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Enhancing UHPC Beam Performance with GFRP Sheets

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ABSTRACT

A cement-based composite, ultra-high-performance concrete (UHPC) helps both new and old buildings last longer in service. The growing demand for quality building materials and applications has led to the emergence of various commercial UHPC formulations after decades of research and development. Nevertheless, they are costly and necessitate strict design specifications. Infrastructure like bridges commonly experience structural vibration and static loads during traffic congestion, which can reduce their service life. This study examines the impact of the length and pattern of Glass Fibre Reinforced Polymer (GFRP) sheets wrapped around UHPC beams to strengthen them. The tested UHPC beams had dimensions of 100 × 100 × 500 mm. One beam was tested without GFRP reinforcement, while six beams with various GFRP patterns were subjected to a four-point loading test. The study assessed the initial fracture load, energy absorption, deflection, and ultimate load capacity. Compared to unwrapped beams, the experimental results indicated that GFRP-wrapped beams exhibit substantially higher initial and final load-carrying capacities. The results reveal that GFRP reinforcement can greatly enhance the longevity and structural efficiency of UHPC beams.

Keywords: Ultra-high-performance concrete; fiber-reinforced polymer; glass fiber-reinforced polymer; flexural test

INTRODUCTION

Ultra-high-performance concrete (UHPC) has become a revolutionary material in the construction industry, particularly in applications that necessitate exceptional durability and strength, such as bridges, high-rise structures, and other critical infrastructure. A substantial improvement over conventional concrete, UHPC has compressive strengths between 150 and 810 MPa, or about three to sixteen times that of regular concrete (Ullah et al. 2022). Combining highly refined ingredients, such as high-quality aggregates, lower water-to-cement ratio, and fibres that boost the material's overall performance, allows for this remarkable durability improvement (Richard & Cheyrezy 1995).

A recent study has delved into how UHPC can be used to fix broken reinforced concrete (RC) beams. Research conducted by Gao et al. (2023) discovered that damaged RC beams may have their flexural performance greatly enhanced using post-installed reinforcing bars coupled with UHPC layers. A UHPC plate reinforced with FRP grids and 12-mm-long polyethylene (PE) fibres significantly increased the flexural capacity (Zeng et al. 2022). According to Al-Huri et al. (2023), corroded RC beams strengthened with UHPC layers on three sides significantly improved finalised flexural strength.

Although UHPC has many outstanding qualities, it has certain limits, the most notable of which is its weak tensile strength compared to its compressive strength. Due to the weakness caused by tension, further reinforcement is necessary, especially for users who encounter flexural loads. According to Baggio et al. (2014), fiber-reinforced polymer (FRP) materials have emerged as a preferred option for reinforcing UHPC due to their exceptional resistance to corrosion, simplicity of application, and high strength-to-weight ratio. UHPC beams reinforced with FRP greatly improve their structural performance, increasing their service life and resilience to flexural loads (Graybeal 2006).

There have been a lot of studies on using FRP plates and sheets to repair and fortify UHPC buildings in the last few years. Baggio et al. (2014) have investigated the potential of FRP sheets, specifically glass fiber-reinforced polymer (GFRP) sheets, to enhance the load-bearing capacity and endurance of undamaged and damaged UHPC beams. These tests show that the performance of reinforced beams can be drastically altered by experimenting with various wrapping arrangements and installation processes. Some GRFP sheet configurations include full wraps, U-wraps, and bottom wraps; these variations offer different benefits in load distribution and confinement (Kobayashi & Fujisaki 1995).

Using carbon fiber-reinforced polymer (CFRP) plates can further optimise the performance of UHPC beams under flexural loads. It is widely recognised that CFRP plates possess remarkable durability and rigidity, which can substantially improve the flexural capacity of UHPC beams. For efficient load transmission and maximisation of reinforcing advantages, the bonding of CFRP plates and UHPC is critical. According to Zhang et al. (2023), UHPC beams can enhance their static behaviour by strategically using CFRP plates. This leads to larger load capacities and better deflection characteristics.

Zhang (2020) and Zhang (2023) examined the flexural performance of damaged and undamaged UHPC beams strengthened with FRP sheets and plates. Zhang (2020) discovered that adding a reinforced UHPC layer substantially enhanced the cracking and ultimate loads of fractured RC beams. The most substantial improvement was observed with the application of steel wire mesh. In addition, Zhang (2023) suggested an innovative approach to fix broken RC beams by using a steel plate and UHPC composite. This made the beams much stronger and better at resisting cracking. Incorporating UHPC into BFRP-reinforced beams enhanced their flexural performance in terms of moment capacity, fracture patterns, and deflection response (Alhoubi 2022). Despite advances in UHPC and FRP reinforcement, few studies assess the efficacy of various FRP strengthening patterns on damaged and undamaged beams. There is also a lack of knowledge on the energy absorption properties of UHPC beams supplemented with different FRP designs when subjected to dynamic loading forces.

The study aims to thoroughly analyze how strengthened and un-strengthened UHPC beams perform in bending tests using FRP sheets and FRP plates. The load-deflection response, static behaviour, and failure modes of the beams are the primary parameters. The experimental configuration includes testing twelve UHPC beams, including undamaged and damaged specimens, with varying CFRP and GFRP strengthening patterns. This research intends to find the best strengthening pattern that adds structural performance and maximises load capacity by measuring various beam's performance (Mahaini et al. 2023).

The study delves into the reinforced beam's static behavior and energy absorption capacities. The discovered capacity of a material to dissipate energy during loading by energy absorption is a critical parameter that enhances its resilience to dynamic loads and impact. The results of the flexural tests offer valuable insights into the efficacy of various FRP reinforcement strategies in improving the structural strength and durability of UHPC beams.

EXPERIMENTAL PROGRAM

The research involved the preparation of twelve UHPC beam specimens, with dimensions of 100 × 100 × 500 mm per specimen with M-150 grade. Table 1 indicates the obtained specimens from Dura Technology Sdn. Bhd (dura.com.my). were intended to satisfy the BS EN 12390-1 strength and serviceability standards. Two categories were created for the beams of damaged and undamaged. Each group was subjected to three FRP strengthening patterns, while a single beam acted as the control specimen, devoid of any FRP reinforcement. All specimens were subjected to a four-point flexural test to determine the performance criteria.

TABLE 1. Technical characteristics of the UHPC beam from DURA Technology Sdn.Bhd

Properties	Value
Flexural Bending	25 – 35 MPa
Young Modulus (E)	45 – 50 GPa
Elastic tensile	> 8 MPa
Post–cracking tensile	>10 MPa
Durability	
Chloride ion diffusion	0.08×10^{-12} m^2/s
Carbonation penetration depth	<0.1 mm
Freeze or thaw (after 300 cycles)	100%
Rapid chloride permeability	<100 coulomb
Water absorption	<0.2%
Abrasion resistance	< 0.03 mm
Other properties	

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Density	2400 – 2500 kg/ m^3
Entrapped air content	2 – 4 %
Capillary porosity (>10 mm)	<1 %
Total porosity	2 – 6 %
Post cure shrinkage	$<10^{-5}$
Creep coefficient	0.2 – 0.5

The experimental goals were met by meticulously preparing the GFRP sheets and applying them to the beams in predetermined patterns. The sheets were cut to size using scissors (Figure 1) to the appropriate dimensions for binding with the samples. Cleaning the surfaces of the GFRP sheets to remove any debris, grime, or additional impurities was necessary to guarantee optimal bonding. The process was accomplished with the use of compressed air or brushes.

FIGURE 1. Preparation of GFRP sheet

It was necessary to smooth out the concrete surface of the UHPC beam before pouring the epoxy. After the surface was prepared, the GFRP sheet was connected to the UHPC beam surface using epoxy adhesive, following the typical wet layup process (Figure 2). The GFRP sheets were subsequently marked and measured to match the specified patterns, including complete wrap, U-wrap, or bottom wrap configurations.

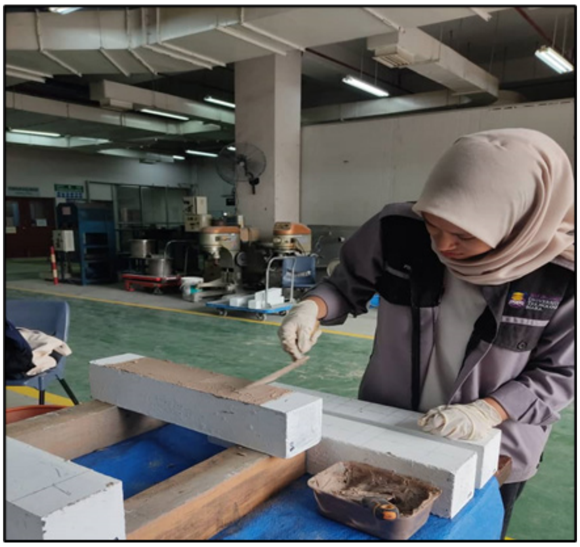


FIGURE 2. Applying the adhesive

STRENGTHENING PROCEDURE SETUP

Pattern A, which stands for U-wrapping, was utilised in this study's GFRP sheets. The dimensions of each pattern were modified to meet the study's specifications (Figure 3). The proportions of the U-wrap pattern were 300 × 100 mm, which allowed for a higher level of containment, improved confinement effect, and limited lateral expansion of the concrete or masonry. Seismic retrofitting applications requiring resistance to lateral loads benefit from this configuration's increased flexibility and strength.

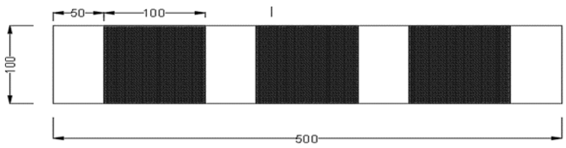


FIGURE 3. Detailing of Pattern A (U-wrap pattern)

Meanwhile, Figure 4 shows Pattern B, a full-wrap layout with dimensions of 300 × 400 mm, was picked since it looks smooth and continuous, rendering the application better overall. This pattern is paramount in architecture and design, where a uniform, striking appearance is essential. In contexts with a cohesive and integrated look, the full-wrap design's assurance of uniformity and consistency across the surface is crucial to preserving the design's integrity.

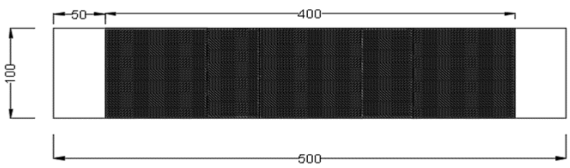


FIGURE 4. Detailing of Pattern B (Full-wrap pattern)

Figure 5 shows that the GFRP sheets were bonded solely to the bottom surface of the beam using the bottom-wrap pattern (Pattern C), which had dimensions of 400 × 100 mm. It is common practice to use this design when reinforcing the foundation of a building to increase its strength and capacity to support loads. Applying fiber-reinforced plastic (FRP) sheets to the bottom of a structure is an ideal method to control cracks and increase its flexural strength. The practicality of this application is contingent upon the construction being in accessible locations, as concrete structures may crack for various reasons.

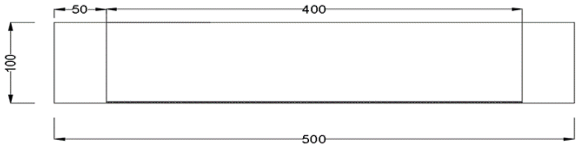


FIGURE 5. Detailing of Pattern C (Bottom-wrap pattern)

The Sikadur 31 CF adhesive was applied to attach the GFRP sheets. The process used a roller to prevent air pockets and ensure the epoxy adhered well to the concrete and sheets throughout the application. It was critical to ensure the GFRP surface was flat before applying the strain gauge using duct tape. Once the surface preparation was finished, the strain gauge was carefully installed on top of the Epoxy Bond Primer-treated concrete.

FLEXURAL TEST

Table 2 shows the size of the GFRP sheet used in the testing of the specimen beams under four-point flexural loading until failure, with no longitudinal reinforcing. The beams, size 100 × 100 × 500 mm, were chosen based on early calculations and experiments, taking into account the dimensions and capacity of the testing apparatus, as well as the practicality of performing all strengthening patterns. GFRP sheet patterns of three distinct varieties were implemented on both the undamaged and damaged UHPC beams.

TABLE 2. Details of the size of the GFRP sheet

Specimen	Type of specimen
CBA	Control beam
UDA	Undamaged U-wrap
DA	Damage U-wrap
UDB	Undamaged full wrap
DB	Damaged full wrap
UDC	Undamaged bottom wrap
DC	Damaged bottom wrap

Using the methodology and procedures outlined in ASTM C1609, every test variable was applied to each beam. A uniaxial load was applied at a rate of 0.2 mm/min using a 250 kN Universal Testing Machine (UTM). Figure 6 shows that the beams had a 500 mm clear span and were stabilised at both ends by a pin-type construction. A steel frame with two LVDTs was built up at the beam's midpoint to allow for precise measurements of mid-span deflection independent of support settlement.

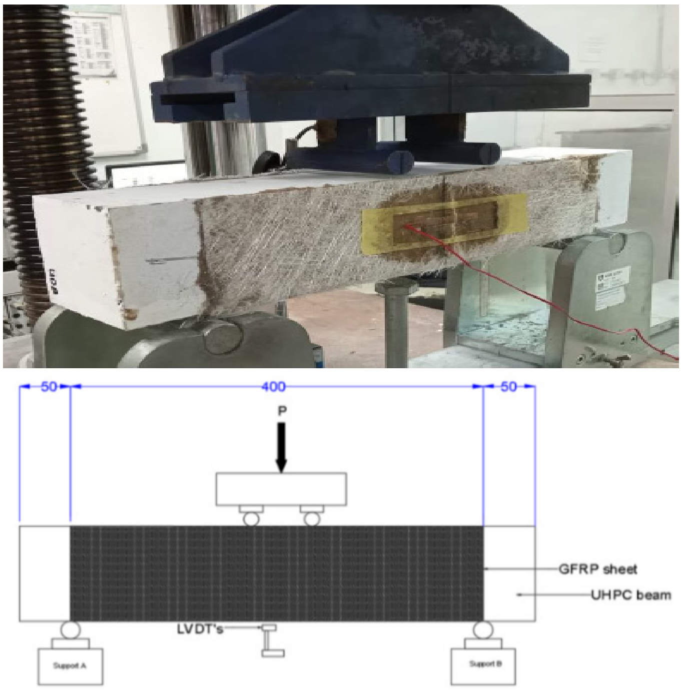


FIGURE 6. Setting up for the flexure test

RESULTS AND DISCUSSION

FAILURE MODE

The four-point bending flexure test is essential for illuminating the failure modes of UHPC beams. The failure mode describes how a beam breaks or gets severely damaged while being tested. Flexure tests provide visual inspection of the beams undergoing loading, enabling the detection of failure modes. As the weight is applied, observing the beam for any apparent indications of distress, fractures, or damage is vital. Beam cracks beginning to develop, concrete spalling, or complete rupture can be early warning signs of the likely failure mode.

Internal cracks in the UHPC beam could develop and spread as the stress grows. These fractures offer valuable insights into the failure mode due to their shape, size, and location. For example, tensile strains might be to blame for failure if cracks mostly appear on the tension face. In contrast, fractures that mostly occur at the compression face suggest that compressive forces caused the failure. As the first fracture formed under load, the failure mode was visually identified during the flexure test.

Table 3 shows the UHPC beam findings that are categorised as either damaged (DA, DB, DC) or undamaged (UDA, UDB, UDC), with a control beam (CBA). UDA and DA used a U-wrap pattern (Pattern A); DB and UDB used a full-wrap pattern (Pattern B); and DC and UDC used a bottom-wrap pattern (Pattern C).

TABLE 3. Load at initial crack visible for specimens

Specimen	Initial cracks (kN)
CBA	70.52
UDA	71.91
DA	37.23
UDB	85.34
DB	59.00
UDC	81.20
DC	58.72

Besides, Table 3 also shows that the presence of GFRP wraps was seen to delay the crack formation. Beams with GFRP wrapping are more resistant to crack onset and propagation, which increases their load-bearing capability. The undamaged UHPC beams had greater ultimate failure and beginning cracking loads compared to the damaged beams. It was noted that the amount of GFRP layers increased both the failure load and the first cracking load for beams with full-wrap designs. The control beam showed lower initial cracking loads than the UDB and UDC beams. For instance, UDB had a load-carrying capability similar to UDC because the full-wrap structure successfully stopped cracks from starting on the underside of the beam.

The damaged UHPC beams had a lower load-carrying capability within the same set than the intact beams. This enhancement corresponds to the improved confinement that the longer GFRP wraps provide. Compared to the UHPC-damaged beams, the control beams showed earlier signs of crack formation. Several recorded failure scenarios employing GFRP-enhanced reinforced concrete beams demonstrate that the specimens are subjected to increasing stresses until failure. At first, the lack of cracking suggests that the material is elastic. Stage two involves cracking, which reduces the moment of inertia and hence the beam's bending stiffness; stage three, the last loading phase, involves the longitudinal tensile reinforcement yielding. In contrast to the yielding of the steel reinforcement, the external FRP strengthening is elastic and can sustain more significant stresses.

Consistent with the results of Attari et al. (2012), who examined concrete beams using GFRP sheets, this study shows that UHPC beams utilising GFRP sheets with varied patterns experience first crack formation. The study employed a four-point bending device to instrument and evaluate UHPC beams with flexural strengthening while subjected to multiple loading sequences.

According to the findings, Attari et al. (2012) reported, the initial crack was observed at a load of 3.07 kN, and further cracks were more common in PB6 beams than in the others. Among the materials tested, UDB showed a substantial first crack load. The results of this research suggest that the strength values are higher than those published by Attari et al. (2012). Cracks did not form at lower loads because the strength was affected by the full-wrap pattern and the particular kinds of beams utilised for UDB. Figure 7 indicates the result of the cracking on the beam.

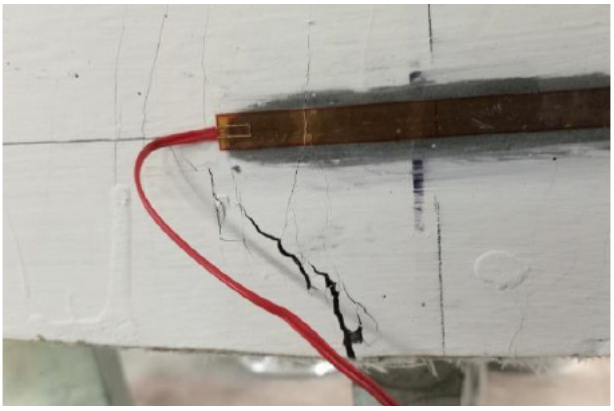


FIGURE 7. Beam cracking

The mechanical qualities of the material and the strengthening arrangements influenced the failure modes displayed by the tested specimens. Research in this area was based on the premise that a material's modulus or stiffness would dramatically change just before the first crack appeared.

ENERGY ABSORPTION

Energy absorption is a significant parameter that indicates a material's capacity to release energy while loading, thereby increasing its endurance to dynamic loads and impacts. This research used four-point flexural testing to assess the energy absorption capacity of UHPC beams reinforced with various GFRP designs. The analysis focused on determining the reinforcing pattern's effects on beam energy absorption and structural performance.

Data on the load-deflection relationship was continuously recorded during flexural testing, and the total area under the load-deflection curve was calculated to determine the energy absorption capabilities of each sample. This region corresponds to the cumulative energy absorbed by the beam until it reaches failure, which is directly linked to the deflection at the point of failure. The results showed that damaged and undamaged beams and different GFRP reinforcing schemes absorbed energy differently.

Figure 8 reveals that the undamaged beams reinforced with GFRP had greater energy absorption capacities in comparison to the damaged beams. Within the intact beams, the U-wrap pattern (Pattern A) slightly improved energy absorption. In contrast, the full-wrap design (Pattern B) substantially increased the energy absorption capacity. The bottom-wrap design, Pattern C, similarly enhanced energy absorption, albeit to a smaller degree than the full-wrap pattern. According to these results, the full-wrap pattern is the most efficient reinforcement approach for increasing the durability of UHPC beams since it dissipates energy the most effectively.

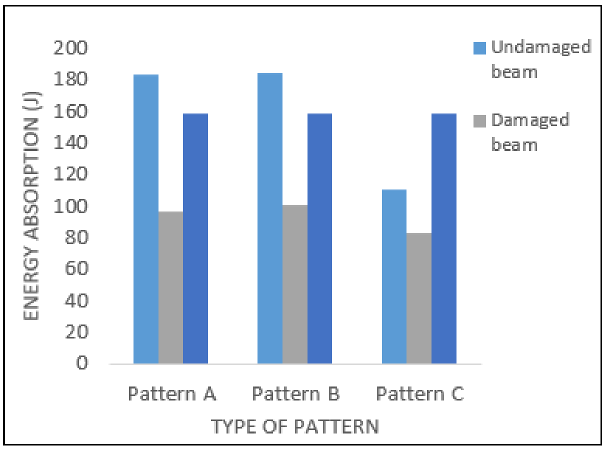


FIGURE 8. Energy absorption for specimens

A comparable pattern was noted for the impaired beams. The U-wrap pattern demonstrated enhanced energy absorption in comparison to the control beam, while the full-wrap pattern exhibited the most remarkable improvement in energy absorption capacity. Including the bottom-wrap design also enhanced energy absorption, although its effectiveness was inferior to that of the full-wrap configuration. This suggests that the full-wrap pattern is the most efficient strengthening method, even when circumstances are compromised.

Furthermore, the outcomes show that the undamaged beams, reinforced with the full-wrap pattern, had the highest energy absorption. The bottom-wrap and U-wrap patterns followed but absorbed less energy in comparison. The UDA beam absorbed a total of 183.56 J, greater than the amount of energy absorbed by the control beam CBA, which was 158.43 J. This indicates that an increased surface area of GFRP wrap signifies a higher capacity to absorb energy. Integrating the area under the load-deflection curve yields the total energy absorption, which is then added to the incremental energies between the data points. The methods carried out on the beam throughout the test is reflected in its energy measurement, which shows its ability to absorb and spread energy.

These findings are corroborated by the research conducted by Altun et al. (2013), which demonstrated that hybrid fiber-reinforced concrete specimens were produced by incorporating steel and polypropylene (PP) fibres in varying ratios, resulting in improved energy absorption. Pattern B, the undamaged beam with the full-wrap pattern, exhibited the highest energy absorption in this investigation, absorbing 184.4 J, surpassing all other specimens. Consequently, a load-deflection curve develops as the specimen is subjected to a constant load while simultaneously measuring its deformation.

The bending moment at any given position during the test is obtained by multiplying the applied force by the distance between the load application point and the specimen's neutral axis, which creates a load-deflection curve. The stress is then computed by dividing the bending moment by the section modulus of the material. The load-deflection behaviour and strength of the various beam types utilised in this investigation were factors that contributed to the higher energy values. Moreover, the GFRP sheets substantially increased the overall strength of the beams by enhancing the strength of higher specimens.

The study's findings highlight the crucial significance of GFRP reinforcing patterns in improving the energy absorption abilities of UHPC beams. The full-wrap pattern, specifically, delivered enhanced performance by guaranteeing a higher level of load dispersion and averting premature failure. The setup facilitated a more uniform distribution of loads along the beam, enabling it to absorb more energy before reaching a state of failure. The beam is more resistant to dynamic loads and has greater longevity and structural integrity due to the enhanced energy absorption.

Aside from the quantitative analysis, the failure modes found during the experiments yielded qualitative observations into the energy absorption behaviour. Beams that received reinforcement with the full-wrap pattern showed a higher distribution of fractures and less severe cracking, suggesting a flexible and more resilient failure mode. It differs from the more fragile breakdown exhibited in control beams and those with ineffective reinforcement patterns.

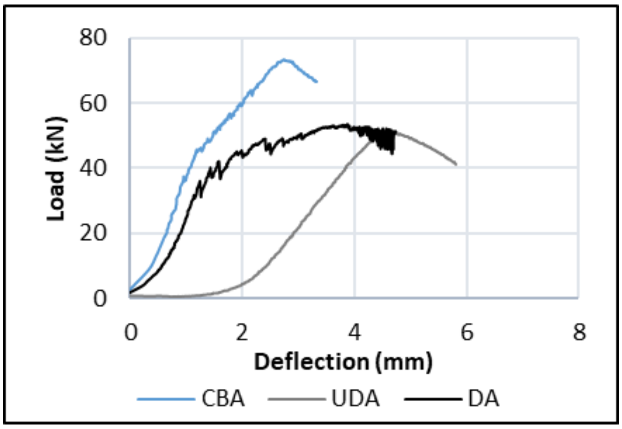
LOAD-DEFLECTION RELATIONSHIP

A flexure test places a specimen under bending force delivered at two locations, usually at the supports. The specimen undergoes deformation in response to the applied force, and the measured deflection is used to establish a correlation between the two variables. A load-deflection curve represents this connection graphically and offers essential information about the material's mechanical properties under bending stress.

The load-deflection curve includes important points, including the yield point, elastic limit, failure point, and ultimate strength. For bending applications, these points are utilised by material scientists and engineers to evaluate the material's flexibility, stiffness, and strength. The load-deflection curve's data is vital for assessing the material's performance and structural integrity.

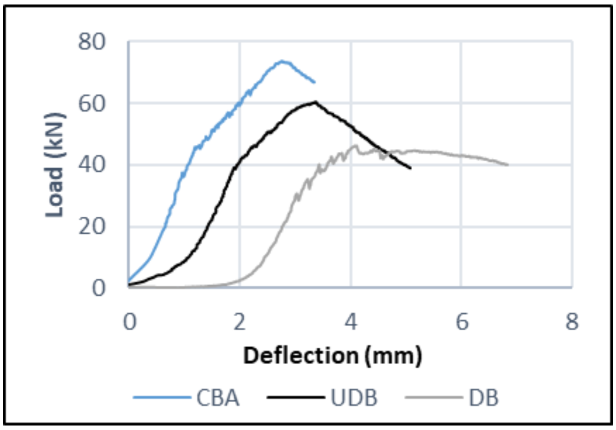
Figure 9 displays the load-deflection responses of beams with various GFRP patterns, including both damaged and undamaged conditions. The graphic illustrates the consistency of outcomes among various samples since the curves for comparable patterns exhibit strong concurrence. It implies that the test findings are repeatable and reliable.

Figure 9 (a) displays the load-deflection contours for beams with the U-wrap pattern (Pattern A). The GFRP wrapping effectively improves the load-bearing capability of the beams, as evidenced by the closely aligned contours of both damaged and undamaged beams. The undamaged beam (UDA) has a higher load-deflection response in comparison to the damaged beam (DB), indicating that the U-wrap pattern substantially enhances the structural performance of UHPC beams. The findings suggest that the U-wrap GFRP design is a highly successful method for repairing and reinforcing damaged beams.



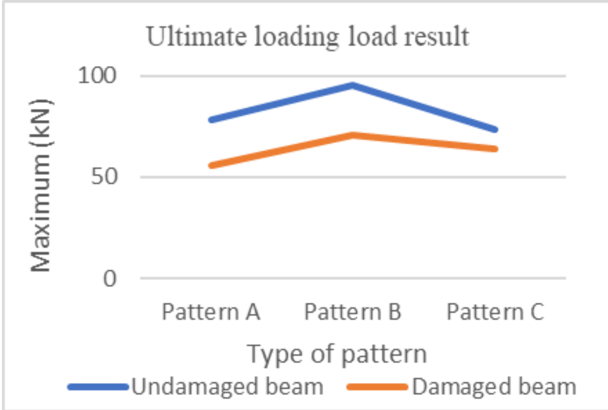
(a) Load deflection Pattern A

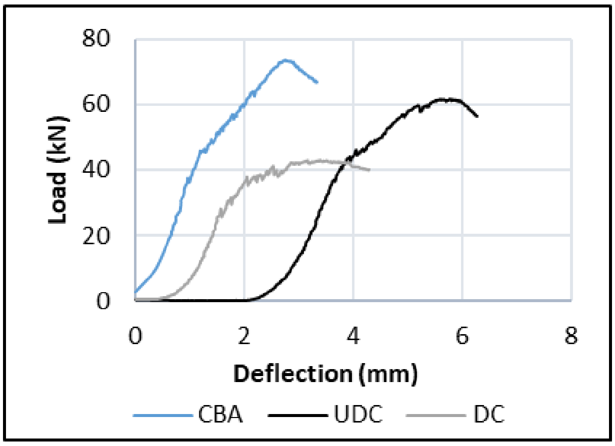
Meanwhile, Figure 9 (b) displays the load-deflection curves for beams with a full-wrap pattern (Pattern B). The undamaged beam demonstrates an enhanced load-deflection response compared to the damaged beam, resembling the outcomes found in Pattern A. Nevertheless, the correlation between the two categories of beams is not as uniform as in the U-wrap configuration. However, the full-wrap pattern substantially improves the load-bearing capacity of both damaged and undamaged beams.



(b)Load deflection Pattern B

Figure 9 (c) exhibits the load-deflection curves for beams featuring the bottom-wrap pattern (Pattern C). Similar to the preceding patterns, the undamaged beam exhibits a greater load-deflection response than the damaged beam. This pattern provides evidence that using GFRP reinforcement improves the structural performance of UHPC beams. Undamaged beams (UDA, UDB, UDC) consistently perform better than damaged beams (DA, DB, DC).





(c) Load deflection Pattern C

FIGURE 9. Load deflection result

A study by Yoo et al. (2015) evaluated the load-deflection relationship, the failure mode, ultimate load, and reinforcement yielding. The research yielded valuable insights into the impact of various reinforcing designs and materials on the structural integrity of beams. In addition, Additionally, Choi et al. (2013) investigated the load-deflection behaviour of RC beams using three different specimens made of aggregates with different compositions: one with 100% natural aggregate, one with 100% recycled coarse aggregate, and one with 50% recycled fine aggregate. The specimens were exposed to continuous loading at 50% of their flexural capacity.

Yoo et al. (2015) reported that the bottom-wrap pattern (Pattern C) was the most effective in achieving the maximum load deflection in beams. However, load deflection was higher in both damaged and undamaged beams in this study than in Yoo et al. (2015). This suggests that the type of beams and the particular patterns of the GFRP sheets used for reinforcement impact the maximum load capacity.

The ideal load capacity for strength varies based on the material and the particular use case. In materials science and engineering, the strength of a material is frequently assessed based on its ability to endure the highest level of stress or strain before it breaks down. The appropriate load capacity is often determined using layout or application criteria and safety considerations.

Figure 10 further *depicts the ultimate loading capacity, energy absorption, and initial fracture resulted from this research. The* ultimate load capacity of 95.08 kN was achieved by the undamaged beam with the full wrapping pattern (Pattern B). The load capacity of the specimens was significantly affected by the wrapping patterns of GFRP, with the full-wrap pattern resulting in the highest improvement in strength.

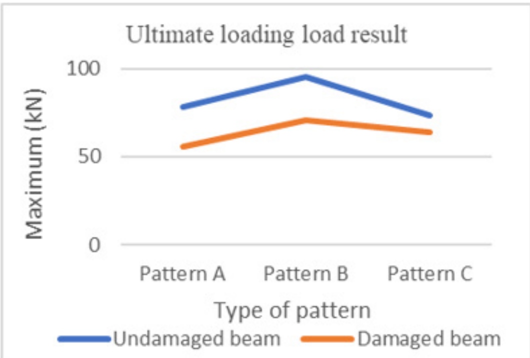


FIGURE 10. The ultimate load capacity for specimen

CONCLUSION

The primary objectives of this study were to quantify the energy absorption throughout flexural tests involving damaged and undamaged beams and to investigate the static behaviour of UHPC beams under various conditions, such as failure modes and load deflection, using FRP sheets. Additionally, the study aimed to determine the optimal load capacity for reinforced UHPC beams with varying FRP patterns. Tests were conducted on two sets of beams, one damaged and the other undamaged. Each beam was reinforced with a single GFRP layer and several patterns.

The experimental analysis revealed that the use of FRP sheets has a substantial impact on the static behaviour of UHPC beams. FRP-wrapped beams demonstrated a more significant moment of resistance as opposed to the control beam. Although the load-bearing capacity was improved by FRP wrapping, the flexibility of the beams was decreased. Particularly, the failure pattern of fully wrapped beams transitioned from ductile to brittle. In addition to enhancing the structural durability of the beams, the strategic positioning of FRP sheets mitigated the negative impacts of damage.

Pattern B (full wrap) was the most effective among the several GFRP sheet patterns reviewed in enhancing the strength between the damaged and undamaged beams. This design effectively prolonged the crack's initiation and spread, boosting the ultimate load-bearing capacity. The beams wrapped with FRP, particularly those with the full-wrap pattern, exhibited a significant enhancement in moment resistance in comparison to the control beams.

The energy absorption values acquired from the flexure tests varied depending on the type of wrapping implemented. The study found that the full-wrap pattern (Pattern B) absorbed energy most. The undamaged full-wrap beam (UDB) absorbed 184.4 J, the highest among all the specimens evaluated. This arrangement ensured optimal distribution and support of applied loads. The comprehensive analysis of energy absorption in flexural tests provided valuable insights into the structural behaviour of UHPC beams under bending conditions.

Overall, the study effectively achieved all of its objectives. The results highlight the importance of using FRP wrapping to improve the load-carrying capacity, structural reliability, and capacity to absorb the energy of UHPC beams. The results offer a thorough comprehension of how various FRP patterns impact the performance of UHPC beams, providing useful insights for designing and implementing these materials in practical building situations. The implementation of the full-wrap Glass Fibre Reinforced Polymer (GFRP) pattern was found to be the most effective method of reinforcement, leading to a considerable enhancement in the performance of both damaged and undamaged Ultra-High Performance Concrete (UHPC) beams.

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DECLARATION OF COMPETING INTEREST

None.

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