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Flexural and Bond Behavior of Concrete Beams Strengthened with Carbon Fiber-Reinforced Polymer Sheet

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Abstract

Concerns have been expressed regarding the issue of using conventional steel rebar in civil engineering structures. One contributing factor is the corrosion that occurred on the steel rebar. The corrosion process was not promptly detected due to the gradual reaction time exhibited by the steel, concrete, and environmental conditions. Corrosion problems often manifest when corrosion has progressed to a critical point and damaged the concrete structure. Consequently, to address this issue, this research proposed the application of carbon-fiber reinforced polymer sheet (CFRP). The aim is to measure the flexural load of conventional and FRP-reinforced concrete beams, to test the effects of cracking and deflection on concrete beams strengthened with FRP sheet, and to determine the degree to which these loads damaged these beams. A repair method was implemented by applying two distinct diameters of CFRP: 50 mm × 100 mm and 100 mm × 200 mm. The finding shows that the concrete beam's significantly higher flexural strength resistance was observed for CFRP of greater dimensions. This is mostly because the CFRP can disperse the applied stress more effectively. Alternative applications of fibre-reinforced polymer should be explored for further research to facilitate the development of substitutes for CFRP.

1. Introduction

Recent years have seen an increase in the rate of degradation of steel rebars. Numerous factors, including carbonation and chloride attacks, design mistakes, increased live loads, and corrosion, can lead steel rebars to deteriorate. The requirement to repair reinforced concrete structures has a negative impact on their serviceability performance, durability, and cost [1]. Alternatively, the structure's slabs, beams, and columns could be strengthened and repaired by introducing external reinforcement [2]. However, conventional repair procedures frequently do not tackle the underlying problems of corrosion and structural integrity.

The concrete structural components could be repaired in several ways using external reinforcement. The methods include revising the concrete using steel plates or fiber-reinforced polymer (FRP), and it is also possible to fix the broken beams using steel strips or plates or epoxy resin. Bolted or epoxy-attached steel plates are another option for beam rehabilitation. Using novel materials such as FRP, steel strips/plates, and epoxy resin has revolutionised repair procedures by improving durability and corrosion resistance. Research into the beam-repairing technique employing steel plates and bolts found that the shear capacity might be enhanced by as much as 59% [3]. FRP was used with reinforced concrete beams due to its low weight, maneuverability, high strength-to-weight ratio, corrosion resistance, and exceptional rigidity. The reinforced concrete beam has been externally supported using FRP, such as basalt (BFRP), glass fiber reinforced polymer (GFRP), and carbon fiber reinforced polymer (CFRP). The reinforced concrete beam can be externally strengthened with near-surface-mounted (NSM) bars or strips attached with epoxy adhesives, or it can be wet-laid at the site with pre-prepared laminates. As an alternative to more traditional forms of repair, these cutting-edge materials provide adaptable solutions for structural strengthening.

In environments where corrosion is prevalent, traditional steel reinforcement can corrode. These issues caused structural damage, including a fracture in the beam. Nonetheless, a new approach to this age-old issue emerged with the development of CFRP materials. CFRP materials have gained significant global adoption as a viable resolution. Further investigation is being conducted to evaluate the durability of CFRP materials across diverse environments. In recent years, there has been an increased industry focus on concerns regarding the corrosion of concrete structures [4]. Corrosion is a major factor, but other factors like carbonation, chloride attacks, lousy design, increased live loads, increased interfacial tensions and transportation and handling issues contribute to concrete degradation [5]. Thus, it is imperative to consider the long-term benefits of CFRP materials in enhancing the strength and durability of concrete structures [2].

CFRP materials have gained significant traction as an alternative to conventional steel reinforcement in concrete structures to extend their durability and inherent resistance [6]. Due to its non-metallic composition, CFRP remains corrosion-free even when subjected to demanding transportation, storage, and application conditions. CFRP reinforces the concrete in two distinct ways. It prevents the concrete from being eroded by acting as a barrier against aggressive and corrosive substances. Consequently, implementing CFRP streamlines construction processes and reduces maintenance requirements by obviating the necessity for supplementary safeguards typically required in steel reinforcement.

The most recent developments in CFRP applications include advancements to the CFRP trimming process, encompassing traditional and innovative machining methods [7]. The evaluation of each approach is based on factors such as surface integrity, defect occurrence, accuracy, and productivity. The potential for increased efficiency and quality is highlighted by exploring recent developments and cutting-edge trends in CFRP trimming procedures. Furthermore, current discussions revolve around CFRP emerging materials, including nanostructured carbon fibres, hybrid fibre reinforcement, and self-sensing CFRP [8]. These innovations boost sustainability by boosting the durability and longevity of structures.

This study delves into the flexural behaviour of CFRP sheets as an innovative approach to strengthening and repairing beams. The flexural behaviour of the beam was studied by installing CFRP as a repair approach to reinforce the beam. External bonding of the CFRP was achieved through the application of epoxy. Additionally, the size of the CFRP was increased, and its response to a four-point load test was monitored.

This research examines the bond strength and flexural capacity of a reinforced concrete beam that utilizes CFRP materials. A four-point bending test determined the ultimate load, ultimate shear stress, and bond failure type by subjecting two CFRP sheets of different diameters. Besides it also assesses the effectiveness of CFRP materials as structural reinforcement to promote environmentally sustainable and resilient building practices.

2. Materials and Methods

2.1 Concrete Preparation

The concrete mix used in this study adhered to the guidelines outlined in British Standard, BS1881 [9]. Through a diligent mix design process, water, coarse aggregate, fine aggregate, and cement proportions were attentively measured to ensure optimal efficiency and compliance with industry standards. Table 1 presents a comprehensive analysis of the components and amounts used in the experimental phase derived from the mixture design.

All elements were blended together using a machine mixer to ensure a cohesive and effective mixture. During the process, adhering to a particular sequence is significant, beginning with the cement addition and then proceeding to include coarse and fine aggregates accordingly. Proper blending of the ingredients is guaranteed when the mixer is turned on with the lid firmly closed. Water is added to the mixer gradually so that each component is completely submerged and the mixture is evenly hydrated and distributed.

Intermittent breaks during the mixing process enable the detection and manual integration of any persistent lumps that might impede the attainment of the desired texture. Following each adjustment, the process continues for 2-3 minutes until the mixture reaches the desired texture. Afterwards, the mixture's consistency was assessed by performing a slump test in a wheelbarrow to ensure it met the necessary standards.

Table 1 *The material and quantity used in the experiment*

Material	Quantity	Unit
Water	30.78	kg/m³
Cement	57.51	kg/m³
Fine aggregate	110.97	kg/m³
Coarse Aggregate (10 mm)	66.42	kg/m³
Coarse Aggregate (20 mm)	132.02	kg/m³

The steel forms employed for concrete casting measured 100 × 100 × 500 mm. A set of formworks with six compartments, each of identical size, facilitated the casting of concrete cubes measuring 100 × 100 × 100 mm. Additionally, prism samples, adhering to American Society for Testing Materials, ASTM C78/C78M-18 [10] standards, measuring 100 x 100 x 500 mm were utilized.

To enhance the durability and adhesion of the concrete samples, CFRP sourced from local suppliers was incorporated into the prism samples, aligning with ASTM D7958/D7958M-17 [11] standards. This methodological approach, combining FRP composites with a concrete substrate, was tested for flexural strength. Notably, the FRPS technology enabled efficient evaluation of flexural strength [12]. Fig. 1(a) and Fig. 1(b) depict the pre-oiled formwork prior to concrete placement, ensuring smooth demoulding post-curing.

Fig. 1 *Formworks that were used in the experiment consists of 12 cube formworks and oiled formworks*

2.2 Notch Preparation

The notch preparation specification is denoted by ACI 440.9R-15 [13]. The specimen's form-finished face must be saw-cut at the midspan with a depth of h/2, according to the standard outlined in the specimen fabrication and preparation section. The breadth, referred to as the "kerf," was achieved by slicing the concrete with a diamond or composite blade. Enhanced repeatability is attained by employing a single blade throughout all cutting operations of each beam. In this experiment, the width of the gap is 3 mm, which is within the recommended range of 1 to 3 mm for the notch. Fig. 2(a) shows a cutter with a width of 3 mm that was used to cut the beam until it reached a depth of 50 mm, while Fig. 2(b) displays the presence of the notch on the beam.

Fig. 2 *The notch cutting process by using the saw cut*

2.3 Carbon-Fiber-Reinforced Polymer Sheet Preparation

The CFRP was cut using scissors with dimensions of 50 mm × 100 mm and 100 mm × 200 mm. Putting on a mask and double-layered mittens is advisable before handling the CFRP. It is crucial to take CFRP carefully when cutting it so the fibres do not become tangled, damaged or break apart from their original form. The CFRP cannot be used again when there is a fibre mess because the fibres cannot be merged. This will result in a financial loss, given that CFRP is an extremely costly material. Table 2 provides information regarding the properties of CFRP.

Table 2 *The typical properties of CFRP*

Typical of Carbon Fiber Properties	UK Design Value	Unit
Tensile Strength	4,900	MPa
Tensile Modulus	230	GPa
Ultimate Elongation	1.80	%
Density	1.79	g/cm^3
Approximate Yield (12K)	1.31	m/g
Filament Diameter	6.7	µm

2.4 Adhesive Preparation

In this research, Sikadur-31 CF Normal was used as the adhesive. This thixotropic epoxy adhesive requires two components, Part A and B, with a mixing ratio of 2:1. The CE mark attests that this glue satisfies the requirements of EN 1504-4 [14] requirements. The mixture of the white hue of Part A and the grey shade of Part B [14], as observed in Fig. 3(a) to Fig. 3(b), make a concrete grey colour.

2.5 Slump Test

Slump testing requires an impermeable surface to set the steel slump cone. At regular three-layer intervals, concrete was poured into the cone. Each stratum must be compacted by applying a steel rod 25 times. Completing the last layer and ensuring it is level with the top of the cone is important. It is possible to raise the cone, allowing part of the concrete within to slump. When the concrete slumped, the turned-over cone was checked with a measuring tape to figure the height difference between the slumped cone and the slumped one (Fig. 4).

2.6 Compression Test

The concrete in this study was compressively tested after 27 days of curing; the design goal was to achieve a strength of 30 N/mm^2. The outcome of the compression test, which measures the concrete's compressive strength, typically provides insight into the concrete's quality. The concrete cube, measuring 100 mm × 100 mm × 100 mm, was subjected to a compression test that follows the BS EN 12390-3:2001 [15]. A testing period spanning 7, 14, 21, and 28 days was accumulated. A 3 mm/min speed was achieved using the Universal Testing Machine 1000.

Fig. 3 *The mixture of adhesive between two parts: Part A and Part B mix and concrete colour after mix*

Fig. 4 *The settlement of the concrete was measured by using measuring tape*

2.7 Flexural Test

The beam specimen was subjected to a flexural test using a hydraulic-type universal testing machine 1000 kN, capable of conducting four-point flexural tests up to that maximum load. The reference standard for the four-point flexural test is BS EN 12390-5:2009 [16]. Failure occurs at a loading rate of 2 mm/s. The length of the bottom support roller is 300 mm, which results in a 100 mm separation between the loading rollers. The size of the CFRP sheet was determined by dividing the distance between the bottom supporting rollers by 1/3. The strain gauges were affixed to the concrete surface at the top of the beam and the composite laminates at the bottom. The data acquisition system measures the strain using the applied gauges. LVDTs were installed with L-shaped metal at random intervals along the beam to quantify the deflection. All stresses and load-deflection responses were recorded up until the beams failed. Marks were made on the beam to indicate the presence of each crack, no matter how little, until the beam failed (Fig. 5).

2.8 Bond Strength of Beam Specimens

A bond was formed between the CFRP and the tension side of the specimens of notched beams to study the bond behaviour with the nearby concrete surfaces. Eq. (1) was applied to determine the ultimate shear stress (τ).

$$\tau = \frac{3PL}{5hwS} \tag{1}$$

where P = applied ultimate load (kN), L = length of the specimen (mm), h = specimen height (mm), w = width of the composite sheet (mm), and S = total length of the composite sheet (mm).

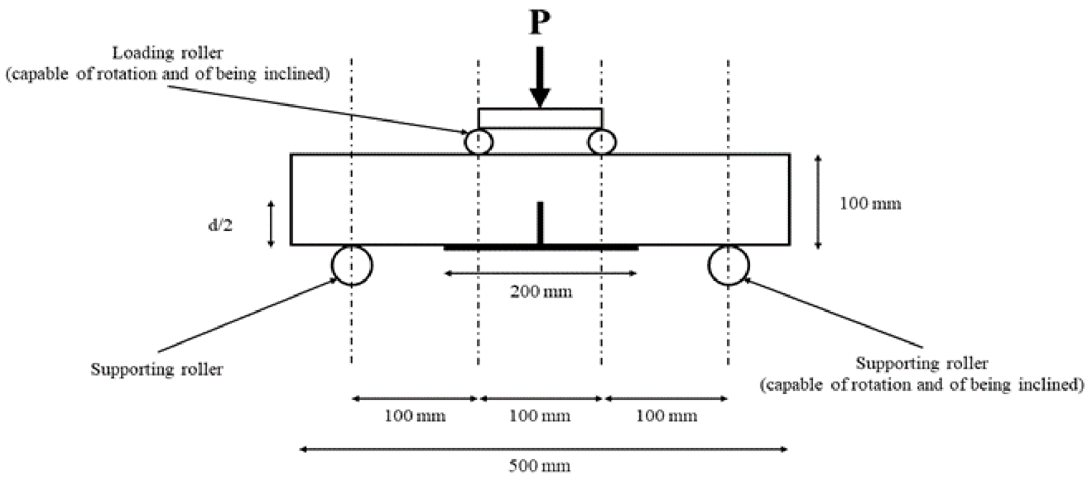

Fig. 5 *The settlement of the concrete was measured by using measuring tape*

In reinforced concrete beams, the bond strength of the CFRP material is defined as its capacity to attach to and transmit loads from the concrete substrate firmly. The bond's strength significantly influences the integrity and efficacy of the reinforcement system in boosting the beam's structural capacity.

Efficient load transfer from the concrete to the CFRP material relies on a solid bond. Beam specimens are commonly subjected to loading tests, like four-point bending tests, to determine the bond strength [2]. These tests quantify the ultimate shear stress at the interface involving the CFRP and the concrete.

Several factors can affect the bond strength of beam specimens. These include the concrete's surface preparation, the adhesive's quality, and the installation method of the CFRP material. Adhesion between the CFRP and the concrete is facilitated by appropriate surface preparation, which includes cleaning and roughening the concrete surface.

The efficacy of CFRP reinforcement in enhancing the flexural capacity and overall performance of concrete beams can be evaluated by examining the bond strength of specimens. It is necessary to comprehend how the CFRP bonds to the concrete substrate for structural strengthening applications. The insight benefits in properly designing and applying CFRP reinforcement.

3. Results and Discussion

3.1 Compression Strength

Results for the concrete cube's compressive strength after 7,14,21 and 28 days are shown in Table 3. After 28 days of curing, the specified compressive strength was 30 N/mm^2. From day 7 to day 28, the average stress level rises. By the 21st day, it had lost part of the stress. This is because the strength during the compression test was reduced in cube number seven, which had an inadequate quantity of aggregate when the concrete was placed in the mould. The loss is also caused by the air cavity in cube number 7, which impairs its performance.

According to the results, the concrete cube surpassed the design stress of 30 N/mm^2 at day 7 with an average stress of 39.19 N/mm^2. After 28 days, the strength increased by 153.53 %, with an average stress of 49.06 N/mm^2. There are no unsatisfactory cube specimen failures, even though the increase was unexpected. According to Fig. 6(a), the cube primarily encountered the explosive failure mode on day 7, which is considered satisfactory according to the norm. Fig. 6(b) shows that the cube experienced the failure mode, which was also an explosive failure mode, on day 14. The failure modes, as depicted in Fig. 6(c) and Fig. 6(d), were deemed satisfactory, except for one specimen that lacked a tensile fracture, which could have led to an unsatisfactory outcome. The failure on day 28 also went through an explosive failure mode, as seen in Fig. 6(e). According to BS EN 12390-3:2001 [15], all of the failures are satisfactory failures of cube specimens.

Table 3 *The compressive strength obtained on days 7, 14, 21, and 28*

Day	Cube	Load (kN)	Stress (N/mm^2)	Average Stress (N/mm^2)
7	1	382.51	38.25	
	2	402.94	40.29	39.19
	3	390.37	39.04	
14	4	438.85	43.89	44.82
	5	427.36	42.74	

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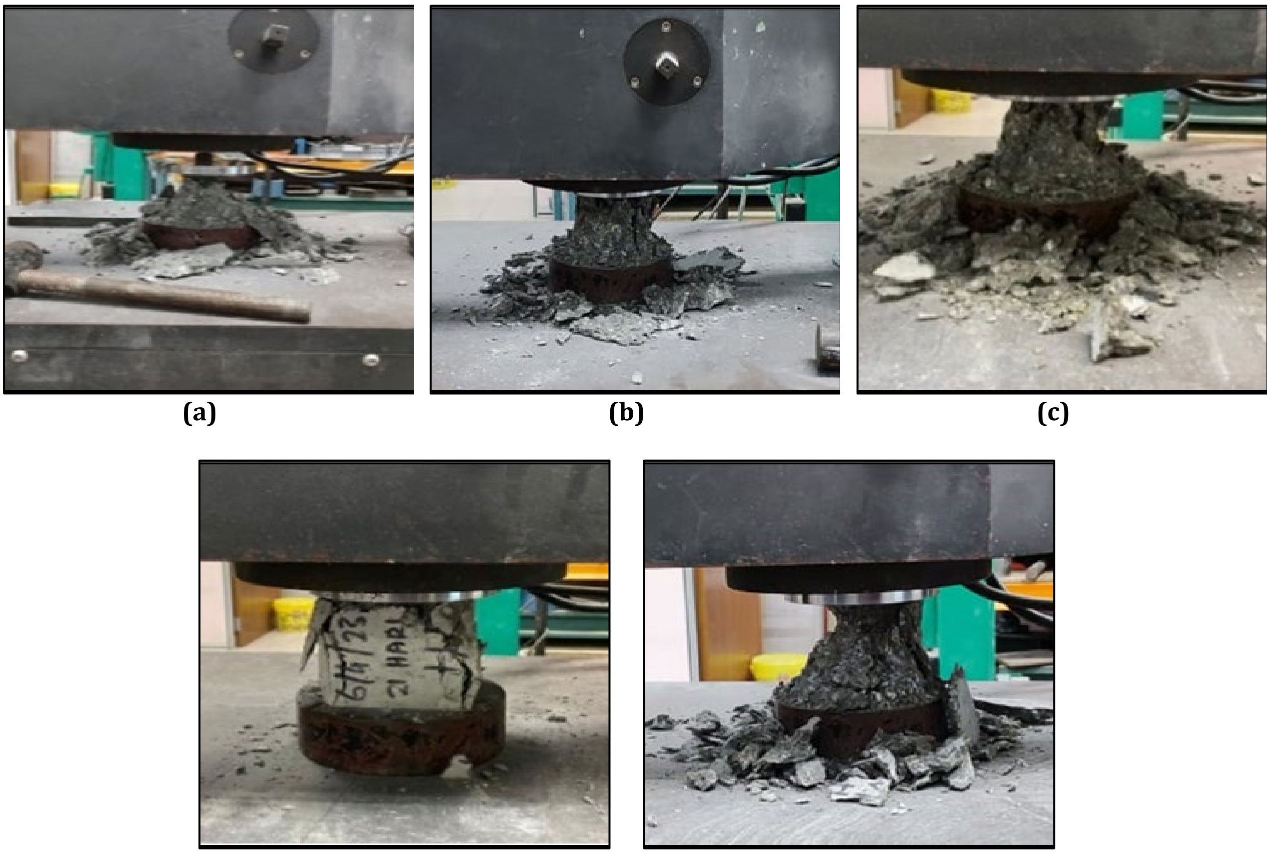
	6	478.27	47.83	
21	7	373.50	37.35	
	8	476.00	47.60	43.62
	9	459.08	45.91	
28	10	491.34	49.13	
	11	494.42	49.44	49.08
	12	486.60	48.66	



(a) (b) (c)

(d) (e)

Fig. 6 *The failure mode of concrete cube for (a) day 7; (b) day 14; (c) day 21; (d) day 21 (no tensile line); and (e) day 28*

3.2 Flexural Strength and Deflection

The concrete beams CB1, CB2, and CB3 have ultimate load, P_u of 17.63 kN, 14.41 kN, and 16.61 kN, respectively (Table 4). The samples are labelled as CFRP-50-1, CFRP-50-2, CFRP-50-3, CFRP-100-1, CFRP-100-2, and CFRP-100-3. In Table 4, CFRP-50-2 and CFRP-50-3 demonstrated an ultimate load, P_u, of 18.44 kN and 19.76 kN higher than the controlled beam when contrasted with the CFRP-50. The ultimate load, P_u, was higher in the CFRP-100 group compared to the control concrete beam and the CFRP-50 group. There are three CFRP-100 models: 100-1, 100-2, and 100-3, with respective ultimate loads of 29.11 kN, 40.00 kN, and 38.96 kN. The ultimate load of the CFRP-50-1 is lower than that of the control beam. The controlled concrete beams CB1, CB2, and CB3 demonstrated flexural strengths of 5.29 kPa, 4.32 kPa, and 4.98 kPa, respectively. Flexural strength followed the same pattern as ultimate load, P_u, when compared to the CFRP-50 group; however, CFRP-50-2 and CFRP-50-3 exhibited more significant flexural strengths of 5.53 kPa and 5.93 kPa. The flexural strength behaviour of the CFRP-100 group is consistent with the ultimate load, P_u, demonstrating a higher flexural strength than both the controlled concrete beam and the CFRP-50 group. The CFRP-100-1, 100-2, and 100-3 exhibit flexural strengths of 8.73 kPa, 12.00 kPa, and 11.69 kPa, respectively.

Table 4 *The classification and results of flexural testing of samples of the concrete beam*

No.	Designated Name	P_u (kN)	Flexural Strength (kPa)	Deflection (mm)	Strain (%)
1.	CB1	17.63	5.29	2.8	1.06
2.	CB2	14.41	4.32	2.6	0.98
3.	CB3	16.61	4.98	2.7	1.02
4.	CFRP-50-1	8.84	2.65	2.74	1.03
5.	CFRP-50-2	18.44	5.53	2.72	1.02
6.	CFRP-50-3	19.76	5.93	2.89	1.08
7.	CFRP-100-1	29.11	8.73	3.41	1.28
8.	CFRP-100-2	40.00	12.00	3.58	1.34
9.	CFRP-100-3	38.96	11.69	3.80	1.42

Table 5 and Fig. 7 show the mean flexural strength and ultimate load that exhibited a positive correlation with the expansion of the CFRP due to the increase in tensile strength. CFRP became an exterior reinforcement when attached to a beam's tension face. The lower fibres of the beam can withstand the tensile forces that occur during compression [17]. A composite effect develops between the concrete and the CFRP due to the efficient transmission and distribution of these tensile forces along its length. CFRP has a remarkable tensile strength, allowing it to bear a significant portion of the applied load. It mitigates the impact of the entire tensile force on the concrete, which is generally its most vulnerable region. By reinforcing the beam with CFRP, it becomes stronger and more capable of handling heavier loads, minimizing the risk of experiencing tensile strains.

As an external reinforcement, CFRP allows this to occur because it increases the beam's strength and the structure's stiffness. The epoxy employed as an adhesive improved the adhesion between the CFRP and the concrete beam when connected to the beam [2]. The concrete beam receives extra rigidity and strength from the bonding process. Improving the CFRP's strengthening mechanism enables it to support greater loads. The flexural strength of the beam was boosted by the CFRP, which increased its capacity to resist bending and flexural stresses.

Multiple factors contributed to the CFRP-50-1's declining ultimate load, P_u, and flexural strength. An element contributing to this is the calibre of the CFRP implementation. When reinforced with concrete, CFRP strengthens the bond between the two materials; however, how well this works depends on the installation process [2]. When compared to the control beam, problems like improper surface preparation and inefficient adhesive application result in poor bonding, reducing performance and impacting the ultimate load capacity. Additionally, the concrete sample has distinct properties compared to the other samples. When the beam is cast, the concrete undergoes inconsistencies. The production of voids in the concrete is caused by the inadequate distribution of the aggregate proportion while placing the concrete in the formwork. Consequently, the ultimate capacity of the beam was impacted, as well as the overall performance. Thirdly, the dimension of the depth produced by the saw incision differs. The effectiveness of the concrete beam is highly dependent on the breadth and depth of the saw incisions. The minor variation in the saw cut influenced both the distribution of tension and the weakened section's strength.

As CFRP is applied to reinforce the concrete beam, the beam experiences an increase in deflection. Deflections of 2.8 mm, 2.6 mm, and 2.7 mm are displayed by the controlled concrete beams CB1, CB2, and CB3, respectively. A deflection greater than 2.7 mm was observed in all of the strengthened beams compared to the CFRP group. The deflection measured by the CFRP-50-1, CFRP-50-2, and CFRP-50-3 is 2.74 mm, 2.72 mm, and 2.89 mm, respectively. The deflection increased even more after reinforcing the beam with the CFRP-100 group. The deflection measured by the CFRP-100-1, CFRP-100-2, and CFRP-100-2 is 3.41 mm, 3.58 mm, and 3.80 mm, respectively. The average deflection results in the CFRP-100 group is greater than that of the other two groups (Fig. 8).

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Table 5 *The classification and results of flexural testing of samples of the concrete beam*

Name	Ave P_u (kN)	P_u Increase (%)	Ave Flexural Strength (kPa)	Flexural Strength Increase (%)	Ave Deflection (mm)	Ave Strain (%)
CB	16.22	-	4.86	-	2.7	1.02
CFRP-50	19.1	17.76	5.73	17.90	2.78	1.04
CFRP-100	39.48	143.40	11.85	143.83	3.60	1.35

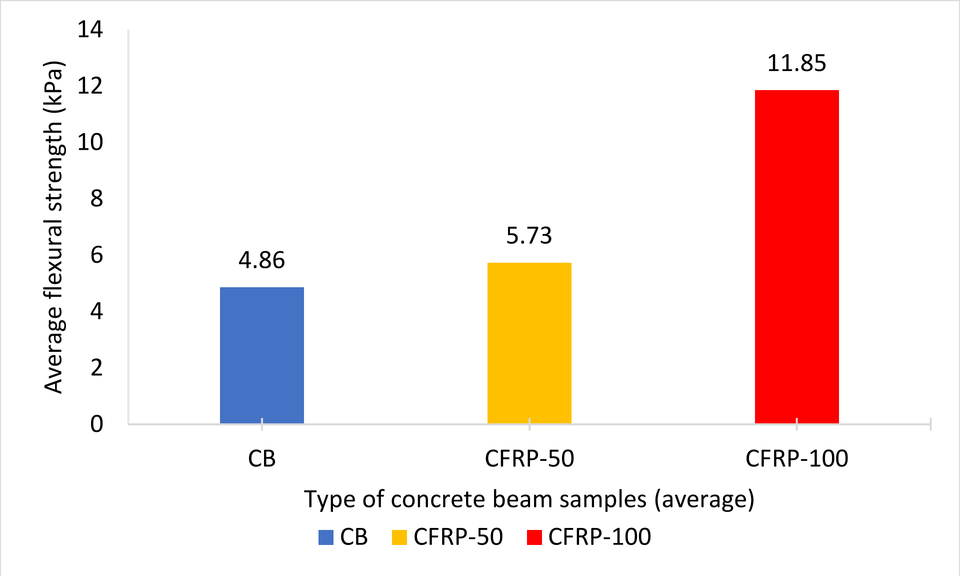


Fig. 7 *The graph of average flexural strength (kPa) vs the type of concrete beam samples (average)*

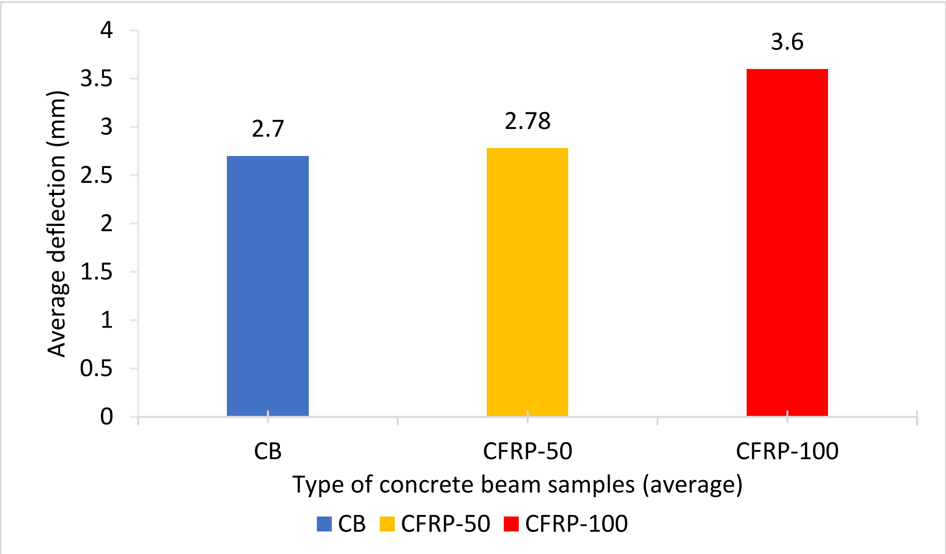


Fig. 8 *The graph of average deflection (mm) vs the type of concrete beam samples (average)*

Meanwhile, Fig. 9 displays the increase in deflection for each beam specimen. The beam reinforced with CFRP shows a higher deflection compared to the controlled beam. The primary factor contributing to the increased deflection observed in CFRP-reinforced beams is their non-linear behaviour, which initially exhibits a linear-elastic behaviour. After it surpasses that threshold, its conductivity starts operating non-linearly. As the load on the tested beam increases, the CFRP undergoes non-linear deformation, increasing deflection [2]. Next, the stiffness of the concrete beam differs from the CFRP. When there is inconsistency in the elastic modulus, it can lead to a difference in deflection. In this case, the concrete beam may experience more deflection compared to the

CFRP [12]. The third element is load redistribution. By utilizing CFRP, the applied load on the beam can be distributed, reducing stress at critical locations such as the saw cut [2]. Nevertheless, more deflection could happen due to the weight shifting throughout the road transfer procedure. Overall deflection at the interfaces may result from deformation when the load is conveyed between the CFRP and the concrete beam.

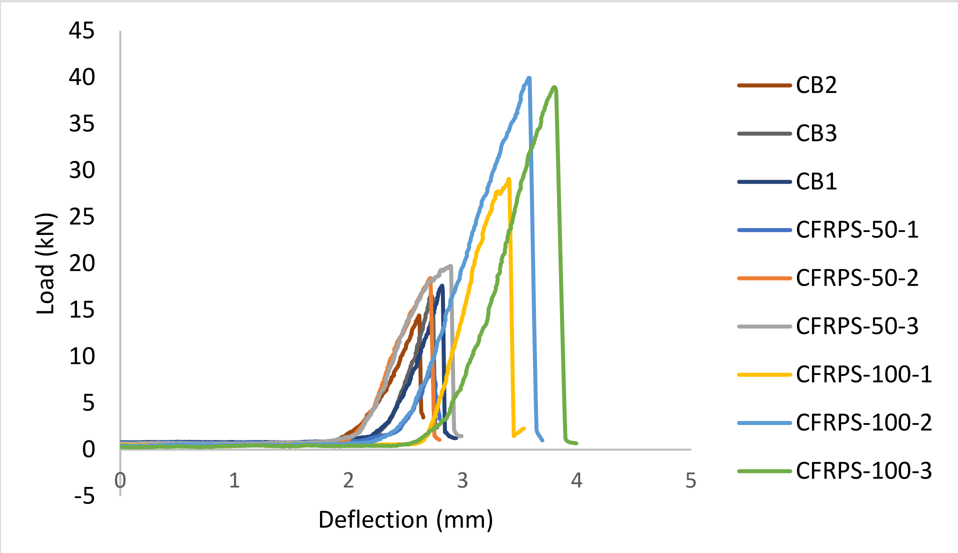


Fig. 9 *Load (kN) vs deflection (mm)*

The study shows that incorporating CFRP as external reinforcement greatly improves concrete beam's flexural strength and deflection properties. The group with larger dimensions (CFRP-100) exhibited substantial outcomes concerning flexural strength and deflection compared to the other group. The findings indicate that enlarging the CFRP dimensions results in enhanced load distribution, minimized stress concentrations, and heightened overall stiffness of the beams. Reinforced concrete structures must achieve this performance enhancement to increase their load-bearing capacity and durability.

3.3 Strain Relationship with the Size of the CFRP

The result implies significant findings as there is a direct correlation between the size of CFRP and the level of strain (Fig. 10). This insight is crucial for comprehending the impact of CFRP on the overall behavior of concrete beams when subjected to stress. It is critical to emphasize that the augmentation in strain with the size of CFRP is not abrupt but occurs gradually.

Strain results from stress on a material, causing it to deform or lengthen. Regarding CFRP, its capacity to display greater stresses suggests that it can experience substantial deformation under stress without breaking. It plays a major role in structural applications, especially when reinforcing concrete elements.

The average strain values recorded for various samples provide additional evidence to support this correlation. The strain of the concrete beam alone (CB) is 1.02%, while CFRP-50 and CFRP-100 have strains of 1.04% and 1.35%, respectively. According to these values, the strains in the concrete beam are greater in the presence of CFRP than in its absence. It is the outcome of the tensile strength and resistance to forces exhibited by CFRP.

Under loading conditions, CFRP exhibits a strong resistance to the forces exerted on the composite system. Its tensile strength permits it to endure these stresses effectively. In addition, CFRP's inherent ductility and flexibility allow it to effectively distribute and absorb loads, resulting in improved structural performance of the composite system. The strength and endurance of the system are enhanced by this feature of CFRP, which is crucial for absorbing and dispersing tensile loads [2].

3.4 Energy Absorption of the Beam Specimen

The key feature used to comprehend the fracture process of the specimens was the determination of the energy absorption of the beam specimens. In this context, energy absorption relates to the composite system's capacity, consisting of a concrete beam reinforced with CFRP, to efficiently absorb and distribute tensile strains. The energy absorption capability was determined by contrasting the energy absorption of the control beams (CB) to that of the strengthened beams utilizing CFRP (CFRP-50 and CFRP-100). The energy absorption values were quantified in joules (J) and used to assess the performance of the various beam specimens during loading conditions.

Table 6 and Fig. 11 show that compared to the CB group, the CFRP-50 and CFRP-100 groups increased their energy absorption by 9.97 % and 19.08 %, respectively. The cracks propagate far more quickly in this group than in the CFRP group, which experiences a delay in the initiation of crack formation and increases yield load. It was discovered that energy absorption rises with increasing CFRP size. This is due to the energy absorption that necessitates continued load level and post-yielding stiffness [2].

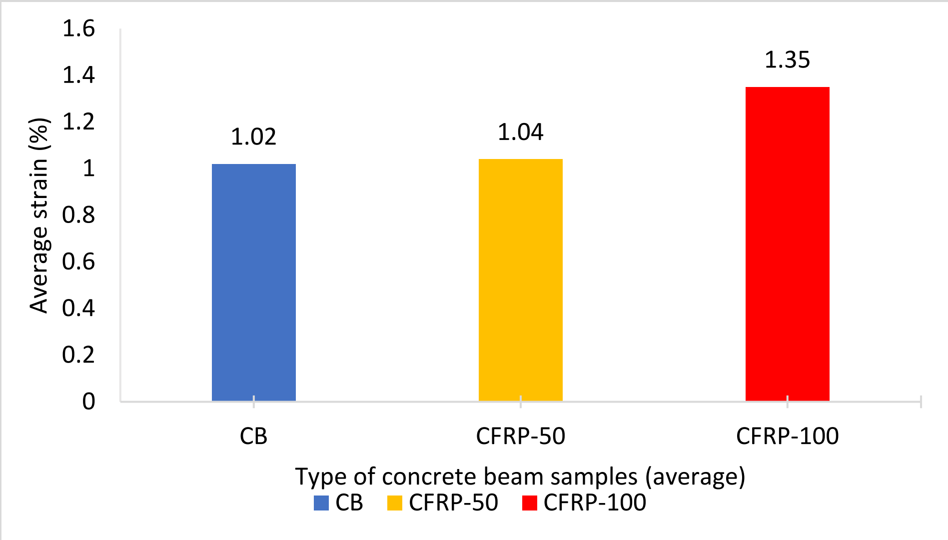


Fig. 10 *The graph of average strain (%) vs the type of sample (average)*

Table 6 *Energy absorption capacity of control and strengthened specimen*

Specimen Designation	Energy Absorption (J)	Increase over CB (%)
CB-1	6.97	-
CB-2	6.02	-
CB-3	5.31	-
Average	6.1	-
CFRP-50-1	4.00	-
CFRP-50-2	8.22	-
CFRP-50-3	11.71	-
Average	9.97	63.44
CFRP-100-1	13.27	-
CFRP-100-2	24.88	-
CFRP-100-3	0.89	-
Average	19.08	212.79

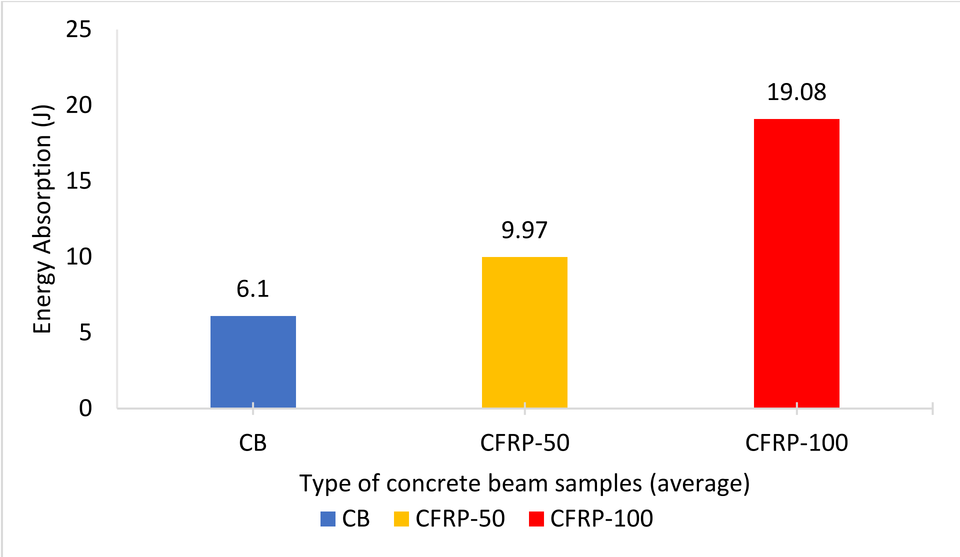


Fig. 11 *Energy absorption (J) vs the type of samples*

The projected failure mode in this study is consistent with the results of the prior study [12]. The configuration of the beam is displayed in Fig. 12(d). The controlled beams all fail in the flexural direction, as shown in Table 7 and Fig. 12 (a), Fig. 12 (b), and Fig. 12(e). This occurs when the tension zone reaches the beam's tensile strength. A common misconception is that concrete can withstand high compression pressures without breaking or failing; however, concrete possesses a low tension strength. Therefore, the beam experienced tension and compression over its cross-section as a result of the bending stress. A beam that experiences flexural failure exhibits deflection or sagging.

The ultimate shear stress denotes the highest shear force that the link between CFRP and concrete can endure prior to experiencing failure. In this study, CFRP was connected to the tension side of notched beam specimens to evaluate the bond behaviour.

Table 7 displays the ultimate shear stress CFRP-50-3 outcomes recorded as 11.86 Pa. These findings provide valuable insight into the strength of the bond between concrete and CFRP. An elevated ultimate shear stress indicates a strong bond between the materials, while decreased values might suggest possible weaknesses in the bond interface.

Table 7 *The failure mode of each beam after flexural testing*

No.	Designated Name	Ultimate Load, P_u (kN)	Shear stress, τ (Pa)	Failure Mode
1.	CB1	17.63	0	Flexural failure
2.	CB2	14.41	0	Flexural failure
3.	CB3	16.61	0	Flexural failure
4.	Average	16.22	0	-
5.	CFRP-50-1	8.84	5.304	Flexural failure
6.	CFRP-50-2	18.44	11.30	Interfacial failure
7.	CFRP-50-3	19.76	11.86	Interfacial failure
8.	Average	19.1	11.46	-
9.	CFRP-100-1	29.11	4.37	Interfacial failure
10.	CFRP-100-2	40.00	6.00	Cohesive failure
11.	CFRP-100-3	38.96	5.84	Cohesive failure
12.	Average	39.48	5.92	-

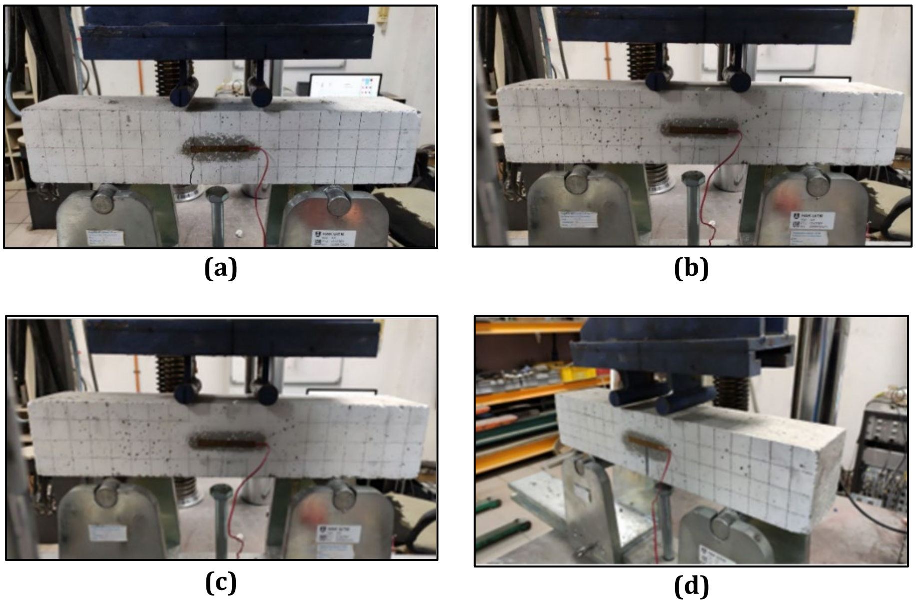


Fig. 12 *Failures that occurred on beam and beam setup for (a) CB1 flexural failure; (b) CB2 flexural failure; (c) CB3 flexural failure; (d) and beam setup*

The results of this experiment corroborate the observation of interfacial failure [12] (Fig. 13). The reduced internal cohesion within the CFRP material caused the link between the concrete surface and the CFRP to collapse at the interface. The bond was disrupted, resulting in debonding and separation from the concrete surface. The four-point flexural testing causes tensile strains in the CFRP due to the beam experience. The link between the two materials must be strong for the load to be transferred from the concrete to the CFRP reinforcement. Typically, when the epoxy reaches its limit strength, interfacial failure occurs. Interfacial failure is a common symptom of CFRP material separating or delaminating from the concrete surface. The failure mode at the CFRP-concrete contact was determined by analysing visible cracks or fractures. The adhesive significantly influenced the efficacy of the bond between the concrete and the CFRP material. Ergo, the bond can turn ineffective and cause interfacial failure if the surface is not adequately prepared.

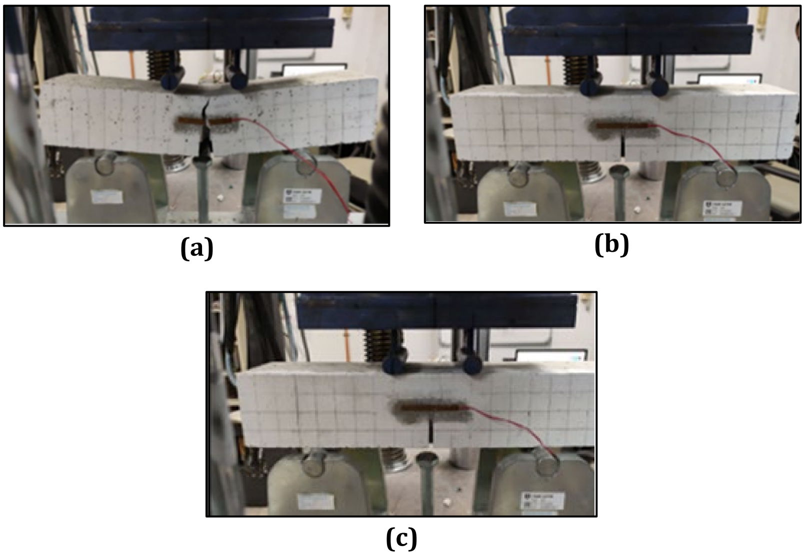
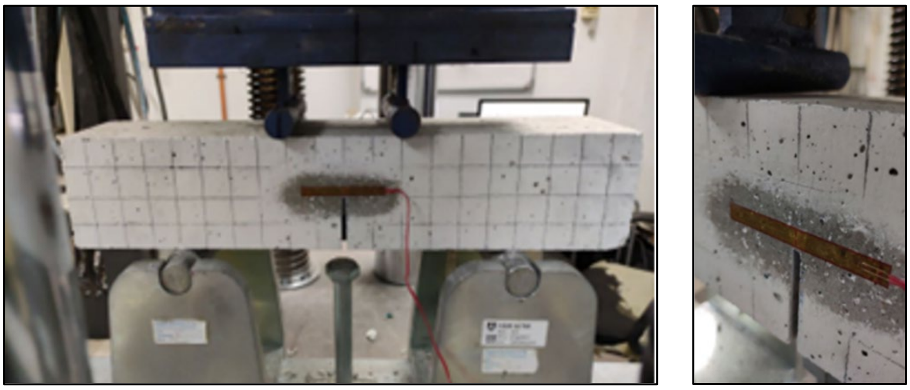


Fig. 13 *Interfacial failure that occurred on the beam after applying the repairing method for (a) CFRP-50-2 interfacial failure; (b) CFRP-50-3 interfacial failure; and (c) FRP-100-1 interfacial failure*

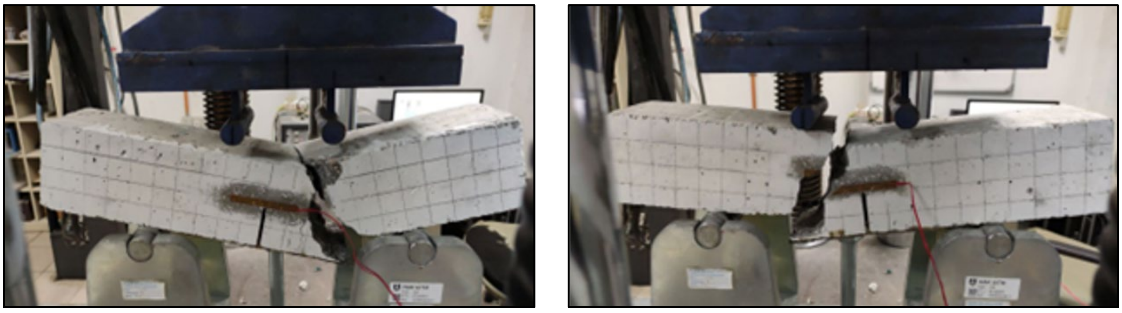
This study also revealed cohesive failure, consistent with [12]. Fig. 14(a) and Fig. 14(b) demonstrate this coherent failure behaviour. Cohesive failure occurs when the external link between the concrete and CFRP material is more powerful than the internal cohesion of the CFRP material. This demonstrates that the breakdown of the CFRP occurs at the material level, not at the bond level with the concrete surface. The failure occurred because the applied load was more significant than the cohesive strength of the CFRP material. Cohesive failure occurs in the CFRP-100-2 and CFRP-1003 for various reasons. As a primary cause, the tensile strength exceeds what the CFRP can handle. One example is a tensile strength of more than 3000 MPa, resulting from the applied loading. Secondly, the CFRP that was used might not have been appropriately prepared. Cutting the CFRP is the first step before applying it to the concrete. When cutting through CFRP, the fibres could become entangled. When applied to the beam, this can degrade the CFRP's quality, making it more prone to cohesive failure even under lesser loads. In cases when the bond strength is lower than the cohesive strength of the CFRP material, cohesive failure may also occur due to inadequate bond strength.

Fig. 15(a) and Fig. 15(b) indicate that the beam experienced flexural failure. The beam failed in flexural strength because of the saw cut. Proper distribution of the applied load by the CFRP is necessary to prevent the beam from failing directly in flexure. If the saw cut depth is incorrect, the flexure will fail, diminishing the beam's strength. When reinforcing the beam with CFRP, the adhesive's placement was crucial in preventing flexural failure. In this case, the glue and beam bonding may be insufficient or improperly positioned. While applying the adhesive, a small pocket of air could form, which would reduce the glue's ability to attach the CFRP to the concrete beam firmly. The final possible cause is issues with the concrete's quality or defects. Pouring concrete into the formwork increases the likelihood of defects and quality issues. Inadequate distribution of aggregates during concrete laying can cause voids in the mixture, reducing the material's overall performance once cured.



(a) **(b)**

Fig. 14 *The flexural failure that occurred on the beam for (a) CFRP-50-1 flexural failure, and (b) close up flexural failure*



(a) **(b)**

Fig. 15 *The cohesive failure that occurred on the beam for (a) CFRP-100-2 cohesive failure, and (b) CFRP-100-3 cohesive failure*

4. Conclusion

The goals of this experiment were accomplished: to measure the flexural load of conventional and FRP-reinforced concrete beams, to test the effects of cracking and deflection on concrete beams strengthened with FRP sheet, and to determine the degree to which these loads damaged these beams. This four-point bending test aims to determine the reinforced concrete beam's flexural capability by subjecting it to two varying sizes of FRP sheet. Extending the size of the CFRP was discovered to enhance the beam's ultimate load. Compared to the CB, the average ultimate load of the CFRP-50 groups is 19.1 kN. The average ultimate load in the CFRP-100 size class increased to 39.48 kN. Results from the CB group show that the ultimate load of a beam reinforced with external reinforcement, such as CFRP, increases as the size of the CFRP increases, with a 17.76 % increase for CFRP-50 and a 143.83 % increase for CFRP-100. Moreover, the larger the contact area between the CFRP and the beam surface, the better the load distribution. The beam's ultimate load capacity was increased due to the efficient transmission of loads that transpired when the load was applied. As the size of CFRP increases, the stress concentrations at the reinforcement's margins are lowered, meaning localised failure or premature debonding is less likely to occur.

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Hence, increasing loads and eventually reaching ultimate load capacity are possible at higher levels. The beam's overall stiffness also rises as the outcome of the increase in the CFRP. Beams with increased deformation resistance can support heavier loads with less deflection or failure.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Haziq Najmi Mohd Isa, Sakhiah Abdul Kudus;* ***data collection:*** *Haziq Najmi Mohd Isa;* ***analysis and interpretation of results:*** *Haziq Najmi Mohd Isa, Sakhiah Abdul Kudus Hussein Muhammad;* ***draft manuscript preparation:*** *Haziq Najmi Mohd Isa, Sakhiah Abdul Kudus Hussein Muhammad, M. S. Haji Sheik Mohammed, V. Roopa. All authors reviewed the results and approved the final version of the manuscript.*

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