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A Study on Flexural Enhancement in Beam Strengthened with CFRP Plate and Toughened Mussel Epoxy as Bonding Agent

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Abstract

Structural concrete beams in old and historic buildings are not designed to resist increasing applied loads. Therefore, flexural beam strengthening is mandatory. Fibre Reinforced Polymer (FRP) is used as a reinforcing material to increase its flexural loading resistance. In structural retrofitting, carbon fibre reinforced polymer (CFRP) plates, composed of carbon fibres bonded with epoxy resin, have grown in popularity. However, the inherent brittleness and low shear strength of neat epoxy resin require modification with fillers such as micro-silica and zirconia. As a sustainable alternative, mussel powder, which is rich in calcium carbonate ($CaCO_3$) compound, acts as a rigid bio-filler, enhancing the toughness, bonding strength, and impact resistance of pure epoxy resin. This study incorporates a 7.5% volume fraction of mussel powder into epoxy resin, an optimised percentage reported in previous studies. The selection of a 7.5% composition was justified because it demonstrated improved mechanical performance without significantly compromising the resin's workability. The research investigates the influence of CFRP plate lengths (50-250 mm) bonded with 7.5% Toughened Mussel Epoxy (TME) by volume fraction on the flexural strength of plain concrete beams. Four-point bending tests were conducted to record failure modes, load-displacement behaviour, and ultimate load capacities. Results indicate that longer CFRP plates enhance load-carrying capacity, with a 200 mm CFRP length providing an optimal balance between material efficiency and structural performance, yielding a 26% increase in strength compared to unstrengthened beams. Failure modes varied with CFRP length; shorter plates primarily exhibited shear failure, while longer plates (i.e., CFRP length more than 200 mm) displayed delamination failure. The study concludes that using a 200 mm CFRP plate with TME provides a significant improvement in flexural strength, offering a cost-effective

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and environmentally friendly alternative to conventional strengthening techniques.

1. Introduction

Beam flexural strengthening is crucial in structural engineering, particularly in old and historic buildings and bridges, to enhance their flexural resistance and associated beam ductility. This is due to a number of factors, such as increased loads from earlier as-built designs, structural degradation over time, and design flaws, all of which necessitate strengthening works. Although these issues were addressed using steel plates and beam jacketing, these traditional approaches have drawbacks in cost, efficiency, and aesthetics [1].

Although neat epoxy resin is commonly used as a bonding adhesive, its effectiveness in flexural strengthening applications is limited by its naturally low shear strength. To improve its mechanical properties and bond strength with the concrete substrate, fillers are usually added. Previous research has successfully incorporated artificial fillers, such as micro silica and Nano-carbon fibres, into pure epoxy resin to improve its mechanical performance. According to Samad et al. [2], increasing the filler concentration in nano-carbon composites such as silica and zirconia greatly enhanced the mechanical properties of epoxy composites, including hardness and storage modulus. Artificial fillers in filled epoxy are composed of particles produced from minerals and are susceptible to greenhouse effects, even though they may improve mechanical qualities more than their plain epoxy counterparts. Alternatively, the use of bio-fillers promotes a more environmentally friendly, sustainable material. According to recent studies, waste bio-fillers can enhance the shear strength and overall mechanical performance of epoxy resins because they contain significantly stiffer particles, such as calcium carbonate from eggshells. For example, Fong et al. [3] found that the addition of 7.5% eggshell powder raised the final stress at failure as well as the fracture energy values in the opening and shear modes. When mussel powder was added to pure epoxy resin, Velayutham et al. [4] also demonstrated a comparable pattern of improved elastic characteristics. This study demonstrated that adding waste bio-fillers could enhance epoxy systems and promote the development of eco-friendly building materials. The rigid particles in mussel powder inspired their incorporation into the epoxy resin matrix, owing to their exceptional toughness and adhesion in damp conditions. The durability and bonding strength of mussel-toughened epoxy resins on concrete substrates are noticeably better than those of plain epoxy resins. Improved performance in structural applications is achieved by incorporating catechol functional groups, similar to those present in mussel adhesive proteins, which enable strong contact with the concrete surface [5].

The efficiency of externally bonded CFRPs for flexural strengthening of concrete beams has been extensively studied. Compared with conventional techniques, CFRP offers a high strength-to-weight ratio, corrosion resistance, and ease of installation. CFRP systems are also a popular option for many retrofitting projects because of their design flexibility and ability to be customised to meet specific structural requirements [6]. Hawileh et al. [7] claim that FRP applications are adaptable and efficient means of enhancing structural performance across a variety of structural elements, including beams, columns, and slabs. For ageing infrastructure to maintain its structural integrity, the adaptation and flexibility of FRPs are crucial. The class and kinds of CFRP reinforcing fibres, the surface preparation of the concrete substrate, and environmental conditions are among the factors that affect the effectiveness of CFRP strengthening. The bonding behaviour between the CFRP and the concrete surface is critical to the overall performance of the reinforced beam. Proper surface preparation processes, such as texture roughening and cleaning, are critical to ensure proper bond strength and long-term durability of the strengthening system.

The long-term integrity and durability of the bond interface between the CFRP plate and the concrete substrate are critical considerations in the design of CFRP strengthening systems. Over time, environmental factors such as moisture ingress, temperature fluctuations, and chemical exposure can degrade the adhesive layer, resulting in reduced bond strength, premature interfacial debonding, and diminished strengthening effectiveness. As the primary medium responsible for transferring stresses between the CFRP reinforcement and the concrete substrate, the adhesive largely governs the overall structural performance of externally bonded strengthening systems. Previous studies have reported that conventional epoxy adhesives are susceptible to moisture absorption and thermal instability, leading to deterioration of their mechanical and interfacial properties under service conditions. The incorporation of toughening agents or bio-fillers, such as mussel shell powder, has emerged as a promising strategy to enhance both the mechanical performance and environmental resistance of epoxy adhesives. The bio-filler contributes to improved fracture resistance, crack propagation resistance, and moisture durability through its rigid calcium carbonate particles and hydrophobic characteristics.

Furthermore, Azhar et al. [8] experimentally demonstrated that CFRP-strengthened concrete beams bonded with mussel shell-modified epoxy (MME) exhibited superior flexural behaviour compared with those bonded using neat epoxy. An optimum mussel shell content of 7.5% increased the ultimate load capacity by approximately 22%, while delaying interfacial debonding and improving the ductility of the strengthened beams. These improvements were attributed to enhanced interfacial bonding and more efficient stress transfer between the CFRP plate and the concrete substrate. Building upon these experimental findings, Azhar et al. [9] developed and

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validated an XFEM–CZM numerical model that accurately predicted the crack initiation, propagation, and interfacial debonding behaviour of MME-bonded CFRP-strengthened concrete beams, with prediction errors of less than 10% compared with the experimental results. The numerical simulations further confirmed that the MME adhesive provided improved traction–separation behaviour and cohesive bond performance, leading to enhanced load transfer efficiency and delayed debonding. Collectively, these findings demonstrate that mussel shell-modified epoxy is not only capable of improving the structural performance of CFRP-strengthened concrete beams but also provides a reliable and predictable bonding mechanism suitable for long-term applications in ageing reinforced concrete structures exposed to aggressive environmental conditions [8], [9].

In addition, the length of CFRP strips used for strengthening is a key factor influencing the effectiveness of externally bonded reinforcement systems. An increase in CFRP bond length generally improves the load-carrying capacity by providing a larger bonded area for stress transfer between the CFRP and the concrete substrate, thereby enhancing the flexural performance of reinforced concrete beams. Azhar et al. [10] experimentally demonstrated that the bond length of adhesively bonded composite joints plays a crucial role in determining the load transfer mechanism and overall joint performance. Their study revealed that increasing the overlap length significantly enhanced the static shear strength of both single-lap and double-strap joints by promoting a more efficient stress distribution across the bonded interface. However, beyond the optimum bond length, the improvement became marginal because stress concentrations remained localized near the joint ends, indicating that excessively long bonded regions do not proportionally increase structural performance. Similarly, Omar et al. [11], who employed Kenaf FRP (KFRP) to enhance the flexural performance of concrete beams, investigated the effectiveness of various FRP geometries, including different strengthening lengths. Their findings showed that optimal bonding conditions increased beam stiffness by 36% and the ultimate load by 84%, thereby enhancing structural integrity and delaying the onset of failure. Likewise, Ridhwan et al. [12] reported that appropriate KFRP lengths and woven fabric configurations improved the load-carrying capacity of foamed concrete beams by up to 154% while increasing stiffness by 41%. Nevertheless, excessively long strengthening lengths may result in inefficient material utilization and increase the likelihood of premature interfacial debonding or stress concentration at the laminate ends, ultimately limiting the strengthening efficiency [10], [13]. The investigation of flexural beam strengthening with a toughened CFRP plate at different CFRP plate lengths is important for concrete structures. This study seeks an optimum toughened CFRP plate and a sustainable material to increase the structural capacity and resilience of concrete beams by addressing the limitations of traditional strengthening methods and optimising the performance of toughened CFRP plates.

2. Experimental Work

The experimental efforts are explained in this section. In order to investigate the effectiveness of using Toughened Mussel Epoxy (TME) as a binder by focusing on varying CFRP lengths in flexural beam strengthening.

2.1 Testing Series

For each testing series, three specimens were created, averaged, and utilised as experimental datasets for further discussions. The test specimens were mechanically tested using a Universal Testing Machine (UTM) in a four-point bending test, in accordance with ASTM Standard C1609/C1609M. Table 1 shows the testing series investigated in the present study to determine the flexural strength of a strengthened concrete beam as a function of CFRP length.

Table 1 *Testing series investigated with a variation of CFRP length*

No.	Concrete Grades	TME Volume Fractions (%)	CFRP Architectures	CFRP Length (mm)	No. of Testing Beams
1.	G25	7.5	Plain weave *(0/90)*	50	3
2.	G25	7.5	Plain weave *(0/90)*	100	3
3.	G25	7.5	Plain weave *(0/90)*	150	3
4.	G25	7.5	Plain weave *(0/90)*	200	3
5.	G25	7.5	Plain weave *(0/90)*	250	3

A toughened CFRP plates of one ply of twill weave carbon fibres were chosen, i.e., a stacking sequence of *(0/90)* plates with a nominal thickness of 0.5mm, with varying CFRP plate lengths ranging from 50mm to 250mm. The testing series involves a systematic approach to assess the optimal CFRP length to enhance the flexural resistance of the concrete beam. A concrete beam of size 100mm × 100mm × 400mm is used in this study, as shown in Fig. 1.

2.2 Preparation of Toughened Mussel Epoxy

Mussel shells were incorporated as a matrix filler in the epoxy resin due to their high calcite ($CaCO_3$) content, which imparts rigidity and enhances the mechanical performance of the polymer composite. These rigid particles serve as reinforcement within the epoxy, increasing its impact resistance, stiffness, and overall durability. The use of mussel shells also aligns with sustainable material practices, as it repurposes a readily available bio-waste into a value-added engineering material. Previous studies have demonstrated that mussel-shell-based materials can improve mechanical performance and durability in cementitious systems, particularly due to their fine-particle composition and high calcium content [14], thereby supporting their suitability as bio-fillers in epoxy systems.

The modified resin, known as Toughened Mussel Epoxy (TME), was developed by adding processed mussel shell powder to the epoxy matrix. In this study, a 7.5% volume fraction of mussel powder was used, based on the findings of Velayutham et al. [4], who identified this as the optimal concentration for improving toughness without adversely affecting workability or curing behaviour.

As illustrated in Fig. 2, the preparation of TME began with the collection of discarded mussel shells from seafood waste. The shells were thoroughly cleaned to remove organic residue and then air-dried. After drying, the shells were crushed and finely ground using a ball mill to produce a uniform powder. This powder was sieved through a 75 μm mesh to ensure fine and consistent particle size. The sieved mussel shell powder was then slowly incorporated into the epoxy resin under continuous mechanical stirring to ensure even dispersion. To eliminate air bubbles introduced during mixing, the mixture was subjected to vacuum degassing for 30 minutes. This step is essential to prevent internal porosity, which can compromise the mechanical strength and bonding effectiveness of the epoxy. Once fully prepared, the TME was ready for use in structural applications, particularly for bonding CFRP plates to the surfaces of concrete beams during strengthening.

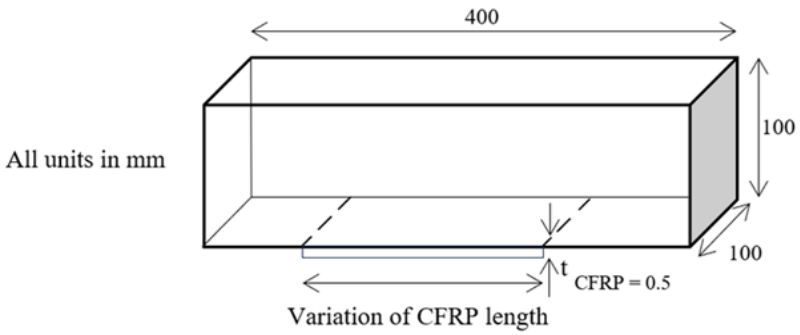


Fig. 1 *Testing specimens of the concrete beam and toughened CFRP*

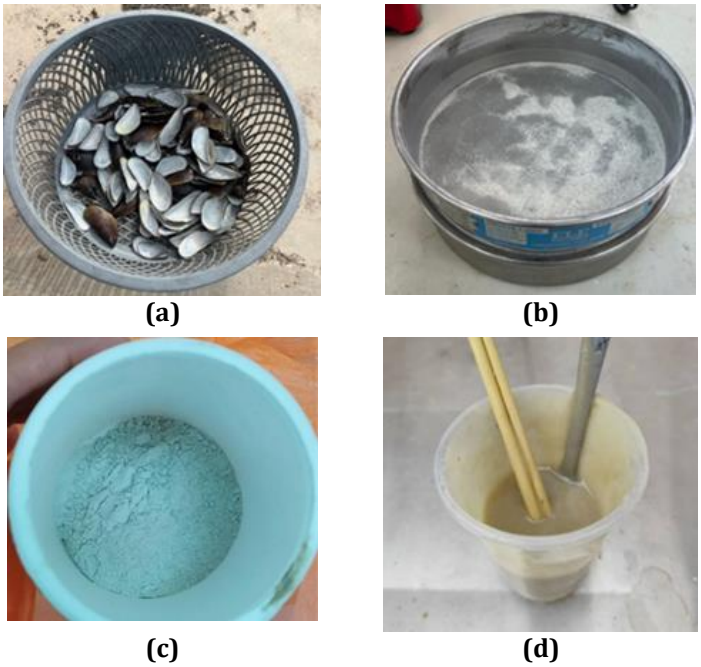


Fig. 2 *(a) Mussel shells; (b) Sieved mussel powder; (c) Mussel powder; and (d) Toughened mussel epoxy*

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2.3 Fabrication of CFRP Plates Incorporating Mussel Powder as Matrix Binders

The production of CFRP plates with mussel powder as matrix binders begins with the wet lay-up of CFRP panels. A thin, uniform coat of silicon spray is applied once to both the top and bottom aluminium moulds, serving as a releasing agent to prevent adhesion during curing. A single layer (one ply) of twill weave carbon fibre, arranged in a (0/90) orientation, is then carefully placed on the bottom mould surface. This is followed by the application of the matrix binder system, consisting of SP84 epoxy resin and SP76 hardener at a 2:1 ratio. The carbon fibre ply is combined with toughened mussel epoxy to form a toughened CFRP plate. During this process, care is taken to prevent entrapped voids or bubbles by gently squeezing out any visible voids, ensuring a homogeneous bond. The panels are then subjected to a steady applied pressure of 40 psi using a compression machine and left to cure for at least 24 hours at room temperature. After curing, the aluminium moulds are carefully removed to avoid surface damage to the composite panel. The cured CFRP panels are then sectioned into specified plate sizes, with all edges trimmed to prevent edge damage that could affect testing results, and cut into woven fabric CFRP plates of various lengths.

2.4 Batching of Concrete Beams

The batching process for concrete beams was carefully carried out to ensure accurate mixing of materials, targeting Grade 25 concrete strength (25 N/mm^2) in accordance with structural requirements. The concrete mix design followed the proportions recommended by Teychenne et al. [15], adopting a water-cement ratio of 0.59 to achieve the desired compressive strength of 25 MPa. The slump range was controlled between 10–30 mm, and the nominal fresh concrete density was maintained at approximately 2400 kg/m^3. Fine aggregates used passed through a 5 mm sieve, while coarse aggregates ranged between 5 mm and 10 mm. The mixing ratios by weight for water, cement, fine aggregate, and coarse aggregate were 0.59:1.00:2.78:3.13, respectively. An additional 0.022 m^3 of concrete was prepared for slump testing, and 60 kg/m^3 of water was added to compensate for aggregate water absorption, ensuring proper consistency without compromising the mix proportions.

As shown in Fig. 3, a total of fifteen beams were prepared using materials mixed according to Design of Experiments (DOE) specifications. The concrete mixture was poured in three layers, with each layer compacted using 25 strokes to ensure proper consolidation. Approximately 20% extra material was prepared to avoid shortages during casting. Beam specimens were cast in greased moulds measuring 400 mm × 100 mm × 100 mm, then covered with wet gunny sacks for 24 hours to retain moisture before being submerged in water for 28 days of curing. Following curing, the beams were air-dried for three days to prepare the surfaces for CFRP plate installation.



(a) **(b)** **(c)**

Fig. 3 *(a) Slump test; (b) Casting specimens; (c) Curing process*

Table 2 presents the detailed mix proportions used for batching the normal concrete. The table includes the weight of each constituent material, which is cement, water, fine aggregates, and coarse aggregates per cubic meter of concrete. These values are calculated based on the target strength, workability, and aggregate characteristics, ensuring the mix meets both structural and handling requirements. The addition of compensating water for aggregate absorption is also included in the table to maintain uniformity and consistency throughout the mixing process. This mix design serves as the basis for producing all beam specimens in the study.

Table 2 *Mix design of normal concrete*

Mixing referring	Water	Cement	Fine aggregate	Course aggregate
Mix ratio	0.59	1.00	2.78	3.13
Concrete mix design (1 kg/m^3)	190	320	890	1000
Total for 15 concrete prisms (0.06 m^3), kg	11.4	19.2	53.4	60

2.5 Installation of CFRP Plates at the Tension Face of the Concrete Beam

Toughened Mussel Epoxy is used as a bonding agent to attach the CFRP to the beam sample. To ensure good adhesion, the concrete beam surface is treated with a low-speed-mode grater and a wire brush to roughen the surface, thereby improving mechanical interlocking between the beam and the CFRP plate. Dirt and debris are cleaned with a hand brush to ensure a clean bonding surface. The CFRP plate is then marked at its centreline on the roughened surface with a permanent marker, as shown in Fig. 4(a), to ensure accurate placement. The adhesive thickness between the CFRP plate and the concrete surface is fixed at 0.2 mm. The plate is pressed firmly against the prepared surface, as shown in Fig. 4(b), to ensure proper adhesion and alignment. This rigorous preparation ensures the strength and effectiveness of the bond, optimising the structural strengthening process.



(a) **(b)**

Fig. 4 *(a) CFRP placement; and (b) Bonding of CFRP*

2.6 Mechanical Testing

In accordance with BS EN 12390-5:2019 [16], a four-point bending standard test was used to determine the flexural load displacement. After 28 days of age, every beam specimen is tested. Testing specimens were configured as supported beams and subjected to a four-point bending test. Fig. 5 shows a Universal Testing Machine (UTM) with a 50 kN load-cell capacity and a constant crosshead speed of 0.5 mm/min. This loading rate provides sufficient time to monitor crack propagation and prevent unanticipated catastrophic failure. Mid-span deflection can be measured because the UTM machine's load cell has an integrated vertical linear displacement (stroke) sensor. Visual inspection and documentation of the fracture patterns and failure mechanisms were done. A data-gathering system was used to analyse the load-deflection datasets collected by connected data loggers. Steel offers little deformation between the two supports. The diameter and breadth of the steel rollers, including the punches and support, are 10 mm and 120 mm, respectively.

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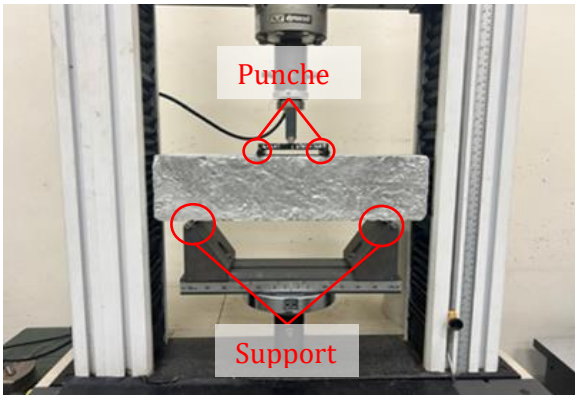


Fig. 5 *Specimen tested under four-point bending test*

3. Results and Discussions

3.1 Failure Modes

The failure modes observed in CFRP-strengthened beams during testing primarily included shear failure and delamination, both of which were significantly influenced by CFRP plate length, adhesive strength, and bonding techniques. Beams with longer CFRP plates (e.g., 200 mm and 250 mm) exhibited improved resistance to early debonding and a more gradual failure progression due to enhanced stress transfer and improved composite action between the CFRP and concrete. These observations are consistent with findings by Azhar et al. [8], who reported that increasing the effective bond length in beams strengthened with co-cured CFRP and mussel shell-modified epoxy delays the onset of premature debonding and promotes more stable crack propagation. Conversely, shorter plates (e.g., 50 mm and 100 mm) were prone to abrupt shear failures, particularly at the CFRP plate edges, due to stress concentrations.

Shear failure, illustrated in Fig. 6(a), typically initiates at the tip of the CFRP plate, where high shear and peel stresses are concentrated. The failure process began with the formation of cracks on the surface of the concrete beam under extreme tension. As the applied load increased, these cracks propagated diagonally, eventually splitting the concrete and leading to catastrophic failure. This failure mode was more prominent in specimens with shorter CFRP lengths, as these lengths were less effective in redistributing stresses away from critical zones. Ding et al. [17], who demonstrated that an insufficient CFRP bond length intensifies stress concentrations at the laminate ends, reported similar behaviour. This leading to premature shear cracking and a rapid loss of load-carrying capacity.

Delamination failure, shown in Fig. 6(b), involved the separation of the adhesive bond between the CFRP and concrete. This process is typically initiated at the plate edges, where shear and peel stresses are highest, and progresses towards the beam's centre. The composite action between the CFRP and concrete initially delayed crack propagation, but as the stress increased, the bond weakened, leading to delamination. Eventually, complete detachment of the CFRP occurred, followed by the propagation of flexural cracks in the concrete beam, culminating in catastrophic failure. Notably, delamination could initiate simultaneously at both edges or eccentrically from one side due to uneven stress distribution.

Overall, longer CFRP plates demonstrated better performance by delaying the onset of both shear and delamination failures due to improved stress transfer and bond strength. However, under continued loading, failure remained inevitable, underscoring the importance of optimising plate length and bonding techniques to enhance the durability and performance of CFRP-strengthened beams.

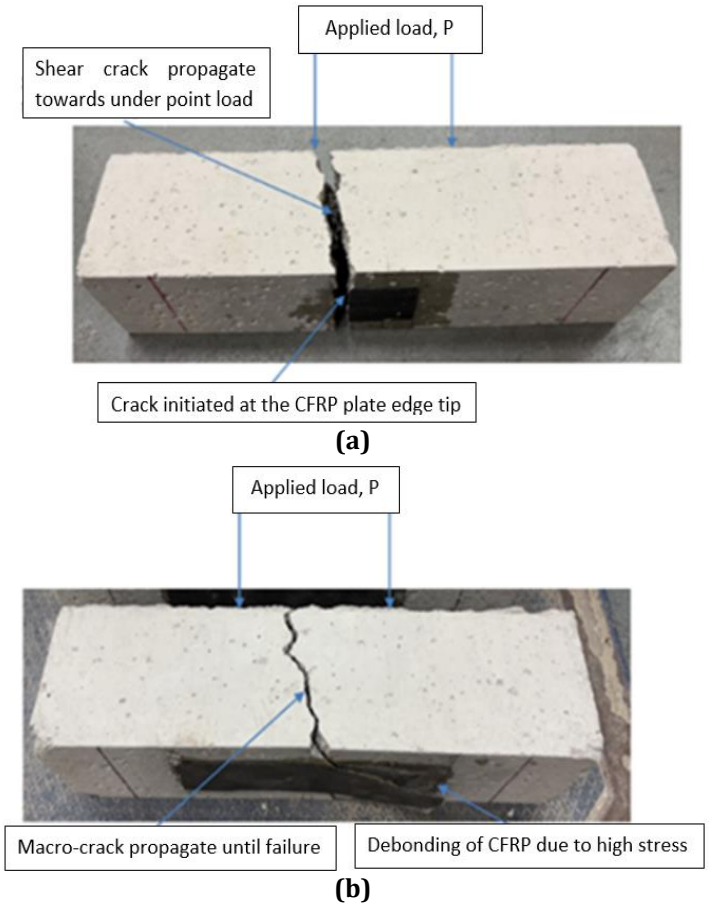


Fig. 6 *(a) Shear failure; and (b) Delamination failure*

3.2 Typical Load-Displacement Profiles

Four-point bending tests were conducted to analyse the load-displacement profiles of beams reinforced with CFRP plates of varying lengths to understand their structural behaviour. A Universal Testing Machine (UTM) with a 50 kN load-cell capacity was used to perform the tests at a constant crosshead speed rate of 0.5 mm/min. Depending on the CFRP plate length, the results indicated several failure scenarios.

Shorter CFRP plates (50 mm and 100 mm) primarily experienced shear failure. The load-displacement curves for these specimens demonstrated an initial linear elastic response, followed by a rapid increase in load until the peak load was reached. A sudden and sharp drop in load ensued, attributed to stress concentrations at the CFRP plate edges, leading to shear crack propagation from the CFRP tip towards the under-point load. This phenomenon occurred because the short CFRP plates were less effective at developing sufficient composite action with the concrete substrate, resulting in less noticeable strengthening effects and a higher susceptibility to abrupt shear failure. Such premature shear failures are consistent with the findings of Al-Rousan et al. [18], who reported that inadequate bonding length of externally bonded CFRP results in localised shear stress spikes and abrupt loss of load-carrying capacity. In the present study, the short CFRP plates provided insufficient anchorage, limiting composite action and reducing the strengthening contribution.

Longer CFRP plates (200 mm and 250 mm) exhibited a different failure behaviour, primarily dominated by delamination. The load-displacement curves for these beams showed a gradual increase in load, indicating effective composite action. The initial crack formed at the beam's mid-span, and as the load increased, the CFRP plates progressively delaminated from both edges due to high peel and shear stresses. The delamination process delayed significant crack propagation, but as the adhesive bond weakened, ultimate failure occurred marked by a gradual decrease in load. This progressive debonding behaviour is consistent with observations by Wang et al. [19], who noted that increased CFRP bonding length enhances stiffness and delays crack propagation, but eventually shifts failure toward plate-end debonding. Although delamination ultimately led to failure, the longer plates exhibited a more ductile response, characterised by a gradual reduction in load rather than a sudden drop.

Beams with intermediate CFRP plate lengths (150 mm) exhibited a combination of the two failure modes. The load-displacement curves exhibited a sudden drop in load, indicating the onset of shear failure, followed by a secondary phase of gradual decline as delamination progressed. This transition from shear to delamination failure reflects the complex stress interactions within the beam structure and is influenced by the CFRP length. This

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transitional behaviour highlights the partial engagement of composite action and reflects the incomplete stress redistribution across the plate. Such mixed failure modes were reported by Liu et al. [18], who found that intermediate anchorage lengths often trigger combined shear and debonding behaviour due to variations in bond development along the CFRP-concrete interface.

The graph in Fig. 7 illustrates the influence of CFRP plate length on beam failure modes and overall performance, highlighting that longer CFRP plates enhance ductility and delay catastrophic failure, whereas shorter plates are prone to sudden shear failure. For comparative purposes, a control beam without CFRP strengthening (CTL) was included in the load-displacement analysis. The control data were adopted from a previous study by Omar et al. [11], which involved beams of similar dimensions and concrete grade. The control beam recorded a peak load of 10.6 kN under the same four-point bending configuration.

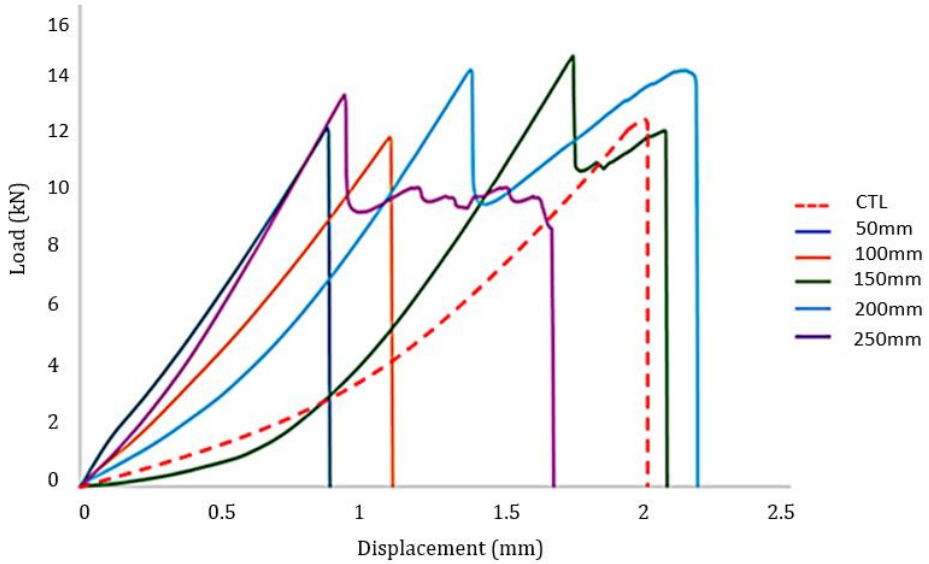


Fig. 7 *Load-displacement graph failure modes of beams*

3.3 Typical Load-Displacement Profiles

The impact of CFRP length on the ultimate load was examined by comparing CFRP plates with control beams of a similar concrete grade (target strength 25 N/mm^2; Omar et al. [11]). The findings show that longer CFRP plates improve load-bearing capacity. The impact of CFRP plate length on the ultimate load was evaluated, showing that longer plates generally enhance load-bearing capacities. As depicted in Fig. 8, there is a clear trend where increased CFRP length correlates with improved load capacity. Beams with a 50 mm CFRP plate recorded an average ultimate load of 11.78 kN, indicating minimal reinforcement contribution. This is likely due to insufficient bonding area and inadequate shear transfer between the CFRP plate and the concrete substrate, leading to premature shear failure. A slight improvement was observed with a 100 mm plate, yielding 11.89 kN, but the short length still limited effective stress transfer, thereby maintaining susceptibility to shear failure.

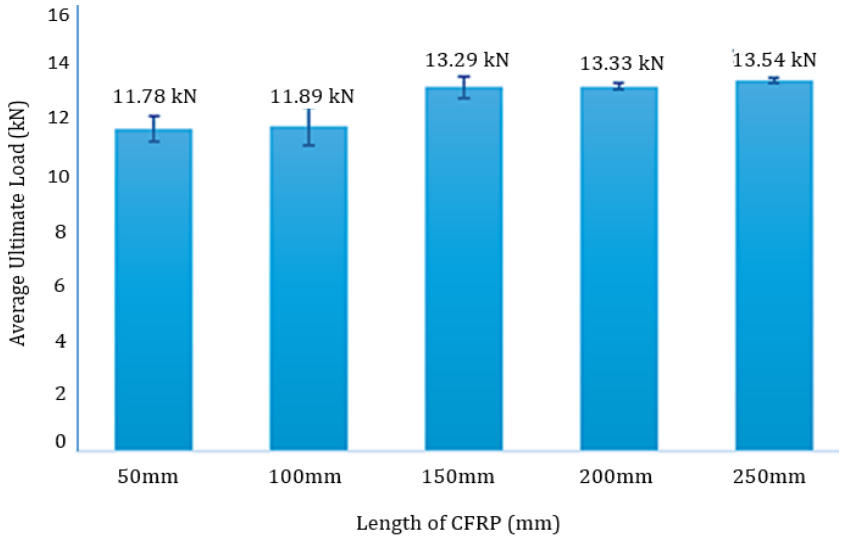


Fig. 8 *Average ultimate load graph*

A notable increase occurred at 150 mm, with the ultimate load reaching 13.29 kN. This increase is attributed to the larger bonding surface, which allowed for better stress distribution and delayed the onset of failure, although mixed failure modes were still observed. As the CFRP length increased to 200 mm (13.33 kN) and 250 mm (13.54 kN), the failure mode shifted predominantly to delamination. The longer plates facilitated greater composite action between the CFRP and concrete, enhancing load resistance. However, the gains beyond 200 mm became marginal, suggesting that additional length resulted in diminishing returns due to potential stress concentrations at the plate edges and increased susceptibility to delamination initiation. Thus, a 200 mm CFRP plate appears to provide an optimal balance between structural enhancement and material efficiency.

To quantify the flexural improvement achieved by CFRP strengthening, the percentage enhancement was calculated by comparing each specimen's ultimate load to that of an unstrengthened control beam. The control result, adapted from Omar et al. [11], recorded a peak load of 10.6 kN under similar testing conditions and beam configuration. The enhancement was determined using Eqn. (1) as follows:

$$\text{Enhancement}(\%) = \frac{F_{ult,strengthened} - F_{ult,control}}{F_{ult,control}} \times 100 \quad (1)$$

Table 3 elaborates the relationships among CFRP length, failure modes, and improvements in load capacity. Shear failure was predominant in beams with CFRP lengths of 50 mm and 100 mm, resulting in 11% and 12% increases, respectively. The limited length led to high stress concentrations at the CFRP tips, causing premature shear crack propagation. The 150 mm length exhibited mixed failure modes, transitioning from shear to delamination, and showed a significant 25% enhancement. This is because the longer bonding length allows for more effective stress transfer, reducing stress concentrations and promoting better load distribution. Beams with 200 mm and 250 mm CFRP plates demonstrated delamination failures, with enhancements of 26% and 28%, respectively. The improved performance is due to a greater contact area, which enhances bond strength and load distribution. However, excessive length beyond 200 mm may not yield significant benefits and could increase the risk of peel stresses and edge delamination.

These findings align with previous observations indicating that while longer CFRP plates enhance flexural stiffness, excessive lengths may introduce complications, including increased bending stresses and potential FRP fracture. According to Alhassan et al. [21], the performance factors, displacement ductility, energy absorption, and ultimate load and deflection all improved as the length of the primary CFRP sheets grew. For the first and second layers of the primary CFRP sheets, this pattern was nearly identical. Fayyadh & Razak [22] also have highlighted that longer CFRP plates can result in significant bending stresses, increasing the risk of failure. Moreover, the transition in failure modes from shear to delamination as length increases underscores the role of improved stress distribution and bonding efficiency in enhancing load capacity. It suggests that optimising CFRP length is critical to maximising structural performance while maintaining material efficiency.

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Table 3 *Experimental datasets*

CFRP Length (mm)	Sample No.	Failure Mode	F_{ult} (kN)	Δ at Failure (mm)	Average F_{ult} (kN)	Δ_{avg} at Failure (mm)	Enhancement (%)
CTL	-	Flexural	-	-	10.61	1.75	-
50	1	SF	12.29	1.81	11.78 ± 0.45	1.05	11
	2	SF	11.61	0.46			
	3	SF	11.43	0.88			
100	1	SF	11.11	1.10	11.89 ± 0.70	1.21	12
	2	SF	12.08	1.27			
	3	SF	12.47	1.25			
150	1	DF	13.70	2.00	13.29 ± 0.39	1.59	25
	2	SF	12.92	1.65			
	3	DF	13.26	1.12			
200	1	DF	13.30	1.29	13.33 ± 0.11	1.40	26
	2	DF	13.46	0.73			
	3	DF	13.24	2.17			
250	1	DF	13.49	1.64	13.54 ± 0.09	1.58	28
	2	DF	13.65	1.74			
	3	DF	13.47	1.35			

4. Conclusions

The effectiveness of CFRP and toughened mussel epoxy (TME) as strengthening materials for concrete beams was thoroughly investigated, focusing on the impact of CFRP length on flexural load at failure. Incorporating toughened CFRP plates, especially those 150 mm in length, significantly enhanced the flexural load capacity of the beams, with the 250 mm CFRP length yielding the highest ultimate load. However, improvements beyond 26% were minimal, indicating diminishing returns. Mussel powder incorporated into the epoxy resin matrix effectively enhanced the toughness and bonding properties of the CFRP, increasing fracture toughness and durability, while also offering an eco-friendly alternative to traditional epoxy systems. The use of TME in CFRP plates led to substantial improvements in load-carrying capacity, with enhancements of up to 28%. The flexural load at failure showed a clear correlation with CFRP length, with shorter CFRP plates exhibiting limited load-bearing capacity due to premature shear failure. The 200 mm CFRP length demonstrated the optimal balance, providing significant load enhancement while minimising material use. Delamination failure was preferred due to its more progressive nature. The flexural strength achieved was comparable to that of other FRP systems, with the incorporation of TME addressing common issues such as premature debonding and improving durability. Recommendations for future research include further exploration of the long-term performance of TME under varying environmental conditions, optimisation of mussel powder content, investigation of different beam sizes and reinforcement configurations, and comparative studies with other FRP systems, including hybrid materials. The use of non-destructive testing methods, such as ultrasonic pulse velocity or acoustic emission, is also recommended to monitor internal distress in CFRP-strengthened beams over time, thereby aiding the development of better design guidelines for practical applications.

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Conflict of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***Study conception and design:*** *Syahrin Azhar, Nabila Azhar, Hilton Ahmad;* ***Data collection:*** *Syahrin Azhar, Nabila Azhar;* ***Analysis and interpretation of results:*** *Syahrin Azhar, Nabila Azhar, Hilton Ahmad;* ***Draft manuscript preparation:*** *Syahrin Azhar, Nabila Azhar, Hilton Ahmad. All authors reviewed the results and approved the final version of the manuscript.*

References

[1] ACI 440.2R-08 (2008). Guide for the design and construction of externally bonded FRP systems for strengthening concrete structures. American Concrete Institute.

[2] Samad, U. A., Alam, M. A., Abdo, H. S., Anis, A., & Al-Zahrani, S. M. (2023). Synergistic effect of nanoparticles: enhanced mechanical and corrosion protection properties of epoxy coatings incorporated with SiO_2 and ZrO_2. Polymers, 15, 3100. https://doi.org/10.3390/polym15143100

[3] Fong, C., Chin, D. D., & Ahmad, H. (2023). Static shear strength of single-lap joint using eggshell-toughened epoxy as adhesive agent. International Journal of Integrated Engineering, 15, 104–112. https://doi.org/10.30880/ijie.2023.15.02.010

[4] Velayutham, S., Sugiman, S., Ahmad, H., & Mohd Jaini, Z. (2024). Shear strength of adhesively bonded joint with toughened epoxy mussel powder. International Journal of Integrated Engineering, 16, 201–212. https://doi.org/10.30880/ijie.2024.16.01.016

[5] Wang, L., Hu, W., Wang, H., Liu, Z., Li, D., Ge, Y., & Zheng, Z. (2024). Mussel adhesive protein inspired functionalization of steel fibers for better performance of steel fibers reinforced concrete. Construction and Building Materials, 436, 136887. https://doi.org/10.1016/j.conbuildmat.2024.136887

[6] Soudki, K., El-Salakawy, E., & Craig, B. (2007). Behavior of CFRP strengthened reinforced concrete beams in corrosive environment. Journal of Composites for Construction, 11, 291–298. https://doi.org/10.1061/(asce)1090-0268(2007)11:3(291)

[7] Hawileh, R. A., Musto, H. A., Abdalla, J. A., & Naser, M. Z. (2019). Finite element modeling of reinforced concrete beams externally strengthened in flexure with side-bonded FRP laminates. Composites Part B: Engineering, 173, 106952.

[8] Azhar, S., Sugiman, S., Omar, Z., & Ahmad, H. (2025). Experimental investigations of strengthened beam with co-cured carbon FRP and mussel shell-modified epoxy. Ain Shams Engineering Journal, 16, 103563. https://doi.org/10.1016/j.asej.2025.103563

[9] Azhar, S., Sugiman, S., Omar, Z., & Ahmad, H. (2026). Numerical modelling of concrete beams strengthened with co-cured CFRP plates with a mussel shell modified epoxy (MME): An XFEM-CZM traction–separation framework with experimental works validation. Multiscale and Multidisciplinary Modeling, Experiments and Design, 9, 103. https://doi.org/10.1007/s41939-026-01192-z

[10] Azhar, S., Velayutham, S., Sugiman, S., Chin, D. D., & Ahmad, H. (2024). Static Shear Strength of Double-Strap and Single-Lap Joints Incorporating Toughened Mussel Shell Powder with Epoxy. International Journal of Sustainable Construction Engineering and Technology, 15, 178-191. https://doi.org/10.30880/ijscet.2024.15.03.016

[11] Omar, Z., Sugiman, S., Yusoff, M. M., & Ahmad, H. (2022). Predicting the flexural behaviour of CFRP-strengthened concrete beam using combined XFEM and cohesive zone model. Journal of Applied Science and Engineering (Taiwan), 25, 925–938. https://doi.org/10.6180/jase.202212_25(6).0003

[12] Ridhwan, M. M., Ahmad, H., & Mansor, H. (2022). FEA modelling of externally-strengthened concrete beam with CFRP plates under flexural test. International Journal of Integrated Engineering, 14, 258–271.

[13] Teng, J. G., Chen, J. F., Smith, S. T., & Lam, L. (2003). Behaviour and strength of FRP-strengthened RC structures: A state-of-the-art review. Proceedings of the Institution of Civil Engineers: Structures and Buildings, 156, 51–62. https://doi.org/10.1680/stbu.2003.156.1.51

[14] Sainudin, M. S., Othman, N. H., & Shahidan, S. (2019). Performance of concrete containing mussel shell (Perna viridis) ash under effect of sodium chloride curing. IOP Conference Series: Materials Science and Engineering, 601, 012033. https://doi.org/10.1088/1757-899X/601/1/012033

[15] Teychenne, D. C., Franklin, R. E., & Erntroy, H. C. (1988. Design of Normal Concrete Mixes. Building Research Establishment (BRE).

[16] BS EN 12390-5 (2019) Testing Hardened Concrete - Part 5: Flexural Strength of Test Specimens. British Standards Institution.

[17] Ding, J., Wang, F., Huang, X., & Chen, S. (2024). Bond–slip characteristics and effective anchorage length of CFRP-strengthened concrete beams under flexural loading. Construction and Building Materials, 412, 133078. https://doi.org/10.1016/j.conbuildmat.2023.133078

[18] Al-Rousan, M. A., Alhassan, E. A., & Alshuqari, M. A. (2018). Behavior of plain concrete beams with DSSF strengthened in flexure with anchored CFRP sheets: Effects of DSSF content on the bonding length of CFRP sheets. Case Studies in Construction Materials, 9, e00195. https://doi.org/10.1016/j.cscm.2018.e00195

[19] Wang, X., Liu, Y., Li, J., & Zhang, Z. (2022). Debonding behavior and flexural performance of RC beams strengthened with externally bonded CFRP sheets under four-point bending. Composite Structures, 288, 115359. https://doi.org/10.1016/j.compstruct.2022.115359

[20] Liu, D., Qin, F., Di, J., & Zhang, Z. (2023). Flexural behavior of reinforced concrete (RC) beams strengthened with carbon fiber reinforced polymer (CFRP) and ECC. Case Studies in Construction Materials, 19, e02270. https://doi.org/10.1016/j.cscm.2023.e02270

[21] Alhassan, M., Al-Rousan, R., & Ababneh, A. (2021). Anchoring of the main CFRP sheets with transverse CFRP strips for optimum upgrade of RC beams: Parametric experimental study. Construction and Building Materials, 293, 123525. https://doi.org/10.1016/j.conbuildmat.2021.123525

[22] Fayyadh, M. M., & Razak, H. A. (2021). Externally bonded FRP applications in RC structures: A state-of-the-art review. Jordan Journal of Civil Engineering, 15, 157–179.