E-ISSN: 2528-388X
P-ISSN: 0213-762X

INERSIA
Vol.21, No.1, May 2025

The Behavior of Reinforced Concrete Beams with Various Carbon Fiber Retrofitting Methods in Enhancing Stiffness

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Keywords:
Retrofitting
Stiffness
NSM
CFRP Sheet
CFRP Rods

ABSTRACT

This study investigates the effectiveness of Carbon Fiber Reinforced Polymer (CFRP) sheets and rods in improving the structural performance of reinforced concrete beams. Three beam specimens were tested: a control beam (BN), a beam reinforced with CFRP rods (BTC), and a beam reinforced with CFRP sheets (BLC). The experimental evaluation focused on key parameters, including first crack load (P_{crack}), yield load (P_{yield}), maximum load (P_{max}), and deflections at critical points. The stiffness of the beams was assessed at both the cracking stage (K_{crack}) and the yielding stage (K_{yield}). The results demonstrate that the beam reinforced with CFRP sheets (BLC) exhibited the highest improvements in stiffness, with an increase of 184.89% in K_{crack} and 221.21% in K_{yield} compared to the control beam (BN). The CFRP rod-reinforced beam (BTC) also showed enhanced performance, but to a lesser extent, with increases of 72.69% in K_{crack} and 64.78% in K_{yield} compared to BN. The data reveals that BLC significantly reduces deflection and enhances load-bearing capacity, particularly in resisting initial cracking and yielding. The discussion highlights that CFRP sheets provide superior stiffness improvement compared to CFRP rods, making them more suitable for applications where increased stiffness and reduced deflection are critical. While CFRP rods effectively increase the ultimate load capacity, their impact on stiffness is less pronounced than CFRP sheets. In conclusion, CFRP sheets offer a more effective reinforcement solution for enhancing stiffness and controlling deflection in concrete beams, especially in structures requiring high resistance to cracking and yielding.

1. Introduction

Strengthening building structures is a critical aspect of civil engineering aimed at improving structural performance and ensuring long-term stability. Several factors necessitate the retrofitting of existing buildings, including changes in building use, structural deterioration, and damage caused by seismic activity [1]. Among these, the most common scenario involves modifications to building function, often triggered by changes in ownership or operational requirements. Such changes typically lead to increased loads beyond the initial design capacity of the structure, necessitating reinforcement measures to accommodate the new functional demands [2]. When the function of a building changes, especially when there is a substantial increase in the live or dead loads, retrofitting becomes essential to prevent structural failure [3]. This need is particularly pronounced in buildings where the original design did not anticipate such increases in loading. For instance, a warehouse repurposed as a manufacturing facility may experience much higher live loads than it was initially designed to support [4]. Structural retrofitting in these cases serves to enhance the load-bearing capacity of beams, columns, and other critical structural elements, thereby extending the useful life of the building.

In addition to functional changes, building structures are often subjected to deterioration over time. Deterioration may result from environmental exposure, leading to concrete degradation or the corrosion of reinforcing steel [5]. Such conditions weaken the structural integrity, posing risks to occupants and reducing the overall safety of the building [6]. The need for structural strengthening also arises in the aftermath of seismic events, where buildings may suffer damage such as cracks in beams and columns. Seismic forces cause flexural and shear cracks in reinforced concrete beams, requiring targeted interventions to restore and improve the building's structural performance [7].

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https://doi.org/10.21831/inersia.v21i1.78313
Received 14th October 2024; Revised 31st May 2025; Accepted 1st June 2025
Available online 2st June 2025

Cracks in beams, especially in seismic zones, are a key indicator of structural distress. If left unaddressed, they can lead to catastrophic failures during subsequent seismic events [8]. Strengthening strategies typically focus on improving the beam's flexural capacity, stiffness, and shear resistance, depending on the specific vulnerabilities observed [9]. One of the most effective modern methods for structural strengthening involves the use of fiber-reinforced polymers (FRPs), particularly carbon fiber-reinforced polymer (CFRP) sheets. This technique has become highly popular due to its versatility and the substantial performance improvements it offers. In reinforced concrete (RC) beams, the tensile zone often fails first due to the low tensile strength of concrete. Traditionally, this is counteracted by embedded steel reinforcement. However, for existing structures, more effective techniques are required to improve structural performance without significantly altering the original design [10].

CFRP offers several advantages over conventional strengthening methods, such as increasing the cross-sectional area of structural members. The conventional approach of increasing section size, while effective in some cases, is often inefficient and requires significant labor and materials [11]. CFRP, in contrast, is lightweight and can be easily applied to existing structures without major modifications. This material can be externally bonded to the tensile zones of beams, working in tandem with existing steel reinforcement to increase both the flexural and shear capacity of the structure [12].

One of the most commonly employed techniques involves the application of CFRP sheets using an epoxy adhesive. While this method has been widely adopted and proven effective in numerous case studies, it also has certain drawbacks [13]. The application of large CFRP sheets can be labor-intensive and material-intensive, resulting in an inefficient use of resources [14]. More critically, the bond between the CFRP and the concrete substrate is highly dependent on the quality and durability of the adhesive, which can fail under extreme conditions [15].

To overcome some of the limitations of sheet-applied CFRP, researchers and engineers have increasingly turned to alternative methods, such as the use of CFRP rods in a near-surface-mounted (NSM) configuration. This technique is more efficient and offers greater performance improvements in terms of flexural and shear strengthening. NSM involves embedding CFRP rods into pre-cut grooves on the surface of concrete members, which are then filled with epoxy adhesive to ensure a strong bond [16].

The NSM method has demonstrated superior performance compared to externally bonded CFRP sheets. It provides more effective load transfer between the concrete and the CFRP reinforcement, enhancing the stiffness of the beam and preventing premature failure due to adhesive delamination [17]. Additionally, NSM offers a more streamlined installation process, reducing both labor costs and the amount of CFRP material required. This makes NSM a highly efficient method for strengthening existing structures, particularly in situations where minimizing the impact on the building's appearance and function is important [18].

Numerous studies have highlighted the effectiveness of NSM CFRP strengthening in enhancing the structural performance of RC beams. When applied to the tension zone of beams, NSM CFRP rods significantly improve the flexural stiffness, leading to higher load-bearing capacities and reduced deflection under service loads. This method is particularly advantageous for structures that require both flexural and shear strengthening, as the CFRP rods can be strategically placed to resist shear forces in addition to improving flexural capacity [19] .

In comparison with traditional CFRP sheet applications, NSM CFRP rods have been shown to produce greater increases in the ultimate load capacity and overall stiffness of RC beams . The rods, being placed within the concrete rather than bonded externally, provide a more direct reinforcement that better integrates with the existing concrete matrix and steel reinforcement. This integration reduces the risk of premature adhesive failure, which is a common problem in externally bonded CFRP systems, especially under dynamic loading conditions such as earthquakes [16].

In conclusion, structural strengthening is essential for ensuring the continued safety and functionality of buildings, especially when changes in use, deterioration, or seismic damage are present [20]. Carbon fiber reinforced polymer (CFRP) systems have emerged as a highly effective solution for strengthening reinforced concrete structures, offering significant improvements in flexural and shear capacity [21]. Among the various methods of applying CFRP, the near-surface-mounted (NSM) technique has proven to be particularly advantageous due to its efficiency, performance benefits, and ease of application.

The use of NSM CFRP rods represents a substantial improvement over traditional CFRP sheet applications, providing enhanced stiffness, better load distribution, and greater resistance to adhesive failure. As this technique continues to gain acceptance in the engineering community, it is expected to play a crucial role in the future of building retrofitting and structural rehabilitation. Further research into the long-term performance and optimization of NSM CFRP systems will continue to enhance our understanding of their capabilities and limitations, ensuring that they remain a reliable and cost-effective solution for decades to come.

Several studies on reinforced concrete beam testing with NSM (Near-Surface-Mounted) CFRP strengthening have been conducted using experimental methods. The two-point loading experimental method is commonly employed to assess flexural strength and stiffness. Building upon this previous research, the author intends to test reinforced concrete beams strengthened with NSM CFRP reinforcement and compare them to beams strengthened with externally bonded CFRP sheets. The experimental method involving two-point loading will be applied in this study.

The conventional strengthening method using externally bonded CFRP sheets has been widely applied in structural retrofitting for buildings [22]. However, this technique is often considered less effective and efficient in certain scenarios. The use of CFRP reinforcement through the Near-Surface-Mounted (NSM) method represents a more recent and advanced technique. Previous studies have demonstrated that the NSM method significantly enhances the load-bearing capacity of beams. Given that this research is still relatively new and has not yet been extensively explored in Indonesia, further investigation is necessary to expand knowledge regarding structural strengthening using NSM CFRP reinforcement. This study aims to contribute to this growing body of research, providing valuable insights into the application of NSM CFRP in local structural practices and advancing the understanding of its potential benefits compared to conventional methods.

2. Methods

The method of strengthening using Carbon Fiber Reinforced Polymer (CFRP) involves two primary reinforcement techniques: the use of CFRP rods and CFRP sheets. The beams used in this study have a rectangular cross-section with dimensions of 24 cm in height and 12 cm in width, and the overall length of each beam is 3.2 meters, as illustrated in Figure 1. The loading setup follows a four-point bending arrangement, which is designed to apply loads at two points symmetrically along the span of the beam. The four-point load configuration can be seen in Figure 2, which facilitates a region of constant moment between the loading points, making it ideal for flexural testing.

The longitudinal reinforcement in the beams consists of 10 mm diameter steel rebars, while the stirrups, placed at regular intervals along the length of the beam, have a diameter of 6 mm. These internal reinforcements serve to provide additional tensile strength and shear resistance, respectively, during the flexural testing process.

For the external strengthening, CFRP sheets with a thickness of 0.5 mm are used, extending along a 3-meter length of the beam. Additionally, CFRP rods with a diameter of 7 mm. Figure 3 and Table 1 provide detailed specifications regarding the dimensions and materials used in the beam reinforcements, including the positioning of the CFRP components.

The installation of CFRP rods and sheets is a critical step in the strengthening process. As shown in Figure 4, this involves multiple stages. First, grooves are created along the bottom surface of the beam to house the CFRP rods. Figure 4a illustrates the notching process for the installation of the CFRP rods. These grooves are later filled with epoxy adhesive, ensuring that the rods are securely bonded to the concrete surface. Next, CFRP sheets are externally bonded to the bottom of the beam using the same epoxy adhesive, as seen in Figure 4b. Finally, Figure 4c depicts the process of applying the epoxy adhesive to glue the CFRP sheets and rods firmly into place.

The experimental setup for testing the strengthened beams follows a four-point bending test configuration, where the load is applied through a hydraulic actuator, and the response of the beams is monitored. The testing arrangement is shown in Figure 5, which captures the beam setup in the laboratory, including the load application points and the supports. During the test, the load is incrementally increased while monitoring the deflection at the midspan using a Linear Variable Differential Transformer (LVDT), and a load cell is employed to accurately measure the applied force.

The goal of this comparative analysis is to evaluate the performance of both strengthening techniques—CFRP rods (BTC) and CFRP sheets (BLC) under static loading conditions. For the CFRP rod reinforcement, the rods are embedded into the beam by creating grooves along the bottom surface, which are filled with epoxy adhesive to ensure strong bonding. In contrast, the CFRP sheet reinforcement involves externally bonding the sheets to the beam's bottom surface, also using epoxy adhesive. This method of external bonding provides a uniform distribution of reinforcement, which is critical for improving the overall performance of the structure.

The experimental process involves continuous monitoring of the applied load and the resulting deflections throughout the test. A data acquisition system is employed to record the data, ensuring that both load and deflection are tracked in real-time. Additionally, the crack patterns that develop during testing are closely monitored to understand the failure mechanisms and crack propagation. The documentation of these cracks will provide valuable insights into the flexural behavior of the beams. A thorough documentation process, including visual observations and photographs before and after testing, will be conducted to support the experimental data. This documentation will help track the progression of damage, crack development, and any structural changes that occur during the test.

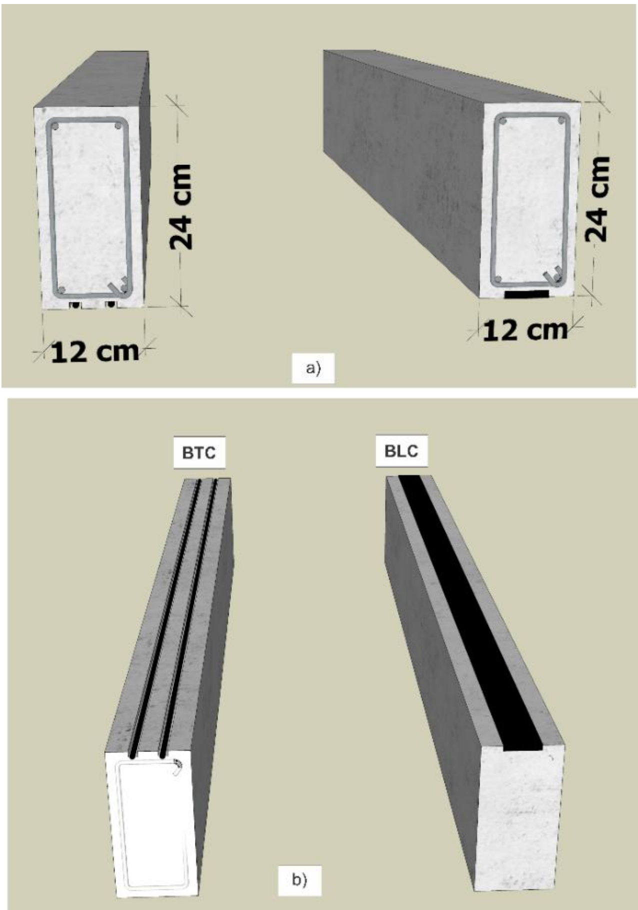

Figure 1. a) Beam cross-section and b) CFRP Installation Sketch

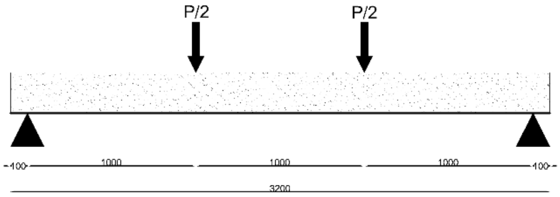

Figure 2. Flexural four-point-load test sketch

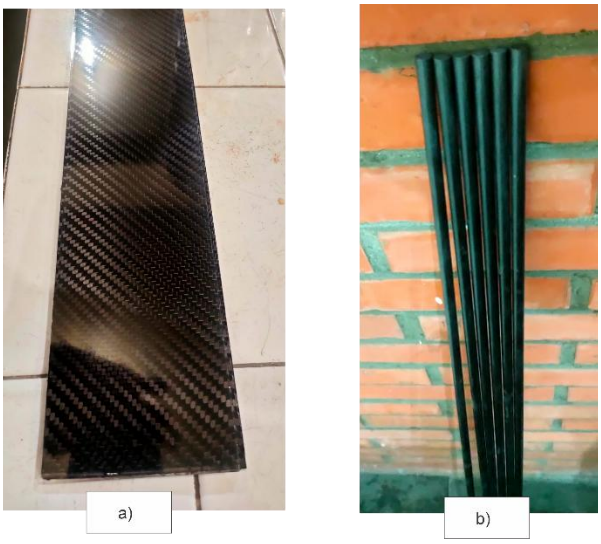

Figure 3. a) Carbon fiber sheet and b) rod rebar Carbon Fiber

By conducting this comparative study, the performance of beams strengthened with CFRP rods (designated as BTC) and beams strengthened with CFRP sheets (designated as BLC) can be thoroughly evaluated. The research aims to determine which technique provides superior structural performance in terms of load-bearing capacity, stiffness, and ductility. Such findings will be invaluable for engineers and researchers seeking to optimize CFRP reinforcement strategies in structural concrete applications, particularly in regions where enhancing the load capacity and durability of existing infrastructure is crucial.

Table 1. Sheet and rebar carbon fiber

Type	Cross-Section Dimension (mm)	Quantity	Cross-Section Area (mm^2)	Tensile Strength (MPa)	Modulus of Elasticity (GPa)
CFRP Sheet	0.5 mm x 83.33 mm	1 sheet	41.67	4100	350
CFRP Rebar	Diameter 7 mm	2 bars	76.93	2180	148

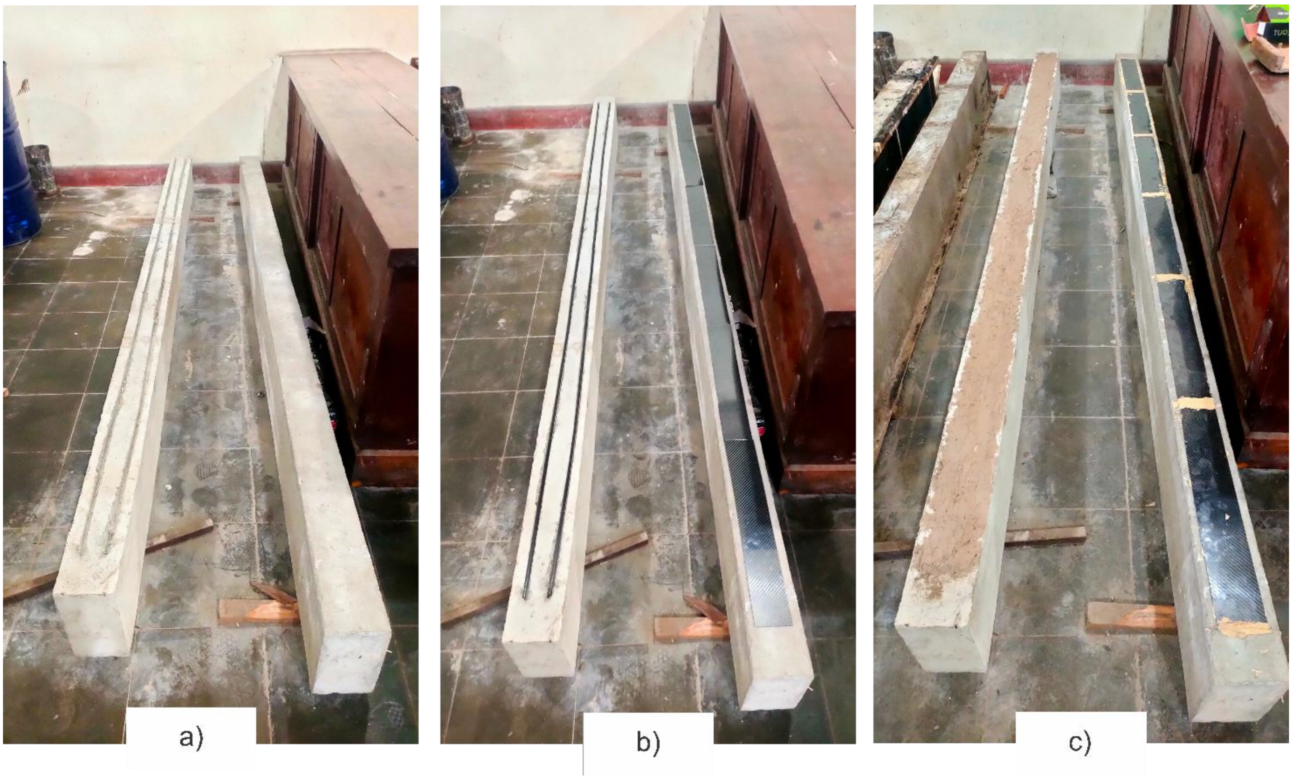

Figure 4. Installation of Sheet CFRP (BLC) and Rebar Rod CFRP (BTC) with a) before installation, b) installation sheet and Rebar CFRP c) glue with epoxy adhesive

Figure 5. Setup flexural test in Laboratory of HKBP Nommensen University

Ultimately, this research will contribute to a broader understanding of how advanced composite materials, such as CFRP, can enhance the performance of concrete structures under various loading conditions. The results of this study are expected to provide critical insights into the effectiveness of different CFRP reinforcement techniques, offering guidance for future applications in civil engineering and construction projects. These findings will have a direct impact on improving the safety, efficiency, and longevity of reinforced concrete structures.

3. Result and Discussion

3.1. Loading Test Result

The crack patterns of the BN, BTC, and BLC specimens can be seen in Figure 6, while the stiffness test results showed in Table 2. The first crack load (P_{crack}), which marks the onset of cracking, was significantly improved by CFRP reinforcement. The BLC specimen exhibited the highest P_{crack} at 769.8 kg, followed by BTC at 674 kg, and BN at 512.8 kg. Compared to the control beam (BN), this corresponds to an increase of 50.1% for BLC and 31.5% for BTC, highlighting the greater crack resistance of CFRP sheets. This can be attributed to the higher modulus of elasticity of CFRP sheets, which allows for better distribution of stresses and delays crack initiation more effectively than CFRP rods.

Figure 7, Figure 8, and Figure 9 illustrate the load-deflection curves for the three specimens throughout the entire loading process. At the early stage, BLC demonstrated the greatest stiffness, as shown by the lowest deflection at first crack (Y_{crack} = 0.9 mm), compared to BTC (1.3 mm) and BN (1.708 mm). This means that deflection at crack formation was reduced by 47.3% in BLC and 23.9% in BTC relative to BN, confirming that CFRP sheets effectively increase beam rigidity and reduce early deformation.

The yield load (P_{yield}), which represents the load at which significant plastic deformation begins, also increased with CFRP reinforcement. BLC reached a P_{yield} of 1758.6 kg, slightly higher than BTC's 1735.7 kg, while BN had the lowest at 1538.8 kg. These represent improvements of 14.3% and 12.8% for BLC and BTC respectively, compared to BN. The minor difference of 1.3% between BLC and BTC indicates that both CFRP sheets and rods similarly enhance the yield capacity of reinforced beams. Regarding maximum load capacity (Pmax), the BTC specimen achieved the highest value at 1832.9 kg, outperforming BLC (1760.6 kg) and BN (1552.8 kg). The increases compared to BN were 18.1% for BTC and 13.4% for BLC. This suggests that CFRP rods may contribute more to the ultimate strength of beams, possibly due to their rigidity and ability to provide concentrated reinforcement in the tensile zone. Nonetheless, the difference in maximum load between BTC and BLC was relatively small, confirming that both reinforcement types significantly improve beam strength.

Deflection at yield (Y_{yield}) further emphasizes the differences in stiffness and ductility. BLC showed the smallest deflection at yield with 9.2 mm, compared to BTC's 17.7 mm and BN's 25.858 mm. These values indicate that BLC reduced yield deflection by 64.4% relative to BN, while BTC reduced it by 31.5%. This finding supports the greater stiffness performance of CFRP sheets, especially under large deformations near yielding, whereas CFRP rods enhance strength but with less stiffness improvement.

CFRP sheets (BLC) provide greater initial stiffness and better crack control, making them more suitable for applications where deflection and serviceability are critical. On the other hand, CFRP rods (BTC) offer higher ultimate load capacity and better performance in the plastic deformation stage, which is beneficial for scenarios demanding high ductility and strength. The choice of reinforcement should therefore be based on the structural performance requirements and design priorities.

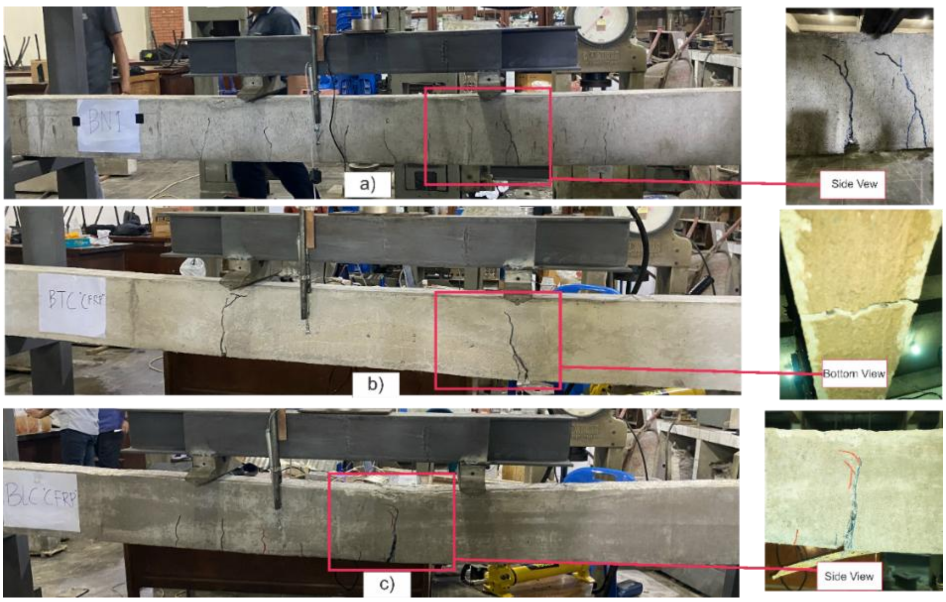

Figure 6. Crack Pattern of a) specimen BN, b) specimen BTC, and c) specimen BLC

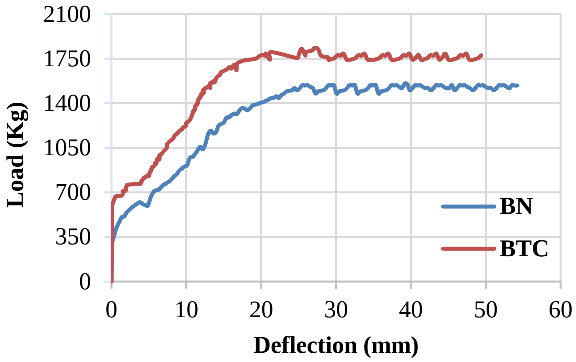

Figure 6. Load-deflection curve specimen BN vs BTC

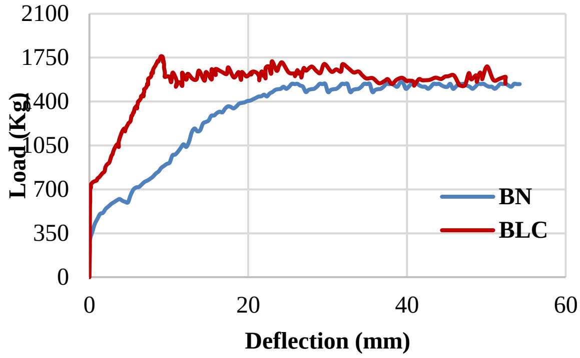

Figure 7. Load-deflection curve specimen BN vs BLC

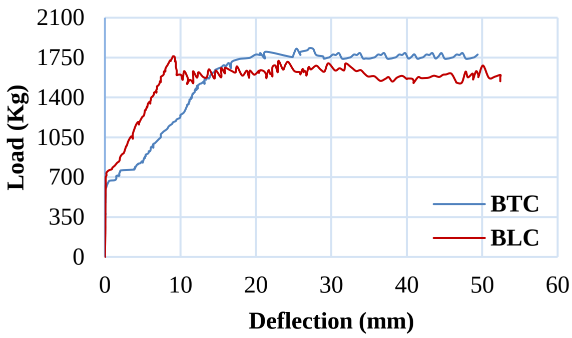

Figure 8. Load-deflection curve specimen BTC vs BLC

Table 2. Stiffness Results at Cracking and Yielding Points

Specimen	P_{crack} (Kg)	P_{yield} (Kg)	P_{max} (Kg)	Y_{crack} (mm)	Y_{yield} (mm)	K_{crack} (Kg/mm)	K_{yield} (Kg/mm)
BN	512.8	1538.8	1552.8	1.708	25.858	300.23	59.51
BTC	674	1735.7	1832.9	1.3	17.7	518.46	98.06
BLC	769.8	1758.6	1760.6	0.9	9.2	855.33	191.15

3.2. Discussion

The stiffness of beams reinforced with CFRP sheets (BLC) and CFRP rods (BTC) was compared against the control beam (BN), revealing notable differences in structural behavior.

At cracking, the control beam (BN) exhibited a stiffness (K_{crack}) of 300.23 Kg/mm. The BTC beam showed a 72.7% increase with a stiffness of 518.46 Kg/mm, while BLC demonstrated a substantially higher K_{crack} of 855.33 Kg/mm, corresponding to a 184.9% improvement over BN. This significant increase for BLC can be attributed to the greater modulus of elasticity and more uniform stress distribution of CFRP sheets, which effectively delay crack initiation. In contrast, the localized reinforcement of CFRP rods in BTC limits their capacity to enhance stiffness to the same extent.

Stiffness at yield (K_{yield}) followed a similar trend. BN recorded 59.51 Kg/mm, BTC improved by 64.8% to 98.06 Kg/mm, and BLC showed an exceptional 221.2% increase reaching 191.15 Kg/mm. This indicates that CFRP sheets are more effective in maintaining beam rigidity under plastic deformation, reducing deflections significantly. The relatively lower stiffness in BTC suggests that although CFRP rods improve load capacity, their impact on deformation control is limited compared to sheets.

These findings align with deflection measurements, where BLC exhibited the smallest deflections at cracking and yielding stages, reinforcing the superiority of CFRP sheets in enhancing stiffness and minimizing deformation.

In practical terms, CFRP sheets are preferable when controlling deflection and stiffness is critical, such as in beams subjected to frequent or service loads. Conversely, CFRP rods, while increasing strength, may be more suitable where ultimate load capacity is the main concern.

In summary, this analysis confirms that CFRP sheets provide greater enhancement in beam stiffness at key loading stages compared to CFRP rods, making them a more effective choice for improving both structural performance and serviceability.

The analysis of stiffness for beams reinforced with CFRP sheets (BLC) and CFRP rods (BTC) compared to the control beam (BN) reveals significant differences in their structural performance.

3.3. Stiffness Comparison

The control beam (BN) shows a stiffness at cracking (K_{crack}) of 300.23 Kg/mm. BTC, the beam reinforced with CFRP rods, achieves a K_{crack} of 518.46 Kg/mm, representing a 72.69% increase in stiffness compared to BN. BLC, the beam reinforced with CFRP sheets, reaches a much higher K_{crack} of 855.33 Kg/mm, which is a remarkable 184.89% increase over BN. The stiffness at yield (K_{yield}) for BN is 59.51 Kg/mm.BTC shows a K_{yield} of 98.06 Kg/mm, which corresponds to a 64.78% increase in stiffness compared to BN. BLC has an impressive K_{yield} of 191.15 Kg/mm, showing a 221.21% increase over BN.

The data indicates that the introduction of CFRP materials, whether in sheet or rod form, significantly improves the stiffness of reinforced concrete beams. However, the extent of this improvement differs greatly between the two reinforcement types. At the first crack, the beam reinforced with CFRP sheets (BLC) shows a much greater ability to resist deformation, achieving nearly 185% higher stiffness than the control beam (BN). This enhancement can be attributed to the superior modulus of elasticity of CFRP sheets, which allows for better distribution of stress across the beam, thereby delaying the onset of cracking. In contrast, while BTC shows a 72.69% improvement over BN, the stiffness at cracking remains significantly lower than BLC. This suggests that the more concentrated nature of stress distribution in the CFRP rods, compared to the distributed stress in CFRP sheets, limits the rods' ability to delay initial cracking.

When evaluating the stiffness at yield, the differences become even more pronounced. BLC's stiffness at yield is more than three times that of the control beam (BN), showcasing a 221.21% increase. This reflects the effectiveness of CFRP sheets in maintaining the beam's integrity as it approaches plastic deformation. The high stiffness provided by the sheets minimizes deflection, preventing the beam from experiencing large deformations under load. BTC, while still performing significantly better than BN with a 64.78% improvement, lags behind BLC in its ability to prevent deflection at higher loads.

The stiffness trends observed at both the cracking and yielding stages point to a clear advantage of CFRP sheets (BLC) over CFRP rods (BTC) in enhancing the overall stiffness of the beam. The sheets' ability to distribute stress more uniformly across the surface of the beam makes them particularly effective in resisting both cracking and yielding. The high stiffness values of BLC at both stages also correlate with lower deflection values (Y_{crack} and Y_{yield}) further reinforcing the conclusion that CFRP sheets are more effective at reducing deformation.

On the other hand, the relatively lower stiffness values for BTC indicate that, while CFRP rods enhance strength and load capacity, they are less effective at increasing stiffness. The rods focus their reinforcement in a more localized manner, which leads to a lower ability to resist deformation, particularly as the beam approaches yielding. This is reflected in BTC's deflection values, which, although improved over BN, remain significantly higher than those of BLC.

In terms of practical applications, the findings suggest that CFRP sheets should be the preferred reinforcement method when stiffness and reduced deflection are critical factors, such as in beams that must resist frequent loading or where minimal deformation is required for structural integrity. CFRP rods, while still beneficial, may be more suited to applications where ultimate load capacity is the priority, as their contribution to stiffness is less substantial than that of CFRP sheets.

In conclusion, the analysis clearly demonstrates that BLC outperforms both BTC and BN in terms of stiffness, particularly at the critical stages of cracking and yielding. The use of CFRP sheets offers a more effective solution for enhancing the stiffness of concrete beams, making them a better choice for improving structural performance where both strength and minimal deflection are necessary.

4. Conclusion

Based on the results and analysis, it is evident that the use of CFRP sheets and rods significantly improves the structural performance of reinforced concrete beams. The beam reinforced with CFRP sheets (BLC) exhibited the highest stiffness at both the cracking and yielding stages, with increases of 184.89% and 221.21% compared to the control beam (BN). This enhancement demonstrates the effectiveness of CFRP sheets in distributing stress uniformly, thereby reducing deflection and delaying the onset of cracking and yielding. The increased stiffness also translates to improved load-bearing capacity, particularly in resisting early-stage deformations.

In contrast, the beam reinforced with CFRP rods (BTC) also showed notable improvements in stiffness, though to a lesser extent than BLC. BTC achieved a 72.69% increase in stiffness at cracking and a 64.78% increase at yielding, indicating that while CFRP rods enhance load-bearing capacity, they are less effective in minimizing deflection compared to CFRP sheets. However, BTC recorded the highest maximum load (Pmax), suggesting that CFRP rods are more efficient at increasing the beam's ultimate strength.

In conclusion, CFRP sheets are superior in enhancing stiffness and controlling deflection, making them ideal for structures requiring high crack resistance and reduced deformation. Meanwhile, CFRP rods are better suited for applications where maximizing ultimate load capacity is the priority. These findings highlight the importance of selecting the appropriate type of CFRP reinforcement based on the specific performance requirements of the structure.

Acknowledgment

The authors would like to express his gratitude to the Directorate General of Higher Education, Research, and Technology for providing financial assistance through the DRTPM program, enabling the publication of this paper may place your acknowledgments here. Write only essential acknowledgments.

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