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Original Article

Carbon Fiber Reinforced Polymer Surface Area and Bond Thickness Variation in Shear Strengthening of Reinforced Concrete Beam

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Abstract *- This paper presents the results of carbon fibre reinforced polymer (CFRP) fabric surface area and bond thickness variation in shear strengthening of the reinforced concrete beam. Fifteen (15) single-span reinforced concrete beams with a span of 1100mm, and a cross-sectional area of 100mm x 150mm were subjected to static loading. Two 10mm and two 8mm diameter steels were provided at each beam sample's bottom and top. the depth of the internal steel reinforcement was 135mm. Two Carbon Fiber Wraps (also known as carbon fibre reinforced polymer fabric) of thickness 200g/m2 (0.111mm) and 300g/m2 (0.167mm) were bonded to the longitudinal axis on 1 side and 2-sides with 2mm, 4mm, 6mm, and 8mm adhesive thickness. the glue applied in this investigation was a mortar-like structural two-part Sikadur (R)-31 epoxy adhesive. 6 mm diameter shear links were introduced at 220 mm centre to centre in a constant moment region to ensure sliding failure developed in the shear region. One of the beams was a reference sample and not bonded with CFRP fabrics. the remaining samples were investigated to ascertain the response of various FRP surface areas and bond thickness variation to the shear strength of the beams. Each beam sample was supported and loaded with a two-point load positioned at one-third of the beam length. A hydraulic jack with a loading capacity of 200kN was used to apply the load. Vertical displacements at mid-span were measured using a dial gauge. the results show that the CFRP fabric to bond thickness ratio for RC beams strengthened along the longitudinal axis on 1-side and 2-sides should not be greater than 0.075; reinforced concrete beams strengthened along the longitudinal axis on both faces with the same surface area as the single face performed better than RCC strengthened on single. This improved performance can be ascribed to stress distribution via the bond on both sides rather than just one, which increases its shear capacity. Furthermore, beams strengthened with carbon fibre reinforced polymer fabric along the longitudinal axis lower stiffness while greatly reducing the surface area of CFRP while still reaching the requisite shear strength.*

Keywords *- Bond thickness variation, CFRP Contribution to shear, Ductility index, FRP surface Area, Shear Strength, Shear strengthening.*

1. Introduction

The externally glued fibre-reinforced polymer (FRP) strengthening scheme has become a more and more prevalent retrofitting approach for reinforced concrete (RC) elements ([1],[2],[3]-[4]). FRP strengthening systems are simple to install because of the formability and lightweight of FRP material ([5][6],[7]-[8]). FRPs are also an excellent solution for external strengthening. This is because the materials used are non-magnetic, non-corrosive and chemically stable ([9],[10],[11]-[12]). According to a survey conducted by [13],[14]-[15], carbon FRP can be utilized to increase influence strength by enhancing load resistance and energy absorption.

FRPs are synthetic composite materials developed from fibres and polymer matrices. Carbon, glass, and aramid are the most utilized fibres [16]-[17]. Other FRPs are rarely utilized. These less popular FRPs include; wood, paper and asbestos. Although phenol-formaldehyde resins are still considered, the polymer is commonly a thermosetting plastic, epoxy, polyester, vinyl ester. Such materials might lead to premade laminates or sheets, fabrics and other choices [16].

Externally bonded FRP sheets or laminates effectively strengthen a variety of RC members [18]. This technology is now being used to strengthen constructions such as tunnels, columns, walls, beams and slabs. Flexural strengthening, enhancing the bending stiffness and ductility of RC members [19], and shear strengthening are some of the applications of external FRP sheets or fabrics ([20], [21]-[22]).

The response of FRP bonded laminates used to improve the moment resistance of flexural components has been investigated in a number of research ([23], [10]). the shear strength of the element is finally surpassed, which is a restriction to increasing the moment capacity. It has been demonstrated that FRP bonded sheets may be employed to boost shear resistance in certain conditions ([21], [22]). Nevertheless, little research has focused on the RC beam's shear strengthening (side configuration) [16].

Completely wrapped   3-sided “U-wrap”   2-sides

Fig. 1 Shear strengthening arrangement using FRP

One of the concerns in characterizing the shear behaviour of RC elements bonded FRP laminate or sheets is the enormous choice of potential FRP shear strengthening configuration or schemes. According to [24], there are three shears strengthening configurations (Complete wrap, U-wrap and 2 sides) as depicted in Fig. 1, which faces will be glued or bonded, if to use continuous or a sequence of FRP strips and if mechanical anchoring is required. the mechanical properties of FRP vary in all directions (it is an anisotropic material), meaning it has high strength in the direction of fibre orientation. the fibres can be orientated in directions that best strengthen flexure or shear failure. This study intends to investigate the FRP surface area and bond thickness variation in shear strengthening of reinforced concrete beams. the authors use carbon FRP fabrics as external reinforcement and intend to address the structural response of CFRP fabrics bonded on one face and both faces shear strengthening configurations and determine the limit of the bond thickness.

2. Materials and Method

2.1. Test Samples

Fifteen (15) single-span RC beams having a cross-section of 100mm by 150mm were subjected to static loading. Two 10mm and two 8mm diameter steels were provided at each beam sample's bottom and top. the depth of the internal steel reinforcement was 135mm. the yield and ultimate resistance of the internal reinforcement were 420MPa and 500MPa, correspondingly. the mix ratio used in casting the concrete beams was l: 2:4, which had 29MPa after 28 days. Two Carbon Fiber Wraps (also known as carbon fibre reinforced polymer fabric) of thickness 200g/m2 (0.111mm) and 300g/m2 (0.167mm) were used for single, and both sides shear strengthening. the engineering properties are presented in Table 1. the glue applied in the investigation was a mortar-like structural two-part Sikadur (R)-31 with a tensile strength of 15-20MPa, the tensile modulus of elasticity of 3300MPa, and bending strength 30-40MPa, and tensile bond strength 4-15MPa. 6 mm diameter shear links were introduced at 220 mm centre to centre in a constant moment region to ensure sliding failure developed in the shear region. Beam FA-0 was a reference sample and was not bonded with CFRP fabrics. the remaining samples were investigated to ascertain the response of various FRP surface areas and bond thickness variation to the shear capacity of the beams. the beam samples, internal reinforcement ratios and CFRP fabric properties are itemized in Table 1.

Table 1. Beam section details and Mechanical properties of CFRP fabric

Beam	Bond thickness	ρ (%)	Beam cross-section parameters				CFRP fabric properties			
			b_w (mm)	h (mm)	d (mm)	h_f (mm)	t_f (g/m^2)	E_f (GPa)	f_f (MPa)	Wrap scheme
FA-0	-	1.16	100	150	135	-	-	-	-	-
BSA-2	2	1.16	100	150	135	152	200	237	3964	2-Sides
BSA-4	4	1.16	100	150	135	154	200	237	3964	2-Sides
BSA-6	6	1.16	100	150	135	156	200	237	3964	2-Sides
BSA-8	8	1.16	100	150	135	158	200	237	3964	2-Sides
BSB-2	2	1.16	100	150	135	152	300	237	3964	2-Sides
BSB-4	4	1.16	100	150	135	154	300	237	3964	2-Sides
BSB-6	6	1.16	100	150	135	156	300	237	3964	2-Sides
BSB-8	8	1.16	100	150	135	158	300	237	3964	2-Sides
SSC-2	2	1.16	100	150	135	152	200	237	3964	1-Side
SSC-4	4	1.16	100	150	135	154	200	237	3964	1-Side
SSD-2	2	1.16	100	150	135	152	300	237	3964	1-Side
SSD-4	4	1.16	100	150	135	154	300	237	3964	1-Side
BSE-2	2	1.16	100	150	135	152	200	237	3964	2-Sides
BSF-2	2	1.16	100	150	135	152	300	237	3964	2-Sides

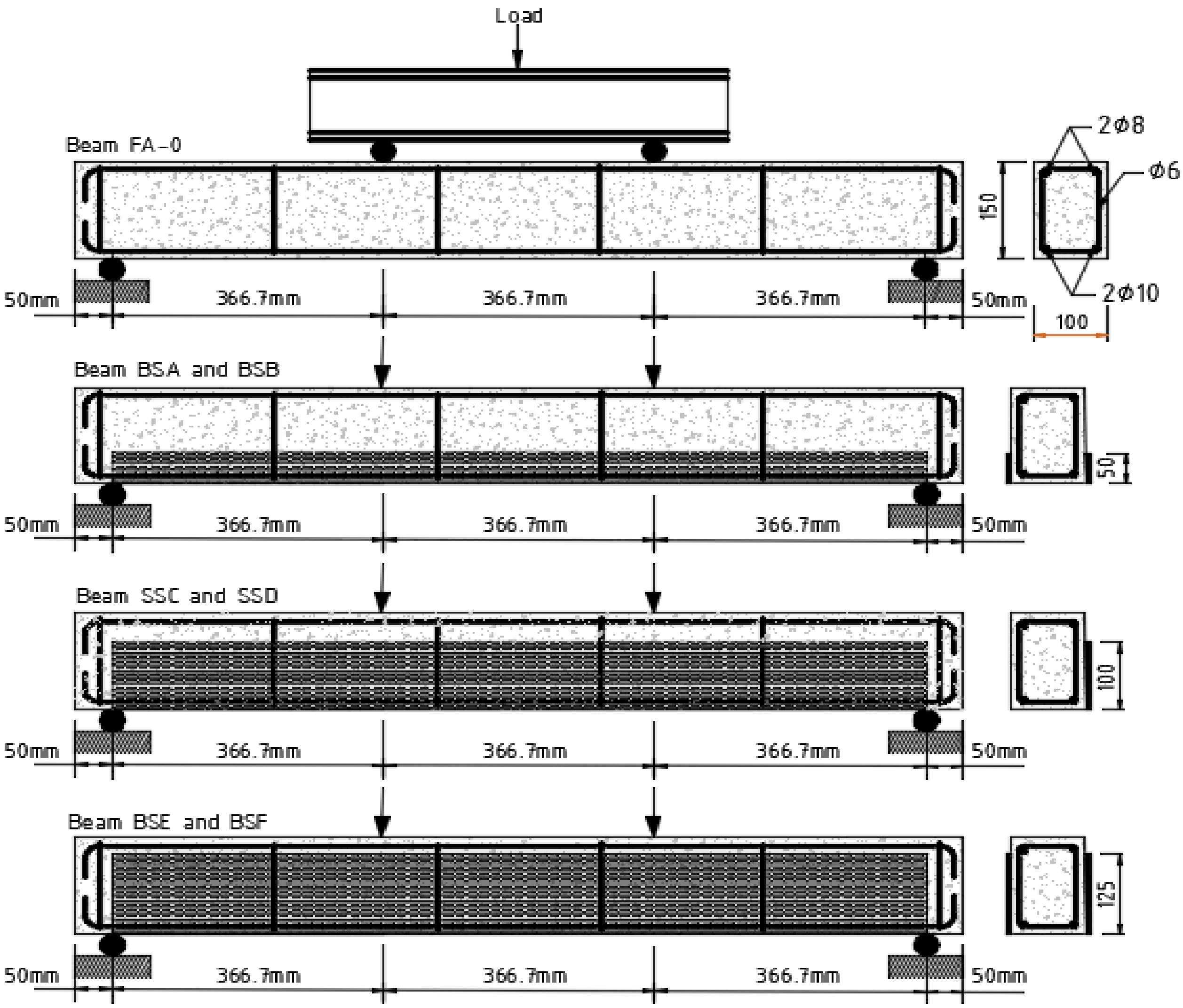

Fig. 2 Strengthening configuration detail

2.2. Strengthening Configuration

Fig. 2 depicts the CFRP shear strengthening configurations utilized in the investigation. Except for FA-0, which was not strengthened, the CFRP fabrics were wrapped to the side faces of the test beams. the vertical beam sides to be wrapped were thoroughly cleaned of loose material before wrapping. After vertical sides preparation, the CFRP fabric was trimmed to size and then bonded to the vertical sides at the appropriate locations. Beam BSA-2, Beam BSA-4, Beam BSA-6, and Beam BSA-8 were strengthened with 200g/m2 (0.111mm) CFRP fabric strips of 50mm by 1100mm with 2mm, 4mm, 6mm and 8mm bond thickness respectively bonded on both vertical sides of the test beam at the tension zone. Beam BSB-2, Beam BSB-4, Beam BSB-6, and Beam BSB-8 were strengthened with 50mm by 1100mm 300g/m2 CFRP fabric strip with 2mm, 4mm, 6mm and 8mm bond thickness respectively bonded on both vertical sides of the test beam at the tension zone. Beam SSC-2 and SSC-4 were strengthened with 100mm by 1100mm 200g/m2 CFRP fabric strip with 2mm and 4mm bond thickness respectively bonded on one vertical side of the beam from the tension zone while SSD-2 and SSD-4 were strengthened with 100mm by 1100mm 300g/m2 CFRP fabric strip with 2mm and 4mm bond thickness respectively bonded on one face of the beam from the tension zone. Beam BSE-2 was strengthened with 125mm by 1100mm 200g/m2 CFRP fabric strip with 2mm, and Beam BSF-2 was strengthened with 125mm by 1100mm 300g/m2 CFRP fabric strip with 2mm bond thickness bonded on both sides of the beam from the tension zone.

2.3. Test set-up

As illustrated in Fig. 2, each beam sample was supported and loaded with two-point loads positioned at one-third of the beam length. A hydraulic jack with a loading capacity of 200kN was used to apply the load. Vertical displacements at mid-span were measured using a dial gauge. Fig. 2 depicts the crack patterns.

3. Results and Discussion

3.1. Results for Beam Group BSA

This group consist of FA-0, BSA-2, BSA-4, BSA-6, and BSA-8. Beams in this group were strengthened on both sides with a 50mm strip width of 200g/m2 (0.111mm) CFRP fabrics at the tension zone. These beams were subjected to two points static load, deformations were recorded in all load steps, and comparisons were made between the strengthened and reference beam. Attention was given to the deformation and the post-test observation of the failure mode, the crack patterns load-carrying capacity, ductility, and the shear contribution by 200g/m2 (0.111mm) CFRP fabrics. All the test results under this group are presented in Table 2. Also, the load against the mid-span deformation graph of the test specimens is presented in Fig. 3. Table 3 and Fig. 4 present CFRP contribution to shear capacity and failure load vs bond thickness, respectively.

Table 2. Test Results for BSA

Sample ID	Yield Load (kN)	Deformation at Yield load (mm)	Failure Load (kN)	Deformation at Failure load (mm)	Mode of Failure
FA-0	28.7	3.85	37.3	4.05	Flexure
BSA-2	40.0	6.52	44.2	8.00	Flexure
BSA-4	39.0	5.60	54.0	10.4	Flexure
BSA-6	38.7	5.59	52.0	11.2	Shear
BSA-8	31.5	3.40	42.8	7.30	Flexure

Table 3. CFRP Contribution to Shear for Beam BSA

Sample ID	Failure Load (kN)	Experimental Shear Force $V_{exp,}$ (kN)	FRP Contribution to Shear (%)
FA-0	37.33	18.67	
BSA-2	44.15	22.08	18.0
BSA-4	54.00	27.00	45.0
BSA-6	52.00	26.00	39.3
BSA-8	42.80	21.40	14.6

3.1.1. Ultimate Load-Carrying

FA-0 beam was a control beam and was not retrofitted, which was used to compare with the remaining beams in this sample group in relation to bending and load-carrying capacity. the first crack was noticed directly at the constant moment region at a load of 71.85kN. the crack was found to be a result of flexural stresses. As the load steps increases, the crack propagates to the web. Fig. 3 shows the load-versus-midspan graph for FA-0. the beam failed by yielding internal reinforcement and by compression failure of concrete directly at the mid-span. the FA-0 had a yield load of 71.85kN and an ultimate load of 93.33kN due to tension failure.

Beam BSA-2 was strengthened with 200g/m^2 (0.111mm) CFRP fabric measuring 50mm by 1100mm with 2mm bond thickness glued on both faces of the beam element at the tension zone. in the course of testing, it was detected that the initial flexural crack was developed at a load of 10.14kN. the cracks were generated close to the loading points as the loading steps increased. As the loading progressed, more vertical flexural cracks began to form, and the beam yielded at 40.0kN and failed at a load of 44.12kN due to flexure and crushing of concrete at the compression. Beam BSA-2 is 19% greater than the failure load of reference beam FA-0). Although ductile behaviour was observed, only a 1.2 ductility index was recorded at failure (Fig. 8). Fig. 3 shows the load-deformation of Beam BSA-2. Debonding was the failure mode due to the localization of shear stress originating from the diagonal fracture.

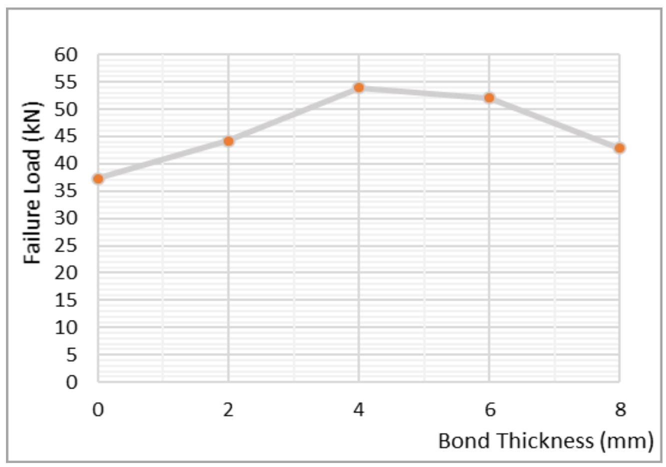

Fig. 3 Failure load against bond thickness for BSA

Beam BSA-4 was strengthened with 200g/m^2 (0.111mm) CFRP fabric measuring 50mm by 1100mm with 4mm bond thickness glued on both faces of the beam element at the tension zone. Two-point loading was used in the testing of this beam. During testing, the initial crack was seen directly below the loading point at a load of 13.69kN. BSA-4 exhibited shear and flexural cracks. Shear cracking was observed near the left support, and also, between the loading points and the CFRP fabric, there is a major inclined crack. the beam yielded at 39.0kN and failed at a load of 54kN due to flexure and crushing of concrete at the compression. Beam BSA-4 is 45% higher than reference beam FA-0 at failure. Though ductile behaviour was attained, only a 1.9 ductility index was recorded at failure. the test result supports what [25] found.

Beam BSA-6 was strengthened with 200g/m^2 (0.111mm) CFRP fabric measuring 50mm by 1100mm with 4mm bond thickness glued on both faces of the beam element at the tension zone. During testing, it was observed and recorded in Table 2 and Fig. 3 that the initial vertical flexural crack was considered at a load of 13.5kN. BSA-6 also exhibited shear cracks. These cracks were observed close to the support, and also, diagonal cracks were observed. the beam BSA-6 yielded at 38.7kN and failed at a load of 52.0kN due to flexure and shear. However, a 39 per cent increase in load was detected compared to that of the FA-0 beam. the ductility index 2.0 was recorded at failure. the text results show that the maximum recorded deformation at failure was 4.46mm. Fig. 3 shows the load versus midspan deformation at every load step.

Beam BSA-8 was strengthened with 200g/m^2 (0.111mm) CFRP fabric measuring 50mm by 1100mm with 4mm bond thickness glued on both faces of the beam element at the tension zone. At a load of 10.10kN, vertical flexural fractures began to form during loading. As loading progressed, more shear and flexural cracks were formed. Fig. 3 shows that the deformation is about 1.8 times the reference beam FA-0. At the same time, the load at failure increased by about 14kN. Table 2 shows that the beam yielded at 31.6kN and failed at a load of 42.8kN due to flexure and shear. Table 2 shows that Beam BSA-8 had 7.3mm deformation at ultimate failure, compared to the reference beam, which is 4.1mm. This indicates that CFRP fabric strengthened beams increase the ductility of the structural element. A ductility index of 2.2 was achieved, i.e., an 80% increase at failure load compared with the reference beam.

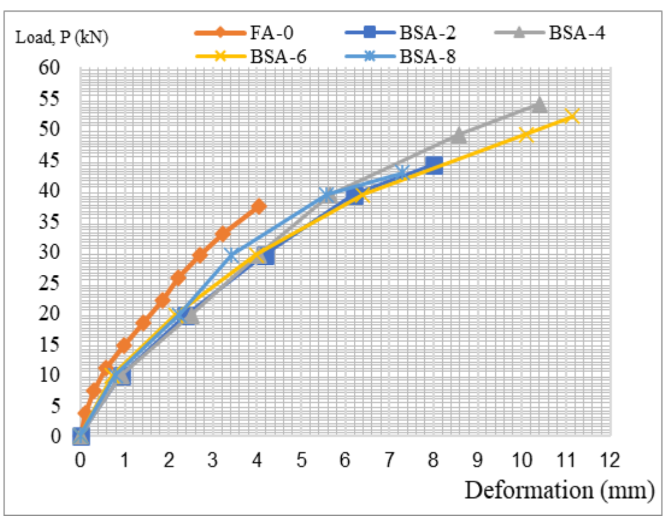

Fig. 4 Load against deformation for BSA

3.1.2. Load–Deflection Behaviour

According to [26], deformation is one of the conditions of ductility to study the behaviour of strengthening reinforced concrete beams because generally, there is no specific yield point in strengthened beam elements. the load-versus-midspan deformation presented in Fig. 3 shows that the reference beam, FA-0, is stiffer than the CFRP-fabric strengthened beams on this group. the deformations of BSA-2, BSA-4, BSA-6, and BSA-8 beams at 37.33kN (failure load for FA-0) were greater compared to the beam without CFRP fabrics. the highest deformation was noted in beam BSA-6. in the course of testing, it was observed that BSA-2, BSA-4, BSA-6, and BSA-8 exhibited ductile failure. the research also revealed the likelihood of altering a brittle to ductile behaviour by changing CFRP fabric orientation. in testing beams BSA-4 and BSA-6, it was observed that the CFRP fabric presented good performance to further loading beyond the first crack. These beams showed a smaller crack width and spacing with the CFRP fabric arrangements.

3.1.3. Shear Strength

The shear resistance of simply supported RC beams may be significantly improved by reinforcing with CFRP fabric externally, as shown in Table 3. Table 3 showed a substantial decrease (50%) in the section area of the adhesive of beam BSA- 8 compared to beam BSA-4. Though, the CFRP fabric contribution to shear of beam BSA-8 was 21% less than beam BSA-4. Favourable results were achieved with the less sectional area. Bonding 50mm by 1100mm CFRP fabric strip on both sides of the beam at the tension zone was effective for simply supported beams. Nevertheless, suitable end anchorage is needed to attain optimum utilization of the CFRP fabric, as the beam BSA-2, BSA-4, BSA-6, and BSA-8 showed a 16%, 38%, 33%, and 12% increase in shear strength, respectively. the results are similar to those [20] and [22] reported.

3.2. Results for Beam Group BSB

The strengthening configuration of this group is the same as Beam Group BSA except for CFRP thickness. This group consist of FA-0, BSB-2, BSB-4, BSB-6, and BSB-8. Beams in this group were strengthened on both sides with a 50mm strip width of 300g/m2 (0.167mm) CFRP fabrics at the tension zone. These beams were subjected to two static load points to ascertain deformations, load-carrying capacity, ductility, and the shear contribution by 300g/m2 (0.167mm). CFRP fabrics were recorded in every load step, and comparisons were made between the externally strengthened and the reference beam. All the test results under this group are presented in Table 4. Also, the load against the mid-span deformation graph of this group is presented in Fig. 6. Tables 5 and 6 present FRP contribution to shear capacity and failure load vs bond thickness.

Table 4. Test Results for BSB

Sample ID	Yield Load (kN)	Deformation at Yield load (mm)	Failure Load (kN)	Deformation at Failure load (mm)	Mode of Failure
FA-0	28.74	3.85	37.33	4.05	Flexure
BSB-2	45.00	7.15	58.86	9.55	Flexure
BSB-4	47.05	6.65	54.00	9.65	Shear
BSB-6	39.50	5.84	50.00	8.22	Flexure
BSB-8	35.00	3.39	44.15	6.80	shear

Table 5. CFRP Contribution to Shear for BSB

Sample ID	Failure Load (kN)	Experimental Shear Force V_{exp}, (kN)	FRP Contribution to Shear (%)
FA-0	93.33	46.67	
BSB-2	147.15	73.58	57.7
BSB-4	135.00	67.50	44.6
BSB-6	125.00	62.50	33.9
BSB-8	110.38	55.19	18.3

3.2.1. Ultimate Load-Carrying

Beam BSB-2 was strengthened with 50mm by 1100mm 300g/m2 CFRP fabric strip with 2mm bond thickness glued on 2-sides of the beam below the neutral axis. in subjecting to two-point static loading, the initial flexural cracks developed in the constant maximum moment zone at 8.5kN. More cracks occurred and spread toward the shear span when the static stress was increased. At a load of 21.8kN, more apparent shear fractures with around 450mm from near the supports developed as the loading increased. As a result of failure in the shear region, beam BSB-2 yielded at 45.0kN and completely failed at a load of 58.9kN, which is 58% greater than beam FA-0. Fig. 5 shows that Beam BSB-2 had 9.60mm mid-span deformation at ultimate failure, relative to the reference beam, 4.10mm. This shows that 50mm by 1100mm 300g/m2 CFRP fabric strip with 2mm bond thickness glued on both faces of the beam at the tension zone increase the ductility of the structural element. A ductility index of 1.3 was achieved, a 136% increase at failure load relative to the reference beam.

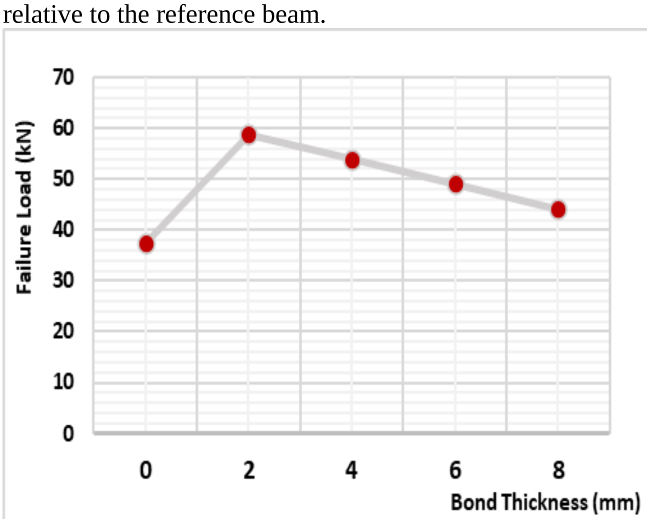

Fig. 5 Failure load against bond thickness for BSB

Beam BSB-4 was strengthened with 50mm by 1100mm 300g/m2 CFRP fabric strip with 4mm bond thickness glued on 2-sides of the beam below the neutral axis, as shown in Fig. 2. in the course of loading, the first crack was noticed at the centre at a load of 9.8kN. the inclined critical shear cracks with a small slope were observed when further loads were applied. the beam yielded at 47.1kN and failed at a load of 54.0kN attributable to shear failure as the concrete in the compression area cracked and further cracks formed and spread toward the loading points. Fig. 5 shows the structural performance because of the load capacity of BSB-4. Also, the load against the deformation curve of the experimental results for the specimen BSB-4 is presented in Fig. 5. the test shows that BSB-4 is 45% higher than the reference beam FA-0. This beam shows a ductility index of 1.4, as presented in Fig. 9.

Beam BSB-6 was strengthened with 50mm by 1100mm 300g/m2 CFRP fabric strip with 6mm bond thickness glued on 2-sides of the beam below the neutral axis, as shown in Fig. 2. Despite the difference in bond thickness between BSB-6 and BSB-2, the failure mode and pattern of cracks remained comparable during loading. the first shear crack on the BSB-6 beam propagated in the support's area at a load of 10.5kN, while the flexural cracks with a large crack's width close to the applied point loads developed at a load 43.8kN. the beam yielded at 39.5kN, and finally, at a load of 50kN, the concrete in the upper fibre failed due to coupled flexure and shear. the load versus deformation plot of the data for the specimen BSB-6 are accessible in Fig. 5. Test results show that BSB-6 is 34% higher than the reference beam FA-0. This beam exhibited a ductility index of 1.5.

Beam BSB-8 was strengthened with 50mm by 1100mm 300g/m2 CFRP fabric strip with 8mm bond thickness glued on 2-sides of the beam below the neutral axis, as shown in

Fig. 2. During loading, it was discovered that the cracks were substantially less than they had been at a previous loading value of 10.9kN. the concrete in the upper fibre began to fail at a load of 44.2kN, and a crack developed at the support point and progressed toward the loading point as the load increased. the load at failure in this beam was higher than FA-0 but lower than BSA-2, BSB-4, and BSA-6. the load versus deformation plot of the data for the specimen BSB-6 are presented in Fig. 5. This beam exhibited a ductility index of 2.0, as shown in Fig. 9.

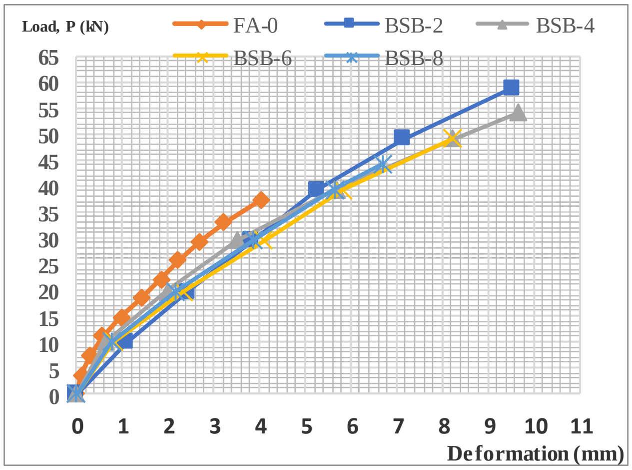

Fig. 6 Load against deformation for BSB

3.2.2. Load–Deflection Behaviour

The load-versus-midspan deformation presented in Fig. 5 of FA-0, BSB-2, BSB-4, BSB-6, and BSB-8 show that the extent to which the FA-0 was able to resist deformation under load was higher than BSB-2, BSB-4, BSB-6, and BSB-8, this means FA-0 is stiffer relative to strengthened beams on this group. Also, the deformations of BSB-2, BSB-4, BSB-6, and BSB-8 beams at 37.33kN (a failure load for FA-0) were greater than the beam without CFRP fabrics. the highest deformation was noticed in beam BSB-4. in the course of testing, it was observed that BSB-2, BSB-4, BSB-6, and BSB-8 showed ductile behaviour.

3.2.3. Shear Strength

Table 5 and Fig. 5 revealed that the shear capacity of simply supported reinforced concrete beams can be meaningfully improved by gluing 50mm by 1100mm 300g/m2 CFRP fabric strip with 2, 4. 6. and 8mm bond thickness on both faces of the beam element at the tension zone. More favourable results were achieved with lesser bond thickness. However, appropriate end anchorage is the desire to utilise the CFRP fabric strips fully, as the beam BSB-2, BSB-4, BSB-6, and BSB- 8 contributed 10.8, 8.34, 6.34, and 3.41kN in shear strength, respectively.

3.3. Results for Beam Group SSC

This group envelopes FA-0, SSC-2, SSC-4, SSD-2, SSD-4, BSE-2 and BSF-2 beams. This group was strengthened with a 100mm strip width of 200g/m2 and 300g/m2 CFRP fabrics bonded on one face and 125mm strip width of 200g/m2 and 300g/m2 CFRP fabrics on both sides of the beam at the tension zone the beams were tested and the deformations, ductility, load-carrying capacity, and FRP contribution to shear by 300g/m2 (0.167mm) CFRP fabrics were recorded. Comparisons were made relative to the reference beam. Table 6 shows the presentation of the results. Similarly, the load versus mid-span deformation plot is highlighted in Fig. 7. Table 7 presents FRP contribution to shear capacity.

Table 6. Test Results for FA-0, SSC-2, SSC-4, SSD-2, SSD-4, BSE-2 and BSF-2

Sample ID	Yield Load (kN)	Deformation at Yield load (mm)	Failure Load (kN)	Deformation at Failure load (mm)	Mode of Failure
FA-0	28.7	3.9	37.3	4.1	Flexure
SSC-2	34.3	4.4	39.3	7.9	Shear
SSC-4	39.0	5.5	54.0	10.7	Shear
SSD-2	39.2	6.3	45.1	9.8	Flexure
SSD-4	45.0	9.0	51.0	11.9	Flexure
BSE-2	48.0	8.5	52.0	10.0	Shear
BSF-2	49.0	6.3	58.9	9.7	Flexure

3.3.1. Ultimate Load-Carrying

Beam SSC -2 was strengthened with 100mm by 1100mm 200g/m2 CFRP fabric strip with 2mm bond thickness bonded on one face of the beam from the tension zone. in the testing, close to the support, first shear cracks with about 450 were observed at a load of 9.81 kN. More cracks occurred and expanded toward the constant moment span when the load steps were increased. the beam yielded at 34.34 kN due to shear cracks in the shear span and eventually failed in shear, followed by flexure failure at a load of 39.3 kN with an ultimate deformation of 7.9 mm, as shown in Fig. 7. the Fig. also shows that the reference beam is stiffer than SSC-2. This beam records a ductility index of 1.8.

Table 7. CFRP Contribution to Shear for Beam Group SSC, SSC, SSD, SSD, BSE and BSF

Sample ID	Failure Load (kN)	Experimental Shear Force V_{exp}, (kN)	FRP Contribution to Shear V_f, (%)
FA-0	37.3	18.67	
SSC-2	39.3	19.60	5.0
SSC-4	54.0	27.00	44.6
SSD-2	45.1	22.60	21.0
SSD-4	51.0	25.50	36.6
BSE-2	52.0	26.00	39.3
BSF-2	58.9	29.40	57.5

Beam SSC -4 was strengthened with 100mm by 1100mm 200g/m2 CFRP fabric strip with 4mm bond thickness bonded on one face of the beam from the tension zone. the first crack developed between the two static loading points at a load of 9.77 kN during testing. the diagonal cracks were formed when more static loads were applied. the beam yielded at 39.0kN and failed due to shear, followed by flexure failure at a load of 54.0 kN with ultimate deformation of 10.7 mm, which is 164% higher than the reference beam as presented in Fig. 7 load versus deformation. This beam shows a ductility index of 2.0. However, the load-carrying capacity is about 45% higher than the reference beam. to examine the effectiveness of the adhesive interface in sustaining composite behaviour, the beam was carefully studied before and after testing. Although the deformation measurements depicted extensive rupture of the CFRP, the cracks became visible after releasing the load. After examination, it was revealed that failure did not occur at the bond interface, but the fracture was observed in the concrete cover.

Beam SSD -2 was strengthened with 100mm by 1100mm 300g/m2 CFRP fabric strip with 2mm bond thickness bonded on one face of the beam from the tension zone. the initial crack on this beam SSD-2 extended in the support's area at 10.27kN. the number of cracks in SSD-2 was observed more, mainly at the shear region. When the cracks expanded, the beam achieved a load of 39.15kN and failed at a load of 45.13kN owing to flexure and shear. Beam SSD-2 exhibited an ultimate deformation of 9.75mm at failure, which is 141% greater than the beam FA-0 as appeared in Fig. 7 as load versus deformation. This beam exhibited a ductility index of 1.6, though the load-carrying capacity is about 21% better than the reference beam. the flexural strength of the SSD-D beam was lower than the reference beam FA-0, as shown in Fig. 7.

Beam SSD -4 was strengthened with 100mm by 1100mm 300g/m2 CFRP fabric strip with 4mm bond thickness bonded on one face of the beam from the tension zone. the load versus deformation graph of the experimental results for the SSD-4 is presented in Fig. 7. At a load of 9.4kN, the first crack on the SSD-4 beam developed within the two-point loads; as the loading progressed, further cracks appeared beyond the two loading points. When the applied load was increased, the crack width quickly expanded, and the concrete in the compressive zone failed with a combined flexure and shear failure mode at a value of 51.0kN. the ductility index of this beam was 1.3. Beam SSD-4 has a load-carrying capability roughly 37% greater than the reference beam.

Beam BSE-2 was strengthened with 125mm by 1100mm 200g/m2 CFRP fabric strip with 2mm bond thickness bonded on both sides of the beam from the tension zone. During testing, it was noticed that the initial crack on the beam BSE-2 was detected in the shear zone at a load of 10.6kN with deformation of 1.0mm; as loading progressed, more cracks developed at the mid-span. the beam yielded at 48.0kN and failed finally at a load of 52.0kN with deformation of 10.0mm, 147% higher than the reference beam as presented in Fig. 7 as load versus deformation. This beam exhibits a ductility index of 1.2. the beam had about 39% greater load-carrying capacity than beam FA-0. the test results show that external reinforcement in glued CFRP has a clear outcome on structural performance. the subsequent higher load resistance increases as the CFRP thickness increases. the presence of bonded CFRP controls the crack width to a very considerable extent.

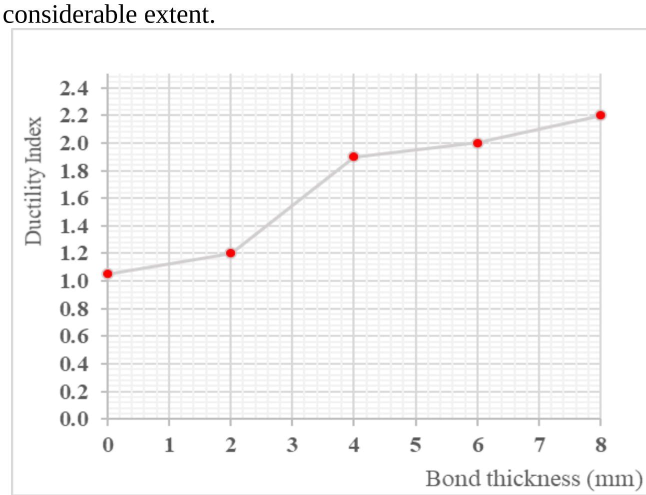

Fig. 7 Ductility Index against bond thickness for group BSA

Beam BSF-2 was strengthened with 125mm by 1100mm 300g/m2 CFRP fabric strip with 2mm bond thickness bonded on both side of the beam from the tension zone. in the course of testing, it was seen that the first crack originating on the constant moment zone corresponds to a load of 10.08kN with a deformation of 0.6mm. More cracks appeared in the shear zone as the load steps increased. the beam yielded at a load of 49.0kN with deformation of 6.24mm and failed at a load of 58.8kN with a deformation of 9.7mm, which exhibited a ductility index of 1.6. the load-carrying capacity of BSF-2 is about 58% higher than the reference beam. the test results confirmed that this strengthening configuration increased the shear capacity in RC beams relative to the controls. the test results show that external reinforcement in the form of glued CFRP has a vivid outcome on the structural response. the subsequent higher load resistance increases as the CFRP thickness increases. the presence of bonded CFRP controls the crack width to a very considerable extent.

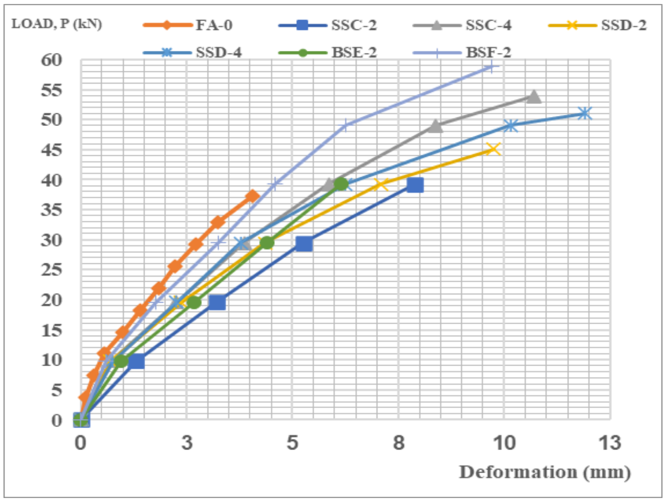

Fig. 8 Load against deformation for BSB

3.3.2. Load–Deflection Behaviour

To know the effect of the bonded CFRP fabric on the deformational response, deformations were recorded at every load step. the load-versus-deformation graph is presented in Fig. 7. in a beam strengthened externally, the whole stiffness of the reinforced concrete beam is a role or function of concrete, external reinforcement (CFRP) and the epoxy resin. the overall flexural rigidity of the strengthened member has no persistent value; however, it varies with load application, applied load, the extent of cracking, external reinforcement thickness, and bond thickness. Also, Fig. 7 shows that the bonded CFRP causes an increase in deformation at failure, and the rate of increment varies with bond thickness.

3.3.3. Shear Strength

Table 7 presents the shear contribution of Beam Group SSC, SSC, SSD, SSD, BSE, and BSF demonstrated that the shear resistance of reinforced concrete (RC) beam can be improved by shear strengthening with 125mm by 1100mm 300g/m2 CFRP fabric strip with 2mm bond thickness bonded on both side of the beam from the tension zone. It can also be recorded in Table 7 that the shear contribution of the CFRP fabric of beams SSC-2, SSC-4, SSD-2, SSD-4, BSE-2 and BSF-2 were 5.1%, 45%, 21%, 37%, 39% and 58%, respectively, relative to FA-0. the study showed that BSF-2 (strengthened with 125mm by 1100mm 300g/m2 CFRP fabric strip with 2mm bond thickness bonded on both sides of the beam from the tension zone was recorded to be highest in sheer contribution. the results are similar to those [20] and [22] reported.

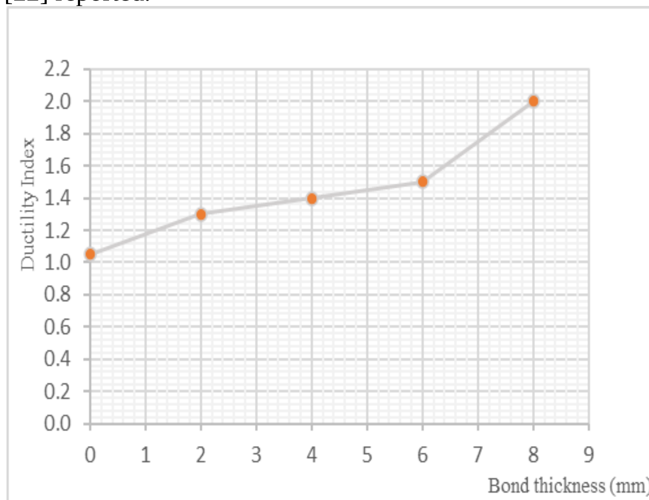

Fig. 9 Ductility Index against bond thickness for group BSB

4. Conclusion

This paper evaluates the CFRP fabrics surface area and bond thickness variation in shear strengthening of reinforced concrete beam experimentally: Two points load tests were performed on all the beams, and the necessary structural responses were analyzed. the following deductions were reached based on the data:

- CFRP fabric to bond thickness ratio should not exceed 0.075
- Reinforced concrete beams strengthened along the longitudinal axis on both faces having the same surface area as the single face performed better than the RCC strengthened on single. This superior performance is attributed to stress distribution through the bond on both faces instead of one, hence increasing its shear capacity.
- Beam members strengthened with carbon FRP fabric along the longitudinal axis reduce bending stiffness.
- the carbon FRP's surface area can be significantly reduced while still achieving the desired structural performance.
- Bond thickness improved the bending significantly, and the shear strength of RC beams was strengthened externally by bonded CFRP/steel plate.

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