NIPES Journal of Science and Technology Research 4(4) 2022 pp. 164-171 pISSN-2682-5821, eISSN-2682-5821

NIPES

Journal of Science and Technology Research

Journal homepage: www.nipesjournals.org.ng

Characterized Indices of Bond Thickness Variation on RC Beams Strengthened Externally by Bonded Carbon FRP

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Article Info

Keywords:
Flexure, Strengthening, Beam, Adhesive, thickness, Bending, Ductility index

Received 26 November 2022
Revised 06 December 2022
Accepted 06 December 2022
Available online 9 December 2022

https://doi.org/10.5281/zenodo.7417784

https://nipesjournals.org.ng

Abstract

Carbon fiber-reinforced polymer (CFRP) is a structurally sound and cost-effective material for strengthening and rehabilitation. The understanding of how to strengthen existing structural elements has progressed significantly, but the appropriate adhesive layer thickness for increased strengthening impact remains a gap in the literature. This study is designed to investigate and optimize bond layer thickness for enhanced strengthening of concrete structures. Nine (9) reinforced concrete beams were designed as prototypes and modelled using a 2.5 scale ratio in accordance with ACI 444. The dimensions of the modelled beam were 100 x 150, or 1100 mm. These beams were internally reinforced with 2Φ10 mm bars based on a 2.5 scale ratio as flexural reinforcement. 2Φ8 hanger rebars were provided at the compression zone. Φ6, bend in a rectangular shape and are spaced at 220 mm, which serves as shear reinforcement for the beams. The beam had a shear span to effective depth ratio (av/d) ratio of 2.5. The beam samples were externally strengthened by 200 g/m2 and 300 g/m2 of CFRP fabric, with bond thicknesses of 2 mm, 4 mm, 6 mm, and 8 mm. The experimental program was divided into phases in order to investigate the effects of adhesive layer thickness on bending strength, load carrying capacity, and ductility index. The beams were investigated as single-span on a 20-ton capacity loading frame with a one-third point load application over an effective length of 1100 mm. Results show the possibility of using an epoxy-bonded CFRP fabric to enhance the bending resistance of RC beams. The shear failure model was found dominant in the epoxy-bonded CFRP fabric in flexural strengthening. CFRP-strengthened fabric beams provide not only increased load resistance but also increased structural ductility. Results reveal that RC beams strengthened with CFRP fabrics with a bond thickness greater than 20 times the thickness of the CFRP fabric reduce the bending capacity and the ductility index. The authors recommend that a CFRP fabric to bond thickness ratio of not more than 0.05 for flexure strengthening could be structurally effective.

1. Introduction

Fiber-reinforced polymer (FRP) materials have recently gained popularity in the strengthening of structural elements as a result of their enormous advantages, such as ease of application, corrosion resistance, weight to high strength ratio, and durability, over steel sheet or beam section enlargement strengthening methods [1-3]. Several investigations have been reported on flexural and shear strengthening with epoxy-bonded external reinforcement (EBR) using FRP sheets [4-8]. Moreover, Ozden et al [9] conducted various experimental studies to examine the RC elements strengthened externally with FRP sheets. However, the results presented by the authors are occasionally arguable. As a result, many areas of FRP laminate flexural strengthening still require experimental examination.

In reinforced concrete beams, the application of CFRP to the tension face of RC elements improved flexural strength, delayed cracks, and reduced crack breadth [10]. Studies that used the EBR approach for strengthening structural elements concluded that bonding FRP composites to the reinforced concrete beams enhances the shear and flexural strengths of the element. The fiber-reinforced polymer materials must debond from the structural element before the tensile strength of the fiber-reinforced polymer can be exploited, which is the fundamental limitation of this technique. Toutanji and Deng [11] conducted an experiment on RC beams that had been upgraded with FRP sheets. It was concluded that carbon fiber reinforced plastic (CFRP) strengthening effectively increased the flexural capacity of RC beams. Maghsoudi and Bengar [12] noted that improving bending strength by carbon fiber FRP epoxy-bonding would spread the initially developed cracks into the contra-bending zone. The authors also investigated the effect of carbon fiber reinforced plastic (FRP) on the crack geometry of reinforced RC concrete beam specimens. They stated that the width of the cracks was moved to the post-yielding stage from the pre-yielding stage.

The bond strength between the FRP material and the concrete substrate determines the effectiveness of externally strengthened RC concrete members. The adhesive layer that bonds the FRP and the concrete together presents problems for the behaviour of the strengthened member. It's very important for concrete and FRP to form a bond in order to transmit force tensities from concrete to FRP. Hence, the strength of the concrete bonded to the surface of the FRP is an important aspect in evaluating the strength of the structural elements strengthened with fiber-reinforced polymer. According to [13-17], stresses formed during loading in the concrete are transferred to FRP via the bond, and that the external reinforcement to concrete interface is critical to studying the structural response of externally bonded (EB) beams. Having understood the important role played by bond strength in the strengthening of reinforced concrete elements, it will be of great importance to establish an optimal bond thickness that would be structurally acceptable, and this will serve as an engineering knowledge database for the field of strengthening for effective practice.

2. Materials and Method

2.1 Design of concrete beams

All the reinforced concrete beams were designed as prototypes and modelled using a 2.5 scale ratio in accordance with ACI 444 [18]. These beams were internally reinforced with 2Φ10 mm bars based on a 2.5 scale ratio as flexural reinforcement. 2Φ8 hanger rebar were provided at the compression zone. Φ6, bend in a rectangular shape and spaced at 220 mm, which served as shear reinforcement for the beams. The beam had a shear span to depth ratio (a_v/d) ratio of 2.5. Nine (9) RC beams with a length of 1100 mm and a sectional area of 100 x 150 mm were produced. The beam configurations are itemized in Table 1 and Figure 1.

From Table 1, out of nine (9) reinforced concrete beam samples tested, FA0 was used as a control beam and was tested without CFRP fabric. Beam FA2, FA4, FA6, and FA8 were strengthened with 100 mm by 1100 200 g/m^2 CFRP fabric strips of 2 mm, 4 mm, 6 mm, and 8 mm bond thickness, respectively, bonded at the tension face as a model. Beam FC2, Beam FC4, Beam FC6, and Beam FC8 were strengthened with 300 g/m^2 CFRP fabric of 100 mm width and 1100 mm length of 2 mm, 4 mm, 6 mm, and 8 mm bond thickness, respectively, bonded at the tension face.

Table 1: Beams details

CFRP Fabric	Epoxy Thickness (mm)	Beam geometry parameters		Strengthening configuration	Sample ID
		h, mm	h, mm		
0	0	150	100	flexure	Type-FA0
200g/m²	2	150	100	flexure	Type-FA2
	4	150	100	flexure	Type-FA4
	6	150	100	flexure	Type-FA6
	8	150	100	flexure	Type-FA8
300g/m²	2	150	100	flexure	Type-FC2
	4	150	100	flexure	Type-FC4
	6	150	100	flexure	Type-FC6
	8	150	100	flexure	Type-FC8

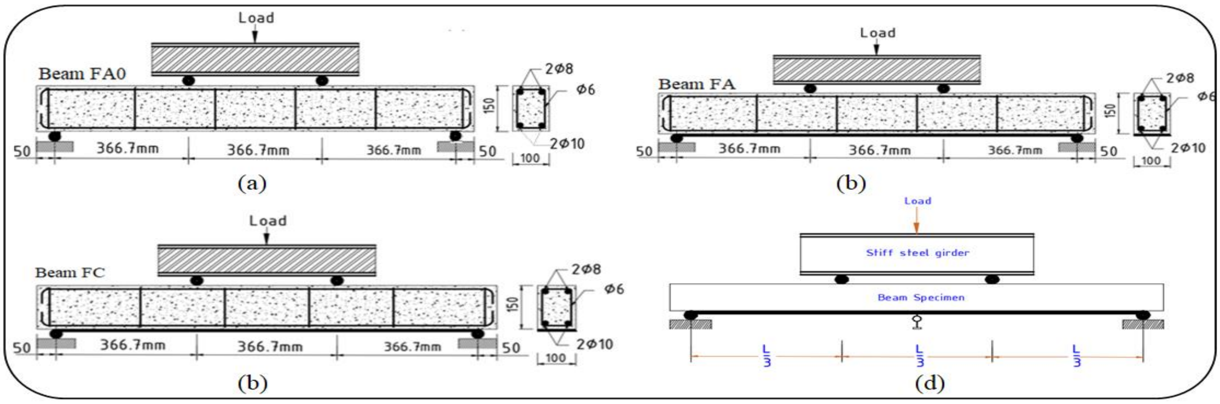

Figure 1: (a) Control beam; (b) beams strengthened with 200g/m2 CFRP; (c) beams strengthened with 300g/m2 CFRP; (d) Test setup

2.2 Material properties

The two types of unidirectional carbon fiber wraps, 200 g/m^2 and 300 g/m^2 depicted in Table 1, were used as external reinforcements. The epoxy resin, which is a two-part structural adhesive, was used to bond the CFRP fabric strips and the concrete together. The engineering properties of CFRP fabric and epoxy resin are presented in Table 2. The concrete's strength was investigated after 28 days of production. The estimated concrete strength (fck) was 20 MPa. The elastic modulus and yield strength of the internal steels were 400 MPa and 210 GPa, respectively.

Table 2: Properties of CFRP fabrics and epoxy adhesive

Material	Thickness (mm)	Tensile Strength (MPa)	Tensile Modulus of Elasticity (MPa)	Elongation at Break (%)	Bending Strength (MPa)
200g/m^2	0.111	3964	2.3 x 10^5	1.74	744
300g/m^2	0.167	3964	2.3 x 10^5	1.74	744
Epoxy resin	-	15 – 20	3300	4.3	30 – 40

2.3 Strengthening and instrumentation procedure

The tension faces of the beams were scraped until the layer of cement paste was removed prior to bonding, as presented in Figure 2. The required surfaces of the beam specimens were thoroughly cleaned to eliminate the loose paste particles. The CFRP fabric strips were trimmed to size. The epoxy paste was scraped onto the concrete surface to the desired thicknesses of 2 mm, 4 mm, 6 mm, and 8 mm, as shown in Figure 4. After placing the CFRP in the right location, a roller was used to apply pressure to the CFRP strips' surface to achieve adequate bonding between the concrete and the external reinforcement strips, and excess epoxy paste was removed. The epoxy resin was cured for seven days before testing. The beams were investigated as single-span on a 20-ton capacity loading frame, with a one-third point load application over an effective length of 1100 mm.

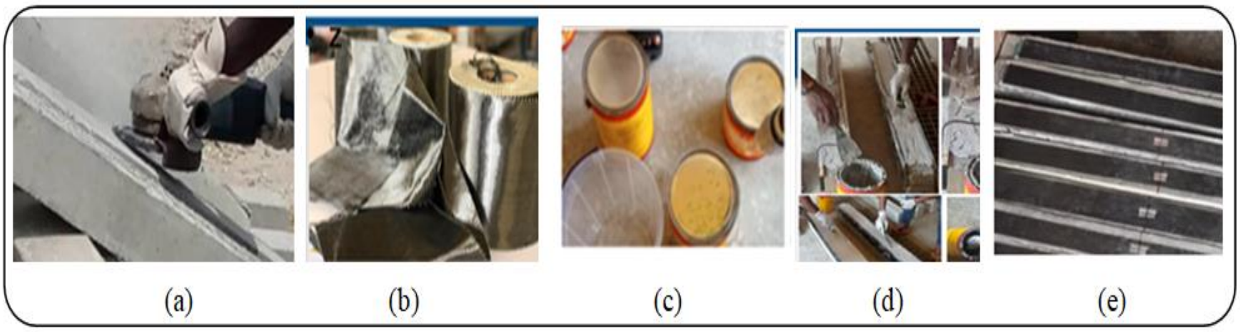

Figure 2: (a) Beam surface treatment; (b) CFRP fabric; (c) Epoxy resin; (d) strengthening process; (e) Strengthened beam sample

3. Results and Discussion

Beam FA0, FA2, FA4, and FA6 were strengthened with 200 g/m^2 CFRP at the tension face while FC2, FC4, FC6, and FC8 were strengthened with 300 g/m^2 of CFRP fabric of 100 mm in width and 1100 mm in length with varying bond thickness to study the load-carrying capacity, CFRP contribution to bending capacity, and the effect of adhesive layer thickness on the flexural and shear behaviour of the beam. The yield load, ultimate failure loads, and modes of failures are presented in Table 3. Out of the nine (9) beams investigated, FA0 was a reference beam; it was considered as benchmark for the remaining beams.

Tables 4 and 5 presents the CFRP contribution to bending capacity and percentage increase in bending capacity and ductility index for beams strengthened in flexure**,** while Figures 3 and 4 showed load versus deformation and load against bond thickness respectively. The mode of failure is shown in Figure 5. However, the results as discussed are those of prototype beams.

Table 3: Test Results for CFRP

Sample ID	Yield Load (kN)	Deformation at Yield load (mm)	Failure Load (kN)	Deformation at Failure load (mm)	Mode of Failure
FA0	71.85	9.625	93.33	10.125	Flexure
FA2	73.28	9.65	124.28	22.00	Shear
FA4	91.60	9.13	121.44	19.80	Shear
FA6	95.63	16.25	122.63	23.73	Shear
FA8	72.00	11.83	98.20	14.50	Shear
FC2	98.10	16.25	147.15	27.50	Shear
FC4	98.35	16.50	134.90	25.00	Shear
FC6	96.15	21.55	127.53	27.50	Shear
FC8	89.58	20.03	122.50	26.38	Shear

Table 4: CFRP Contribution to Bending Capacity

Sample ID	Failure Load (kN)	Bending Capacity $M_{exp,}$ (kNm)	FRP Contribution to Bending Capacity $M_{f, exp,}$ (kN)
FA0	93.33	17.11	-
FA2	124.28	22.78	5.67
FA4	121.44	22.26	5.15
FA6	122.63	22.48	5.37
FA8	98.20	18.00	0.89
FC2	147.15	26.98	9.87
FC4	134.90	24.73	7.62
FC6	127.53	23.38	6.27
FC8	122.50	22.46	5.35

3.1 Load Capacity

The maximum failure load of the reference beam, FA0, which had the same, internal reinforcement, is less than that of strengthened beams as presented in Table 3. The strengthened beams FA2, FA4, FA6 FA8, FA0, FC2, FC4, FC6, and FC8 had a better load-resistance than FA0 by 33.1, 30.1, 31.4, 5.2, 57.7, 44.5, 36.6, and 31.3% as given in Table 5. Referring to deformation values in According to Table 3, CFRP fabric-strengthened beams enhance the ductility of the beams as well as the load and bending capacities. Table 3 confirmed that strengthening reinforced concrete beams externally shifts their behaviour from ductility to brittleness behaviour, which is similar to Maghsoudi and Bengar [19] findings. Results in Table 3 demonstrated that shear failure is dominant in RC beams strengthened externally in flexure by CFRP fabric. During loading, it was observed that FA0 exhibited relatively ductile behaviour.

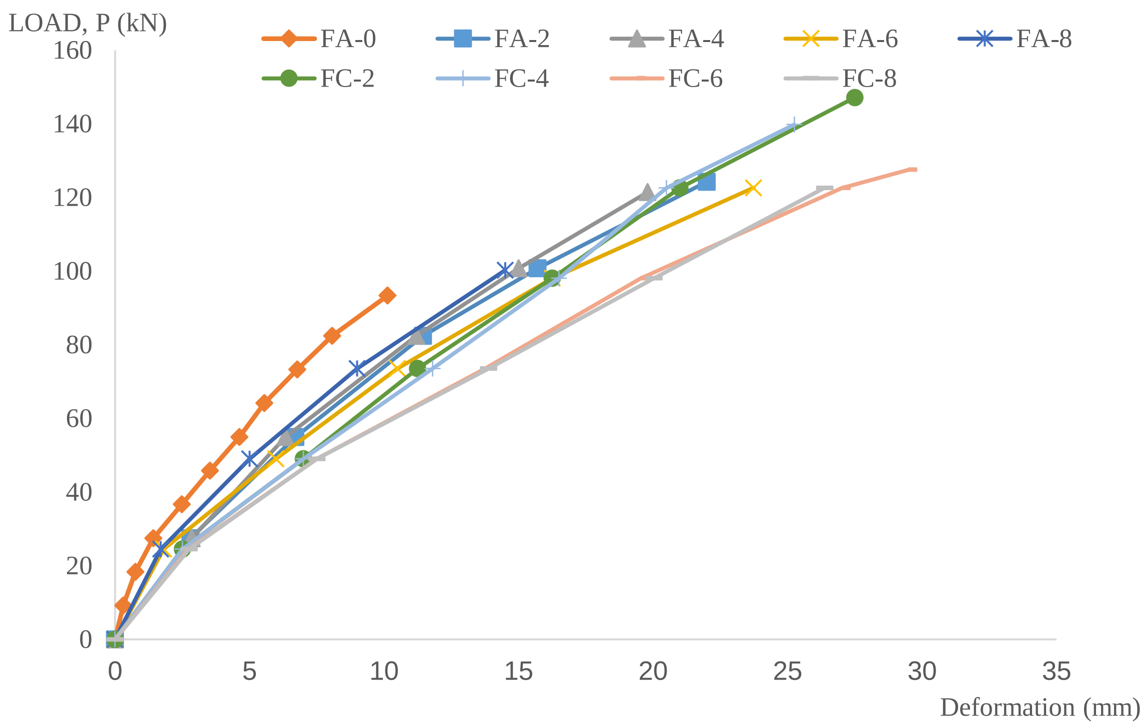

Figure 3: Load against Deformation response

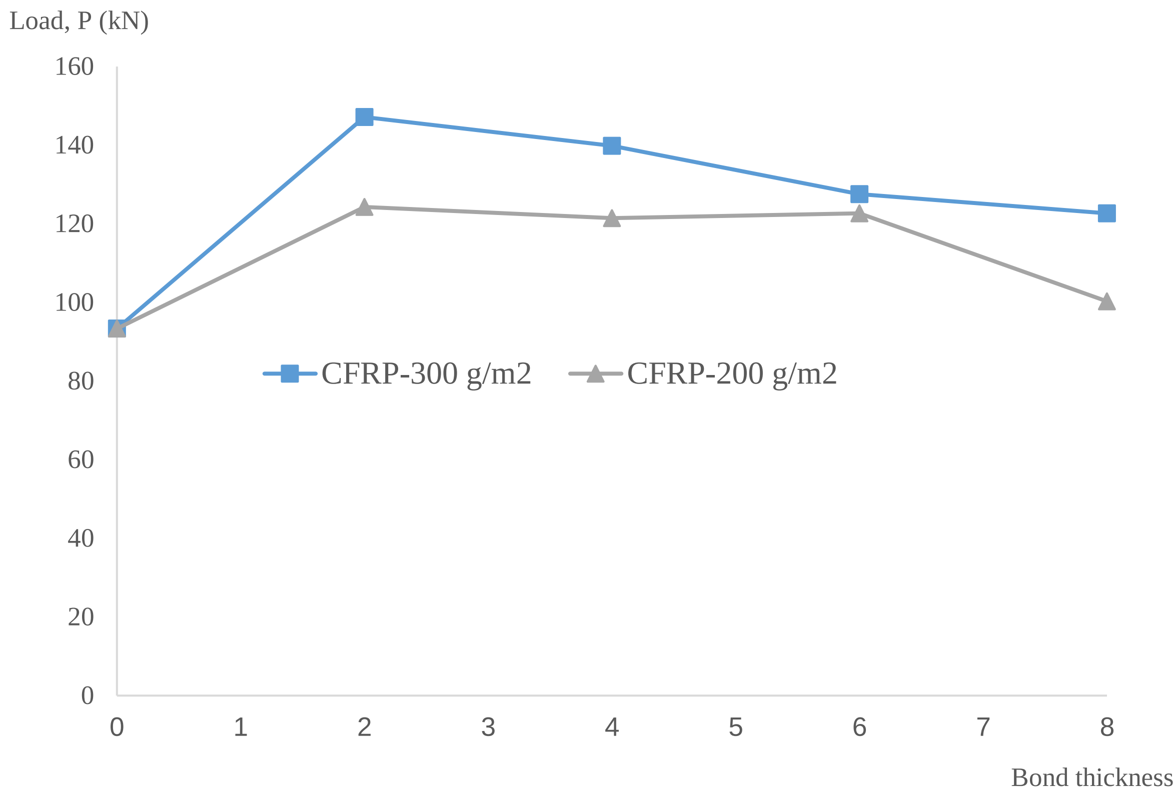

Figure 4: Failure Load against Bond Thickness

3.2 Bending Capacity

The carbon FRP contribution to bending capacity is computed by deducting the bending strength of the strengthened beam from the bending strength of the corresponding reference beam, which is given in Table 4. Referring to Table 4, the bending capacity of RC beams can be considerably enhanced by strengthening them with CFRP fabric. Beam FA2, FA4, FA6, FA8, FA0, FC2, FC4, FC6, and FC8 had the same surface area of CFRP fabric; however, the bending capacity contributed by the CFRP fabric of beam FA2, FA4, FA6, FA8, FA0, FC2, FC4, FC6, and FC8 is 5.67 kNm, 5.15 kNm, 5.37 kNm, 0.89 kNm, 9.89 kNm, 7.62 kNm, 6.27 kN, and 5.35kNm, respectively. This suggest that these beams contributed approximately 33.1, 30.1, 31.4, 5.2, 57.7, 44.5, 36.6, and 31.3, as shown in Table 5. The results are similar to those of Rahimi and Huchinson's [20] and Kim and Heffernan's [10] findings. Beam FA8 was found to be lower in terms of bending capacity due to a delay in transferring stress to the CFRP, leading to higher stress concentration compared with FA2, FA4, and FA6 beams.

3.3 Effect of Bond Thickness

The bond thickness of the strengthened RC beam is the primary factor that affects the load-carrying capacity and stiffness of the structural element directly. The results presented in Figure 4 reveal that, from both a bending capacity and a ductility perspective, there is a limiting bond thickness that would be structurally adequate for strengthening RC beams in flexure. FA8 and FC8 have the least bending capacities for beams strengthened with 200 g/m^2 and 300 g/m^2, respectively. Beam FA8 and FC8 suffered sudden shear failure and are attributed to a delay in transferring stress to the CFRP, leading to higher stress concentration, which is structurally not okay. Figure 4 revealed that the load resistance increased from 93.33 kN to 147.15 kN for the same beam (FC2) and from 93.33 kN to 124.28 kN for the same beam (FA2) bonded with 2 mm of adhesive. However, the load resistance reduces as the bond thickness increases.

3.4 Load-Deformation Behaviour

The load versus deformation history is also use in understanding the behaviour of strengthened RC beam members. The values of deformation at failure and the load against deformation behaviour of the elements throughout the loading history are significant. Table 3 presents results related to the deformations of all the beams at failure. From Figure 3, it can be undoubtedly stated that the FA0 sample is much stiffer compared to FA2, FA4, FA6, FA8, FA0, FC2, FC4, FC6, and FC8, which is similar to Ahmad et al [21] findings. This was not expected because the transformed second-area moment for the strengthened beams has increased. At failure, the deformations of all strengthened beams were higher than the reference beam. The beams exhibit very consistent load-deformation behaviour. However, the deformation at failure is significantly lower for FA0. Consequently, the failure of the CFRP strengthened member can be characterized as brittle. The CFRP-strengthened members do not reflect the ductility generally associated with reinforced concrete elements.

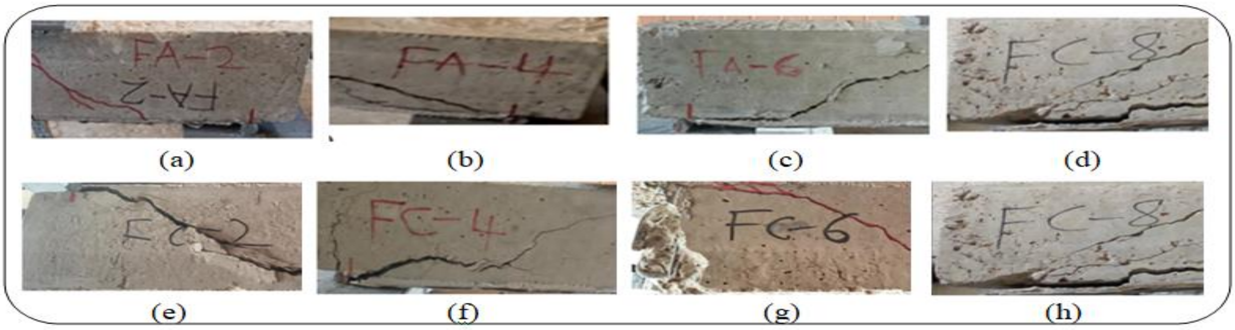

Figure 5: Mode of failure

In the course of loading, it was observed that beam FA2, FA4, FA6, FA8, FA0, FC2, FC4, FC6, and FC8, exhibited brittle failure, whereas the FA-0 exhibited relatively ductile behaviour; this may possibly be the reason that the load-carrying capacity of strengthened beams would have been attained with little inelastic deformation. Increased deformation in FA2, FA4, FA6, FA8, FA0, FC2, FC4, FC6, and FC8 could be attributed to the internal reinforcement's high ductility. The use of CFRP fabrics revealed the possibility of shifting from a ductile failure mode to a relatively brittle failure mode. Table 5 shows the percentage increment in bending capacity and ductility index for beams strengthened in flexure. The ductility index was computed by dividing the deformation at ultimate failure by the deformation at yield load. From Table 5, it is clear that the bond thickness reduces the percentage increment in both bending capacity and ductility, and this is attributed to the delay in transferring stresses to the CFRP fabric, which causes cracks in the adhesive layer.

Table 5: % Increase in Bending Capacity and Ductility index for beams strengthened in flexure

Sample ID	Bending Capacity kNm	% Increase in Bending Capacity kNm	% Increase in Ductility Index
FA-0	17.11	-	-
FA-2	22.78	33.10	116.72
FA-4	22.26	30.10	106.16
FA-6	22.48	31.40	38.82
FA-8	18.00	5.20	16.52
FC-2	26.98	57.70	60.87
FC-4	24.73	44.50	44.03
FC-6	23.38	36.60	21.31
FC-8	22.46	31.30	25.20

4. Conclusion

This study examines the effect of variations in bond thickness on the bending capacity and ductility index of RC beams strengthened by bonded carbon FRP. All the beam specimens were statically loaded, and the load-deformation behaviour graphs were examined. The following conclusions were reached based on the findings:

- CFRP fabric to bond thickness ratio should not be more than 0.05 for an effective practice.
- Shear failure is dominant in RC beams strengthened externally in flexure by CFRP fabric.
- CFRP is useful in upgrading existing RC beams externally. However, it reduces the ability of the beam to resist deformation under an applied load.
- Strengthening concrete beam members externally shifts the structural behaviour from ductility, which is recommended by the code, to brittleness.
- In the case where adhesive thickness cannot be measured, the thickness should be kept as low as possible.

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