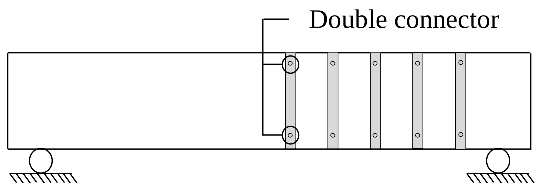
Specimen ID	Description	JFRP shear strip		Anchor system	
		Width (mm)	Spacing (mm)	Anchor type	Material
CB	Control beam				
JP0	Strengthened beam without anchor	25	100	-	-
JBDC	Strengthened beam with double-connector anchor	25	100	Double connectors, 2 connectors	16-mm diameter steel bar
JBMC	Strengthened beam with multiple-connector anchor	25	100	Multiple connectors, 4 connectors	16-mm diameter steel bar
JBEB	Strengthened beam with embedded-bar anchor	25	100	Embedded bar	16-mm diameter steel bar

Preparation of Beam Specimens

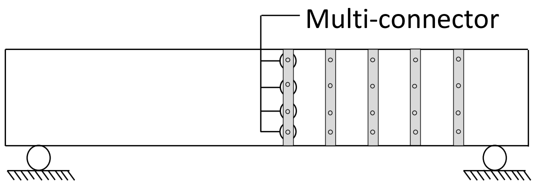
The beams were reinforced with 2-16 mm steel bar as flexural bottom reinforcement. Shear reinforcement had not been provided at the deficient shear span of the beam for investigating the maximum shear contribution of strengthened beam using JFRP laminate. Another shear span of the beam had been over-reinforced using 8-mm shear reinforcement with the spacing of 55 mm to make sure that the strengthened beam would not fail by shear from that side. It was anticipated that, in the unreinforced shear span, the beam would fail by shear. Based on theoretical assessment of flexural and shear capacities of strengthened beams, the shear-reinforcement spacing of the beams was chosen to be 55 mm. Figure 2(e) shows the details of reinforcements of the beams.



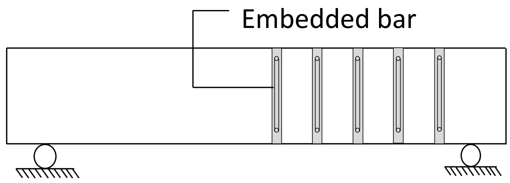
a. Shear-strengthened beam of JP0



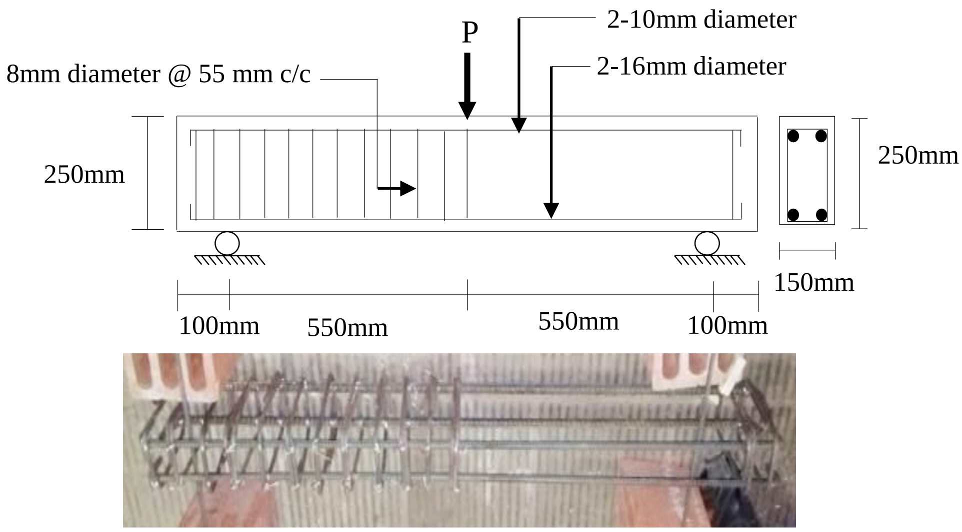
b. Shear-strengthened beam of JBDC



c.: Shear-strengthened beam of JBMC



d. Shear-strengthened beam of JBEB



e. Details of under shear reinforced beam

Figure (2): Details of shear-strengthened beam using JFRP laminate and anchors

Properties of Materials

The tensile and yield strengths of 16-mm flexural reinforcement were 665 MPa and 515 MPa, respectively, whereas the 8-mm shear reinforcement had yield and tensile strengths of 363 MPa and 400 MPa, respectively. The concrete was mixed with a ratio of 1:3.53:5.53 (cements: sand: coarse aggregate) for the target compressive strength of 24 MPa. The water cement ratio of the mix was 0.67. The average concrete compressive strength (cylinder) at 28 days was found to be 22 MPa. The average tensile strength and density of JFRP laminate were 162 MPa and 1.352 g/cm^3, respectively; the lowest tensile strength of JFRP laminate was 135 MPa.

Strengthening of Beam Specimens

A JFRP laminate with dimensions of 7.1 mm x 25 mm x 250 mm was fabricated for shear strengthening of the RC beam. The dimensions of the JFRP laminate were based on the optimal design of strengthened beams in accordance with proposed Equation 7. The lower tensile strength (135 MPa) of JFRP laminate was used to design the strengthened beam. The loose particles of concrete were removed using a diamond cutter from the bonding face of concrete. The holes of embedded connectors were prepared using a drill head. The diameters of holes were 20 mm to insert 16-mm diameter steel connectors for the beams of JBDC and JBMC. The holes were made for the maximum depth of 25 mm from the concrete surface within the clear cover of the concrete. This was because the connector was inserted within the cover of concrete in order to avoid disturbing the core concrete during the strengthening process. The concrete was cut to prepare grooves for embedded bar anchor of beam of JBEB. Figure 3(a) shows the prepared connectors and the bonding surfaces of concrete.

After the completion of drilling, a wire brush and compressed air were used to clean the surface of the beams. The bonding faces of JFRP laminates were cleaned by thinner. Sikadur 31 CF adhesive was used to fix the laminates with bonding surfaces of the concrete beams. The adhesive was mixed properly before placing on laminates and surfaces of concrete. The holes of connectors and groove of embedded bar were filled by well-mixed adhesive and the steel bars of connectors and embedded bar were inserted into the adhesive-filled holes (shown in Figure 3-b). Surplus adhesive was placed on concrete surfaces and adhesive was also placed on bonding faces of JFRP, laminates, as shown in Figure 3(b). The laminates were then placed properly and pressed by hand rollers for better compaction. According to the instructions of manufacturer, the thickness of adhesive was about 3 mm. Instead of concrete or laminate rupture, a thicker adhesive layer may result in failure of adhesive of the laminate. The laminates were installed with a 100-mm spacing on the 550-mm shear span of the beams. Figure 3(b) shows the process of strengthening.

Test Set-up and Testing of Beam Specimens

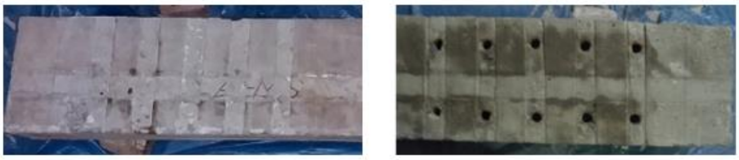
The test set-up of beams is shown in Figure 3(c). All beams were tested under single-point loading. The shear and effective spans of the beams were 550 mm and 1100 mm, respectively. A dial gauge was positioned at the bottom mid-point location of the beams to measure mid-span deflection. The beams were tested using loading frame. Load was applied slowly using control panel and a load cell was used to measure the load. The surface of the beam was marked with the developing crack pattern at each load stage. First crack load, failure load, crack patterns and modes of failures were closely investigated and recorded.

RESULTS AND DISCUSSION

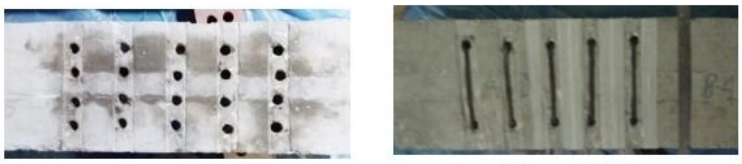
Properties of JFRP Laminates for Shear-strengthening of RC Beam with the Prevention of Interfacial Debonding Failure of Laminates Using Anchors

Five samples of JFRP laminate were tested to investigate physical properties. The laminate was fabricated with the maximum fibre content of 37.5%. Water absorption of the JFRP laminates had been determined as per ASTM D5229/D5229M-92. Specific gravity and density of the JFRP laminates were measured in accordance to ASTM D3800. Due to the low density of natural fiber, the density of natural fiber-based laminates was generally found to be lower (1.352 g/cm^3) as compared to that of CFRP laminate (1.6 g/cm^3) and steel plate (7.8 g/cm^3). A total of three samples of JFRP laminate were tested to investigate tensile properties of laminates. The samples were tested using a Universal Testing Machine. ASTM D3039/D3039M-00 was followed to conduct the tensile test. The test results showed an average tensile strength of JFRP laminate of 162 MPa, which is lower than that of steel (420 MPa) and CFRP (3500 MPa). It was also found that the lowest tensile strength of the JFRP laminate was 135 MPa.

Ahamed et al. (2022), Wagh et al. (2023) and Nayab-Ul-Hossain et al. (2022) had also fabricated JFRP composite plates using epoxy resin. The tensile strengths of their fabricated plates were 93 MPa, 75.2 MPa and 48.2 MPa, respectively. The tensile strength of fabricated JFRP laminate of this research was significantly higher as compared to the findings of existing research, which would be better for shear strengthening of RC beams. Results showed that the JFRP laminate failed due to fracture of laminate near the grip, as shown in Figure 4. The laminate did not show debonding of fibre and failed as composite laminate. However, CFRP laminate showed debonding of carbon fibre rather than failure of composite laminate (Alam et al., 2016), as shown in Figure 4 (b). The fabricated JFRP laminate had been used for shear strengthening of severely deficient RC beams. The soft nature of JFRP laminate reduced the debonding effects of laminates for shear strengthening of RC beams (Figure 5). The high tensile strength of JFRP laminates enhanced the shear capacities of strengthened RC beams significantly, as shown in Figure 6.

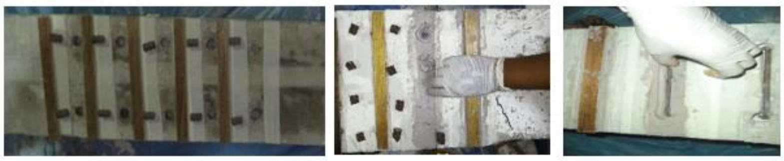


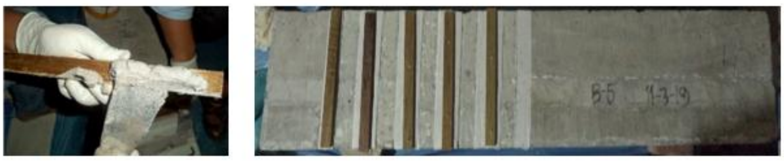
Beam JP0 Beam JBDC



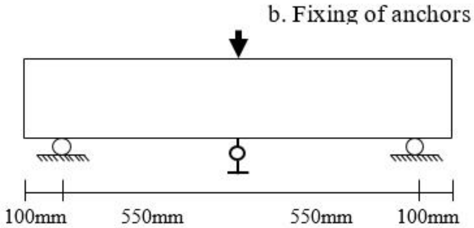
Beam JBMC Beam JBEB

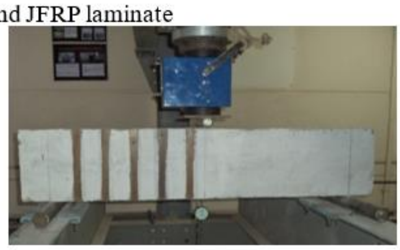
a. Preparation of anchors and surfaces of beams





b. Fixing of anchors and JFRP laminate

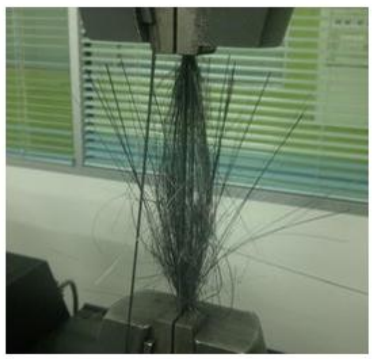




c. Test setup and testing of beam

Figure (3): Strengthening process and test set-up

a. Fracture of JFRP laminate



b. Fracture of CFRP laminate (Alam et al., 2016)

Figure (4): Tensile fracture of JFRP and CFRP laminates

Results showed that un-strengthened control beam (CB) failed by shear with diagonal crack at the shear-deficient part of the beam. The failure mode was observed to be catastrophic brittle, since there was no shear reinforcement in that position. Strengthened beam without anchor (JP0) had failed because of concrete-cover separation and the cover had separated mostly at bottom portion of the beam. Besides, it had been noted that the JFRP laminate debonded from the upper end of the shear crack. Once the cover separated and the laminate debonded, the beam failed due to shear in brittle mode, as observed in Figure 5 (b). The JFRP laminate of shear-strengthened beam with double connector (JBDC) had fractured parallel to the direction of fibres at the location of anchor connector. Once the laminate separated from both ends of connectors, the beam failed by shear. The inclination of shear crack in JBDC beam was comparatively higher compared to JP0.

a: Control Beam (CB)

b: Strengthened beam without anchor (JP-0)

c: Strengthened beam with double connector anchor (JBDC)

d: Strengthened beam with multiple connector anchor

e: Strengthened beam with embedded bar anchor (JBEB)

Figure (5): Failure modes of beam specimens

Multiple connector anchor system (JBMC) completely prevented premature failures. The beam had failed after tensile failure of JFRP laminate. Because of increased number of connectors, the bond strength at the interfaces of concrete to adhesive was increased, which resulted in eliminating premature debonding failures; thus, the JFRP laminate had been fully utilized to increase the shear capacity of the beam. Following the fracture of the laminate, the beam had failed by shear. The failure mode of the beam (JBMC) was also brittle in nature.

Results also showed that the embedded-bar anchor system fully prevented premature failures of the beams. Embedded-bar anchor increased interfacial bond strength; thus, JFRP laminate did not debond at concrete-adhesive or laminate-adhesive interfaces. The embedded bar also contributed to enhance shear capacity of the beam; thus, JFRP laminate did not fail in tension. In case of the (JBEB) beam, failure eventually occurred due to flexure with ductile nature. The failure modes of all beams are shown in Figure 5.

Stiffness and Ductility Enhancement of RC Beams Shear Strengthened Using JFRP Laminate and Anchors

Figure 6 shows the load-deflection behaviours of all beams. As compared to control beam, the shear-strengthened beams using JFRP laminate with anchors had less deflection. In general, JFRP laminate and anchors increased the overall stiffness of the beam, which resulted in reducing the deflection of strengthened beams. Results showed that strengthened beams with multi-connector (JBMC) and embedded bar (JBEB) anchors had larger plastic deflection before failure, which would be the reflection of yielding of flexural rebar in those beams. Although, beam with multi-connector anchors failed by shear followed by rupture of laminate. The flexural reinforcements of that beam might have yielded before failure. Embedded-bar anchor system restrained premature beam failure and allowed the shear-strengthened (JBEB) beam to fail by flexure. A ductile mode of failure was observed in that beam. That beam showed the highest degree of ductility as compared to the un-strengthened control and other strengthened beams, because it had failed because of yielding of flexural reinforcement.

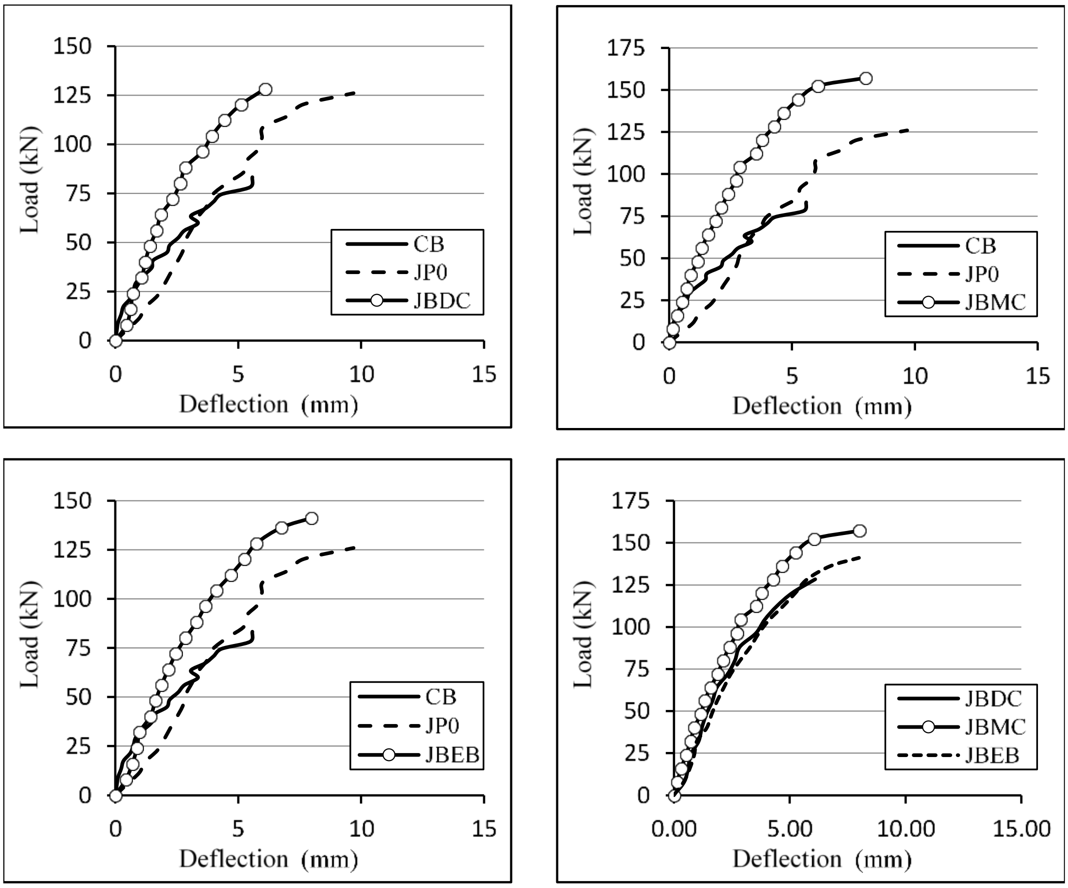


Figure (6): Ductility of shear-strengthened beams

Shear-capacity Enhancement of RC Beam Shear-strengthened by JFRP Laminate and Anchors

The control beam (CB) was designed as a severely shear-deficient beam without providing shear reinforcement; thus, the control beam had a much lower shear capacity, which resulted from the contribution of concrete only. The JFRP laminate-strengthened beam without anchor (JP0) had failed due to premature concrete-cover separation and showed 52% enhancement of shear capacity compared to the control beam (Table 3). Results exhibited that the JFRP laminate had ruptures at the vicinity of double connector. Once the plate separated from the connector, the beam (JBDC) prematurely failed by shear with an enhancement of shear capacity by 54%.

Multiple-connector and embedded-bar anchors were found to be extremely effective in preventing premature failures of strengthened beams. Multiple-connector anchor completely prevented premature failures of laminate from interfacial debonding or concrete-cover separation, where the laminate had shown tensile failure at the middle of the laminate. Since the laminate failed by tension, the JFRP laminate had contributed to the maximum shear enhancement (89%) of the strengthened (JBMC) beam. The embedded-bar anchor prevented premature debonding and shear failures with a shear enhancement of 71% as compared to the control beam.

Table 3. Test results of shear-strengthened beams

Beam ID	Beam description	Shear crack loads (kN)	Failure loads (kN)	Shear-strength enhancement (%)	Failure modes of beams
CB	Control beam	52	83	-	Shear
JP0	Strengthened beam without anchor	80	126	52	Concrete-cover separation at end of laminate
JBDC	Strengthened beam with double-connector anchor	80	128	54	Fracture of laminate at connector (both ends)
JBMC	Strengthened beam with multiple-connector anchor	80	157	89	Tensile failure of laminates at middle of beam, concrete crush at compression strut
JBEB	Strengthened beam with embedded-bar anchor	80	142	71	Fracture of laminate at plate end, flexural failure

Theoretical Analysis of Shear-strengthened RC Beam

The JFRP-laminated shear-strengthened beam may fail by flexure because of yielding or damaging of flexural reinforcement, or it could fail by shear due to fracture of laminate. The flexural failure load of the beam can be predicted using Equations 8 and 9. The theoretical shear capacity of shear-strengthened beam considering fracture of JFRP laminate can be obtained from Equation 10.

Flexural failure load of strengthened beam based on yield strength of flexural steel;

$$P_{(f_y)} = \frac{2M}{0.55} = \frac{2A_s f_y}{0.55}\left[d - \frac{0.588A_s f_y}{f_{ck} b}\right] \quad (8)$$

Flexural failure load of strengthened beam based on tensile strength of flexural steel;

$$P_{(f_{tk})} = \frac{2M}{0.55} = \frac{2A_s f_{tk}}{0.55}\left[d - \frac{0.588A_s f_{tk}}{f_{ck} b}\right] \quad (9)$$

Shear failure load of strengthened beam based on fracture strength of JFRP laminate;

$$P_{Shear} = 2\left(V_c + V_s + V_{JFRP}\right) = 2\left(V_{JFRP}\right) = 2\left[2A_{JFRP}\sigma_{JFRP}\frac{(d-d')cot45}{s_{JFRP}}\right] \quad (10)$$

Table 4. Parameters of beam for theoretical analysis

Dimensions of beam				Properties of steel and concrete				Properties of JFRP laminate			Theoretical failure load		
b	h	d	$d-d'$	f_y	f_{tk}	f_{ck}	A_s	t	w	stress	Flexural (kN)		Shear
mm	mm	mm	mm	MPa	MPa	MPa	mm^2	mm		MPa	Yield	Tensile	kN
150	250	209	168	555	665	22	402	6.77	25	135	137	156	152

Based on the parameters shown in Table 4, the JFRP-laminated shear-strengthened RC beams were theoretically analyzed to predict flexural and shear capacities in accordance to Equations 8, 9 and 10. The flexural failure capacities (loads) of beam based on yield strength and tensile strength of steel bar were 138 kN and 156 kN, respectively. The maximum shear capacity of strengthened beam by fracture of laminate was 152 kN, which was very close to the flexural failure capacity of beam based on tensile strength of bar (156 kN). It was also noted that the maximum shear capacity of strengthened beam was higher than the flexural capacity of beam based on yield strength of flexural reinforcement (138 kN), which ensured that the strengthened beam would not fail by fracture of laminate or shear before yielding of flexural reinforcement. However, since the strengthened beams were designed for the maximum shear based on the consideration of flexural failure of the beam, the JFRP laminate might be fractured at the time of flexural failure of the beam, which presented the maximum contribution of JFRP laminate.

Validation of the Proposed Guidelines for Optimal Shear-strengthening of JFRP-laminated RC Beam

The maximum theoretical design shear of the beam was 78 kN (156 kN of failure load) based on the tensile strength of flexural reinforcement, as shown in Equation 4. The experimental failure loads of shear-strengthened beams with multi-connector (JBMC) and embedded-bar (JBEB) anchors were 157 kN and 142 kN, respectively, which were higher than theoretically predicted flexural failure load of beam by yielding of flexural reinforcement (138 kN load) and close to tensile failure of flexural reinforcement (156 kN load), as shown in Figure 7. Both strengthened beams had failed after yielding of flexural reinforcement. The strengthened JBMC beam had failed by fracture of JFRP laminate and the laminate contributed with its full strength to enhance the maximum shear capacity of the beam. The experimental failure load of that beam was very close to theoretical failure load (152 kN) of the beam by fracture of laminate. Thus, the proposed design guidelines could be used for shear-strengthening of severely shear-deficient RC beam by utilizing full strength of JFRP laminate to enhance maximum shear capacity of strengthened beam.

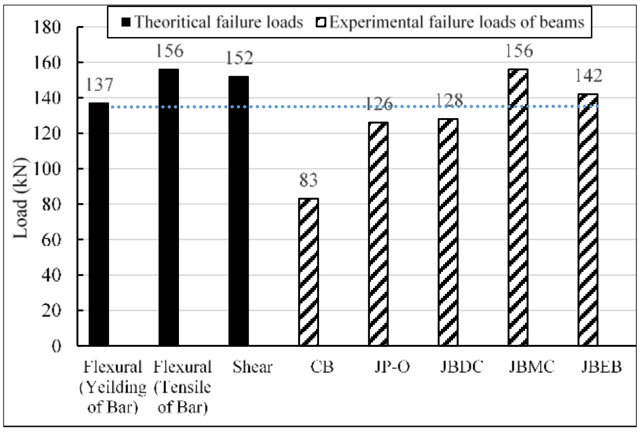


Figure (7): Capacity of shear-strengthened RC beams

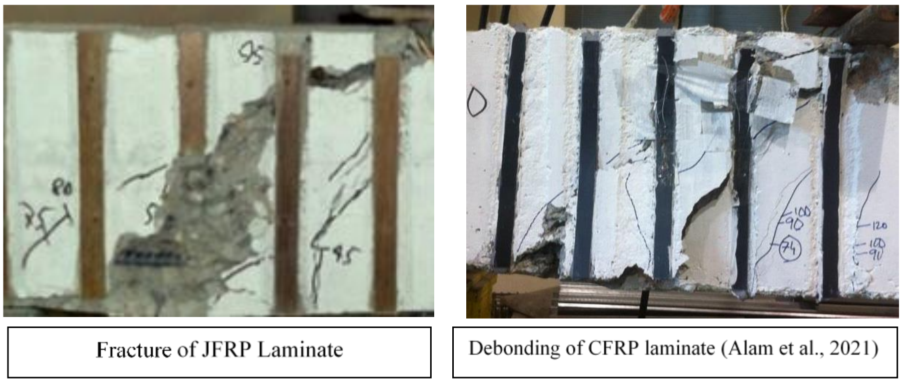


Figure (8): Failure modes of JFRP -and CFRP-laminate shear strips for maximum shear enhancement of beams

Comparative Analysis of JFRP Laminate with CFRP Laminate of Existing Research for Shear Enhancement of Strengthened RC Beam

In this research, the maximum contribution of JFRP laminate for shear enhancement of RC beam had been investigated. In terms of the maximum enhancement of shear strength, CFRP laminate could not be effectively used for shear strengthening because of premature debonding of laminate (Alam et al., 2021) as shown in Figure (8). The tensile strength of CFRP laminate was very high; however, approximately 17% of its full strength could be used for shear strengthening because of premature debonding of laminate. However, since JFRP laminate is a relatively less stiff material, debonding of JFRP laminate was not so critical in shear-strengthening of RC beam; thus, full strength of material could be used. The JFRP laminate fractured after yielding of flexural reinforcement. Alam et al. (2021) also reported that the CFRP laminate debonded after yielding of flexural reinforcement. Thus, both JFRP and CFRP laminates could be used for the maximum enhancement of shear capacities of strengthened beams.

CONCLUSIONS

Jute fiber-reinforced polymer (JFRP) laminate had been fabricated in this research and was used for shear-strengthening of severely shear-deficient RC beam considering full strength of the laminate for the maximum enhancement of shear capacity of strengthened beam. The JFRP laminate could be fabricated with the maximum fibre content of 37.5% using the cold press method. The density of fabricated laminate was 1.35 g/cm^3. The average tensile strength of the JFRP laminate was found to be 162 MPa. Results showed that multi-connector and embedded-bar anchor systems completely prevented premature failure of the beams. JFRP laminate of multi-connector anchor system had shown fracture of laminate, thus having the maximum shear contribution of JFRP laminate by 89% as compared to un-strengthened control beam. The failure of shear-strengthened beam with multi-connector anchor system occurred by rupture of JFRP laminate followed by shear and the mode of failure was catastrophic brittle in nature. Embedded-bar anchors completely prevented premature debonding and shear failure, which resulted in the beam failure in a ductile flexural mode. As compared to the control beam, the shear contribution of JFRP laminate with embedded-bar anchor was 71% higher; whereas beam shear-strengthened without anchor had failed by premature debonding followed by brittle shear. The shear contribution of that beam (JFRP laminate without anchor) was 52% higher than that of control beam. It was found that embedded-bar and multi-connector anchors were more efficient amongst various anchor systems for enhancing shear capacity of severely shear-deficient RC beam. Both beams had failed after yielding of flexural reinforcement and the failure loads of those beams were very close to the maximum flexural capacities of the beams. The proposed guideline could be used for shear-strengthening of severely deficient beams to enhance the maximum shear capacity using the full strength of JFRP laminate with anchor.

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NOMENCLATURE

M : *Moment − resisting capacity of beam*
T : *Tensile force of flexural reinforcement*
z : *Moment arm*
A_s : *Cross − sectional area of flexural reinforcement*
f_{tk} : *Tensile strength of flexural reinforcement*
f_{ck} : *Concrete compressive strength based on cylinder test*
b : *Width of beam*
x : *Depth of neutral axis*
d : *Effective depth of beam*
d' : *Depth of compression reinforcement (top bar)*
V_{ds} : *Design shear force*
L_s : *Shear span*
$V_{Rd.c}$: *Shear force resisted by concrete*
k : *Factor*
p_1 : *Flexural steel ratio*
θ : *Inclination of shear crack*
b_w : *Width of beam*
N_{JFRP} : *Number of JFRP shear strip*
s_{JFRP} : *Spacing of JFRP shear strip*
σ_{JFRP} : *Tensile stress of JFRP laminate*
V_{JFRP} : *Shear contribution of JFRP laminate*
A_{JFRP} : *Required cross − sectional area of JFRP shear strip*

REFERENCES

Abdalla, J.A., Mhanna, H.H., Hawileh, R.A., Sharafi, M., Al-Marzouqi, A., Al-Teneiji, S., and Al-Ali, K. (2022). "Shear-strengthening of reinforced concrete T-beams using carbon fiber-reinforced polymer (CFRP) anchored with CFRP spikes". Procedia-Structural Integrity, 42, 1223-1230.

Ahamed, B., Hasan, M., Azim, A.Y.M.A., Saifullah, A., Alimuzzaman, S., Dhakal, H.N., and Sarker, F. (2022). "High-performance short jute fibre preforms for thermoset composite applications". Composites-Part C: Open Access, 9 (100318), 1-13.

Akid, A.S.M., Wasiew, Q.A., Sobuz, M.H.R., Rahman, T., and Tam, V.W. (2021). "Flexural behavior of corroded reinforced concrete beam strengthened with jute fiber-reinforced polymer". Advances in Structural Engineering, 24 (7), 1269-1282.

Alam, M.A., and Ali, S. (2021). "Strain compatibility model to optimise CFRP laminate for shear-strengthening of RC beam". Australian Journal of Structural Engineering, 22 (1), 59-72.

Alam, M.A., and Riyami, K.A. (2018). "Shear-strengthening of reinforced-concrete beam using natural fibre-reinforced polymer laminates". Construction and Building Materials, 162, 683-696.

Alam, M.A., Hassan, A., and Muda, Z.C. (2016). "Development of kenaf fibre-reinforced polymer laminate for shear-strengthening of reinforced concrete beam". Materials and Structures, 49, 795-811.

Alam, M.A., Riyami, K.A., and Bakkar, S. (2021). "Optimization of kenaf fibre-reinforced polymer laminate for shear-strengthening of RC beams using embedded connector". Engineering Structures, 232. 11790.

Al-Karkhi, H., and Aziz, A. (2018). "Shear-strengthening of reinforced self-compacted concrete hammer-head beams using warped CFRP strips: Experimental and theoretical study". Jordan Journal of Civil Engineering, 12 (4), 629-636.

Ananthi, P., and Sakthieswaran, N. (2015). "Jute fibre-wrapped RC short column". International Journal for Innovative Research in Science & Technology, 2 (1), 54-60.

Arcine, M.F., Menon, N.V., and Krahl, P.A. (2023). "Numerical and experimental study of the interaction between stirrups and Shear-strengthening with CFRP in RC beams". Engineering Structures, 278, 115514.

Arslan, M.H., Yazman, S., Hamad, A.A., Aksoylu, C., Özkılıç, Y.O., and Gemi, L. (2022). "Shear-strengthening of reinforced-concrete T-beams with anchored and non-anchored CFRP fabrics". Structures, 39, 527-542.

Bhuvaneshwari, P., and Mohan, K.S.R. (2015). "Strengthening of shear-deficient reinforced-concrete beams retrofitted with cement-based composites". Jordan Journal of Civil Engineering, 9 (1), 59-70.

Ed-Dariy, Y., Lamdouar, N., Cherrad, T., Rotaru, A., Barbuta, M., and Mihai, P. (2021). "The influence of the curing conditions on the behavior of jute fibers-reinforced concrete cylinders". Periodica Polytechnica Civil Engineering, 65 (4):1162-1173.

Eurocode 2. (2004). "Design of concrete structures-Part 1: General rules and rules for buildings".

Fayyadh, M.M., and Razak, H.R. (2021). "Externally bonded FRP applications in RC structures: A state-of-the-art review". Jordan Journal of Civil Engineering, 15 (2), 157-179.

Jirawattanasomkul, T., Likitlersuang, S., Wuttiwannasak, N., Ueda, T., Zhang, D., and Shono, M. (2020). "Structural behaviour of pre-damaged reinforced-concrete beams strengthened with natural fibre-reinforced polymer composites". Composite Structures, 244, 1-14.

Mhanna, H.H., Hawileh, R.A., and Abdalla, J.A. (2019). "Shear-strengthening of reinforced-concrete beams using CFRP wraps". Procedia-Structural Integrity, 17, 214-221.

Nawaz, W., Elchalakani, M., Karrech, A., and Yehia, S. (2022). "Shear-strengthening of high-strength lightweight SCC beams internally reinforced with GFRP bars and external CFRP strips". Materials Today: Proceedings, 65, 915-919.

Nayab-Ul-Hossain, A.K.M., Sela, S.K., Hasib, M.A., Alam, M.M., and Shetu, H.R. (2022). "Preparation of graphene based natural fiber (jute)-synthetic fiber (glass) composite and evaluation of its multi-functional properties". Composites-Part C: Open Access, 9(100308), 1-12.

Nwankwo, C.O., Mahachi, J., Olukanni, D.O., and Musonda, I. (2023). "Natural fibres and biopolymers in FRP composites for strengthening concrete structures: A mixed review". Construction and Building Materials, 363, 129661.

Omar, Z., Sugiman, S., Yussof, M.M., and Ahmad, H. (2022). "The effects of woven fabric Kenaf FRP plates flexure-strengthened on plain concrete beam under a four-point bending test". Case Studies in Construction Materials, 17, 01503.

Pradeep, P., Dhas, J.E.R., Ramachandran, M., and Retnam, B.S.J. (2015). "Mechanical characterization of jute fiber over glass and carbon fiber-reinforced polymer composites". International Journal of Applied Engineering Research, 10 (11), 10392-10396.

Salih, Y.A., Sabeeh, N.N., Yass, M.F., Ahmed, A.S., and Khudhurr, E.S. (2019). "Concrete beams strengthened with jute fibers". Civil Engineering Journal, 5 (4), 767-776.

Sen, T., and Reddy, J.H.N. (2013). "Pre-treatment of woven Jute FRP composite and its use in strengthening of reinforced-concrete beams in flexure". Advances in Materials Science and Engineering, 1-15.

Shekarchi, M., and Khaloo, A. (2021). "Shear and flexural strengthening of steel beams with thick carbon fiber-reinforced polymer laminate". Journal of Rehabilitation in Civil Engineering, 9 (4), 148-170.

Wagh, J., Madgule, M., and Awadhani, L.V. (2023). "Investigative studies on the mechanical behavior of jute, sisal, hemp and glass fiber-based composite material". Materials Today: Proceedings, 77 (3), 969-976.