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EFFECT OF BOND SURFACE AREA ON THE SHEAR STRENGTH OF CARBON FIBRE REINFORCED POLYMER (CFRP) STRENGTHENED REINFORCED CONCRETE BEAMS

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Abstract

The use of carbon fiber reinforced polymer (CFRP) for shear strengthening of reinforced concrete (RC) elements has grown significantly over the last few decades. The effectiveness of a CFRP strengthened system depends primarily on the bond strength between the CFRP and RC substrate. Since cost of CFRP and bond materials (epoxy adhesive) is relatively high, it is important to reduce CFRP bond surface area to RC when carrying out structural strengthening. This paper reports the effect of bond surface area on the shear strength of RC beams externally bonded with CFRP. Seven RC beams were investigated. One of the beam specimens was not strengthened and was used as a reference. The remaining six beams were strengthened with 200 g/m^2 and 300 g/m^2 CFRP fabrics with three different bond surface areas, i.e., 0.15 m^2, 0.2 m^2 and 0.25 m^2 in a U-wrap configuration. Static bending tests were performed on all the beams. Results show that the CFRP's contribution to shear strength increases as the bond surface area increases. Results also show that the shear strength of the RC beam was increased by 45% due to the presence of CFRP. Fundamentally, this work presents a parametric study to guide engineers on how shear strength and corresponding ductility of beams can be increased with an optimal configuration of the bond surface between CFRP and RC elements. An optimal and cost-effective configuration is proposed for carrying out nominal shear strengthening of RC elements after construction, especially in cases where the construction engineer has concerns about the shear stirrups provided before casting.

Keywords: Shear Strength, Deformation, Ductility, Beam, U-wraps, CFRP, Epoxy resin

1.0 INTRODUCTION

Concerns about the durability and strength of existing reinforced concrete (RC) elements have grown in the construction industry, prompting researchers to investigate alternative materials for improvement. The strengthening and upgrading of the existing deteriorated RC elements by the external bonding has been applied in many projects. Over the last few decades, the application of externally bonded fiber reinforced polymer (FRP) in the retrofitting of aging concrete elements has significantly increased [1, 2, 3]. FRP composites are alternatives to steel reinforcement, especially in harsh environments, because of their high corrosion resistance [4, 5, 6]. While FRP fibers are becoming more popular due to their high strength and lightweight properties, they are viewed negatively due to their high initial costs, and susceptibility to mechanical damage and fire [7, 8].

Strengthening RC beams by externally bonded FRP material has been the subject of several investigations. These investigations have shown that such strengthened RC beams fail in shear predominantly due to one of two mechanisms: FRP debonding or FRP rupture. Chen and Teng [9], Hassan and Rizkalla [10], Li and Leung [11] and Fu et al., [12] investigated the effect of shear span-depth ratio on the behavior of reinforced concrete beams strengthened by full-wrapping with FRP strips. Li and Leung [11] prepared 6 specimens with fully wrapped CFRP strips and 6 control specimens for their study (i.e., samples not strengthened with FRP). The length of the beam specimens ranged between 2 to 2.4 meters. The beam specimens were subjected to four-point loading. The authors concluded that span to depth ratio had a significant effect on the FRP contribution to shear.

Grande et al., [13] noted that the placement of internal FRP rebar along the transverse axis contributed immensely to the shear strength improvement. Particularly, the shear capacity contribution is usually lesser in beams with closer internal stirrups [13]. In the absence of reinforcement along the transverse axis, Tureyen and Frosch [14] subjected RC beams strengthened in shear to two-point loading. In this study, they observed that beam specimens (control and FRP strengthened) with tensile reinforcement of approximately equal axial stiffness exhibited similar shear strengths, and thus concluded that regardless of the reinforcement type used, the required outcomes can still be achieved if the axial stiffness and bond characteristics of tensile reinforcement are appropriately provided. Baggio et al., [15] and Bukhari et al., [16] studied and concluded that due to the stiffness of the CFRP sheets, RC beams experienced a significant increase to the shear strength and deflection.

Previous laboratory researches have demonstrated that fiber reinforced polymer materials are effective in enhancing the shear strength of RC elements [17, 18]. Despite several research in this area, the shear behavior of RC beams bonded with FRP has not been completely explored, and the existing literature in this space is not sufficient to offer a rigorous design specification [19]. U-wrap, complete side wrap and full wrapping of RC beam with CFRP sheets are common external strengthening configuration options. However, in practice, beams are usually cast together with floor slab, eliminating full wrapping as a viable option.

Furthermore, circumstances may occur in which only a portion of the beam requires reinforcement. A vast number of earlier studies [19, 20, 21] has concentrated on shear strengthening of simply-supported beams using externally bonded CFRP. Investigations show a desirable improvement in shear capacity as a result of an increase in the axial rigidity of the RC beam elements [22, 23, 24]. Mostofinejad and Kashani, [24] also reported that an enhancement in the shear capacity up to 23 percent could be attained by grooving the concrete surface below the bonded CFRP. This further enhancement in shear capacity can be attributed to the stiffer bond formed by the grooves.

Ha and Mutsuyoshi [25] investigated the effectiveness of shear strengthening techniques for RC beams, including epoxy-glued thin plates, CFRP, steel strips, and external anchoring stirrups. The behaviour of the strengthened beam was simulated using numerical analysis utilizing the finite element method. Both the epoxy-bonded steel sheets and the CFRP plate were shown to be effective in the reinforcement of RC beams.

Mithaq et al. [26] reported the results of a laboratory investigation of RC elements which were strengthened with CFRP sheets. By using external CFRP reinforcing plates, the maximum deflection is reduced (26.7%) relative to the reference beam. Increasing proportion of steel bars in the pre-crack stage does not significantly affect the load-deflection response.

Kamal et al [27] revealed that the load capacity of CFRP strengthened RC beams increased by 24% and 27% in terms of shear and bending stress, respectively, while the beams strengthened with steel fiber reinforced concrete SFRC had the lowest load capacity. The performance of the reinforced beams was compared with that of RC beams without external reinforcement.

The application of externally bonded CFRP in strengthening RC elements has proven to be a robust repair method. However, the effect of varying the bond surface area (i.e., the area of the RC element to be wrapped) on the shear strengthening of CFRP has not been fully studied. The study aims to establish an optimal bond surface area that would be structurally desirable and economical for engineers desiring to increase the nominal load bearing capacities of existing RC elements. This is intended to fill in the knowledge gap intended to be filled in previous studies on externally bonded CFRP.

2.0 MATERIAL AND METHOD

2.1 TEST SPECIMENS

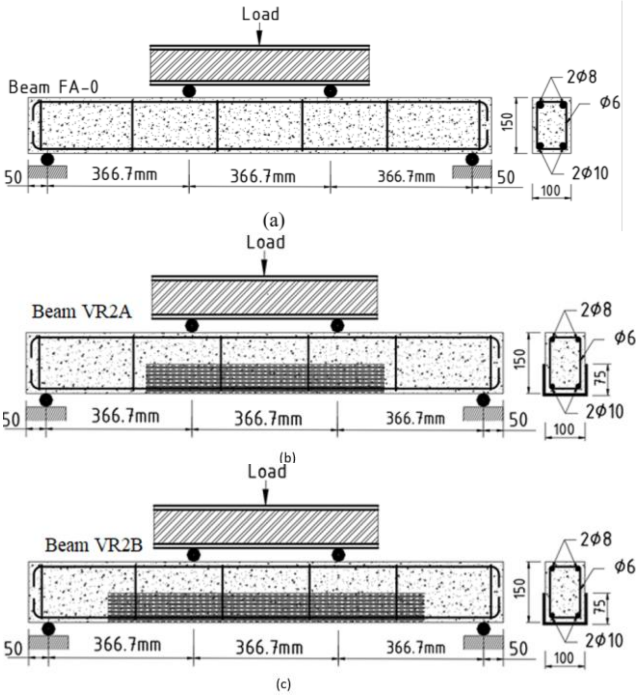
Seven (7) medium-scale single-span RC beams of cross-section (100 mm x 150 mm) with a shear span to effective depth ratio (a_v/d) of 2.5 were investigated. One of the beam specimens (FA-0) was not strengthened and used as a reference as shown in Figure 1a. The remaining RC beams were strengthened with CFRP U-wraps of varying bond surface area as shown in Figures 1b to 1g. Two 10 mm and 8 mm diameter reinforcements were provided throughout the cross-section in all the beams at both the bottom and top, respectively. Two-legged links of 6 mm in diameter were provided in the single span beam at 220 mm center to center. The thickness of 200g/m^2 CFRP fabric used is 0.111mm while the thickness of 300g/m^2 CFRP is 0.167mm. they had similar mechanical properties in terms of tensileStrength, elastic modulus and breaking elongation.

Table 1: Properties of CFRP fabric, Epoxy and Beam details

Beam	**CFRP fabric g/m^2**	**Bond surface area: m^2**	**Beam details**			**CFRP fabric properties**			**Epoxy properties**		
			***b_w* mm**	***h* mm**	***d* mm**	***t_f* (mm)**	***E_f* GPa**	***f_f* MPa**	***E* GPa**	***f_t* MPa**	**Wrapping**
FA-0	-	-	100	150	135	-	-	-	-	-	-
VR2A	200	0.15	100	150	135	0.167	237	3964	3300	15-20	U-wrap
VR2B	200	0.20	100	150	135	0.167	237	3964	3300	15-20	U-wrap
VR2C	200	0.25	100	150	135	0.167	237	3964	3300	15-20	U-wrap
VR2D	300	0.15	100	150	135	0.167	237	3964	3300	15-20	U-wrap
VR2E	300	0.20	100	150	135	0.111	237	3964	3300	15-20	U-wrap
VR2F	300	0.25	100	150	135	0.111	237	3964	3300	15-20	U-wrap

2.2 MATERIAL PROPERTIES

The Portland limestone cement of the 42.5 N grade specified by BS EN 197 [28] was used all throughout this investigation, and the coarse aggregate used was crushed limestone. Coarse and fine aggregates were locally sourced from Wilberforce Island, Nigeria. The constituents of the concrete mix were settled to a ratio of 1:2:4 by weight of binder, fine, and coarse aggregate, respectively. The compressive strength was averaged at 20 MPa at 28 days. The yield strength and elastic modulus of the internal steel rebars were 420 N/mm^2 and 210 GPa respectively. The CFRP fabrics used in this investigation were made of high-strength carbon fiber wrap and were bonded to the RC beam using epoxy adhesives (Sikadur(R)-31). Table 1 shows the properties of the epoxy adhesive and CFRP fabrics as specified by the manufacturers.



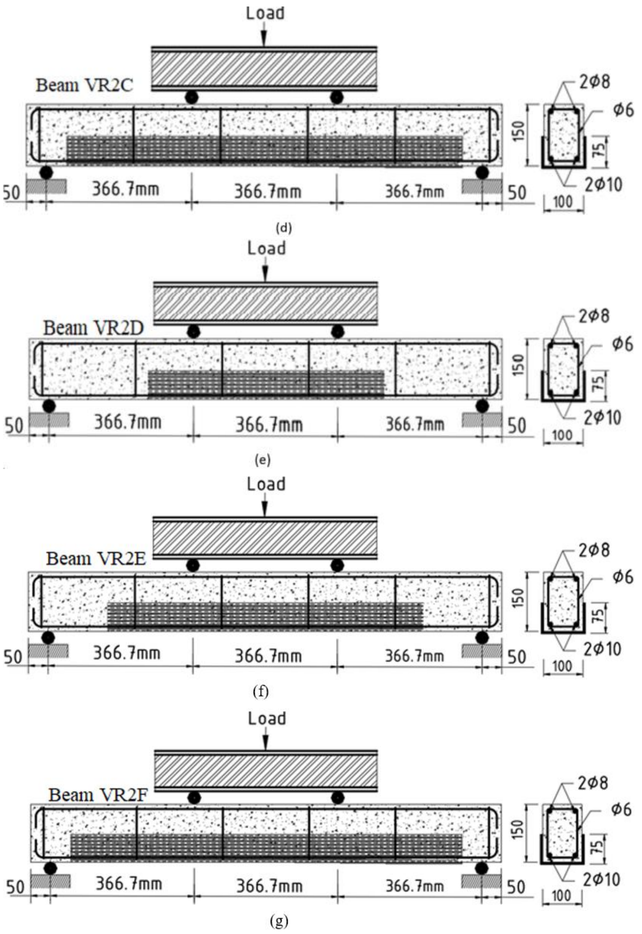


Figure 1: Bonding configuration: (a) Control beam (b) Beam VR2A- 0.15m^2 of the surface of the beam wrapped with 200g/m^2 CFRP (c) Beam VR2B- 0.25m^2 of the surface of the beam wrapped 200g/m^2 CFRP (d) Beam VR2C- 0.25m^2 of the surface of the beam wrapped with 200g/m^2 CFRP (e) Beam VR2D- 0.15m^2 of the surface of the beam wrapped with 200g/m^2 CFRP(f) Beam VR2E- 0.2m^2 of the surface of the beam wrapped with 200g/m^2 CFRP (g) Beam VR2F- 0.25m^2 of the surface of the beam wrapped with 200g/m^2 CFRP

2.3 STRENGTHENING SCHEME

The RC beam details and the engineering properties of epoxy resin and CFRP fabrics are given in Table 1, Figure 2a, and 2b. Prior to carbon FRP application, the beam surfaces to be bonded were treated to remove the cement paste. Except for FA-0, all the other beams were bonded to the three sides of the beam specimens in a U-wrap configuration. Beams VR2A, VR2B, and VR2C were strengthened in a U-wrap configuration with 200 g/m^2 CFRP fabrics with three different bond surface areas: 0.15 m^2, 0.2 m^2, and 0.25 m^2 respectively, as shown in Figure 1b to 1d. As shown in Figure 1e-1g, beam VR2D, VR2E, and VR2F were strengthened in a U-wrap configuration with 300 g/m^2 CFRP fabrics with three different bond surface areas: 0.15 m^2, 0.2 m^2, and 0.25 m^2 respectively.

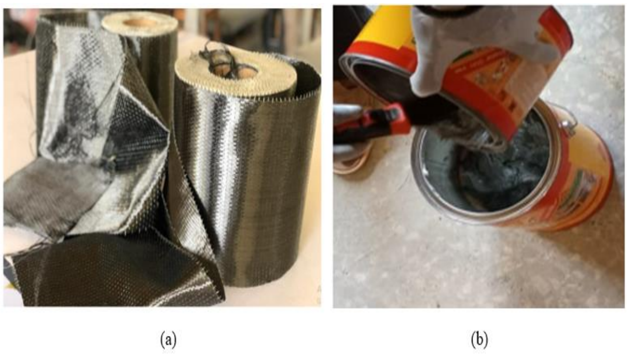

(a) (b)

Figure 2: (a) CFRP and (b) Epoxy Resin

The epoxy resin was mixed properly and was applied to the required surfaces of the beams with a bond thickness of 2 mm. The CFRP fabric strips were placed on the required surfaces and kept in place for proper bonding. A minimum of 7 days was allowed between bonding and testing of the beam specimens. Strengthened beams were tested as simply supported beams. The deflection was monitored at every load increment with dial gauges. Also, the pattern of cracks and positions where these cracks were seen were also noted accordingly during the test.

3.0 RESULTS AND DISCUSSION

The results of the experimental investigation of the effects of bond surface area on the shear strength of RC beams strengthened by CFRP are discussed in detail in sections 3.1 to 3.4. A total of seven RC beams were investigated under four-point bending. Beam FA-0 was selected as a reference beam sample and was compared to beams VR2A, VR2B, VR2C, VR2D, VR2E, and VR2F. The modes of failure of all the RC beams tested are given in Figure 3. The load versus deformation graphs for the various beam configuration is presented in Figure 4. In addition, summaries of failure modes, failure loads, deformation at failure loads, shear strengths of the different beam configurations are shown in Tables 2 and 3. The ductility of each RC beam sample was observed by computing the ductility index as the ratio between the deformation of the beam samples at failure and their deformation at yield.

3.1 ULTIMATE LOAD-CARRYING

It is evident from Table 2 that the reference beam, FA-0, had a yield load of 28.7 kN and an ultimate load of 37.3 kN. This beam FA-0 failed due to the flexure and has a ductility index of 1.05. All beams were strengthened according to the configuration presented in Figure 1.

In Beam VR2A, during loading the first flexural crack was recorded at a load of 9.5 kN and was formed directly below the constant moment region. As loading increased, more cracks were observed. The beam yielded at a load of 29.3 kN and finally failed at a load of 41.2 kN (10.2% higher than the failure load of FA-0) by shear cracks which extended through the loading points. Deformation at failure was 44% higher than beam FA-0. It observed that the application of the CFRP U-wrapped improved the shear capacity and ductility of the beam. These findings support Smith et al., [29]. The authors concluded that CFRP fabric strengthened beams gives not only the increase in ultimate and bending strength, but also increases the ductility of the structural element as well.

Table 2: Test Results

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
VR2A	29.3	3.6	41.2	5.9	Shear
VR2B	28.4	3.3	46.1	6.3	Shear
VR2C	29.5	3.6	54.0	9.5	Shear
VR2D	27.3	3.1	41.4	6.7	Shear
VR2E	29.0	3.6	44.3	7.5	Shear
VR2F	27.4	3.4	49.2	8.6	Shear

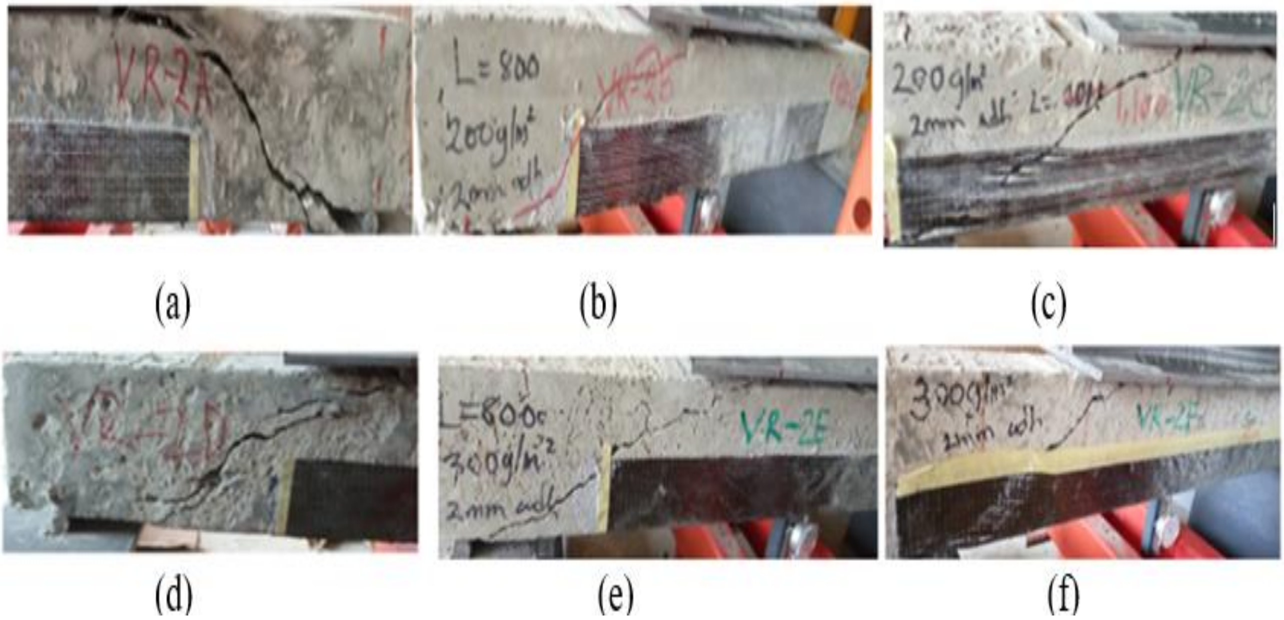


Figure 3: (a) Beam VR2A, (b) Beam VR2B, (c) Beam VR2C, (d) Beam VR2D, (e) Beam VR2E, (f) Beam VR2F

In the course of loading Beam VR2B, it was observed that the cracking of the beam was formed due to flexural stresses and this became visible at a load of 10.5 kN. The crack location was directly below the loading points. The beam yielded at 28.4 kN and failed at 46.1 kN. This beam exhibited a ductility index of 1.9 before failure. The results clearly show that the CFRP fabric strips enhanced the shear strength of the beam. Figure 4 shows the load versus mid span deformation. Failure mode observed here validates Khalifa and Nanni [18] findings, which demonstrated that CFRP materials are effective in improving the shear strength of RC beam.

In the process of loading Beam VR2C, it was observed that the first crack was initiated by shear stress. Failure of this beam occurred as a result of concurrent shear failure of beam and rupture of CFRP fabric at the locations of formed cracks. As the applied load increases the shear cracks widened and the beam yielded at 29.5 kN load and failed load of 54.0 kN. The load carrying capacity increased by 45% as a result of the presence of the CFRP when compared with the reference beam. Beam VR2C showed a ductility index of 2.6 before failure by shear. Furthermore, the ultimate deformation is 132% higher than the reference beam. Cracks were seen on the CFRP fabric surface. Figure 4 shows the load versus mid span deformation.

During the loading of Beam VR2D, it was observed that the first vertical cracks started to form at 9.34 kN, followed by shear cracks. As loading increases, the cracks became wider and visible. Test results show that the amount of deformation it was able carry increased by 64%, while the load-carrying capacity increased about 11%, when compared to the reference beam. The beam yielded at a load of 27.3 kN and failed due to shear at a load of 41.4 kN as shown in Table 2. Table 2 and Figure 4 show that beam VR2D gave large deformation at failure, which was 6.7 mm, when compared to the reference beam, which was 4.1 mm. The beam exhibited a ductility index of 2.08 as shown in Figure 6 before failure shear failure was observed. This beam contributed 2.1 kN to shear strength due to the application of CFRP fabric as depicted in Table 3. This shear response validates the work Khalifa and Nanni [16] findings, which demonstrated that CFRP materials are effective in enhancing the shear strength of RC beam.

During loading of Beam VR2E, the beam developed flexural cracks preceded by vertical shear cracks as the loading of the beam continued. The brittle nature of the beam is vividly illustrated by Figure 3. Beam VR2E yielded at a load 29.0 kN and completely failed at a load of 44.3 kN due to shear failure. Despite the sudden shear failure, the beam ductility index of 2.2 was recorded as against the reference beam which recorded 1.05 ductility index. First crack was formed as a result of flexural stresses at a load of 8.7 kN. The cracks were formed near the support and propagated toward the point loads as the loading progresses. The displacement and ductility of the Beam VR2E was enhanced considerably due to the CFRP wrapped, where the ductility index is 100% higher than that recorded in the un-strengthened beam FA-0. These results validate the work of Smith et al., [29].

During loading of Beam VR2F, it was observed that at a load of 10 kN, the initial crack appeared close to the support. As the load step increases, shear cracks were developed and became visible. The crack extended towards the points load through the CFRP fabric. Both sides of the Beam VR2F suffered debonding of the CFRP fabrics during loading. The beam yielded at a load of 27.4 kN and failed at 49.2 kN. The load carrying capacity was 32% higher than reference beam FA-0. Figure 4 shows the load versus deformation. The beam ductility index was 2.5 as against the reference beam which recorded 1.05 ductility index as presented in Figure 6.

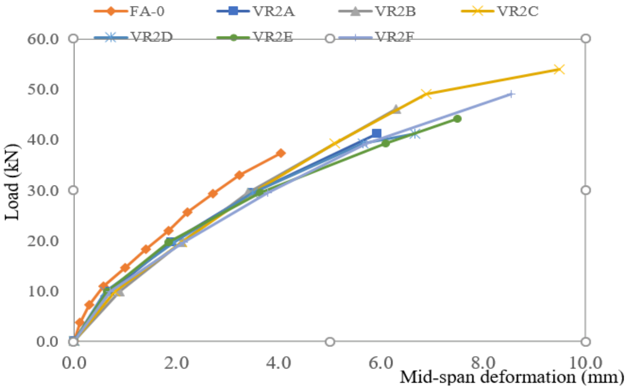


Figure 4: Load versus mid-span deformation

3.2 LOAD-DEFLECTION BEHAVIOUR

It is clear from Table 2 and Figure 4, that the mid-span deformations at failure for Beams FA-0, VR2A, VR2B, VR2C, VR2D, VR2E and VR2F were 4.1, 5.9, 6.3, 9.5, 6.7, 7.5 and 8.6 mm respectively, while the ductility indexes were 1.05, 1.56, 1.9, 2.6, 2.08, 2.2 and 2.5 respectively. Figure 4 shows that beam FA-0 is initially stiffer than all the CFRP fabric U-wrapped strengthened Beams (VR2A, VR2B, VR2C, VR2D, VR2E and VR2F), which is similar to the work of Ahmad et al., [30].

However, Beam FA-0 has a lesser load carrying capacity when compared to strengthened beams. These results show that the CFRP fabric bonded to RC beam externally results allows the strengthened member to carry more load. It is observed that the use of CFRP fabrics had significant influence in delaying the formation of cracks as a result of the initial increase in ductility of strengthened members. This study also shows that there is a significant possibility of shifting from a ductile failure to brittle failure when FRP fabrics are used to strengthen RC elements.

Table 3: CFRP contribution to shear strength

Sample ID	Failure Load P, (kN)	Shear Strength	Contribution to Shear (kN)	Contribution to Shear (%)
FA-0	37.3	18.7	-	-
VR2A	41.2	20.6	1.9	10.2
VR2B	46.1	23.1	4.4	23.5
VR2C	54.0	27.0	8.3	44.4
VR2D	41.4	20.7	2.1	11.0
VR2E	44.3	22.2	3.5	18.8
VR2F	49.2	24.6	6.0	31.9

3.3 SHEAR STRENGTH

Table 3 shows that the shear resistance of RC beams can be improved by epoxy-bonded CFRP fabric strips as U-wrapped placed at 900 to the horizontal axis of the beam. These results are similar to those found by Ahmad et al. [30], who concluded that CFRP material can be used to increase the shear performance. The results demonstrated that the CFRP fabric strips effectively improve the shear strength of RC beams, but the contribution shows variation dependent upon the bond surface area. A comparison with strengthened beams VR2C and VR2F shows that the CFRP shear contribution is 1.28 times that of beam VR2F. The shear contribution of the CFRP fabric strips of beams VR2A, VR2B, VR2C, VR2D, VR2E, and VR2F is 1.9 kN, 4.4 kN, 8.3 kN, 2.1 kN, 3.5 kN, and 6.0 kN respectively when compared to the reference beam as shown in Table 3. Satisfactory results can be achieved with less surface area depending on the scheme and loading conditions.

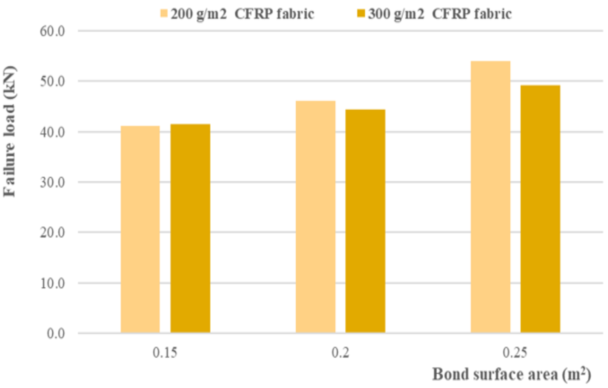


Figure 5: Failure load versus bond surface area

3.4 EFFECT OF BOND SURFACE AREA

It can be observed from Table 3 that the shear capacity of the strengthened Beams VR2A, VR2B, VR2C, VR2D, VR2E, and VR2F is higher than that of the reference beam, FA-0. These results are similar to the findings of Mostofinejad and Kashani [24]. From Figure 5, comparing Beams VR2A and VR2B to VR2C it is observed the VR2C had a higher load bearing capacity. Also, comparing the beams VR2D and VR2E to VR2F, it was observed that VR2F had a higher load bearing capacity. Thus, it is clear that the higher the bond surface area, the higher the load-carrying capacity. In addition, the ductility index of the VR2C sample was 56% and 37% more than the VR2A and VR2B samples, respectively. This shows that bond surface area had an effect on the strengthened RC beam.

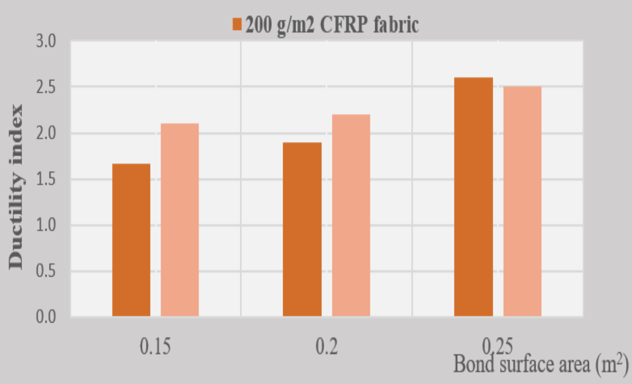


Figure 6: Ductility index versus bond surface area

4.0 CONCLUSION

The effect of bond surface area on the shear strength of concrete beams externally bonded with CFRP has been investigated and the following conclusions are drawn:

1. The CFRP contribution to shear strength increases as the bond surface area increases, suggesting improved structural performance of the system.
2. The shear strength of the RC beam studied in this work was increased by 45% by wrapping up to 50% of its surface area of the test beams with CFRP fabrics
3. Depending on the shear strength increment desired, acceptable shear strengths can be obtained with a lower bond surface area, i.e., by reducing the wrapped area of substrate to be strengthened from 0.25m^2 (i.e., wrapping 50% of the surface area of the beam) to a minimum of 0.15m^2 (i.e., wrapping 30% of the surface area of the beam). Thus, for minimum shear strengthening requirements, significant surfaces of an RC element need not be wrapped. Also, it can be inferred that while 50% surface wrapping produced optimum shear strength increment, a 15% surface wrapping could be used for nominal shear increment, especially in cases where the engineer has concerns about the workmanship of the shear stirrups in an existing or newly cast RC element.
4. The presence of CFRP fabrics alters the failure mode of the RC beam to the brittle nature of CFRP materials. Note that even though CFRP materials could have high tensile strength than steel, they are not as ductile as steel. Thus, they fail suddenly when their ultimate strength is reached. It was shown that samples with higher surface area wrapped with CFRP showed increased ductility but failed suddenly at its maximum load bearing capacity. Thus, it is recommended that a balance be drawn between excessive increase in shear strength, increase in ductility and need to have a ductile failure.
5. The configuration of U-wrap adopted in this study presents a cost-effective scheme for increasing the shear resistance of RC elements. It is important to note that, in some cases, the 300g/m^2 (i.e., fabrics with 0.111mm theoretical thickness) CFRP U-wrapped beams had only marginal shear strength increments when compared to 200g/m^2 (i.e., fabrics with 0.167mm theoretical thickness) CFRP U-wrapped beams. This suggests that increasing the thickness of CFRP fabrics is not a fundamental requirement or the only requirement for increasing the capacity of CFRP strengthened RC elements.

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