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Retrofitting of RCC Beams in the Shear Region Using Carbon Fiber-Reinforced Polymer

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Abstract

In recent years, Fiber Reinforced Polymers (FRPs) have gained significant popularity over traditional materials for enhancing the shear strength of Reinforced Concrete (RC) beams, particularly when they are deficient in shear or prone to shear failure. FRPs are advanced composite materials widely used to retrofit existing RC beams and improve the shear resistance of new ones. Among these, Carbon Fiber Reinforced Polymers (CFRP) stand out due to their lightweight nature, exceptional tensile strength, superior corrosion resistance, and ease of application in construction. Shear failure is commonly observed under seismic and impact loading conditions, making CFRP reinforcement a complex but essential solution. Although extensive research has been conducted in this field, existing studies remain insufficient. This study focuses on strengthening RC beams in shear using CFRP. A total of six simply supported RC beams (150 mm × 200 mm × 1800 mm) were subjected to four-point bending tests. The primary objective is to enhance the shear load-bearing capacity of the beams. The research involved testing RC beams reinforced with CFRP, including two control specimens and four beams wrapped with a single layer of CFRP. The wrapping configurations included two beams with 356 mm CFRP wrapping and two with 508 mm wrapping. The average maximum load capacity of the unwrapped beams was recorded at 84.74 kN, while those wrapped with 356 mm CFRP reached 120.46 kN. Meanwhile, the beams wrapped with 508 mm CFRP demonstrated an increased load capacity of 155.815 kN. Cracking was observed earlier in the unwrapped beams compared to those strengthened with CFRP, indicating improved structural performance. The failure patterns of the beams varied, particularly between those with and without CFRP wrapping. This study highlights CFRP's potential and provides a foundation for future research on optimizing its configurations for infrastructure rehabilitation.

Introduction

In Bangladesh, the increasing demands of a growing economy and expanding population are placing immense pressure on aging and deteriorating infrastructure. Traditional methods of repairing bridge beams and girders, such as grout injection, excessive steel reinforcement, or full beam replacement are often neither cost-effective nor structurally reliable, as noted by the American Concrete Institute (ACI). Research suggests that replacing steel reinforcement with Carbon Fiber Reinforced Polymer (CFRP) is a viable alternative, effectively mitigating the issues associated with steel corrosion in concrete structures [1]. Corrosion in steel-reinforced concrete reduces the material's gross sectional area, leading to a decline in shear strength for both the steel and surrounding concrete [2]. Historically, steel was the primary material used for structural strengthening during rehabilitation efforts. However, Fiber Reinforced Polymer (FRP) presents several advantages, such as a superior strength-to-weight ratio, resistance to corrosion, high fatigue strength, and ease of application [3].

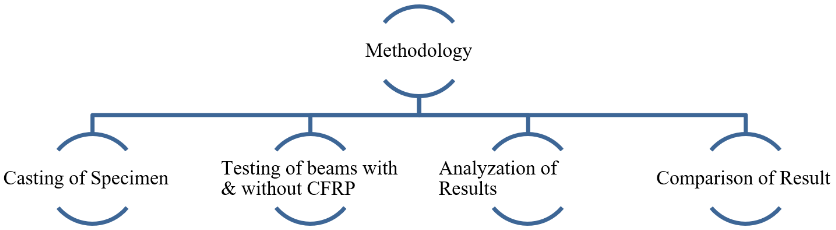
FRP composites typically consist of high-strength carbon, aramid, or glass fibers embedded within a polymer matrix, serving as the primary load-bearing component. Studies indicate that replacing steel reinforcement with FRP reinforcement can effectively address the challenges of corrosion in concrete structures [4]. A comparison of various strengthening techniques reveals that the FRP shear contribution in the proposed methodology is greater than that achieved through external bonding methods, as determined by the Applied Strengthening Material Index (ASMI) [5].

Different anchorage techniques are analyzed based on their impact on FRP shear strength and strain, providing valuable insights into the behavior of FRP shear-strengthened beams. Additionally, strength models from various design guidelines are evaluated against experimental data to predict FRP shear capacity [6].

In recent decades, fiber-reinforced polymer (FRP) composites have gained widespread adoption in civil infrastructure construction due to their durability and high strength-to-weight ratio. FRP tube members have also been explored for use in primary load-bearing structures, such as building frames and space frames, utilizing specialized connections like sleeve attachments [7]. Traditional materials like concrete, steel, and wood decking often suffer from deterioration due to cyclic loading and environmental exposure. Cracks that emerged in the Bangabandhu Jamuna Multipurpose Bridge were successfully repaired using the CFRP retrofitting technique, enhancing its structural integrity. Numerous studies have been conducted on Fiber Reinforced Polymers (FRP). A comprehensive study was conducted on structural strengthening and retrofitting techniques for concrete structures and reinforced concrete (RC) beams [8,9]. An in-depth study was carried out on the repair and strengthening of severely damaged concrete beams using externally bonded CFRP, evaluating its effectiveness in restoring structural integrity [10]. A research study was conducted on shear strengthening techniques for deep beams and T-beams, focusing on enhancing their load-carrying capacity and structural performance [11,12]. The application of FRP composites for retrofitting RC beams following shear collapse was thoroughly investigated, assessing its effectiveness in restoring strength and durability [13]. Seismic retrofitting of shear-critical RC beams was conducted using CFRP, evaluating its effectiveness in enhancing structural resilience and performance under seismic loads [14, 15]. A study was conducted to investigate the behavior of concrete beams reinforced with carbon FRP stirrups, focusing on their structural performance and shear resistance [16, 17]. The performance of externally bonded FRP-strengthened RC beams in shear was investigated, assessing their effectiveness in enhancing shear capacity and structural behavior [18, 19, 20]. Among FRP materials, CFRP, GFRP, and AFRP are widely used for structural strengthening. GFRP is cost-effective but lacks tensile strength, while AFRP resists fatigue but lacks stiffness. CFRP excels with high tensile strength, stiffness, and durability, making it ideal for shear-critical RC beams, offering easy installation and minimal disruption. Strengthening RC beams with CFRP can increase their load-bearing capacity by up to 90% compared to the original beam, making it a highly effective solution for structural enhancement [21, 22]. The primary objective of this research is to evaluate the effectiveness of CFRP reinforcement in strengthening RCC beams in the shear region.

Methodology

In all engineering constructions, ensuring structural safety and durability requires the use of high-quality materials that meet acceptable strength standards. The detailed methodology is illustrated in the flow diagram below.



For this research, essential materials including sand, black stone chips, reinforcement steel, cement, CFRP, and adhesive materials (such as epoxy resins) were procured from the local market. The beam casting process begins with the collection of required materials, including stone, sand, cement, and reinforcement steel, sourced locally. Next, wooden formwork is constructed according to the specified beam dimensions. For the concrete mix, a 1:1.5:3 ratio of cement, sand, and stone chips is used, with a fixed water-cement ratio to ensure high-strength concrete. The beams are then cast using a three-layer tamping method to ensure proper compaction. Finally, the high-strength concrete beams are cured for 28 days to enhance their durability and strength.

A total of six beams B1, B2, B3, B4, B5, and B6 were prepared for this research. Beams B1 and B2 served as control specimens, with no CFRP strengthening applied. The remaining beams were reinforced using CFRP at varying widths from the support position. Specifically, beams B3 and B4 were strengthened with 356 mm wide CFRP, while beams B5 and B6 were reinforced with 508 mm wide CFRP. The load was applied following the ASTM four-point loading method. A single layer of

CFRP fabric was used for reinforcing beams B3, B4, B5, and B6, utilizing only a U-wrap configuration for CFRP application.

Result and Discussion

The testing results for beams with and without CFRP reinforcement are summarized in **Table 1**. A total of six beams B1, B2, B3, B4, B5, and B6 were cast for this study. Among them, four beams were wrapped with CFRP, while two remained unwrapped as control specimens.

For the unwrapped beams, B1 had a maximum load capacity of 80.19 kN, while B2 reached 89.29 kN. The CFRP-wrapped beams showed significant improvements in load capacity. The load capacities for the beams are as follows: B3, with a 356 mm CFRP wrapping, has a capacity of 113.19 kN; B4, also with a 356 mm CFRP wrapping, has a capacity of 127.73 kN; B5, featuring a 508 mm CFRP wrapping, can handle 155.29 kN; and B6, with the same 508 mm CFRP wrapping, has a load capacity of 156.34 kN.

The maximum deflections recorded were as follows: B1 shows a displacement of 3.93 mm, B2 has 4.13 mm, B3 displays 5.57 mm, B4 reaches 6.19 mm, B5 has a displacement of 6.39 mm, and B6 shows the highest displacement at 6.73 mm.

Compared to B1, the increase in load capacity was 11.35% (B2), 41.15% (B3), 59.29% (B4), 93.65% (B5), and 94.95% (B6). The failure mode for B1 through B4 was identified as shear failure, while B5 and B6 exhibited flexural failure due to the enhanced shear resistance provided by CFRP reinforcement.

Table 1: Testing result with CFRP & without CFRP

Beam	Maximum load (kN)	Maximum Deflection(kN)	Load Carrying Capacity increase (%)	Failure Mode
B1	80.19	3.93		Shear Failure
B2	89.29	4.13	11.35	Shear Failure
B3	113.19	5.57	41.15	Shear Failure
B4	127.73	6.19	59.284	Shear Failure
B5	155.29	6.39	93.65	Flexural Failure
B6	156.34	6.73	94.95	Flexural Failure

In specimen B1 without CFRP, the deflection exhibited a gradual increase with the applied load. At 20 kN, the deflection measured 0.5 mm, while at 40 kN, it doubled to 1 mm. As the load increased to 59 kN, the deflection reached 1.5 mm, and at 69.19 kN, it further increased to 2 mm. When the applied load was 72.19 kN, the deflection measured 2.5 mm, and at 76.23 kN, it reached 3 mm. The final recorded load of 79.38 kN resulted in a deflection of 3.2 mm. The specimen ultimately failed due to shear failure. **Figure 1** illustrates that within the 0–1 mm deflection range, the response followed a proportional increase consistent with Young's modulus. However, beyond this range, the load-deflection behavior deviated from proportionality.

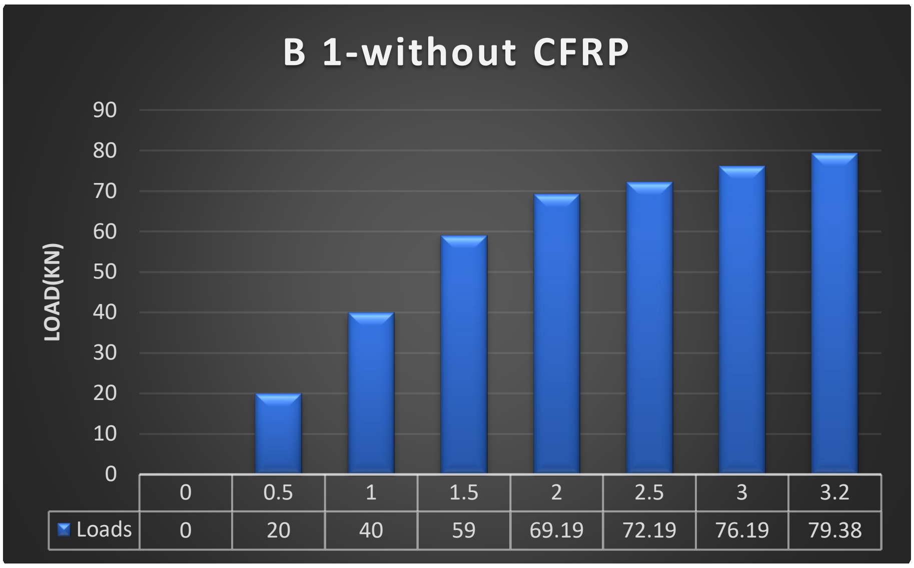


Figure 1: B1 Without CFRP

In specimen B2 without CFRP, the deflection increased progressively with the applied load. At 20 kN, the deflection measured 0.5 mm, doubling to 1 mm at 40 kN. As the load reached 55 kN, the deflection increased to 1.5 mm, followed by 2 mm at 60 kN. Further increments in load resulted in a deflection of 2.5 mm at 65 kN, 3 mm at 75 kN, and 3.2 mm at 80.19 kN. The specimen ultimately failed due to shear failure. **Figure 2** illustrates that within the 0–1 mm deflection range, the response followed a proportional trend consistent with Young's modulus. However, beyond this limit, the load-deflection behavior deviated from proportionality.

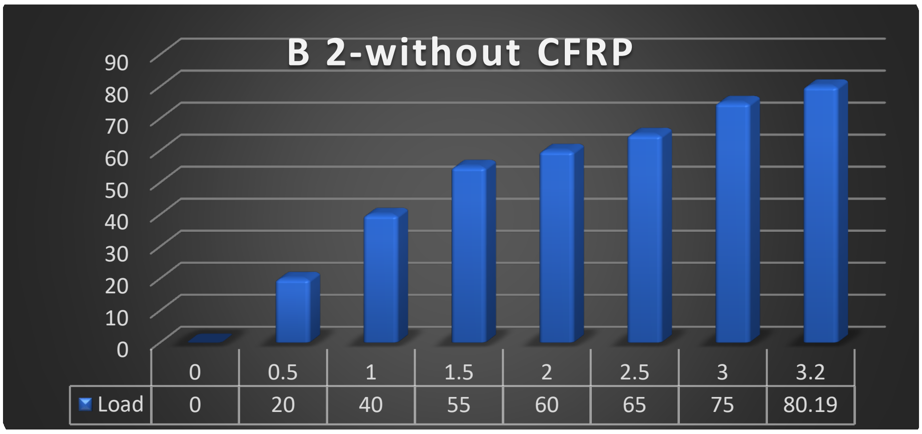


Figure 2: B2 without CFRP

In specimen B3 with CFRP, the deflection exhibited a steady increase with the applied load. At 20 kN, the deflection measured 0.5 mm, reaching 1 mm at 40 kN. When the load increased to 55 kN, the deflection reached 1.5 mm, followed by 2 mm at 65 kN and 2.5 mm at 72 kN. Further increments in load resulted in a deflection of 3 mm at 82.46 kN and 3.2 mm at 86.73 kN. As the load increased to 97.19 kN, the deflection reached 4 mm, and at 113.19 kN, it extended to 5.57 mm. The specimen ultimately failed due to shear failure. **Figure 3** demonstrates that within the 0–1 mm deflection range, the response followed a proportional trend consistent with Young's modulus. However, beyond this limit, the load-deflection behavior deviated from proportionality.

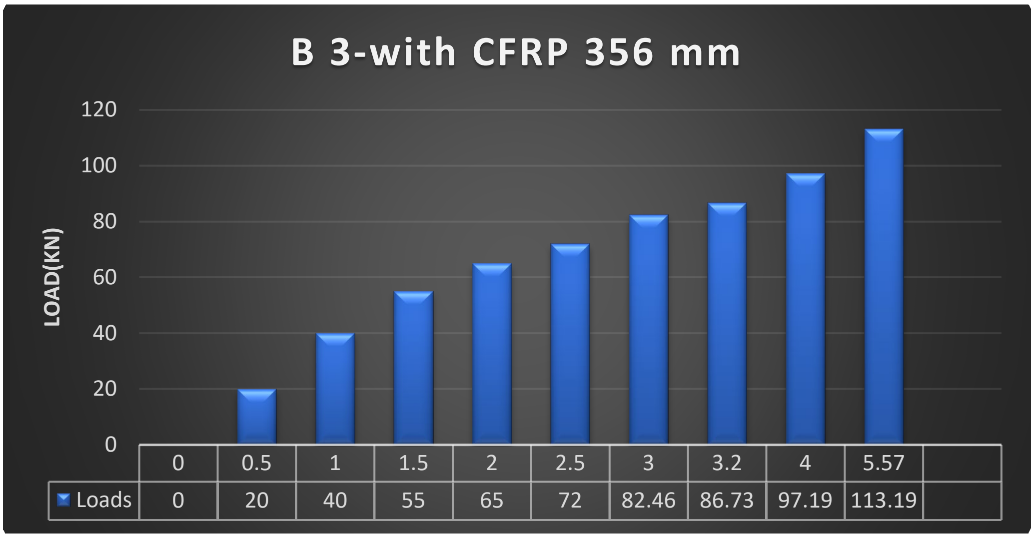


Figure 3: B3 with CFRP 356 mm

In specimen B4 with CFRP, the deflection increased steadily as the applied load increased. At 20 kN, the deflection was 0.5 mm, reaching 1 mm at 40 kN. When the load increased to 49.18 kN, the deflection measured 1.5 mm, followed by 2 mm at 55.76 kN and 2.5 mm at 61.19 kN. The deflection continued to rise, reaching 3 mm at 66.19 kN, 3.2 mm at 72.19 kN, and 4 mm at 78.19 kN. As the applied load increased further, the deflection measured 4.5 mm at 88.76 kN, 5 mm at 98.79 kN, 5.5 mm at 113.25 kN, and finally 6.19 mm at 127.73 kN. The specimen ultimately failed due to shear failure. **Figure 4** illustrates that within the 0–1 mm deflection range, the response followed a proportional trend consistent with Young's modulus. However, beyond this limit, the load-deflection behavior deviated from proportionality.

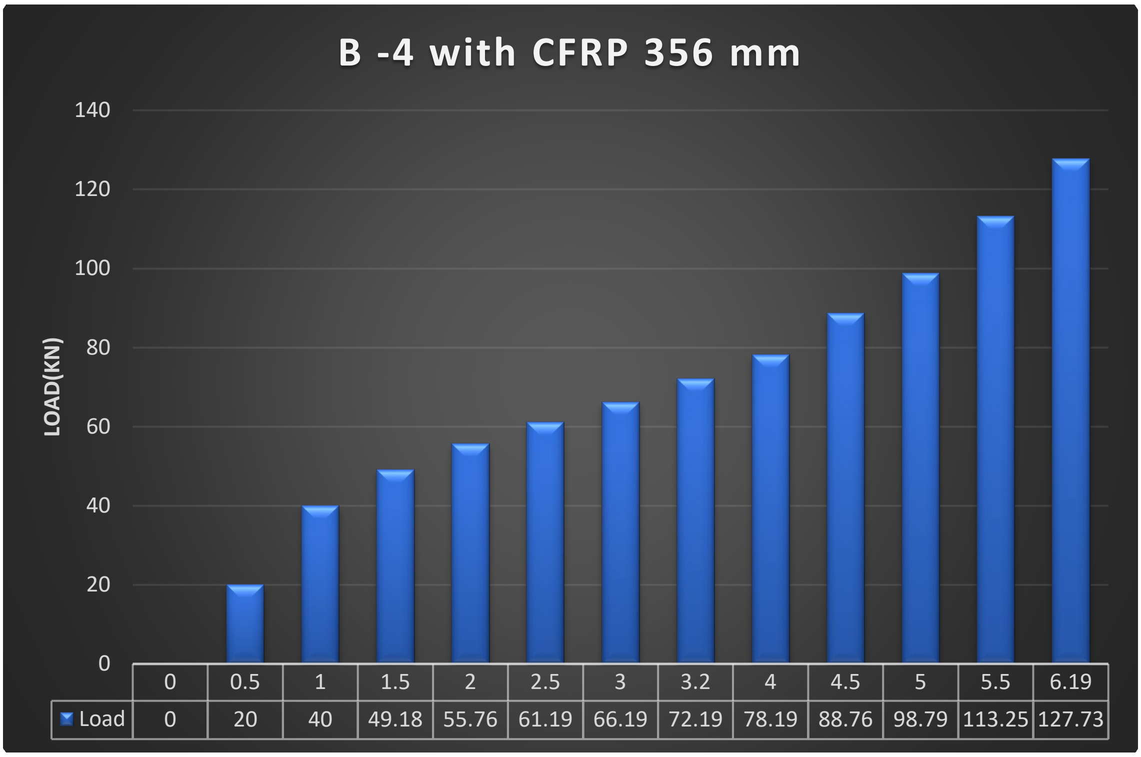


Figure 4: B4 with CFRP 356 mm

In specimen B5 with CFRP, the deflection progressively increased with the applied load. At 15 kN, the deflection was 0.5 mm, reaching 1 mm at 30 kN. As the load increased to 45 kN, the deflection measured 1.5 mm, followed by 2 mm at 60 kN and 2.5 mm at 78.18 kN. The deflection continued to rise, reaching 3 mm at 88.18 kN, 3.2 mm at 98.15 kN, and 3.5 mm at 108.35 kN. Further increments in load resulted in a deflection of 4 mm at 119.6 kN, 4.5 mm at 129.36 kN, and 5 mm at 139.15 kN. As the applied load increased to 147.15 kN, the deflection measured 5.5 mm, followed by 6 mm at 154.19 kN and 6.39 mm at 155.29 kN. Unlike previous specimens, this one failed due to flexural failure. **Figure 5** illustrates that within the 0–1.5 mm deflection range, the response followed a proportional trend consistent with Young's modulus. However, beyond this limit, the load-deflection behavior deviated from proportionality.

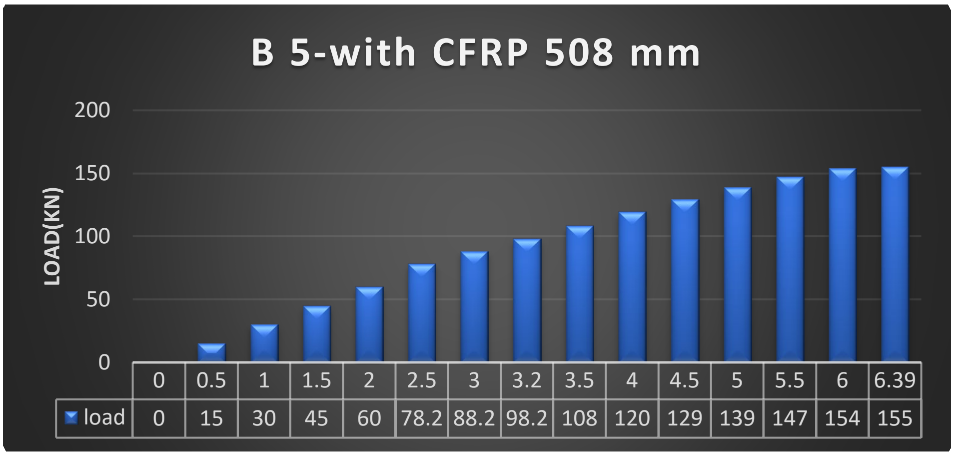
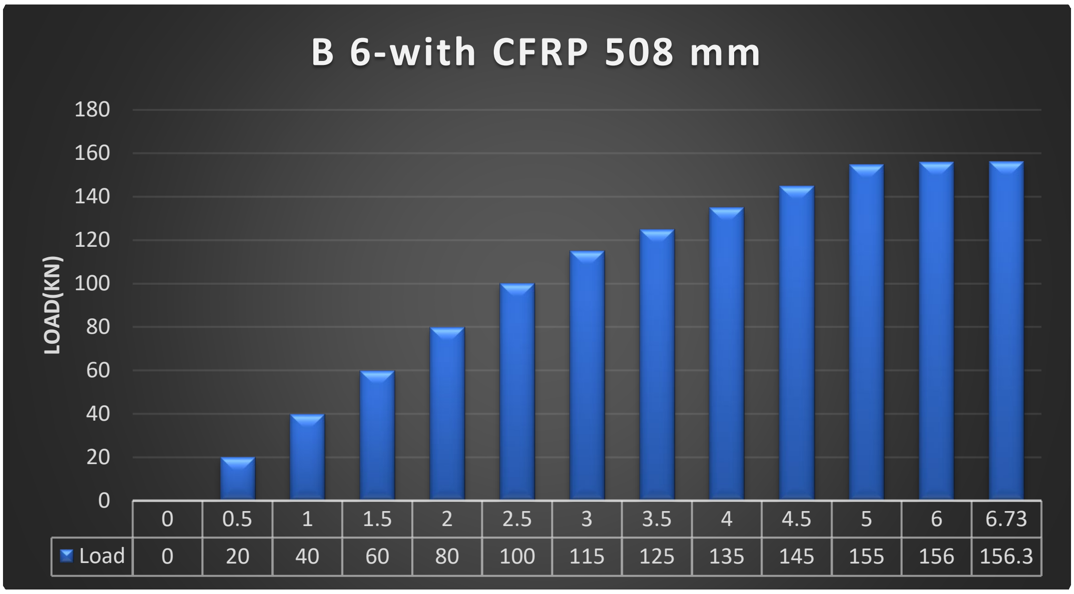


Figure 5: B5 with CFRP 508 mm

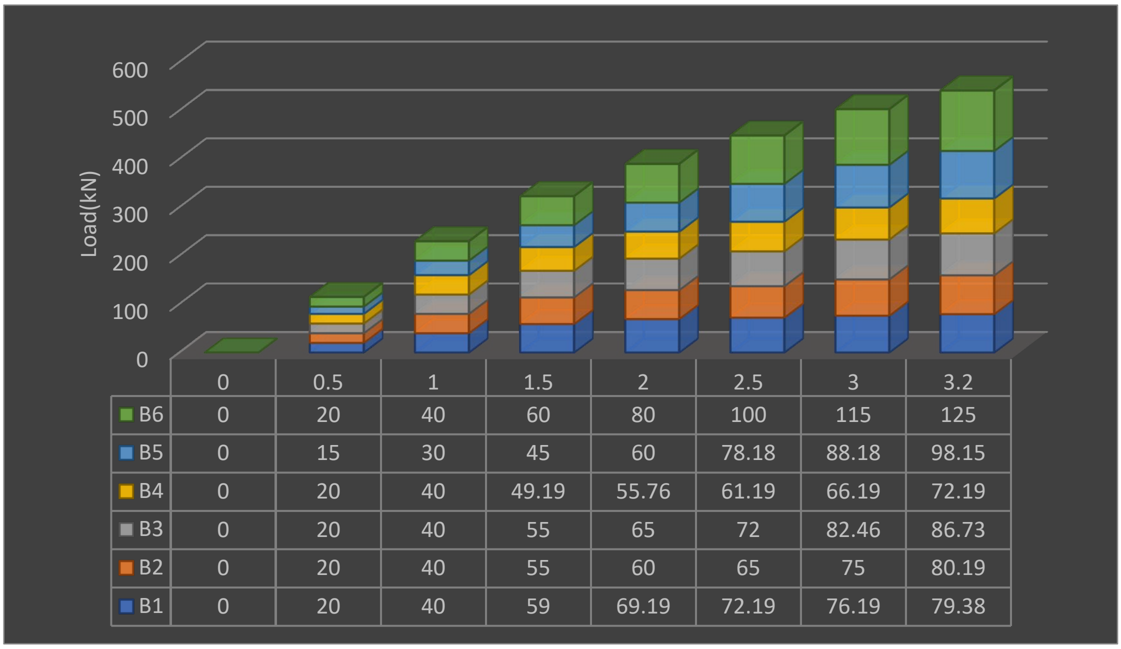
In specimen B6 with CFRP, the deflection exhibited a steady increase with the applied load. At 20 kN, the deflection measured 0.5 mm, reaching 1 mm at 40 kN. As the load increased to 60 kN, the deflection reached 1.5 mm, followed by 2 mm at 80 kN and 2.5 mm at 100 kN. Further increments in load resulted in a deflection of 3 mm at 115 kN and 3.5 mm at 125 kN. The deflection continued to rise, reaching 4 mm at 135 kN, 4.5 mm at 145 kN, and 5 mm at 155 kN. As the applied load increased further, the deflection measured 6 mm at 155.98 kN and finally 6.73 mm at 156.34 kN. The specimen ultimately failed due to flexural failure. **Figure 6** illustrates that within the 0–2.5 mm deflection range, the response followed a proportional trend consistent with Young's modulus. However, beyond this limit, the load-deflection behavior deviated from proportionality.



	0	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5	6	6.73
Load	0	20	40	60	80	100	115	125	135	145	155	156	156.3

Figure 6: B6 with CFRP 508 mm

Figure 7 presents a comparative analysis of the deflection and failure modes of six beams, using Beam B1 (without CFRP wrapping) as the reference. The maximum recorded load among all beams was 125 kN, while the minimum was 79.38 kN at a deflection of 3.2 mm. At a 3 mm deflection, the highest applied load was 115 kN in B6, whereas the lowest was 75 kN in B2. For a deflection of 2.5 mm, the maximum applied load was 100 kN in B6, while the minimum was 61.19 kN in B4. Similarly, at a 2 mm deflection, B6 sustained the highest load of 80 kN, whereas B4 had the lowest at 55.76 kN. For a 1.5 mm deflection, B6 again had the maximum applied load at 60 kN, while B5 had the minimum at 45 kN. The lowest applied load at 1 mm deflection was recorded in B5 at 30 kN. These results highlight the influence of CFRP wrapping on load-bearing capacity and structural behavior, with B6 exhibiting the highest strength across different deflection points.



	0	0.5	1	1.5	2	2.5	3	3.2
B6	0	20	40	60	80	100	115	125
B5	0	15	30	45	60	78.18	88.18	98.15
B4	0	20	40	49.19	55.76	61.19	66.19	72.19
B3	0	20	40	55	65	72	82.46	86.73
B2	0	20	40	55	60	65	75	80.19
B1	0	20	40	59	69.19	72.19	76.19	79.38

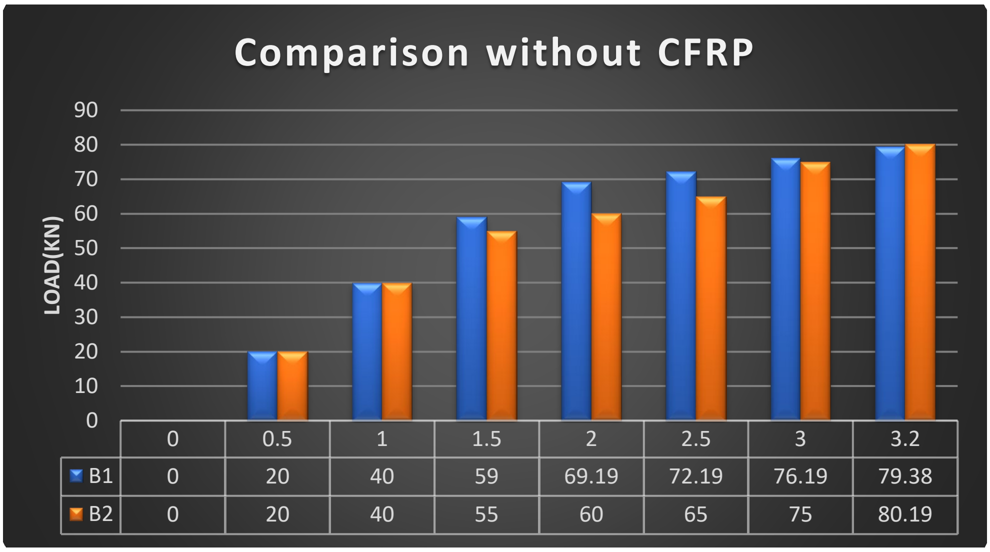
Figure 7: Comparison of Test result

Beams B1 and B2 were not strengthened with CFRP, leaving their support positions, two sides, and soffits exposed. In contrast, beams B3 and B4 were reinforced with 356 mm wide CFRP strips from the support position, while beams B5 and B6 had a wider 508 mm CFRP reinforcement. Under the ASTM four-point loading method, initial cracks appeared in the non-strengthened regions and progressively extended toward the inner sections of the beams as the applied load increased. Beams without CFRP reinforcement (B1 and B2) exhibited visible cracks at lower loads compared to the CFRP-strengthened beams, indicating that CFRP delayed the onset of cracking and improved structural performance.

Regarding failure modes, beams B1 and B2, which lacked CFRP reinforcement, primarily failed due to shear failure. The cracks propagated more rapidly, leading to earlier structural breakdown compared to the CFRP-strengthened beams. This highlights the effectiveness of CFRP in enhancing the load-bearing capacity and delaying failure in beams subjected to flexural and shear stresses.

Figure 8 compares the performance of the two beams without CFRP wrapping, B1 and B2, under applied loads. The maximum applied load was recorded at 80.19 kN for B1 at a 3.2 mm deflection. For smaller deflections (0.5 mm and 1 mm), both beams experienced the same applied load. At 1.5 mm deflection, B1 carried 4 kN more than B2, and at 2 mm deflection, this difference increased to 9.19 kN. When the deflection reached 2.5 mm, B1's load remained slightly higher, exceeding B2's by 1.19 kN.

However, at a deflection of 3.2 mm, B2 surpassed B1, carrying a load that was 0.81 kN greater. This indicates that from 0 to 3 mm deflection, B1 consistently sustained a higher applied load than B2. However, beyond 3 mm deflection, B2 demonstrated slightly better load resistance compared to B1.

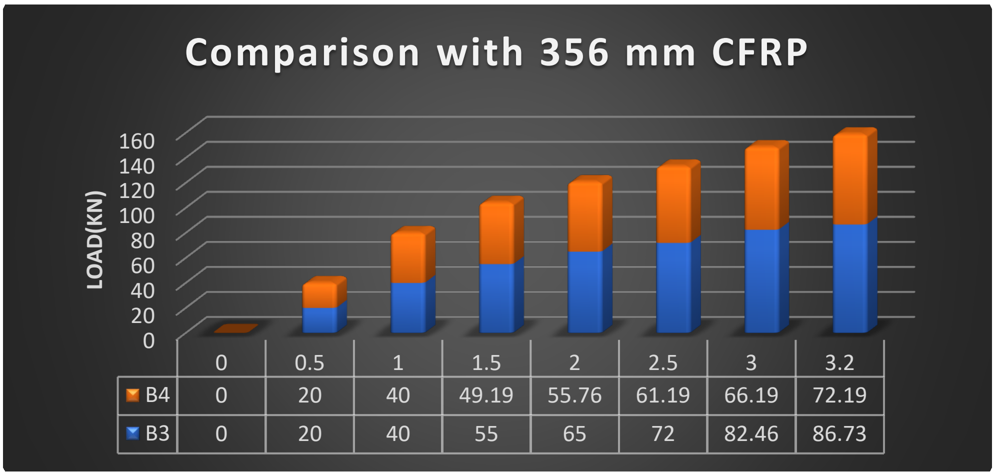


	0	0.5	1	1.5	2	2.5	3	3.2
🟦 B1	0	20	40	59	69.19	72.19	76.19	79.38
🟧 B2	0	20	40	55	60	65	75	80.19

Figure 8: Comparison of B1 and B2 without CFRP

Figure 9 compares the performance of two beams, B3 and B4, both strengthened with 356 mm wide CFRP wrapping. The maximum applied load was recorded at 86.73 kN on B3 at a 3.2 mm deflection. For smaller deflections (0.5 mm and 1 mm), both beams experienced the same applied load. However, as the deflection increased, B3 consistently carried a higher load than B4. At 1.5 mm deflection, B3’s load was 5.81 kN greater than B4. This difference increased to 9.24 kN at 2 mm and 10.81 kN at 2.5 mm.

At the maximum deflection of 3.2 mm, B3’s applied load exceeded B4’s by 14.54 kN. Thus, across the 0 to 3.2 mm deflection range, B3 consistently supported a higher load than B4, highlighting the effectiveness of the CFRP reinforcement in enhancing the structural capacity of the beams.

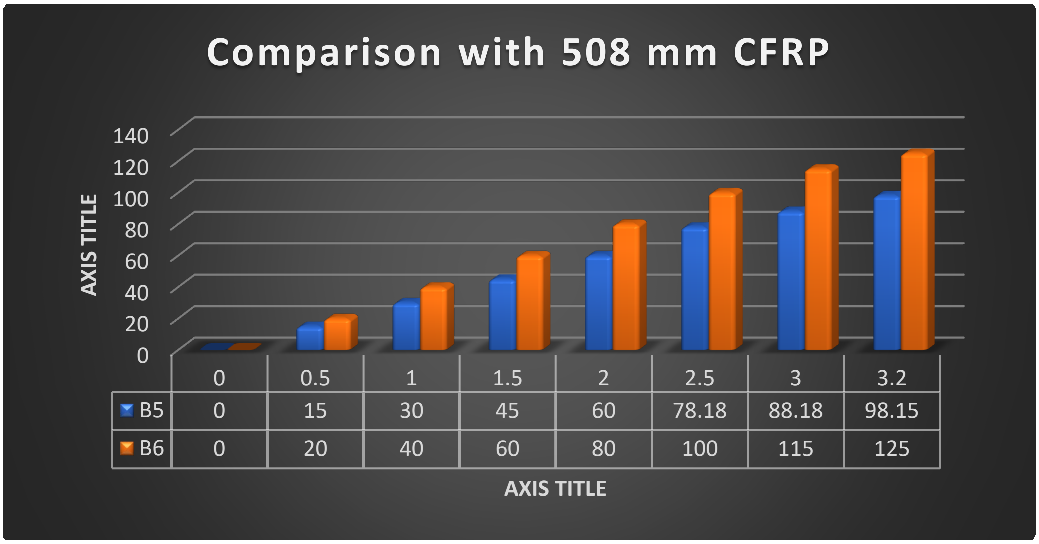


	0	0.5	1	1.5	2	2.5	3	3.2
🟧 B4	0	20	40	49.19	55.76	61.19	66.19	72.19
🟦 B3	0	20	40	55	65	72	82.46	86.73

Figure 9: Comparison of B3 and B4 with 356 mm CFRP

Figure 10 compares the performance of two beams, B5 and B6, both strengthened with 508 mm wide CFRP wrapping. The maximum applied load recorded was 125 kN on B6 at a 3.2 mm deflection. At smaller deflections, B6 consistently carried a higher load than B5. At a 0.5 mm deflection, B6’s load was 5 kN greater than B5. This difference increased to 10 kN at 1 mm deflection, 15 kN at 1.5 mm, and 20 kN at 2 mm.

For the 0 to 2 mm deflection range, both beams exhibited a proportional increase in applied load, following a trend similar to that of Young's modulus. This suggests that the CFRP wrapping significantly improved the load-bearing capacity of both beams, particularly B6, which demonstrated superior performance across the measured deflection points.



	0	0.5	1	1.5	2	2.5	3	3.2
🟦 B5	0	15	30	45	60	78.18	88.18	98.15
🟧 B6	0	20	40	60	80	100	115	125

Figure 10: Comparison of B5 and B6 with 508 mm CFRP

This study reveals a critical shift in CFRP-wrapped RC beams from brittle shear failure to more ductile flexural failure, highlighting CFRP's reinforcement effect. Control beams failed due to rapid shear crack propagation, whereas CFRP-wrapped beams exhibited improved shear resistance, delaying failure and enhancing load capacity. Wider CFRP strips further reinforced bending resistance, leading to flexural failure instead of shear collapse. CFRP confinement also enhanced ductility, strain tolerance, and energy absorption, ensuring a controlled failure progression. These findings underscore CFRP's transformative role in strengthening RC beams, improving safety, and extending structural longevity under high-load conditions.

Unwrapped control beams (B1, B2) experienced shear-dominated failure due to excessive shear stress. Initial cracks formed at support regions, propagating diagonally and rapidly compromising structural integrity. Lacking CFRP reinforcement, the beams failed suddenly and brittlely, unable to redistribute loads. This highlights the need for enhanced reinforcement strategies to improve shear resistance.

CFRP significantly enhanced shear resistance in beams B3 and B4, increasing load capacity by 41.15% and 59.29%, respectively. Unlike unwrapped beams, CFRP reinforcement delayed crack formation, reduced crack propagation, and prevented brittle shear failure. This demonstrates CFRP’s effectiveness as an external reinforcement, improving structural integrity and mitigating premature shear failure.

Beams B5 and B6, wrapped with wider CFRP strips (508 mm), exhibited a transition from shear to flexural failure as load increased. CFRP reinforcement initially enhanced shear strength, delaying failure. Once shear capacity was fully utilized, flexural stresses dominated, leading to bending failure. This highlights CFRP’s dual role in improving both shear and flexural resistance, extending load capacity, and promoting a more controlled, ductile failure mode.

The transition from shear to flexural failure in CFRP-wrapped beams B5 and B6 highlights CFRP's role in enhancing ductility. CFRP's confinement effect slowed crack propagation, redistributing applied loads and delaying failure. This shift to flexural failure increased load capacity and resilience, improving safety and durability under extreme loading conditions. CFRP's ability to arrest crack growth and enhance ductility underscores its potential in strengthening concrete beams for better performance and longevity.

Although fiber and resin materials used in FRP tend to be more costly compared to traditional options, the installation equipment for FRP systems is typically more affordable [23]. The adoption of carbon fiber-reinforced polymers (CFRP) has become a standard practice in strengthening and rehabilitating reinforced concrete structures. Extensive theoretical and experimental research, along with real-world applications, have documented the success of this technique. CFRP reinforcement enhances flexural or shear strength, and the effectiveness of its application largely depends on the quality of the bond and the ability to transfer stress from the concrete structure to the CFRP laminate [24].

This study confirms the effectiveness of CFRP in enhancing both shear and flexural capacities of reinforced concrete beams, with B3 and B4 showing load-bearing improvements of 41.15% and 59.29%. The transition from shear to flexural failure in B5 and B6 aligns with previous research, highlighting CFRP’s dual enhancement of shear and bending resistance. CFRP's ability to delay crack propagation and improve ductility further supports findings from existing literature. Overall, this study reinforces CFRP's potential in strengthening beams and improving their durability and performance in structural applications.

Conclusion

The study examined the strength of both CFRP-strengthened and non-strengthened beams, revealing that the CFRP-strengthened beams were significantly stronger. This supports the conclusion that the CFRP reinforcement plays a crucial role in enhancing the strength of concrete beams. A comparison of beams B3, B4, B5, and B6 further illustrates that the strength improvement correlates with the wrapping area. Beams wrapped with 356 mm of CFRP (B3 and B4) exhibited strength increases of 41.15% and 59.28%, respectively, compared to the standard beams B1 and B2. In contrast, beams wrapped with 508 mm of CFRP (B5 and B6) showed much more significant strength gains, with increases of 94.95% and 93.65%, respectively.

Failure analysis indicated that beams B1 to B4, without CFRP wrapping, failed at the shear zone, while the unsupported sections of beams B5 and B6 ultimately failed. The use of CFRP reinforcement proved highly effective, with credible and promising results. Notably, all beams were reinforced using a single layer of CFRP fabric, and none of the beams experienced premature brittle failure. Instead, the CFRP reinforcement allowed the strengthened beams to undergo substantial deflection under ultimate and failure loads, highlighting its ability to improve structural performance without compromising safety.

CFRP offers numerous practical advantages as a retrofitting solution, including lightweight, high corrosion resistance, and ease of installation. It enhances shear and bending performance, improving safety and extending the service life of aging structures, especially in seismic-prone areas. However, the cost of CFRP materials may impact decisions for large-scale applications, despite long-term benefits.

This study focused on single-layer CFRP wraps, leaving the effects of multiple layers, different configurations, and orientations for future research. Additionally, the long-term durability of CFRP under varying environmental conditions, including temperature changes, moisture, and chemicals, requires further investigation. Future studies should also explore the impact of dynamic and seismic loading on CFRP-reinforced beams to assess performance under real-world conditions.

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