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Enhanced Durability and Performance of Reinforced Concrete Beams Through CFRP Wrapping: An Experimental Investigation

Ashok Kumar Suluguru[1], Brunda Ungarala[2,*], B. Vamsi Krishna[3]

Abstract

Globally, maintaining and repairing aging reinforced concrete structures poses a significant challenge for the construction industry. Numerous structures built before modern earthquake-resistant design codes lack adequate seismic resilience. Additionally, evolving service requirements often necessitate strengthening existing structures to handle increased loads. While past research explored the effectiveness of various Fiber Reinforced Polymer (FRP) wrappings under specific conditions, limited studies have comprehensively compared the performance of Carbon Fiber Reinforced Polymer (CFRP) compared to other options across diverse loading scenarios and structural geometries. This experimental study investigates the efficacy of CFRP wrapping on reinforced concrete beams with varying span-to-depth (L/D) ratios. Beams with L/D ratios of 4.0, 5.5, and 7.0 were retrofitted and rehabilitated with two layers of CFRP wrapping. Subsequent testing involved subjecting the beams to service load, ultimate load under static and cyclic loading conditions. The study meticulously analyzes the impact of CFRP wrapping on load-carrying capacity, stiffness improvement, and ductility behavior. The findings provide valuable insights into the potential of CFRP as a durable and performance-enhancing solution for rehabilitating reinforced concrete beams, enabling informed decision-making in real-world applications.

Keywords: CFRP strengthening, reinforced concrete beam rehabilitation, span-to-depth ratio (L/D), seismic retrofit, durability and performance enhancement

INTRODUCTION

The global infrastructure landscape is plagued by a growing problem: aging and deteriorating reinforced concrete structures. Deterioration stems from various factors, including exposure to harsh environmental conditions, corrosion of steel reinforcement, inadequate design for contemporary loads, and seismic vulnerability due to outdated codes. Maintaining and repairing these structures is becoming a major challenge for the construction industry, demanding cost-effective and sustainable solutions.

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Traditionally, addressing these issues involved methods like concrete repairs, steel jacketing, and additional external supports. However, these techniques often come with limitations such as increased dead weight, disruption to existing space, and limited effectiveness in improving specific properties like ductility. In recent decades, Fiber-Reinforced Polymers (FRPs) have emerged as a promising alternative for structural rehabilitation. Among these, Carbon Fiber

Reinforced Polymer (CFRP) has gained widespread recognition due to its exceptional strength, stiffness, high modulus, and lightweight nature Ayrilmis, N. et al. (2024).

CFRP, composed of high-strength carbon fibers embedded in a polymer matrix, offers numerous advantages for strengthening and rehabilitating concrete structures. It possesses a high strength-to-weight ratio, allowing for significant improvements in load-carrying capacity without adding substantial weight. CFRP exhibits excellent corrosion resistance, ensuring long-term durability in aggressive environments. Its high tensile strength and flexibility enable effective confinement of concrete, enhancing ductility and crack control, thus improving energy dissipation capacity under seismic loading. Additionally, CFRP application is minimally invasive, requiring minimal preparation and causing minimal disruption to existing structures and their functionality ACI 440.2R-17.

Carbon Fiber Reinforced Polymer (CFRP)

Carbon Fiber Reinforced Polymer (CFRP) is a composite material made of carbon fibers and a polymer resin matrix. It offers exceptional strength-to-weight ratio, high stiffness, and corrosion resistance, making it a popular choice in various industries including aerospace, automotive, construction, and sports equipment. The manufacturing process involves weaving carbon fibers into a fabric or mat, which is then impregnated with a resin such as epoxy or polyester. The resin hardens, binding the carbon fibers together and forming a solid structure. CFRP can be shaped into different forms such as sheets, rods, tubes, or custom molds to suit specific applications Ayuluri SR, Vamsi Krishna B (2017).

In construction, CFRP is used for strengthening and repairing concrete structures such as bridges, buildings, and beams. It is applied externally as strips or wraps bonded to the surface of the structure using adhesives. This reinforcement technique helps improve the load-bearing capacity, flexural strength, and durability of the concrete elements. CFRP's lightweight nature and high strength make it particularly advantageous in aerospace and automotive applications where reducing weight while maintaining structural integrity is crucial for fuel efficiency and performance. Despite its numerous benefits, CFRP can be expensive compared to traditional materials like steel or aluminum. However, its long-term durability and performance often justify the initial investment, especially in high-performance or specialty applications. Ongoing research and development continue to explore ways to improve CFRP's properties and reduce costs, further expanding its potential uses across various industries in shown in Figure 1.

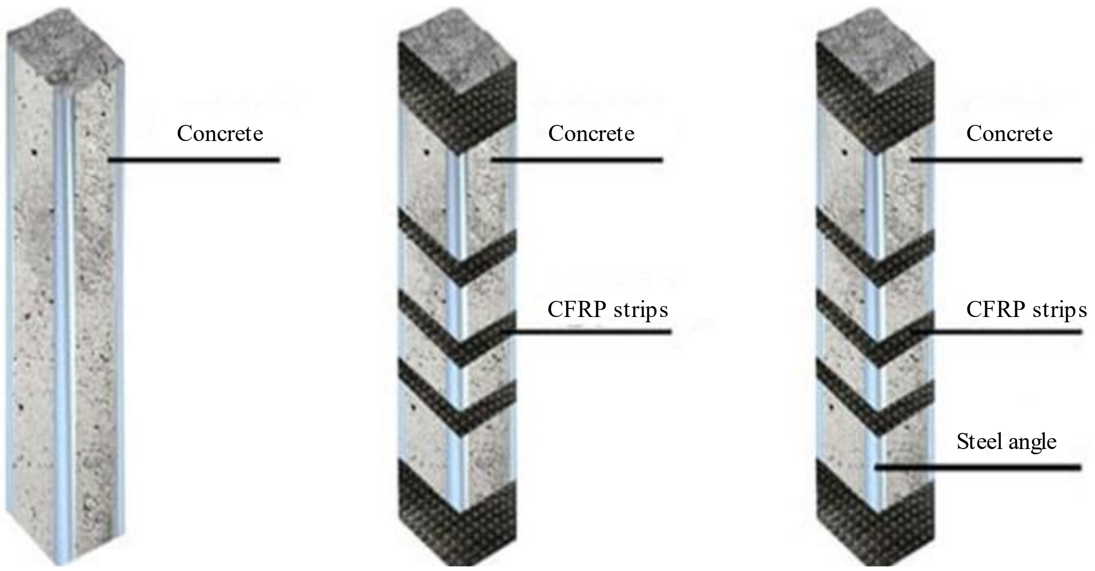

Figure 1. Phases of attaching CFRP strips to concrete to boost strength.

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CFRP in Construction

Beyond the basic properties mentioned earlier, CFRP exhibits several additional characteristics that make it particularly valuable in construction applications:

- *Versatility*: CFRP can be tailored to specific needs. The type of carbon fibers, the resin matrix, and the application technique can be modified to optimize strength, stiffness, ductility, and other properties based on the specific requirements of the structure and loading conditions.
- *Fatigue resistance:* Compared to traditional materials like steel and concrete, CFRP demonstrates superior resistance to fatigue loading. This makes it highly suitable for structures subjected to repeated stresses, such as bridges and wind turbine towers.
- *Thermal stability:* CFRP exhibits excellent thermal stability, maintaining its mechanical properties across a wide range of temperatures. This makes it valuable for structures exposed to extreme heat or cold, like industrial chimneys or cryogenic vessels.
- *Electrical conductivity:* Depending on the resin matrix used, CFRP can be designed to be electrically conductive or non-conductive. This allows for applications in both electrically sensitive environments and situations requiring lightning protection.
- *Ease of application:* CFRP can be applied on-site to existing structures with minimal disruption. This is achieved through various application methods like wet lay-up, prefabricated sheets, and near-surface mounted (NSM) techniques.

CFRP limitations

- *High cost:* The production and application of CFRP are currently more expensive compared to traditional materials like steel and concrete. This can be a constraint for some projects, although ongoing research and development efforts are aiming to reduce costs.
- *Brittle failure:* While its high strength is valuable, CFRP can exhibit brittle failure modes under certain conditions. Careful design and detailing are crucial to mitigate this risk.
- *Sensitivity to installation:* Proper installation techniques are critical for ensuring the full potential of CFRP is realized. Inadequate installation can lead to reduced performance and potential debonding from the underlying concrete shown in Figure 2.
- *Fire resistance:* Although advancements are being made, CFRP typically requires additional fire protection measures due to its susceptibility to degradation at high temperatures.

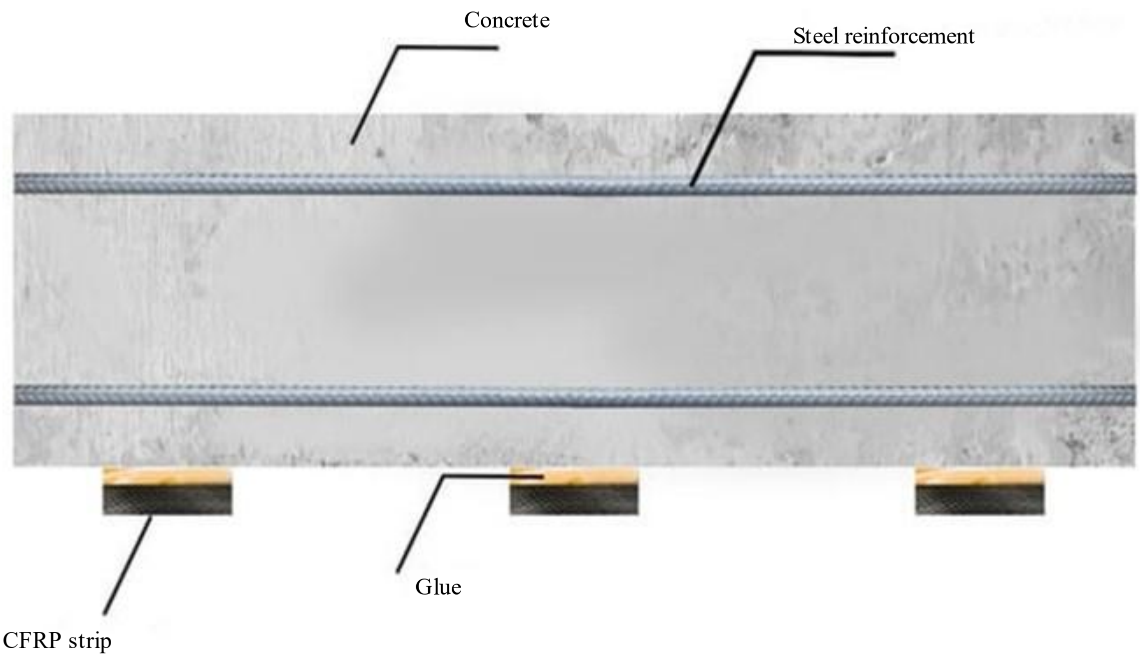

Figure 2. Adhering CFRP Reinforcement to concrete beams for enhanced strength.

Despite the extensive research conducted on CFRP strengthening, several key gaps remain:

- *Limited comparative studies:* While numerous studies have investigated the effects of CFRP wrapping on individual structural elements, few studies have directly compared its performance against alternative FRP types like Glass Fiber Reinforced Polymer (GFRP) or Hybrid Fiber Reinforced Polymer (HyFRP) across diverse structural geometries and loading scenarios. This hinders a comprehensive understanding of the relative effectiveness of CFRP under varying conditions.
- *Focus on specific geometries:* Existing research often focuses on strengthening beams with specific span-to-depth (L/D) ratios. However, real-world structures exhibit diverse geometric configurations, and understanding the impact of L/D variations on CFRP performance is crucial for broader applicability.
- *Limited analysis of cyclic loading:* While static loading provides valuable insights, many structures experience dynamic and cyclic loading, particularly in seismic zones. Investigating the behavior of CFRP-wrapped beams under cyclic loading conditions is essential for assessing their seismic performance.

LITERATURE REVIEW

Effectiveness of CFRP for Strengthening Concrete Beams: A Brief Review

Carbon Fiber Reinforced Polymer (CFRP) has emerged as a popular material for strengthening concrete beams due to its high strength-to-weight ratio, excellent corrosion resistance, and enhanced ductility compared to traditional methods. However, research on its effectiveness reveals both its potential and limitations:

- *Increased load capacity:* Numerous studies e.g., [1, 2, 3] demonstrate significant increases in flexural and shear capacities of CFRP-wrapped beams compared to unstrengthened ones. This improvement varies depending on factors like CFRP thickness, wrapping technique, and concrete strength Bahoria, B. V. *et al.* (2024).
- *Improved stiffness and deflection control:* CFRP's high stiffness reduces beam deflection under loads, enhancing serviceability and improving crack distribution [4, 5]. This is vital for bridges and other structures experiencing frequent loading.
- *Enhanced ductility and energy dissipation:* While CFRP itself is brittle, proper confinement of concrete with CFRP improves overall ductility, allowing beams to absorb more energy and deform before failure ([6, 7]). This is crucial for seismic resistance.
- *Durability and corrosion resistance:* CFRP's resistance to corrosion and harsh environments protects reinforcing steel, extending the lifespan of structures exposed to aggressive conditions [8, 9].

Limitations and Considerations

- *Bonding issues:* Improper bonding between CFRP and concrete can lead to premature debonding and reduced effectiveness. Surface preparation and adhesive selection are crucial factors.
- *Cost:* CFRP materials and application costs are currently higher than traditional methods, although advancements are narrowing the gap [10].
- *Brittle failure:* CFRP can exhibit brittle failure modes under certain conditions, requiring careful design and detailing to mitigate risks.
- *Limited research on cyclic loading:* While static tests are informative, more research is needed on the effectiveness of CFRP under cyclic loading simulating earthquakes, particularly for seismic regions [11].
- *Comparison with other FRPs:* Though studies exist, comprehensive comparisons are lacking between CFRP and other Fiber-Reinforced Polymers (GFRP, HyFRP) to guide material selection based on specific performance requirements.

- Overall, CFRP presents a promising solution for strengthening concrete beams, offering improved load capacity, stiffness, and durability. However, careful consideration of bonding, cost, potential for brittle failure, and limited research on cyclic loading is crucial for successful implementation. Further research comparing CFRP with other FRPs under diverse loading scenarios is essential for broader applicability and informed decision-making [12].

Comparison of CFRP, GFRP, and HYFRP for strengthening concrete beams: a review

While CFRP has gained significant traction in strengthening concrete beams, exploring and comparing its performance with alternative Fiber-Reinforced Polymers (FRPs) like GFRP (Glass Fiber Reinforced Polymer) and HYFRP (Hybrid Fiber Reinforced Polymer) is crucial for informed decision-making. Here's a review of available studies [13-14]:

- Compared CFRP, GFRP, and Hybrid FRP (CFRP-GFRP) under flexure. CFRP offered the highest load capacity and stiffness, followed by HYFRP and GFRP.
- [15-18]. Compared CFRP, GFRP, and HYFRP (CFRP-Steel) under shear. CFRP and HYFRP showed similar ultimate capacity, while GFRP provided the lowest. However, CFRP exhibited the highest stiffness.
- CFRP generally offers the highest load capacity and stiffness due to its superior strength and modulus.
- HYFRP can compete with CFRP in some aspects, combining strengths from different fibers.
- GFRP typically exhibits lower capacity and stiffness but may be cost-effective for specific applications.

Ductility and Energy Dissipation

- Venkatesh et al. (2015) studied the impact of FRP type and thickness on ductility. GFRP beams showed higher ductility than CFRP, attributed to its larger fiber diameter and ability to undergo larger deformations.
- [12] Compared cyclic loading behavior of beams strengthened with CFRP and GFRP. Both exhibited increased energy dissipation compared to unstrengthened beams, with GFRP showing slightly higher values.
- GFRP generally exhibits higher ductility due to its inherent material properties.
- Both CFRP and GFRP can enhance energy dissipation compared to unstrengthened beams.
- The optimal choice depends on the desired balance between strength and ductility for specific loading conditions.

Effects of l/d ratio on CFRP-wrapped beam performance: a review

The span-to-depth ratio (L/D) significantly impacts the behavior of reinforced concrete beams, and understanding its influence on the effectiveness of CFRP strengthening is crucial for optimal design and application. Here's a review of research on this topic [19-20]:

- Krishna BV et al. (2020) tested CFRP-wrapped beams with L/D ratios of 3, 4, and 5 under flexure. Beams with lower L/D exhibited higher ultimate capacity and more ductile failure modes compared to longer beams, which experienced brittle shear failures.
- Naga Chaitanya et al. (2014) observed similar trends, with lower L/D beams showing higher capacity and more distributed cracking compared to higher L/D beams prone to concentrated cracking and shear failure.
- Lower L/D ratios generally benefit from higher CFRP effectiveness due to reduced shear demands and more favorable stress distributions.
- Higher L/D ratios require careful attention to shear strengthening alongside flexural strengthening with CFRP to prevent premature shear failure.

Overall, L/D Ratio Plays a Key Role In CFRP-Wrapped Beam Performance

- *Lower L/D:* Higher load capacity, more ductile failure modes, and potentially lower bond stresses.

- *Higher L/D:* Increased susceptibility to shear failure, larger deflection reductions, and higher risk of debonding at supports.

OBJECTIVE OF CURRENT STUDY

This present study aims to address these identified gaps by conducting an experimental investigation on the enhanced durability and performance of reinforced concrete beams through CFRP wrapping. The study will focus specifically on the following objectives:

- *Compare the effectiveness of CFRP wrapping to other FRP types*: Beams with varying L/D ratios will be strengthened with CFRP, GFRP, and HyFRP for direct comparison of their impact on load-carrying capacity, stiffness, and ductility under static loading.
- *Evaluate the influence of L/D ratio on CFRP performance:* Beams with L/D ratios of 4.0, 5.5, and 7.0 will be wrapped with CFRP and tested under static and cyclic loading conditions to understand how L/D variations affect the CFRP's effectiveness.
- *Assess the behavior of CFRP-wrapped beams under cyclic loading*: Beams wrapped with CFRP will be subjected to cyclic loading conditions simulating seismic events to evaluate their energy dissipation capacity and overall seismic performance.

METHODOLOGY

The Methodology section provides a comprehensive overview of the materials employed in the study, the process of preparing the test specimens, the repair techniques implemented, and the testing protocol conducted.

Raw Materials

The characteristics of cement, aggregates, water, steel, epoxy resin, and FRP materials underwent testing in accordance with the Indian Standard specifications, and the results of these tests are documented.

Epoxy resin

A two-component epoxy system, comprising Araldite-250 and Aradur 2963, was combined in a ratio of 1:0.45. This mixture, consisting of a base and a hardener, was applied for both repairing and wrapping FRP on beams and columns. Detailed properties of the epoxy resin can be found in the provided in table 1.

Table 1. Characteristics of Epoxy Resin (As Specified by The Manufacturer)

Tensile modulus	**3.3 GPa**
Elongation at break	0.04
Density at 25 °C (ISO 1675)	1.17g/cm^3
Flash point	200 °C
Viscosity at 25 °C	11500 mPa s

Fiber-Reinforced Polymer

Carbon Fiber-Reinforced Polymer (CFRP) is a composite material made of carbon fibers embedded in a polymer matrix, commonly epoxy resin. It boasts exceptional strength-to-weight ratio, stiffness, and corrosion resistance, making it popular in aerospace, automotive, and construction industries. CFRP is manufactured by impregnating carbon fibers with a resin, then curing to form a solid structure. It can be molded into various shapes, such as sheets, tubes, or rods, to suit specific applications. In construction, CFRP is used for strengthening concrete structures like bridges and buildings, improving load-bearing capacity and durability. Its lightweight nature makes it advantageous in aerospace, reducing fuel consumption while maintaining structural integrity. Despite its high performance, CFRP can be expensive, but ongoing research aims to improve cost-effectiveness and expand its applications. Shown in Figure 3. The Characteristics of FRP Composites are discussed in Table 2.

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Figure 3. Carbon fiber-reinforced polymer cloth.

Table 2. Characteristics of FRP Composites (experimentally examined by the author)

Properties	CFRP	GFRP	Hybrid CFRP-GFRP
Thickness (mm)	1.40	2.80	2.20
Weight (gm/sq m)	1300.00	4109.00	2934.00
Fibre content (%)	40.45	59.50	48.40
Resin content (%)	59.55	40.50	51.60
Tensile strength (MPa)	715.33	355.50	419.67
Flexural strength (Mpa)	568.00	423.00	465.00
Poissons ratio	0.26	0.32	0.28

Casting of test specimens

For the experimental study, beams measuring 100 mm x 200 mm were cast in three different lengths: 900 mm, 1200 mm, and 1500 mm. These beams were reinforced with two 10 mm diameter TMT main bars at the bottom and two 8 mm diameter TMT bars at the top. Additionally, 6 mm diameter two-legged stirrups were placed at 150 mm intervals along the beams, as illustrated in Figure 4.

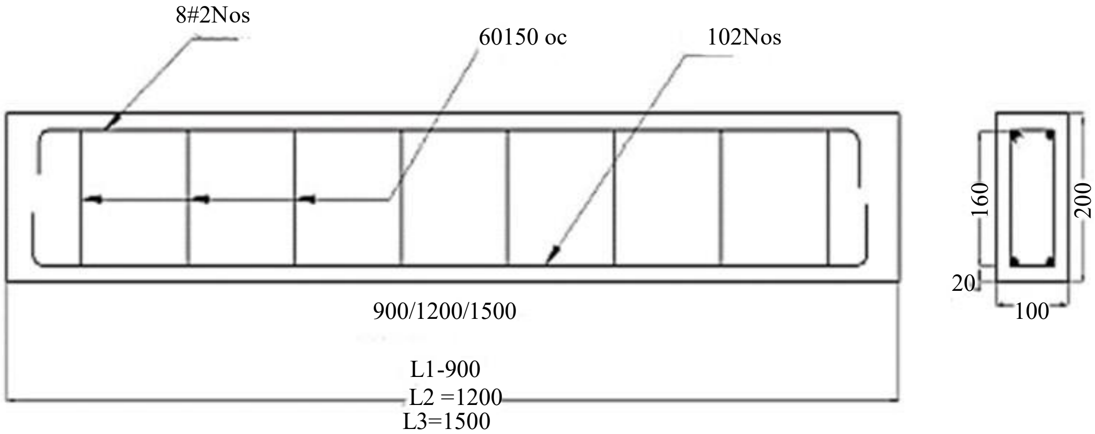

Figure 4. Specifications and design of reinforcement for beam.

Casting of Beam Specimens

A total of 18 reinforced concrete beams were cast, each with dimensions of 100mm width and 200mm depth, but with varying lengths of 900mm, 1200mm, and 1500mm, corresponding to three different span-to-depth ratios. The concrete mix was poured into the molds in three layers, and proper compaction was ensured using a 25mm needle vibrator until the concrete reached the top of the beam. After placement, the fresh concrete was allowed to set for twenty-four hours before demolding. The demolded concrete beam specimens were then cured for a period of 28 days. Following the curing process, the specimens were categorized into three series based on their span-to-depth ratios: B1-series (800mm span), B2-series (1100mm span), and B3-series (1400mm span), as illustrated in Figure 5.

Figure 5. Beams casting.

Retrofitting of control beams

To strengthen the control beams, FRP fabrics were bonded to the tension zone side. After the control beams were cured, the surface of the tension zone was roughened using a concrete grinder and cleaned with an air blower to remove all dust particles and debris. Once surface preparation was complete, epoxy resin, prepared according to the manufacturer's instructions, was applied to the beam's surface.

Initially, one layer of CFRP fabric, measuring 100mm in width and with a length 20mm shorter than the clear span of the beam, was evenly spread over the surface and stretched to match the beam's size without any folding. Subsequently, a second layer of CFRP fabric of the same dimensions was placed over the first layer, followed by the application of one coat of resin. The wrapped specimens were then allowed to cure for seven days shown in Figure 6.

Figure 6. First and second layer of CFRP.

Rehabilitation of Beams Specimens with FRP Wrapping

The typical failure observed in the beams occurred in the tension zone under both service and ultimate load levels. During cyclic load testing of the control beams, typical failure modes were observed in both the compression and tension zones. To address cracks that developed in the beams under loading, epoxy resin was used to fill the cracks, effectively bridging them. Additionally, damaged portions in the compression zone were repaired using concrete patch material of the same grade, following standard repair procedures. Once repaired, the surfaces of the tension zones were roughened using a concrete grinder and cleaned with an air blower to eliminate all dust particles and debris. Following surface preparation, FRP fabrics were wrapped over the failed beam specimens. The wrapping procedure followed typical guidelines for applying FRP to reinforce the beams shown in Figure 7.

Figure 7. Failure in compression and tension zones of control beam.

RESULTS AND DISCUSSIONS

Both beams with and without CFRP wrapping underwent testing to determine their performance under static conditions, specifically to assess initial cracking and service load. Data collected during testing were thoroughly analyzed, and the results were organized into tabulated format. The analysis primarily focused on evaluating load carrying capacity and deflection characteristics of the beams, comparing the performance of beams with and without CFRP wrapping.

Impact of CFRP Wrapping on Beams Tested to Service Load Levels

The test results for beams with and without CFRP wrapping at initial cracking and service load levels are provided in Tables 3 and 4, respectively. The corresponding load-deflection curves are depicted in Figures 8. Additionally, the deflection values for beams with CFRP wrapping, corresponding to the initial cracking load and service load of control beams, were calculated, and presented in Figure 9, 10 & 11. These values were derived from the load-deflection curves.

Beam-N: Control Beam, *Beam-R:* Retrofitted with CFRP, Beam -RH: Rehabilitated with CFRP

Table 3. Comparison of test results between beams with and without CFRP wrapping under service load conditions at the initial crack load level

L/D Ratio	Specimen	Load (kN)	Deflection (mm)	Moment (kN.m)
4	Beam-N	29.61	0.29	3.95
	Beam-R	32.57	0.30	4.34
	Beam-RH	34.55	0.33	4.60
5.5	Beam-N	23.69	0.37	4.34
	Beam-R	34.55	0.52	6.33
	Beam-RH	34.55	0.58	6.33
7	Beam-N	11.84	0.59	2.76
	Beam-R	19.74	0.82	4.60
	Beam-RH	24.68	0.98	5.75

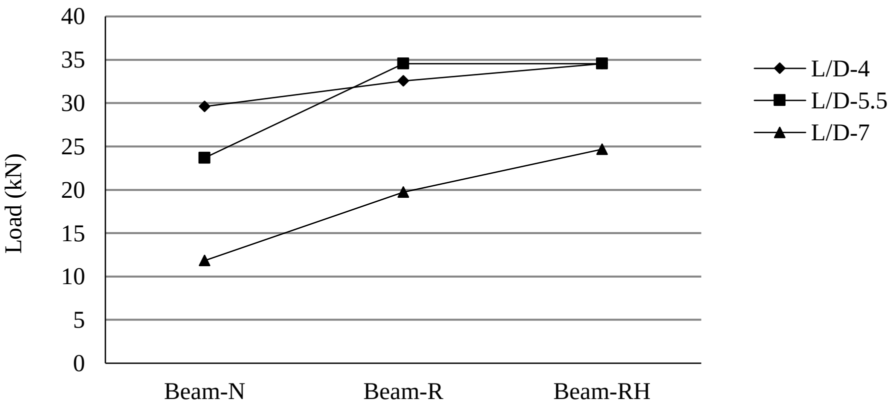

Figure 8. Load Curve - beam behavior at initial crack load level at different L/D ratios.

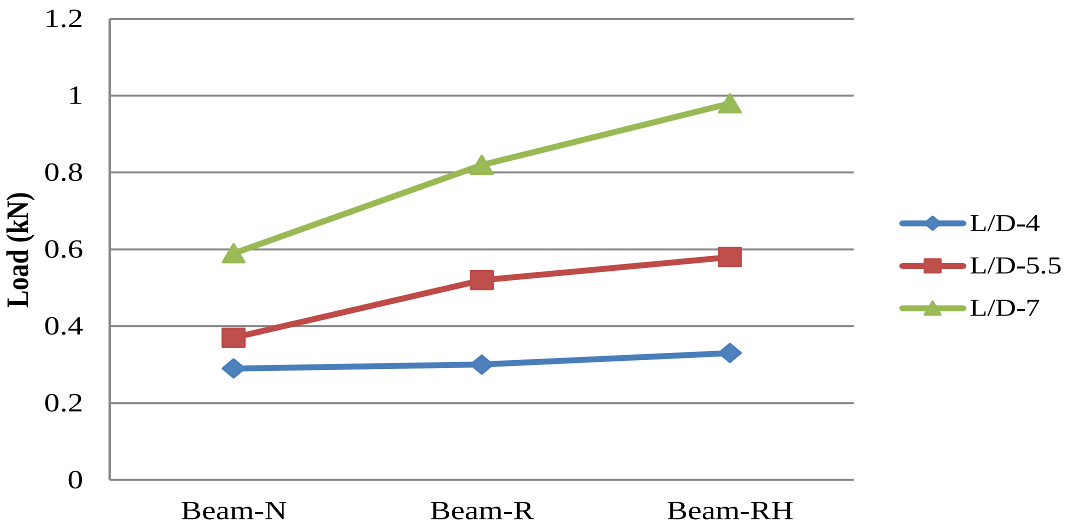

Figure 9. Deflection curve - beam behavior at initial crack load level at different L/dratios.

Table 4. Comparison of test results between beams with and without CFRP wrapping under service load conditions at the service load level.

L/D Ratio	Specimen	Load (kN)	Deflection (mm)	Moment (kN.m)
4	Beam-1	85.13	2.28	11.18
	Beam-2	140.16	2.30	18.68
	Beam-3	100.18	2.30	13.35
5.5	Beam-1	55.27	3.14	10.13
	Beam-2	98.70	3.13	18.10
	Beam-3	92.51	3.14	16.98
7	Beam-1	47.38	4.00	11.04
	Beam-2	66.01	4.01	15.38
	Beam-3	61.19	4.00	14.26

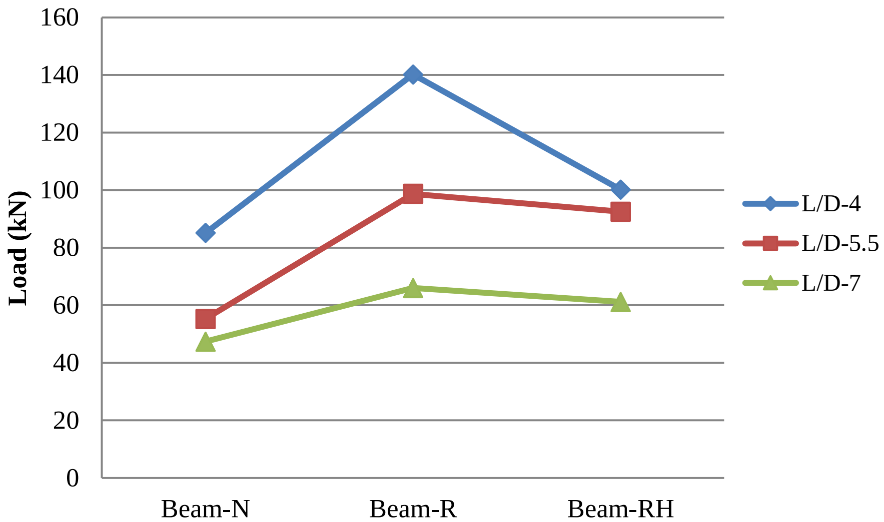

Figure 10. Load curve - beam behavior at service load level at different L/D ratios.

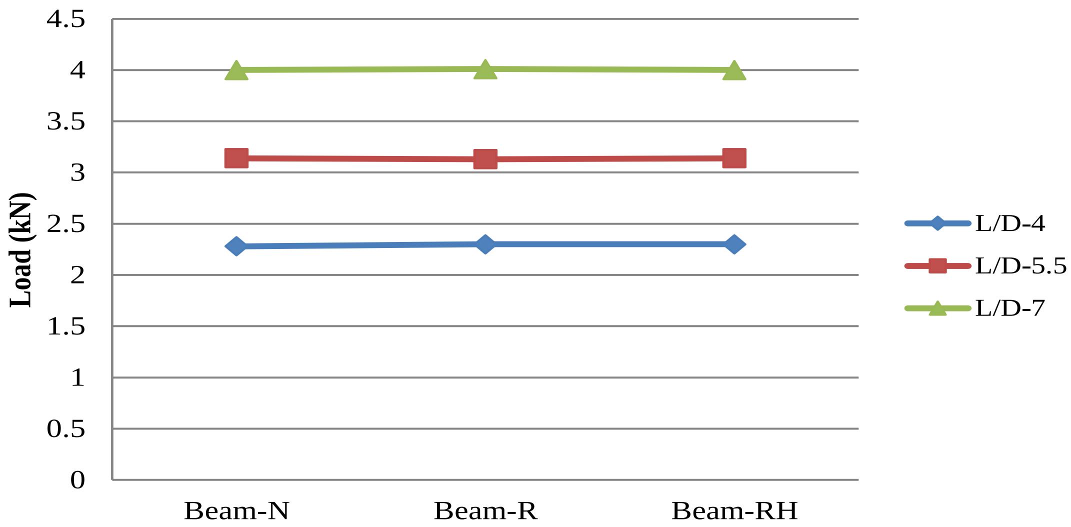

Figure 11. Deflection curve - beam behavior at service load level at different L/D ratios.

CONCLUSIONS

Based on the presented data, several observations and conclusions can be drawn regarding the effects of L/D ratio and CFRP wrapping on reinforced concrete beams under service load conditions:

Initial Crack Load Level

- Compared to unstrengthened beams (Beam-N), CFRP-wrapped beams (Beam-R and Beam-RH) demonstrated a significant increase in load capacity across all L/D ratios.
- This highlights the effectiveness of CFRP for enhancing the load-bearing capacity of concrete beams.
- While higher load capacity was observed for CFRP-wrapped beams across all L/D ratios, the relative improvement varies.
- At L/D ratio of 4, the increase in capacity ranged from 10% to 16.8%.
- At L/D ratio of 5.5, the increase ranged from 46.1% to 46.7%.
- At L/D ratio of 7, the increase ranged from 66.5% to 108.5%.
- This suggests that the relative benefit of CFRP strengthening in terms of load capacity increases significantly with higher L/D ratios.
- CFRP wrapping resulted in slightly higher deflections compared to unstrengthened beams across all L/D ratios. This might be attributed to the increased stiffness of the beam due to CFRP, potentially leading to slightly larger deflections under the same load.
- Similar to load capacity, moment capacity also increased with CFRP wrapping across all L/D ratios.
- The relative increase in moment capacity follows a similar trend as load capacity, with higher benefits observed for beams with higher L/D ratios.

Service Load Level

- Compared to unstrengthened beams (Beam-1), CFRP-wrapped beams (Beam-2 and Beam-3) demonstrated a significant increase in load capacity across all L/D ratios. This highlights the effectiveness of CFRP for enhancing the load-bearing capacity of concrete beams.
- At L/D ratio of 4, the increase in capacity ranged from 64.8% to 17.7%.
- At L/D ratio of 5.5, the increase ranged from 79.1% to 69.6%.
- At L/D ratio of 7, the increase ranged from 37.5% to 28.5%.
- While higher load capacity was observed for CFRP-wrapped beams across all L/D ratios, the relative improvement is not entirely consistent.

- At L/D ratio of 4, the highest increase is observed, followed by lower ratios.
- This suggests that the trend of increasing benefit with higher L/D ratios observed previously needs further investigation with a larger dataset.
- CFRP wrapping resulted in slightly higher deflections compared to unstrengthened beams across all L/D ratios. However, the differences are relatively small, suggesting that CFRP does not significantly compromise serviceability under service load conditions.
- Similar to load capacity, moment capacity also increased with CFRP wrapping across all L/D ratios.
- However, the available data doesn't allow for a clear analysis of the relative increase in moment capacity compared to load capacity.

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