

Behaviour of Concrete Beams in Flexure and Bonding with Fibre-Reinforced Polymer Plate Reinforcement

Muhammad Syahmi Mat Alwi^a, Sakhiah Abdul Kudus^{a,b*}, Mohamad Farid Misnan^c & Hasan Ali Abbas^d

^aFaculty of Civil Engineering, Universiti Teknologi MARA (UiTM),
40450 Shah Alam, Selangor, Malaysia.

^bInstitute for Infrastructure Engineering and Sustainable Management (IIESM),
Universiti Teknologi MARA (UiTM), Shah Alam, 40450, Selangor, Malaysia,

^cFaculty of Electrical Engineering, Universiti Teknologi MARA (UiTM),
40450 Shah Alam, Selangor, Malaysia.

^dDepartment of Building and Construction Techniques Engineering,
Madenat Alelem University College, 10006, Baghdad, Iraq

*Corresponding author: sakhiah@uitm.edu.my

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ABSTRACT

Reinforcing ageing infrastructure with carbon fibre-reinforced polymer (CFRP) plates is a viable alternative to standard steel plate bonding, but it has drawbacks like heavier weight and corrosion exposure. This study assesses the structural efficiency, energy absorption, and failure mechanisms of concrete beams that have been reinforced with CFRP plates, with four-point bending tests to measure the flexural capacity, deflection, and bond strength. The experimental results showed that the load-bearing capacity and deflection of CFRP-reinforced beams were much higher than those of control beams and that larger CFRP plates provided the optimal performance. Results showed significant improvements in structural performance when compared to control beams (CB series) and notched beams (NB series) reinforced with CFRP plates from the CFRP250 and CFRP500 series. The CFRP500-3 beam boasted the maximum load-bearing capacity and flexural strength, which highlights the benefits of larger CFRP plates. A thorough assessment of the bond strength showed strong adhesion, and the CFRP-reinforced beams exhibited noticeably higher ultimate load and shear stress. These results corroborate that the better performance found in CFRP-reinforced beams is contingent upon effective bonding. Overall, CFRP plates are a lasting and effective way to strengthen structures by increasing the bond strength and flexural strength of concrete beams. This study advocates for the expanded use of CFRP materials in infrastructure rehabilitation, providing practical recommendations for optimising CFRP application and fostering more resilient, secure structures.

Keywords: Carbon fiber reinforced polymer plate; fiber reinforced polymer; flexural strength; repairing; energy absorption

INTRODUCTION

The key issue of modern civil engineering is to enhance the functionality and prolong the lifespan of existing concrete structures. It is becoming more vital to develop cost-effective along efficient techniques for repairing and strengthening infrastructure as it ages. In numerous structural systems, concrete beams are vital components

that offer essential stability and support. Nevertheless, cracking, spalling, and a decrease in load-carrying ability are some of the deterioration forms that these beams may encounter over time. Several disadvantages exist such as complex installation process, increased weight, and corrosion vulnerability with regard to traditional repair as well as reinforcement techniques like steel plate bonding.

Alternatively, carbon fibre reinforced plastic (CFRP)

plates offer benefits, including a low weight-to-strength ratio, resistance to corrosion, and minimal application labour. Adding CFRP plates to concrete beams is an innovative and possibly beneficial option. A polymer matrix binds together the carbon fibres in CFRP. This combination produces a material that is both lightweight and exceptionally durable (Miller et al. 2018). Upon binding to the tension face of concrete beams, CFRP plates can substantially increase both rigidity and flexural capacity. The approach is appealing for improvement with maintenance initiatives since it enhances structural performance and beam service life. Previous research has shown that CFRP plates can improve concrete beam's flexural performance (Narmashiri et al. 2011). Nevertheless, there are still many fields that necessitate further investigation, such as the enhancement of bonding techniques to optimise performance, the behaviour under cyclic loading conditions, and the long-term durability of the CFRP-concrete bond. The study intends to address these problems by conducting extensive experimental and analytical assessments.

Civil engineering has made tremendous progress in using Carbon Fibre fiber-reinforced polymer (CFRP) materials to reinforce concrete structures. CFRP plates, strips, sheets, and textiles allow engineers to tailor reinforcement solutions to each construction. Recent advances have produced prestressed CFRP plates that improve concrete beam flexural performance. Recent developments in both production methods and material characteristics have contributed to CFRP's expanding role in the building industry (Fanning & Kelly, 2001). CFRP is an optimal choice for retrofitting and strengthening existing structures to accommodate increased load demands and improve their service life due to its high tensile strength, lightweight nature, simplicity of installation, and corrosion resistance (Deng et al. 2004). Besides, prestressing forces can be applied to CFRP plates to substantially increase the yielding, cracking, and ultimate load of concrete beams (Deng & Lee, 2007).

Additionally, stress distribution and load transfer methods in CFRP plates increase concrete beam flexural capacity. When connected to the tension face of a concrete beam, CFRP materials efficiently transfer tensile stresses due to their high modulus of elasticity, reducing localised concentrations that could cause cracking (Zeng et al. 2021). Bonding CFRP plates to the beam's surface transfers tensile forces during loading to the CFRP material. This leads to an even stress distribution over the beam's length, boosting its load-carrying capacity and flexural performance (Attari et al. 2012). A common technique for reinforcing concrete beams with CFRP plates is an external bonding process that uses epoxy glue to create a strong connection between the two materials. The composite nature of the bonded

system allows the CFRP plates and concrete beam to endure bending moments while also increasing the structural performance through increased tensile strength and stiffness. The incorporation of CFRP plates enhances the beam section's effective moment of inertia, which in turn improves its bending resistance and flexural capacity. This, in turn, aids in the prevention of high deflections and cracking under load (Liu & Dawood, 2019).

The flexural behaviour of reinforced concrete beams (RC beams) reinforced with CFRP laminates has been extensively studied. The research conducted by Havez & Al-Mayah (2023) revealed that beams augmented with prestressed CFRP plates exhibited a significantly greater ultimate load capacity compared to the unreinforced control samples. In particular, the ultimate load capacity of the prestressed CFRP reinforcement was increased by 130% to 150% when compared to the control beams. As an example, non-prestressed CFRP systems only increased load bearing capacity by 40% to 60% (Havez & Al-Mayah, 2023).

The research conducted earlier by Al Nuaimi et al. (2021) demonstrated that after 28 days, the specimens with CFRP reinforcement achieved an ultimate load capacity that surpassed the control specimens by 67%. This enhancement persisted even after extended exposure, rising to 51% higher for specimens exposed to sunlight and 71% higher for those exposed to saline water over a two-year period. Furthermore, after being exposed to salt water for 360 days, the CFRP-strengthened beams showed increased stiffness, increasing by 42% at 28 days and up to 52% at that point. The load-deflection curves showed a bilinear response until failure, with both sets of beams initially displaying similar stiffness. However, after cracking, the CFRP-strengthened beams showed significantly higher stiffness, demonstrating the superior ability of CFRP reinforcement to increase stiffness and load capacity in a variety of environmental circumstances (Al Nuaimi et al. 2021).

Despite its benefits, CFRP has issues such as premature detaching and restricted flexural stiffness improvement. The CFRP plates help with crack control by reducing the size and lateral movement of cracks, which keeps the structure intact and stops catastrophic failure in its tracks. The plates maximise concrete beam load-carrying capacity, allowing the structure to handle heavier loads and withstand deformation (Ye et al. 2018). For CFRP plates to avoid premature debonding, it is crucial to use the right anchorage design. For optimal load transmission and strengthening effectiveness, it is recommended to use anchorage devices like U-jackets or mechanical anchors to reinforce the bond formed between the CFRP material and the concrete substrate (Wang et al. 2022). These mechanisms improve concrete beam strength, load-carrying capacity, and bending performance (Hawileh et al. 2019; Sohail et al. 2021).

There are still challenges and research voids that need to be addressed, regardless of the research on the use of CFRP to strengthen concrete beams. The optimisation of bonding processes to maximise performance, the behaviour of CFRP-strengthened beams, and the endurance of the CFRP-concrete bond are crucial topics that require additional exploration (Berrocal et al. 2018). The primary objective of this study is to assess the structural performance, energy absorption, and failure mechanisms of concrete beams that have been reinforced with CFRP plates. Understanding these aspects helps the study comprehend CFRP plate reinforcement's effectiveness and assists future research.

METHODOLOGY

This section provides an explanation of the methodological method utilised in this study, as seen in Figure 1. The framework highlights the consecutive measures applied to assess the flexural capacity of a strengthened concrete beam using two different sizes of CFRP plate under a four-point bending test.

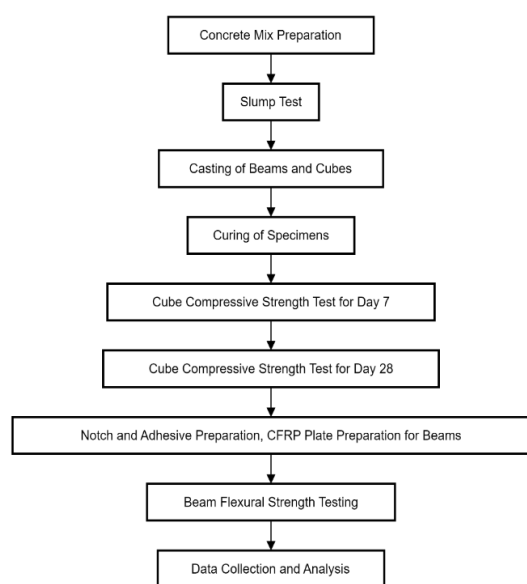


FIGURE 1. Framework of the methodology for this study

This study used a diligently formulated concrete mix that complies with British Standard BS 1881. The accurate measurement of water, coarse as well as aggregate, and cement were crucial in this mix design procedure, which aimed to prioritise efficiency and adhere to industry requirements. Table 1 comprises the precise amounts of each component that were calculated during the mix design process for the experimental trials.

TABLE 1. The material and quantity used in the experiment

Material	Quantity	Unit
Water	10.83	kg/m ³
Cement	20.24	kg/m ³
Fine aggregate	41.33	kg/m ³
Coarse aggregate (10 mm)	22.52	kg/m ³
Coarse aggregate (20 mm)	44.75	kg/m ³

A mechanical mixer was used in a precise sequence to achieve a concrete mix that was both uniform and effective. Coarse and fine aggregates were added after the cement in the process. The lid of the mixer was secured before it was turned on to make sure everything was mixed well. Submerging all components and promoting uniform hydration throughout the mixture, water was added gradually. There were short breaks in the mixing process to manually include any lumps that could have prevented the blend from reaching the proper consistency. The process was carried out for an extra two or three minutes after each adjustment until the desired texture was reached.

The concrete was cast using steel formwork that measured 100 mm x 100 mm x 500 mm (Figure 2). The six identically sized compartments of this formwork enable the effective fabrication of 100 mm cubes of concrete on each side. Furthermore, prism samples were cast pursuant to the requirements of ASTM C78/C78M-18 to ensure consistency in testing. Following ASTM D7958/D7958M-17, locally obtained CFRP was added to the mix to enhance the bonding and durability of these prism samples. This method sought to assess the final product's flexural strength by integrating FRP composites onto a concrete base. This flexural strength was efficiently measured using Fibre Reinforced Polymer System (FRPS) technology.

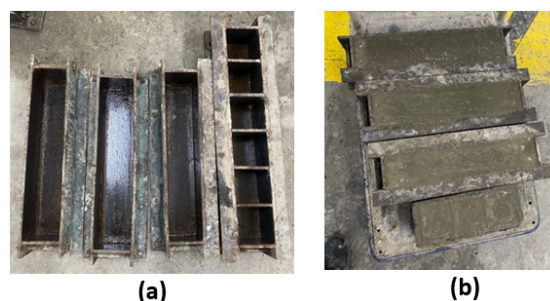


FIGURE 2. Formwork for beam prism and cube

A precise notch was strategically inserted into the concrete beams prior to testing to guarantee controlled failure and uniform results among specimens. Following the ACI 440.9R-15 guidelines, this notch was machined to a depth of 30 mm and a width of 3 mm, which is essential

for establishing a defined weak point (Figure 3) (American Concrete Institute, 2015). During the four-point bending tests, the notch was situated in the middle along the length of each beam, perpendicular to the longitudinal axis, to simulate a fracture and concentrate stress, thus driving uniform failure (Mohammed et al., 2020). A diamond or composite blade was utilised to create the notch, sometimes known as a “kerf,” and a single blade was employed consistently to improve consistency.



FIGURE 3. Notch cutting process

The preparation of CFRP plates is comprised of two different sizes: 250 x 100 mm and 500 x 100 mm. Each plate was carefully cleaned before application to eliminate any potential pollutants that could impact the bonding process. Furthermore, the concrete surfaces on which the CFRP plates were installed were appropriately roughened for greater adhesion. The concrete beams were subsequently attached to the plates using a high-strength epoxy adhesive, with meticulous attention to placement to prevent air gaps and maximise contact. The accurate and reliable findings of the flexural behaviour alongside the cohesiveness of the strengthened concrete columns are contingent upon the thorough preparation and installation of the CFRP plates (Liu et al. 2019). Figure 4 shows the CFRP plate cut to a size of 250 mm x 500 mm.



FIGURE 4. The 250mm x 500mm CFRP plate

The concrete beams were fastened to the CFRP plates using Sikadur-31 CF Normal adhesive. The two portions of this thixotropic epoxy adhesive, A and B, are combined in a mix of 2:1. Sikadur-31 CF Normal satisfies the EN 1504-4 structural bonding standard, assuring that it complies with the demanding standards for materials used in the repair and preservation of concrete structures. This compliance ensures that the material has the attributes required for good structural bonding, such as strong mechanical strength, durability, and environmental resistance. Figures 5 demonstrate that the white hue of Part A and the grey shade of Part B combine to produce a concrete grey colour when blended. An effective bond between the CFRP plates and the concrete substrate is critical for reinforcing dependability, and this colour shift indicates a thorough mixing of the adhesive.



FIGURE 5. The mixture of adhesive

A slump test was performed to produce a slump range of 30-60 mm, ensuring that the concrete mix utilised in this study had the appropriate functionality and consistency. As shown in Figure 6, the concrete mixture was layered three times into a conventional slump cone and compacted with 25 rod strokes each time. After the cone was removed, the slump, which is the concrete’s vertical settling, was measured. When the slump falls anywhere between 30 and 60 mm, it means the concrete is fluid enough to be compacted and placed correctly without sacrificing the strength and durability the beams need. The concrete used to test the CFRP-strengthened beams must adhere to this prescribed slump range to ensure consistent performance and quality (Wang et al. 2022).

After 28 days of curing, the concrete was then subjected to compressive testing. The design objective was to achieve a strength of 30 N/mm². The compressive strength of the concrete is determined by the compression test, providing essential data concerning the concrete’s

performance and quality. The BS EN 12390-3:2001 standard was followed for the testing of concrete cubes with dimensions of 100 mm × 100 mm × 100 mm. The strength development over time was monitored by conducting tests at 7 and 28-day intervals. A Universal Testing Machine 1000, running at a loading speed of 3 mm/min, was used to conduct the testing. The concrete was verified to meet the necessary strength requirements for the flexural testing of the CFRP-strengthened beams by this testing procedure (Abbood et al. 2021).

A piece of hydraulic-type universal testing equipment with a capacity of 1000 kN was used to perform four-point flexural tests on the beam specimens up to the maximum load. The four-point flexural tests were conducted in accordance with the standards set out by BS EN 12390-5:2009 (Cakiroglu et al. 2020). A loading rate of 2 mm/min was used throughout the test until failure was reached. The loading rollers were 100 mm apart, while the bottom support rollers were 300 mm apart. A third of the distance between the bottom supporting rollers was subtracted to get the size of the CFRP plate. A data acquisition system was utilised to measure strain from strain gauges that were attached to the concrete surface at the top of the beam and the composite laminates at the bottom. Using L-shaped metal brackets, Linear Variable Displacement Transducers (LVDTs) were placed at random intervals along the beam to measure deflection. All stresses and load-deflection reactions were documented until the beams failed. The beams were marked to denote the presence of each fracture, regardless of its size, until it eventually failed. A thorough setup was used to accurately quantify the flexural behaviour and performance of the concrete beams reinforced with CFRP (Al-Negheimish et al. 2021).



FIGURE 6. The slump test

Concrete surfaces next to the notched beam specimens were bonded to evaluate the bond behaviour of the CFRP with respect to the tension side of the beams. The calculation of the ultimate shear stress (τ) was performed using Equation (1):

$$\tau = \frac{3PL}{5hws} \quad (1)$$

Where:

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

The capacity of CFRP to attach to the concrete substrate and efficiently transfer loads is the defining characteristic of bond strength in reinforced concrete beams. This bond strength is crucial for the reinforcing system's efficacy and integrity in increasing the beam's structural capacity. Typical loading tests, including four-point bending tests, are used to evaluate the strength of the bond between the concrete and CFRP material, which is essential for efficient weight transfer. The testing procedure determines the ultimate shear stress at the CFRP/concrete interface.

Beam specimen bond strength is affected by several things, such as how the concrete surface is prepared, the adhesive's quality, and the way the CFRP material is installed. For the CFRP to adhere to the concrete, it is crucial to clean and roughen the surface in advance. The performance and reliability of the reinforcement system are contingent upon the strength of this bond, which enhances the beam's structural capacity.

RESULTS AND DISCUSSION

Table 2 and Figure 7 present the results of tests that were conducted to determine the compressive strength of concrete cubes at intervals of 7 and 28 days, respectively. The target compressive strength of 30 N/mm² after 28 days was chosen because it represents a standard strength commonly used in structural applications, ensuring sufficient load-bearing capacity and durability for a wide range of construction projects. This value aligns with industry norms and provides a reliable benchmark for assessing the performance and quality of concrete used in reinforcing beams with CFRP plates. The findings showed that the average level of stress increased from day 7 to day

28. All cubes achieved the anticipated strength milestones, reaching 105 % of their strength by day 7 and 146 % by day 28. The concrete cubes exceeded the design stress of 30 N/mm² on day 7, reaching an average stress of 31.65 N/mm². The average stress had increased by 146 % by day 28, reaching 44.00 N/mm².

An analysis of the compressive strength of concrete cubes in prior research by Kinjawadekar et al. (2024) revealed that the average stress reached 29.10 N/mm² by day 7. On day 28, there was a further rise in compressive strength, reaching an average stress of 38.20 N/mm² (Kinjawadekar et al. 2024). These findings indicate a significant strength development over the 28-day period, although the final strength values were slightly lower compared to the current research results.

TABLE 2 : The compressive strength obtained on days 7 and 28

Days	Cube	Load (kN)	Stress (N/mm ²)	Average Stress (N/mm ²)
7	1	343.3	34.33	31.65
	2	328.7	32.87	
	3	277.4	27.74	
28	4	428.0	42.80	44.00
	5	452.1	45.21	
	6	440.0	44.00	

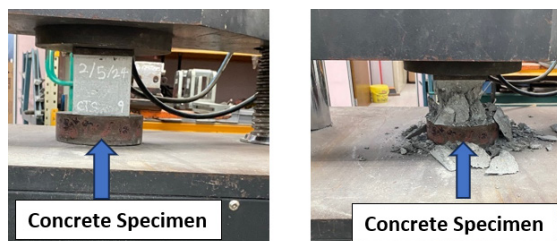


FIGURE 7. The compression test

The comparison of the performance metrics for 12 concrete beams is presented comprehensively through the analysis of the data presented in Table 3. These beams are classified as control beams (CB), notched beams (NB), and beams reinforced with CFRP plates of varying sizes (CFRP250 and CFRP500).

The control beams from the CB series, CB-1 in particular, scored a Pu value of 17.63 kN and a flexural strength of 4.52 MPa, demonstrating impressive load-bearing capacity and bending strength. Both CB-2 and CB-3 exhibited comparable resilience, with Pu values of 14.41 kN and 16.61 kN, as well as flexural strengths of 5.29 MPa and 4.98 MPa, respectively, suggesting that the control specimens performed consistently. However, the performance of the NB series, which were notched beams, was significantly lower. Compared to CB-1, NB-1's 8.06

kN Pu value and 2.42 MPa flexural strength were considerably less. In comparison to the control beams, the other notched beams, NB-2 and NB-3, performed moderately, with Pu values of 10.57 kN and 8.40 kN, respectively, with flexural strengths of 3.57 MPa and 2.52 MPa.

TABLE 3. The classification and results of flexural testing of samples of the concrete beam

No.	Designed Name	Pu (kN)	Flexural Strength (kN)	Deflection (mm)	Strain (%)
1	CB-1	17.63	5.29	2.8	1.06
2	CB-2	14.41	4.32	2.6	0.98
3	CB-3	16.61	4.98	2.7	1.03
4	NB-1	8.06	2.42	2.64	0.99
5	NB-2	8.57	2.57	2.90	1.09
6	NB-3	10.40	3.12	3.29	1.23
7	CFRP250-1	37.01	11.10	3.01	1.13
8	CFRP250-2	39.07	11.72	3.41	1.28
9	CFRP250-3	43.87	13.16	3.75	1.41
10	CFRP500-1	43.96	13.19	4.02	1.51
11	CFRP500-2	43.48	13.04	3.75	1.41
12	CFRP500-3	52.33	15.70	3.34	1.27

Major performance improvements were observed in the beams that were strengthened using CFRP plates. Beam structural capabilities were greatly improved by using the CFRP250 series, which includes reinforcing plates with a diameter of 250 mm. The flexural strength and Pu value of CFRP250-1 were 11.10 MPa and 37.01 kN, respectively. With flexural strengths of 11.72 MPa and 13.16 MPa, respectively, and Pu values of 39.07 kN and 43.87 kN, CFRP250-2 and CFRP250-3 significantly boosted these measures, demonstrating the efficiency of CFRP reinforcement.

Meanwhile, the CFRP500 series, which featured reinforcement plates with a diameter of 500 mm, demonstrated the most outstanding performance metrics. The flexural strengths of CFRP500-1, CFRP500-2, and CFRP500-3 were 13.19 MPa, 13.04 MPa, and 15.70 MPa, respectively, while the noteworthy Pu values were 43.96 kN, 43.48 kN, and 52.33 kN. The most robust specimen examined was CFRP500-3, which stood out among all the beams with the highest load-bearing capacity and flexural strength. As illustrated in Figure 8, the graph depicts the average flexural strength (kPa) of the tested beams. This data provides a clear comparison of the performance characteristics of different beam samples under flexural

stress. The flexural strength of various reinforced concrete beams was compared in the study by Hawileh et al. (2022). These beams included CFRP-reinforced beams, control beams, and beams reinforced with medium and high-cord-density steel mesh (MSM and HSM), respectively. According to the results, the control beams had an average ultimate load of 99.9 kN. A 58% increase was shown by the CFRP-reinforced beams, which had an average ultimate load of 157.79 kN. With an average ultimate load of 154.48 kN, MSM-reinforced beams showed a 55 % increase, while with an average ultimate load of 165.09 kN, HSM-reinforced beams demonstrated a 65 % increase. It is evident from both studies that CFRP reinforcement substantially improves the flexural strength of concrete beams.

Nevertheless, there are discrepancies in the extent of these improvements, which are likely from the dissimilarities in reinforcement types, specimen dimensions, and test settings. The deflection behaviour of concrete beams offers critical observations regarding structural flexibility and load-bearing capacity. This study compared the average deflection of several kinds of beams. A mean deviation of 2.70 mm was observed in the control beams (CB). A slightly greater deflection of 2.94 mm was measured for notched beams (NB). The average deflections for beams reinforced with 250 mm (CFRP250) and 500 mm (CFRP500) CFRP plates were 3.39 mm and 3.70 mm, respectively. Figure 9 shows the average deflection of beams under various loads, while Figure 10 illustrates the Load (kN) versus Deflection (mm) curve, highlighting the relationship between load capacity and beam deformation. Comparatively, Hawileh et al. recorded deflection data for beams reinforced with high and medium-density steel mesh laminates, as well as CFRP laminates, under symmetrical monotonic loading (Hawileh et al. 2022). Nevertheless, the deflection capacity is increased using CFRP, particularly larger plates, which implies enhancements in structural performance and flexibility.

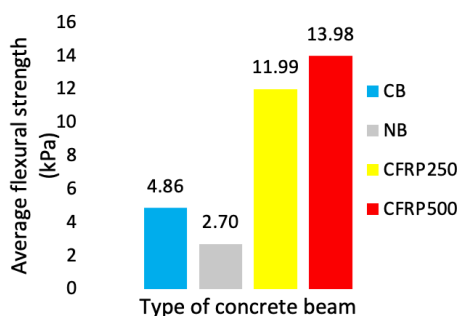


FIGURE 8. The graph of average flexural strength (kPa)

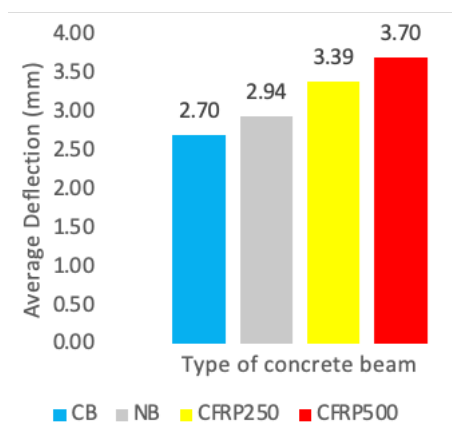


FIGURE 9. The graph of average flexural strength (kPa)

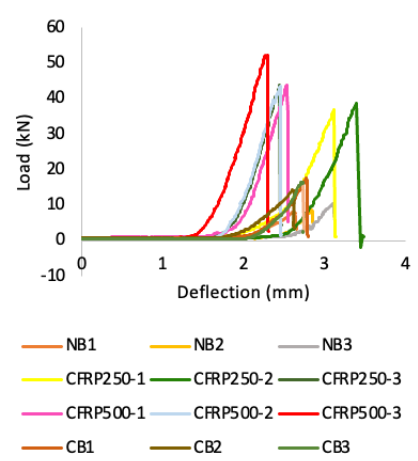


FIGURE 10. The graph of load (kN) VS deflection (mm)

An essential metric for assessing the functionality of concrete beams is strain, which is the distortion of a material when subjected to stress. This analysis investigates the correlation between the strain sensitivity in concrete beams and the size of CFRP reinforcement (Figure 11). The results show that the average strains are higher in beams that have bigger CFRP reinforcements. The average strain in controlled beams (CB) was 1.02 %, but the average strain in notched beams (NB) was 1.10 %. In addition, CFRP250 beams generated an average strain of 1.27 % with a reinforcement size of 250 mm. Beams made of CFRP, which have a bigger 500 mm reinforcement, showed the greatest average strain at 1.40 %. This pattern indicates that concrete beams reinforced with CFRP are more flexible than those unembedded. The growing average strain values show that the beams can resist larger deformations before failure as the amount of CFRP reinforcement increases. The effect of reinforcing strength on the strain capacity of concrete beams is demonstrated by the notable contrast between CFRP250 and CFRP500, with a strain increase of 37.25% for CFRP500.

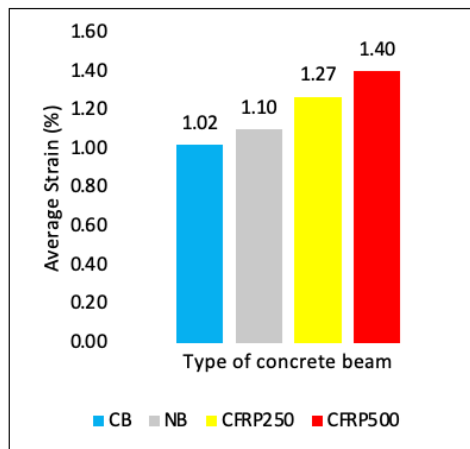


FIGURE 11. The graph of Average strain

Moreover, a crucial performance metric is the capacity of beam specimens to absorb energy under pressure or impact prior to failure. The baseline energy absorption capacity of the control specimens (CB-1, CB-2, and CB-3) ranges from 5.01 J to 6.97 J, as indicated in Table 4. The NB-1, NB-2, and NB-3 notch beam specimens were particularly effective in reducing energy absorption. The average capacity of these NBF specimens was 4.75 J, which is a drop of 22.13 % when compared to the control beams. Fig. 12 demonstrates the energy absorption characteristics of the beams, illustrating how different reinforcement methods impact their ability to absorb energy under loading conditions.

Alternatively, energy absorption capacity was significantly enhanced with the incorporation of carbon fiber-reinforced polymer (CFRP) reinforcement, especially in the CFRP250 and CFRP500 series. Compared to the control beams, the CFRP250 series specimens showed a staggering 204.75 % gain in energy absorption, with an average value of 18.59 J. Following suit, the CFRP500 series attained an even more remarkable average energy absorption of 27.53 J, which translates to a 351.31 % increase when contrasted with the control group. The findings suggest that CFRP reinforcement strongly enhances the strength and longevity of concrete beams. Reinforcing beams with CFRP increases their resistance to damaging or breaking pressures by increasing their energy absorption capacity.

TABLE 4. Energy absorption capacity of control and strengthened specimen

Specimen Designation	Energy Absorption (J)	Increase over CB (%)
CB-1	6.97	-
CB-2	6.02	-

continue...

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CB-3	5.31	-
Average	6.1	-
NB-1	3.95	-
NB-2	4.2	-
NB-3	6.09	-
Average	4.75	-22.13
CFRP250-1	16.88	-
CFRP250-2	17.29	-
CFRP250-3	21.6	-
Average	18.59	204.75
CFRP500-1	25.71	-
CFRP500-2	22.33	-
CFRP500-3	34.54	-
Average	27.53	351.31

The energy absorption values of the control specimens in the previous studies by Hawileh et al. (2022) averaged 1,473.50 kN-mm. Energy absorption increased significantly to 1,625.93 kN-mm, a 10.34 % improvement, in beams reinforced with CFRP plates (CFRP250 series). The pattern also appeared in beams reinforced with MSM, which showed an 8.60 % rise in energy absorption to 1,600.17 kN-mm. Beams reinforced with HSM showed the greatest improvement, increasing energy absorption by 40.10 % above control specimens, with an average value of 2,063.91 kN-mm. These results emphasise the beneficial influence of reinforcement elements on the capacity for energy absorption of concrete beams, which is predominantly due to the delayed formation of cracks and the consequent increase in tensile load (Hawileh et al. 2022).

Moreover, this current research revealed that energy absorption was substantially boosted by using CFRP reinforcement. In comparison to the control beams, the CFRP250 series showed a significant 204.75% increase in energy absorption, with an average value of 18.59 J. In comparison to the control group, the CFRP500 series significantly improved this capability, obtaining an average energy absorption of 27.53 J, an astounding 351.31% improvement. In contrast to the prior study, which found that CFRP reinforcement increased energy absorption by a more moderate 10.34 %, these data show that CFRP reinforcement has a much more noticeable effect.

Comparing previous findings to the current study indicates similarities as well as differences in outcomes. The baseline energy absorption capacity of the control specimens (CB-1, CB-2, and CB-3) in the present study ranged from 5.01 J to 6.97 J. Notches (NB series) reduced energy absorption by 22.13 % compared to control beams, with an average capacity of 4.75 J. This decrease emphasizes the adverse effects of notches on the energy

absorption capability, which is consistent with the consensus that it can compromise the structural integrity of beams.

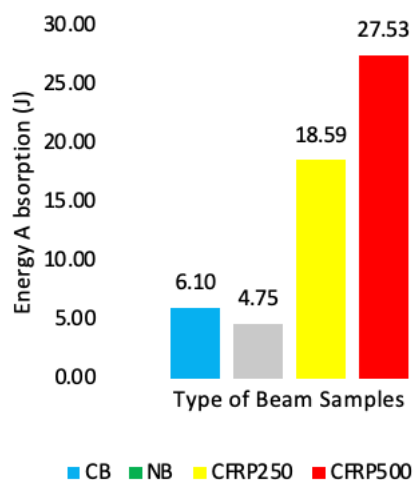


FIGURE 12. The graph of Energy absorption

Flexural testing is essential for comprehending the way concrete columns react to bending stress and ultimately fail. Table 5 provides a classification of the numerous causes of failure that can occur with these beams. Frequent flexural failure occurs when the beam breaks under the load of the bending stress. As an example, the bond between concrete and its reinforcing might degrade with time, leading to interfacial failure in a beam. This degradation makes it possible for the materials to fail when subjected to stress and subsequent separation.

Cohesive failure is another possible failure mode. The concrete crumbles because its internal structure is unable to sustain the continued application of stress. The difference between this and interfacial failure is that, in this case, the concrete breaks apart rather than the bond between the materials. Under stress, the adhesive could break, jeopardising the beam's integrity and increasing the likelihood of accidental collapse. The use of adhesives to bond components within the beam is a distinct consideration regarding adhesive failure.

TABLE 5. The failure mode of each beam after flexural testing

No.	Designated Name	Ultimate Load, P_u (kN)	Shear stress, τ (Pa)	Failure Mode
1.	CB-1	17.63	0	Flexural failure
2.	CB-2	14.41	0	Flexural failure
3.	CB-3	16.61	0	Flexural failure
4.	Average	16.22	0	-

continue...

...cont.

5.	NB-1	8.06	0	Flexural failure
6.	NB-2	8.57	0	Flexural failure
7.	NB-3	10.40	0	Flexural failure
8.	Average	9.01	0	-
9.	CFRP250-1	37.01	4.44	Cohesive failure
10.	CFRP250-2	39.07	4.69	Cohesive failure
11.	CFRP250-3	43.87	5.26	Cohesive failure
12.	Average	39.98	4.80	-
13.	CFRP500-1	43.96	2.64	Cohesive failure
14.	CFRP500-2	43.48	2.61	Cohesive failure
15.	CFRP500-3	52.33	3.14	Cohesive failure
16.	Average	46.59	2.77	-

Figures 13, 14, and 15 illustrate beam failure. Figure 13 shows the flexural failure of beam for the control specimen which the crack is at the middle of the beam. Figure 14 shows the cohesive failure of CFRP250 and figure 15 shows the cohesive failure of CFRP500 which the crack is not on the middle and the plate maintains their connection with the concrete surfaces (Hawileh et al. 2022).

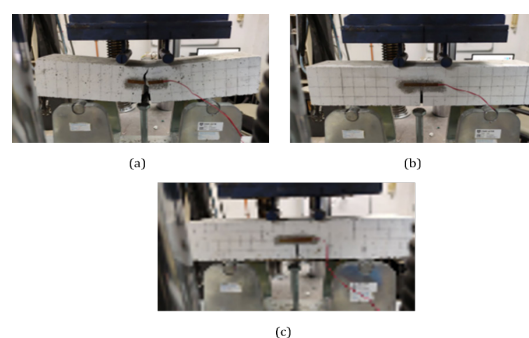


FIGURE 13. The flexural failure of beam

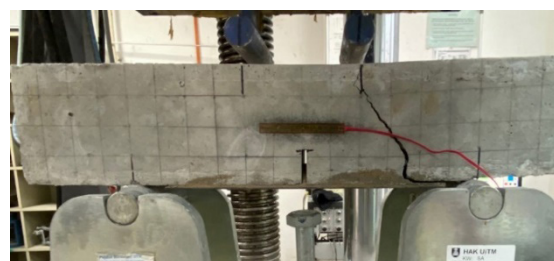


FIGURE 14. The cohesive failure of CFRP250

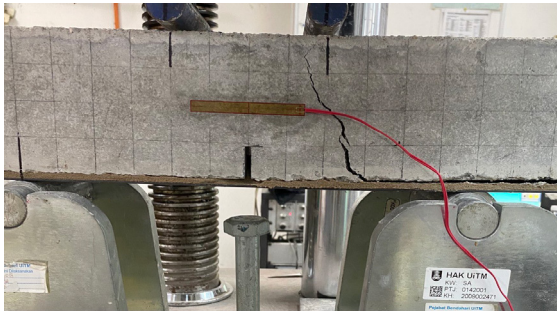


FIGURE 15. The cohesive failure of CFRP500

CONCLUSION

This study concluded that concrete beams bonded with Fiber-Reinforced Polymer (FRP) plates exhibited certain behaviours during flexure. Research objectives included testing control concrete beams for flexural capacity, comparing beams reinforced with CFRP plates of varying diameters, and measuring the strength of the bond between the two materials. The outcomes revealed that in terms of load-bearing and flexural capacities, beams reinforced with CFRP plates from the CFRP250 and CFRP500 series performed far better than the control beams (CB series) and the notched beams (NB series). Larger CFRP plates are effective in strengthening concrete beams, as demonstrated by the CFRP500-3 beam's exceptional load-bearing capability and flexural strength. Furthermore, CFRP-reinforced beams demonstrated greater performance when tested with two diameters of CFRP plates (250 mm and 500 mm) under identical conditions, demonstrating the flexural capacity of reinforced concrete beams. The ultimate load and ultimate shear stress were calculated, and the form of bond failure was identified to assess the bond strength of the reinforced concrete beams. The findings validated that the improved performance detected in the CFRP-reinforced beams is contingent upon effective bonding. Several obstacles arose throughout the investigation, providing chances for future development. One key problem was to ensure constant bonding between the CFRP plates and the concrete beams, since changes in adhesive application and surface preparation may affect the results. Future research might concentrate on standardising the bonding procedure and investigating new adhesives to improve bond dependability.

Furthermore, correctly measuring strain and deflection under load proved problematic, emphasising the need for more precise instruments and calibration techniques. Using sophisticated sensors and real-time data collecting systems may increase measurement accuracy and data quality. The findings of this research have major implications for the engineering discipline and building industry

stakeholders. The exhibited gains in load-bearing and flexural capabilities of CFRP-reinforced beams highlight their suitability for retrofitting and reinforcing existing structures. This may increase the useful life of ageing infrastructure, enhance safety, and save maintenance costs. The results may help construction experts and structural engineers improve the design and use of CFRP plates for a variety of applications, resulting in more robust and lasting buildings.

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DECLARATION OF COMPETING INTEREST

None.

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