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CFRP Length Effect of Externally Strengthened Reinforced Concrete Beams in Flexure

John A. TrustGod[1], Osuji S. Obinna[2], Nwankwo Ebuka.[3]

[1,2,3]*Department of Civil Engineering, University of Benin, Benin City, Nigeria*

ABSTRACT: *Several old reinforced concrete (RC) components have been proven to be inadequate in flexure and require to be upgraded. Inadequacies can occur for a variety of reasons, namely insufficient flexural reinforcement, corrosion-induced provided steel area reduction, changes in design purposes, and construction errors. In these cases, externally strengthened Carbon Fiber Reinforced Polymer (CFRP), is an excellent option. Although, knowledge of epoxy bonded CFRP has advanced significantly, however, CFRP length effect of externally strengthened reinforced concrete beams in flexure need to be study.*

To accomplish the aim, Static load testing was conducted on nine (9) rectangular-section of 100 x 150mm and a total effective length of 1100mm RC beams with various CFRP length. All the beam samples had the same materials and dimensions. Two steel rebars of 10 mm diameter are used for longitudinal internal reinforcement in the tension zone and two 8mm diameter rebars placed at the compression zone of the rectangular beam section. We used stirrups with a diameter of 6mm and a spacing of 220mm. Beam-FA-0, was used as reference beam, to be investigated without being strengthened. A 0.167mm and 0.111 thick CFRP fabrics were used to strengthened the beam FR2A, FR2D, FR2B, FR2C, FR2F, FR2E, FR2G and FR2H. Beam FR2A and FR2E were strengthened with 100mm width and 400mm length of 300g/m2 and 200g/m2 CFRP fabrics respectively with 2mm bond thickness glued at the tension face. Beam FR2B and FR2F were strengthened with 100mm width and 600mm length of 300g/m2 and 200g/m2 CFRP fabrics respectively with 2mm bond thickness bonded at the tension face. Beam FR2C and FR2G were strengthened with 100mm width and 800mm length of 300g/m2 and 200g/m2 CFRP fabrics respectively with 2mm bond thickness glued at the tension face. Beam FR2D and FR2H were strengthened with 100mm width and 1000mm length of 300g/m2 and 200g/m2 CFRP fabrics respectively with 2mm bond thickness glued at the tension face. All beam samples were subjected a static load test.

Results showed that the longer the length of CFRP fabrics glued to the tension face the less stiff the beam and the surface area of CFRP can be significantly reduced while still achieving the desired structural performance. The epoxy-bonded CFRP fabrics concrete beam in flexure is likely to fail in shear while increasing CFRP fabric thickness does not contribute additional load capacity. Serviceability of RC beam member is usually evaluated through deformation and crack width. Study reveals that epoxy-bonded CFRP fabric to strengthen concrete beam member reduces the stiffness of concrete beam elements.

Keywords: *CFRP length; Bending Resistance; Ductility index; Mode of Failure*

I. INTRODUCTION

Concrete and steel are the most commonly employed construction materials in the building industry. They are typically used depending on the conditions they are to be applied. Nonetheless, there are some applications that necessitate the use of a different material. New innovative materials have become available due to technological advancement and with concrete structures becoming old and increasing bar corrosion, these old structures require additional strengthening in other to increase their durability and structural performance [1]. These retrofit materials include steel and fiber reinforced plastic (FRP). Many engineers consider FRP to be among the most novel materials capable of overcoming the hereditary limitation of reinforcing concrete structures with steel bars. FRP are superior to steel due to their ability to resist corrosion, lower weight and higher tensile capacity [2].

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FRP is a composite construction material made up of a polymer matrix with fibers as reinforcement. Aramid, carbon, or glass fibers are most commonly employed as retrofit materials to concrete structures. FRPs are seen as a viable substitute to steel reinforcement, particularly in concrete structures exposed to harsh environments or electromagnetic field effects [2]. To realize the full potential of FRPs in construction, researchers have investigated their suitability in varying environmental conditions and reinforcement configurations.

The most common methods for strengthening reinforced concrete (RC) structures using FRP systems are externally bonded reinforcement (EBR) and near-surface mounted (NSM) reinforcement [3-5]. EBR of carbon FRP laminates has been extensively used to upgrade RC elements over the last several decades, [6]. Some concrete beams, however, cannot be strengthened with FRP sheets due to the general narrow soffit [7]. Salama et al., (2019) examined the viability of strengthening RC beams in bending with side-bonded Carbon FRP laminates. They concluded that the strengthening method of side-bonded Carbon FRP laminates can enhance not only the bending strength but also the shear strength of the RC beams [8]. The effect of adhesive properties and bond length on NSM FRP bar bond behaviour in concrete was investigated by L. Torres et al. [9], and it was concluded that with the FRP axial stiffness held constant, the load capacity of NSM FRP bars was dependent on the bond length and epoxy thickness. Also, Novidis et al., [10] investigated the bond behaviour of NSM bars. According to Novidis et al., [10], the average bond strength for failure controlled by the interface between the bar and the epoxy paste increased as the groove size was increased. Conclusively, [11-13] noted that the behaviour of bond between carbon FRP and concrete substrate is vital in structural applications. This study focuses the CFRP length effect on bending strength of externally upgraded reinforced concrete beams. The significant mechanical and geometric parameters research is; ultimate Load capacity, bending strength, ductility index, mode of failure, and variation in FRP length.

II. MATERIAL AND METHODS

Static load testing was conducted on nine (9) rectangular-section of 100mm x 150mm and a total effective length of 1100mm RC beams with various CFRP length. All the beam samples had the same materials and dimensions, as depicted in Figure. 1. Two steel rebars of 10 mm diameter were used for longitudinal internal reinforcement in the tension zone and two 8mm diameter rebars placed at the compression zone of the rectangular beam section. Stirrups with a diameter of 6mm and a spacing of 220mm was used. The concrete's mean cubic compressive strength was measured to be 29MPa. The yield stress of the internal reinforcing steel was 420 MPa.

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

Beam	Bond thickness (mm)	Beam cross-section parameters			CFRP fabric properties				Epoxy properties	
		b_w (mm)	h (mm)	d (mm)	L_f (mm)	t_f (mm)	E_f (GPa)	f_f (MPa)	E (GPa)	f_t (MPa)
FA-0	-	100	150	135	-	-	-	-	-	-
FR2A	2.0	100	150	135	400	0.167	237	3964	3300	15-20
FR2B	2.0	100	150	135	600	0.167	237	3964	3300	15-20
FR2C	2.0	100	150	135	800	0.167	237	3964	3300	15-20
FR2D	2.0	100	150	135	1000	0.167	237	3964	3300	15-20
FR2E	2.0	100	150	135	400	0.111	237	3964	3300	15-20
FR2F	2.0	100	150	135	600	0.111	237	3964	3300	15-20
FR2G	2.0	100	150	135	800	0.111	237	3964	3300	15-20
FR2H	2.0	100	150	135	1000	0.111	237	3964	3300	15-20

Beam-FA-0, was used as reference beam, to be investigated without being strengthened. A 0.167mm and 0.111 thick CFRP fabrics were used to strengthened the FR2A, FR2D, FR2B, FR2C, FR2F, FR2E, FR2G and FR2H. Beam FR2A and FR2E as shown in Table 1. Beam FR2A was strengthened with 100mm width and 400mm length (surface area of 0.04m2) of 300g/m2 CFRP fabric, with 2mm bond thickness glued at the tension face. Beam FR2B was strengthened with 100mm width and 600mm length (surface area of 0.06m2) of 300g/m2 CFRP fabric, with 2mm bond thickness bonded at the tension face. Beam FR2C was strengthened with 100mm width and 800mm length (surface area of 0.08m2) of 300g/m2 CFRP fabric, with 2mm bond thickness glued at the tension face. Beam FR2D was strengthened with 100mm width and 1000mm length (surface area of

0.1m2) of 300g/m2 CFRP fabric, with 2mm bond thickness glued at the tension face. Beam FR2E was strengthened with 100mm width and 400mm length (surface area of 0.04m2) of 200g/m2 CFRP fabric, with 2mm bond thickness glued at the tension face. Beam FR2F was strengthened with 100mm width and 600mm length (surface area of 0.06m2) of 200g/m2 CFRP fabric, with 2mm bond thickness glued at the tension face. Beam FR2G was strengthened with 100mm width and 800mm length (surface area of 0.08m2) of 200g/m2 CFRP fabric, with 2mm bond thickness glued at the tension face. Beam FR2H was strengthened with 100mm width and 1000mm length (surface area of 0.1m2) of 200g/m2 CFRP fabric, with 2mm bond thickness glued at the tension face. The details of the beam configuration are presented in Fig. 1. The properties of epoxy resin and CFRP fabrics are given in Table 1.

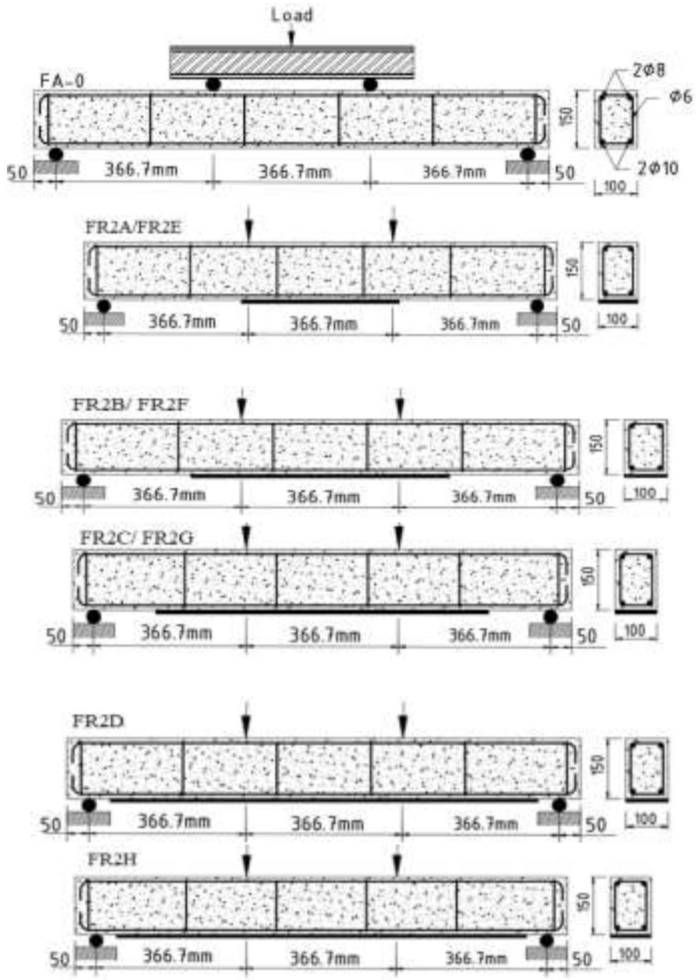


Figure 1: Beam configuration details

2.1 Bonding procedure

Before bonding the CFRP fabrics to RC beam samples, some surface remedy measures for the beam samples were taken. To start with, the RC beam samples were scoured to remove the paste layer of the concrete. Epoxy resin of 2mm thickness was applied to the required surfaces of the beam as instructed by manufacturer. CFRP fabrics strips were then laid on the 2mm thick epoxy resin and a roller was used to apply steady pressure to the fabrics surface. Composite samples were cured for a minimum of 7 days as guarded by the producers.

2.2 Test setup

Figure 1 depicts a schematic representation of the laboratory setup as well as the location of the beam configuration. All beam samples were subjected to a static load test. A 200 kN hydraulic jack was used to apply the load. Loading step was increased until the yield load of the internal reinforcements and CFRP rupture or up to the failure of the composites. The deflections were monitored using dial gauge. The dial gauge was placed at the mid span of the beam for ultimate deformation.

III RESULT

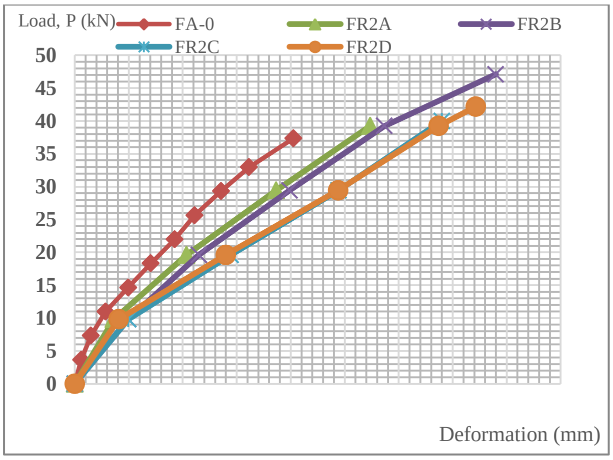
Laboratory study results on the CFRP length effect of externally strengthened reinforced concrete beams in flexure are presented below;

3.1 Beam FR2A to FR2D

Beam FR2A to FR2D was conducted to examine the effect of CFRP length to effective beam length (L_{CFRP} / L_{Beam}) ratio on the load and bending capacity. The load against deformation is shown in Figure 2. All the beams were strengthened with 300g/m2 CFRP fabric. The yield load, ultimate failure loads, and deformations were recorded and presented in Table 2 including their modes of failure. Table 3 and Figure 3 present CFRP contribution to bending capacity and Load vs CFRP length to effective beam length ratio respectively.

Table 2: Test Results for Beam FR2A to FR2D

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
FR2A	27.6	3.7	39.2	5.5	Shear
FR2B	37.0	5.8	47.1	7.8	Shear
FR2C	25.0	4.5	40.0	6.8	Shear
FR2D	34.0	6.7	42.2	7.4	Shear



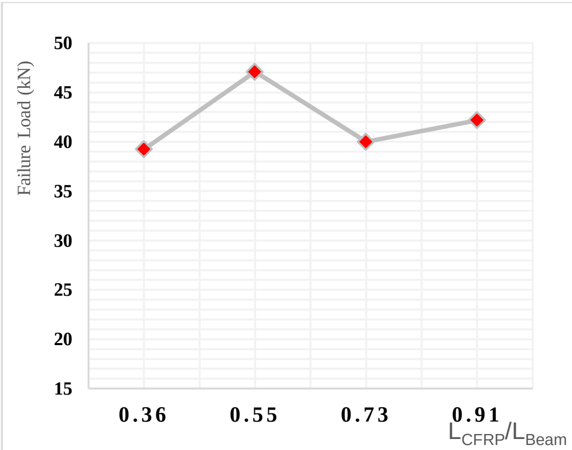


Fig. 2: Load vs deformation

Fig. 3: Load vs CFRP length to effective beam length ratio

Table 3: CFRP Contribution to Bending Capacity

Sample ID	Failure Load (kN)	Bending Capacity $M_{exp,}$ (kNm)	L_{CFRP} / L_{Beam}	FRP Contribution to Bending Capacity (%)
FA-0	37.3	6.8	-	-
FR2A	39.2	7.2	0.36	6.0
FR2B	47.1	8.6	0.54	26.5
FR2C	40.0	7.3	0.72	7.5
FR2D	42.2	7.7	**0.91**	13.2

3.2 Beam FR2E to FR2H

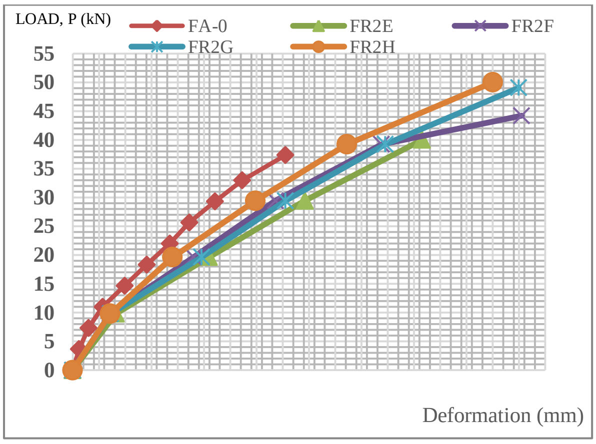
This group was studied to understand the structural implication of CFRP length to effective beam length ratio on the load and bending capacity. Figure 4 presents the load against deformation. All the beams under this group were strengthened with 200g/m2 CFRP fabric. Table 4 presents test results of yield load, ultimate failure loads, failure mode and deformation of Beam group (FA-0, FR2E, FR2F, FR2G, and FR2H). Table 5 and Figure 5 present FRP contribution to bending capacity and failure load again CFRP length to effective beam length ratio.

Table 4: Test Results for Beam FR2E to FR2H

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
FR2E	29.4	4.4	40.0	6.7	Shear
FR2F	29.2	4.2	44.2	7.8	Shear
FR2G	38.0	5.9	49.1	8.5	shear
FR2H	39.3	5.3	50.0	8.0	shear

Table 5: CFRP Contribution to Bending Capacity

Sample ID	Failure Load (kN)	Bending Capacity Mexp, (kNm)	BL/EL	CFRP Contribution to Bending Capacity, (%)
FA-0	37.3	6.8	-	-
FR2E	40.0	7.3	0.36	7.4
FR2F	44.2	8.1	0.54	19.1
FR2G	49.1	9.0	0.72	32.4
FR2H	50.0	9.2	0.91	35.3



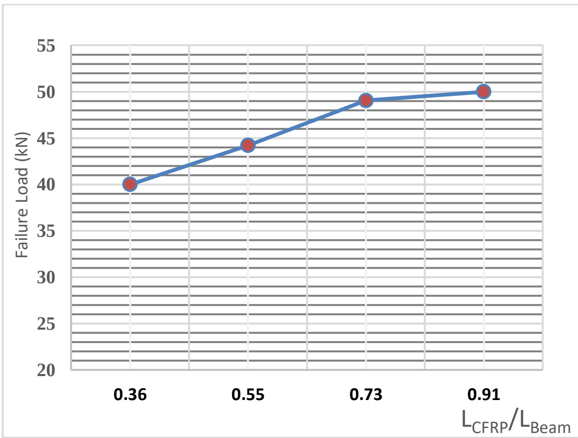


Fig. 4: Load vs deformation

Fig. 5: Load vs CFRP length to effective beam length ratio

IV. DISCUSSION

4.1 Beam FR2A to FR2D

4.1.1 Ultimate Load-Carrying

Beam FR2A

In the course of testing, the first vertical flexural crack was developed at a load of 9.4kN, and followed by shear cracks. As the loading increases, and cracks became wider and visible. Further load increment leads to yielding at a load of 27.5kN and failed CFRP fabric debonding at a load of 39.2 kN before any considerable rupture. The load versus deformation response of FR2A that the ductility index of 1.5 was achieved. From Figure 2, it should be recorded that the deformation increases at failure. The beam showed sudden shear and premature failure. The bending capacity of the beam is presented in Table 3.

Beam FR2B

During testing, the initial crack load in FR-2-B began in the loading at 9.7 kN. There was a rapid increment in crack width after an increased load. The beam yielded at 37.0 kN and failed in shear at 47.1 kN with ultimate deformation of 7.8 mm as presented in Figure. 2 and Table 2 respectively. The ductility index of 1.4 was achieved. From Figure 2, it should be seen that the FR2B is ductile that reference beams. This beam exhibited sudden shear and premature failure also. Figure 2 show the load against deformation of FR2B. The bending capacity of the beam is presented in Table 3.

Beam FR2C

With a quick load decrease immediately after the yield load, the FR2C beam failed in shear. At a load of roughly 9.8kN, two cracks developed, one at the shear span and the other at the constant moment area of the beam. As the strain on this beam was increased to 20.3kN, the cracks became more evident and spread. The beam yielded at a load of 25kN and failed owing to shear at a load of 40kN. The beam shows ductility index of 1.5. From Figure 2, it is evident that the reference beam is stiffer than Beam FR2C. The test data given in Table 2 and demonstrated in Figures 2 depict that deformation is greater than the reference beam conforming to the development of the initial crack in the Beam FR2C beam.

Beam FR2D

During the experiment, it was observed that Beam FR2D failed in shear as presented in Table 2. Beam FR2D had a bending strength of roughly 13% greater than the control beams. Brittle behaviour was observed in the beams, with a rapid load decrease at yield load. The energy produced during the creation of shear fractures was too much for the fiber strips to handle. The beam yielded at 34 kN load and failed at a load of 42.2kN due to shear. The load versus mid span deformation response of FR2D show that ductility index of 1.1 was achieved.

4.1.2 Effect of CFRP Length to Effective Beam Length Ratio on Load Carrying Capacity

The tension face of beams in this group were strengthened with CFRP fabric 100 mm wide and of four different lengths, 400 mm (FR2D), 600 mm (FR2D), 800 mm (FR2D), and 1000 mm (FR2D). The load versus deformation graph for the carbon FRP bonded beams and for the beam FA-0 are shown in Figure 2. As presented in the load versus deformation graph, the stiffness of all beams at early load is approximately the same. As loading increases, the stiffness of the reinforced beams decreases significantly due to the existence of CFRP. The test data exhibited that the longer the length of bonded CFRP, the less stiff the beam. Also, the surface area of CFRP can be significantly reduced while still achieving the desired structural response. Figure 3 clearly depicts the outcome of L_{CFRP} / L_{Beam} ratio on structural response of the beams.

4.2 Beam FR2E to FR2H

4.2.1 Ultimate Load-Carrying

Beam FR2E

This beam was subjected to static loading, which was established into four-point loading. Thus, the load resistance of the CFRP strengthened beam was 7.2% that of reference beam, producing a failure load of 40.0 kN. Figure 4 depicts the deformation against mid-span deformation response of FR2E. The maximum formation at failure for the FR2E beam was recorded as 6.6mm with ductility index of 1.85. The test result showed that the beam failed in a shear response, fully resisting flexural cracks. The first crack initiated from the tensile zone at a load of 10.5 kN and extended towards the compressive zone of the beam. During the testing, the tensile internal steel bars yielded and finally failed as a result of concentrated stresses within the region. The CFRP fabric prevented flexural failure. The external reinforcement helped to carry the load. The FR2E beam yielded at 29.4kN

Beam FR2F

During loading, the cracks formed due to the high application of moment, and cracks propagated upward as loading increase. Cracks were observed within the constant moment region. At the constant shear zone, the cracks became inclined as a result of shearing forces. The Beam FR2F failed as a result of shear at a load of 44.2kN as seen in Figure 4 and at a maximum deformation at mid span of 7.8 mm, where the ultimate load is 18.4% higher than the reference beam and the mid span displacement is 92% higher than that recorded in the reference beam. This beam was more ductile with deformation ductility index of 1.85. The application of CFRP strip increased the ductility and postponed the formation of the first crack to 10.8kN. The FR2F beam yielded at 29.2kN.

Beam FR2G

The Ultimate load carrying capacity which the Beam FR2G reached before failing in shear was 49.1 kN and the deformation at failure was 8.5 mm as presented in Figure 4 and Table 4. Shear failure and yielding of the CFRP fabric were noted after the development of the critical inclined shear crack within the shear span. The effect of CFRP fabric was notable on improving the beam ductility where the deformation ductility index is 36% higher relative to control beam FA-0. Also, the deformation at failure is 109% greater than that recorded in the control beam FA-0. Furthermore, the effect of CFRP fabric was acceptable on increasing the load resistance as shown in Figure 4, where the ultimate load is 31% greater than that observed in the control beam FA-0 which validates Kim and Heffernan, (2008) findings. Kim and Heffernan, [14] in their study revealed that CFRP glued to the bottom fiber of RC beam increases the bending strength. The effect of CFRP fabric was also noticeable on delaying the formation of the first crack. The bending strength of the beam is presented in Table 5.

Beam FR2H

As loading progresses, vertical flexural cracks were the first to be seen, accompanied by web shear crack. The beam showed brittle behavior. At a load of 39.3 kN, the Beam yielded, and at a load of 50.0 kN, it failed (34 percent higher than that of reference beam FA-0). It was observed to be a shear failure. The 100mm width and 1000mm length (surface area of 0.1m2) of 200g/m2 CFRP fabric had considerable effect on improving the concrete beam resistance and ductility. The ductility of the concrete beams was increased by the CFRP fabric, with the ductility index of the FR2H beam being 43 percent greater than that of the reference beam which validates Kim and Heffernan, (2008) findings. Kim and Heffernan, [14] in their study revealed that CFRP glued to the bottom fiber of RC beam increases the bending strength. Furthermore, the beam's deformation at failure is 8.0mm, which is 97 percent larger than that of the reference beam. The existence of CFRP fabric delayed the occurrence of the first crack, which was first detected at a force of 10.4 kN. In Table 5, the beam's bending strength is shown.

4.2.2 Load-Deformation Relationship

Table 4 outlines the data of deformation at yield and maximum loads that were obtained from the test. The deformation at yield and ultimate load of reference beam FA-0 was 3.9 and 4.1mm respectively. By applying CFRP fabric on Beam FR2E, Beam FR2F, Beam FR2G and Beam FR2H, the deformation was enhanced by 15%, 9% 547% and 38% relative to FA-0 (at yield load), and by 64%, 92%, 309% and 97% relative to FA-0 (at ultimate). Figure 4. shows the load-deformation curvatures for all the beam elements beneath this group. The test results presented in Table 4 and the load-versus-midspan deformation data plotted and presented in Figure 4 show that reference beam, FA-0, was evidently stiffer than all the CFRP-fabric strengthened beams. The deformations of Beam FR2E, Beam FR2F, Beam FR2G and Beam FR2H at 37.3 kN which corresponds the failure load of beam FA-0 were greater than the reference beam. The bending capacity of the beam is presented in Table 5, which is similar to Ahmad et al, (2010) conclusion. Ahmad et al, [15] revealed that RC beam retrofitted with CFRP reduces the bending stiffness

4.2.3 Effect of 200g/m2 CFRP Length to Effective Beam Length Ratio on Load Carrying Capacity

Beams in this group were strengthened with CFRP fabric 100 mm wide and four different CFRP lengths, 400 mm (series FR2E), 600 mm (series FR2F), 800 mm (FR2G), and 1000 mm (series FR2H) as depicted in Figure 1. The load-deformation curve for the strengthened and reference beams are shown in Figure. 4. The study revealed that the beams stiffness at early load is approximately the same. As loading progresses, the strengthened beams stiffness decreases due to presence of CFRP. The test data exhibited that the higher the proportion, the lesser the stiffness. Also, the surface area of CFRP can be significantly reduced while still achieving the desired structural response. Figure 4 illustrates the trend of strength performance base on the load carrying capacity.

Fig. 6: Crack patterns

V. CONCLUSION

The study on the CFRP length effect of externally strengthened RC beams in flexure has been carried out. Geometrical and mechanical response were thoroughly studied. The following conclusions were reached;

I. From the test data, it is detected that the longer the length of CFRP fabrics glued to the tension face the less stiff the beam.
II. Also, the surface area of CFRP can be significantly reduced while still achieving the desired structural performance.
III. Increasing CFRP fabrics thickness does not contribute additional load carrying capacity
IV. The epoxy-bonded CFRP fabrics concrete beam in flexure is likely to fail in shear.
V. Study reveals that epoxy-bonded CFRP fabric to strengthen concrete beam member reduces the stiffness of concrete beam elements.

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