Civil Engineering and Architecture 14(1): 356-366, 2026 http://www.hrpub.org
DOI: 10.13189/cea.2026.140122

# Enhancement of RC Beam Flexural Capacity with Carbon Fiber Reinforced Polymer Fabrics

**Shruthi H. G.[1,2,*], Gopalakrishna V. Gaonkar[3], Dushyanth V. Babu R.[3], Sreekeshava K. S.[4]**

[1]Department of Civil Engineering, Jain (Deemed to be) University, India
[2]Department of Civil Engineering, ATME College of Engineering, India
[3]Department of Civil Engineering, Faculty of Engineering and Technology, Jain (Deemed to be) University, India
[4]Department of Civil Engineering, Jyothy Institute of Technology, Affiliated to Visvesvaraya Technological University, India

*Received August 18, 2025; Revised November 26, 2025; Accepted December 22, 2025*

***Cite This Paper in the Following Citation Styles***

***(a):*** *[1] Shruthi H. G., Gopalakrishna V. Gaonkar, Dushyanth V. Babu R., Sreekeshava K. S. , "Enhancement of RC Beam Flexural Capacity with Carbon Fiber Reinforced Polymer Fabrics," Civil Engineering and Architecture, Vol. 14, No. 1, pp. 356 - 366, 2026. DOI: 10.13189/cea.2026.140122.*

***(b):*** *Shruthi H. G., Gopalakrishna V. Gaonkar, Dushyanth V. Babu R., Sreekeshava K. S. (2026). Enhancement of RC Beam Flexural Capacity with Carbon Fiber Reinforced Polymer Fabrics. Civil Engineering and Architecture, 14(1), 356 - 366. DOI: 10.13189/cea.2026.140122.*

**Abstract** In this experimental investigation, CFRP fabrics are wrapped around RC beams to improve their flexural strength. The wrapped beams are then subjected to a two-point loading process, and the following test results, including ultimate load capacity and flexural strength of the wrapped beams, are compared with those of the control beam. A total of 9 RC beams were used in the investigational work, and the beam dimensions are 200 x 250 x 2000mm. The casting work includes three control beams (CB), three beams wrapped in CFRP fabric in the base (BCFRPFB), and three beams wrapped in CFRP fabric in the base and along the two longer sides of the beams that were outwardly bonded with epoxy resin (BCFRPFBS). Experimental analysis was performed to study the outcome of CFRP fabrics on beams with the flexural strength, ultimate load capacity, stress-strain curves and load-deflection relationship. Results show that the average ultimate load capacity of the beam wrapped with CFRP fabrics on the base & along two longer sides is 94% higher than that of the control beam and 27% higher than that of the beam wrapped with CFRP fabrics on the base of the beam.

**Keywords** Flexural Strengthening, RC Beam, CFRP - Carbon Fiber Reinforced Polymer, Fiber Reinforced Polymer (FRP)

## 1. Introduction

In recent decades, FRP has been generally known as a leading material for the enhancement of the flexural strength of RC beams. The RC beams can enhance the flexural strength with common methods, such as externally bonded method or near surface mounted method with high-strength materials, such as steel plates, mesh and fiber reinforced polymer etc. [1]. Ashour et al [2] in their study, examined the mechanical performance of RC beam specimens strengthened with 3D-fiberglass as associated with fiber-reinforced polymers (FRP) sheets. For this purpose, 6 RC beams were fabricated, strengthened, and subjected to testing using the four-point method. Typically, the RC beam experiences flexural and shear failures. Most RC beams require strengthening to resist early failure. The special qualities of CFRP fabrics and GFRP fabrics, such as high strength to weight ratio, excellent tensile strength, corrosion resistance, and low thermal expansion, are more prominent than those of other materials such as steel plates, mesh etc. [3]. Ayesha Siddika et al. [4], in their research, aimed to boost the strength and concert of RC beams by utilizing the CFRP. A variety of strengthening techniques and surface treatments were used and they include normal beam, where strengthening is applied on the tension side and wrapping of the beam is done along the three sides of the with CFRP sheets, CFRP strips were placed at the base of the beam with a spacing of 150 mm c/c and cross strip wrapping is applied to small-scale beams to see how they influenced load capacity and flexibility. The findings indicated that CFRP made a significant difference in enhancing the beams' strength and ductility. The ultimate load capacity of the beam was increased by 60.9% from the beams that served as standard set beams. The results show that using the U wrap system in conjunction with wrapping along the three sides with reinforcement, produced the best results associated with the control beams [4-6]. CFRP fabrics encapsulated in an epoxy matrix have high tensile strengths to their weight. The extent of surface preparation is critical to achieving a good bond between the concrete external and the CFRP [7]. Retrofitting RC structures has developed gradually significantly due to issues like corrosion, overuse, and the need to support heavier loads. The CFRP presents a strong, lightweight, and durable alternative to steel for enhancing shear, flexural, and confinement strength [8,9]. In Kim et al.'s study [10], the CFRP shear strengthening is done with U-wrapping and full wrapping. The full wrapping of the beam affords a 201.6% increase in ultimate load capacity associated with both the U-wrap and control. Although the U-wrap is usually more applicable, it is susceptible to failure by premature debonding. Among the many categories of FRP, the carbon fibre reinforced fabrics are high-performance materials used to reinforce and repair existing structures, enhancing their load-bearing capacity and durability [11,12]. A comprehensive life-cycle exhaustion assessment of reinforced concrete (RC) beams retrofitted with prestressed carbon fiber–reinforced polymer (CFRP) plates is carried out using an analytical modeling approach, rather than treating the analysis as a generalized deterministic method. Crucially, this prediction model uniquely considers the progressive effect of FRP debonding to reflect one of the most significant failure mechanisms experienced under cyclic loading [13]. Guo D et al. [14], in their work, address that temperature effects can greatly accelerate interfacial damage and reduce the efficacy of the strengthening process, which is most helpful for the durability assessment of FRP-strengthened steel structures. The study examines cyclic loading's effect on fatigue-driven crack propagation at the CFRP–concrete interface, and shows that it accelerates the interfacial debonding where fatigue governs the long-term durability of CFRP-strengthened RC beams [15]. The study analyzes the fatigue performance of RC continuous beams strengthened with external CFRP tendons, showing that prestressing with CFRP tendons increases the load-bearing capacity significantly while delaying crack growth and increasing long-term durability when subjected to cyclic loading [16]. It is made up of woven carbon fibers that are bonded to surfaces using resin systems, resulting in composite systems that are strong, lightweight, and durable [17]. The investigation of flexural strengthening effectiveness of NSM-CFRP strips on RC beams showed that they are effective for all concrete compressive strength classes and that when demonstrating load capacity improvement, there is a delay in the formation of cracks and an improvement in ductility irrespective of the concrete compressive strength class [18,19]. The effect of CFRP sheets bonded to the sides of shear walls on the shear behavior of RC T-beams demonstrated that shear capacity improved with the introduction of CFRP reinforcement; cracks were delayed, and ultimately the overall rehabilitation was better than if nothing had been done [20]. The structural behavior of an RC beam strengthened with FRP and reinforced with corroded rebar was examined in the study, and it was decided that FRP reinforcement successfully provided a restoration of load capacity and ductility as well as mitigated the overall effects of corrosion damage [21]. High strength ratio, effective at restoring load capacity and structural stiffness and durability in harsh environments are superior mechanical qualities over the other varieties of FRP fabrics. CFRP fabrics are also the best option for use in seismic maintenance and/or when higher confinement pressure is required to achieve enhanced structural capacities [22]. According to P. Manibalan et al. [23], the flexural performance of BFRP strengthened RC beam is per-formed using repetitive loading to cause failure. The strategy for outward attachment FRP is recognized as an informal way to restore present reinforced concrete structures and provide shelter quickly rather than replace the frail existing structure. Basalt FRP is gaining increasing attention in recent studies owing to its environmentally friendly aspect. The RC beams exhibit greater stiffness, load-carrying ability, and energy absorption capacity due to BFRP strengthening.

Several techniques were investigated in strengthening and rehabilitating using FRPs composites. The external-bonded technique (EB) and near-surface-mounted (NSM) technique were viewed as the promising strengthening systems since they improve the shear and flexural capacity of the RC structures. Shrestha et al. [24] conducted an investigation on the effectiveness of FRP-strengthening techniques on corroded steel reinforcement and deteriorated reinforced concrete beams. Instead of repairing the concrete cover that had corroded, the FRP-strengthening system was employed straight away. Using a 3D optical scanning approach, the average and maximum corrosion levels of steel reinforcement were determined. Even with an average corrosion level, FRP-induced crack corrosion up to 1.9 mm with local corrosion levels up to 57%. Improvement method (was applied directly to the beam without repairing the worsened concrete cover). It was beneficial for the modernization of the rolling capability. Applied the jacket effect, stratification of concrete covers is always removed, leading to GFRP, CFRP plate coefficients up to 64%.

Studies indicate that EBR and NSM CFRP systems improve RC beam flexural strength; however, NSM shows higher bond strength and greater load increases, while EBR is often limited by premature debonding. CFRP strengthening of pre-damaged beams restores 30–57% of the lost capacity, and key factors affecting performance include bond quality, laminate width, and preload level. Common failure modes have changed from steel yielding and debonding (EBR) to concrete crushing and cover separation (NSM). Despite these advancements, a serious research gap exists since there are currently no models with a design orientation that sensibly connect experimental parameters (e.g., bond length and fiber architecture) to recommendations based on code while predicting flexural strength [25].

The present research represents an advanced experimental and analytical investigation into the flexural strengthening of RC beams with externally bonded CFRP fabrics, with a view to optimizing the bond configuration, method of surface preparation, and fiber orientation for maximum flexural efficiency. Unlike most of the past studies that have considered comparisons only for single-layer or single-face wrapping, this study will look into various aspects of multi-face and full-length wrapping schemes under controlled two-point loading conditions for beams made from M40 grade concrete, incorporating strain gauge instrumentation and load–deflection monitoring to quantify the flexural enhancement. The investigation offers an overall performance index relating CFRP thickness, fiber layout, and bond length to the resultant increase in load-carrying and serviceability and provides a design-oriented approach for practical retrofitting applications.

## 2. Materials and Methodology

### 2.1. Test Specimens

The experimental work involves 3 RC control beams, 3 RC beams wrapped with CFRP fabrics on the base, and 3 RC beams wrapped with CFRP fabrics on three sides (the bottom and two longer sides). Each beam measures 2000 mm in length, 200 mm in width, and has a depth of 250 mm. As illustrated in Figure 1, the reinforcement consists of 8mm bars spaced 175mm apart from center to center. The beams are strengthened with 2#12 mm diameter bars in both the tension and compression zones, respectively.

### 2.2. Material Properties

The concrete mix design of M40 grade was prepared for the casting of RC beams. The constituents required for the concrete are OPC 53 Grade of cement, coarse aggregate with a nominal size of 20mm and fine aggregate of particle size greater than 150μm passing through a 4.75mm sieve. The M40 grade of mix design is obtained to attain the characteristic compressive strength of 40 MPa at 28 days as per the guidelines in IS 10262:2019 and IS 456:2000 [26-28], and to attain proper workability, which was ensured to facilitate compaction and placement during beam casting using an appropriate water-cement ratio and admixture of superplasticizer Fosrac 340 added.

The RC beams were cast using the designed M40 grade of concrete. The steel reinforcement considered was HYSD bars with a yield strength of 550 MPa and a modulus of elasticity of 200 GPa. The reinforcement was safely tied and supported with spacers to provide the specified cover. The formwork was cleaned and oiled before placement. Concrete pressure is stipulated to be placed in layers. Individually, the layer was compacted with a mechanical vibrator to eliminate air and unify the concrete mass. The beams were demoulded after 24 hours of casting and water cured in a controlled laboratory environment for 28 days to allow for complete hydration to achieve the desired strength properties. The three standard cubes of size 150mm x 150mm x 150mm were cast from the same batch as the beams and cured for a period of 28 days. After 28 days curing, the cubes were subjected to compressive strength tests, and the average compressive strength (f'c) of the three specimens was 41 MPa, which surpassed the target characteristic strength of 40 MPa and consequently validated the mix design.

Flexural tensile strength, commonly known as the modulus of rupture, is the maximum tensile stress that a beam experiences at its outermost fiber when it bends to the point of failure. In contrast to direct tensile tests, flexural tests assess tensile behavior indirectly via bending, which brands them mainly helpful for inelastic materials such as concrete.

$$fT = PL/ bd^2 \quad (1)$$

Where,

fT = Flexural tensile strength in MPa

P = Total applied load at failure in N

L = Effective span of the specimen between the supports (mm)

b = Width of the beam in mm

d = depth of beam in mm

The equation 1, evaluates the maximum tensile stress developed at the bottom of the beam under bending. It is used to measure the concrete resistance to flexural tension, indicating its cracking strength.

The characteristics of the CFRP fabrics and epoxy adhesive, as specified by the manufacturer, are publicized in Table 1.

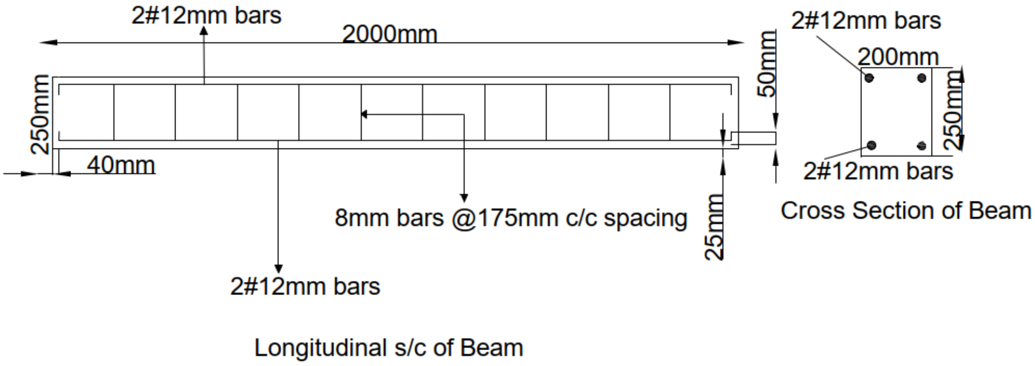

**Figure 1.** Beam reinforcement detailing

**Table 1.** Characteristics of CFRP fabrics & Epoxy adhesive

| Material | Density | Thickness mm | Elastic Modulus (GPa) | Tensile strength (MPa) |
|---|---|---|---|---|
| CFRP Fabrics | 1.78 gm/ cm $^3$ | 0.4 | ≥ 250 | ≥ 4900 |
| Epoxy adhesive | 1.35 kg/liter | - | 2-5 | >19 |

### 2.3. Strengthening Procedure

Before being cleaned, the surfaces of all the cast beams were ground to a rough surface for improved adhesion to CFRP fabrics. Following that, the locations where the CFRP fabrics must be attached were marked. The base and hardener must be mixed in a 4:1 ratio to prepare the epoxy paste. The CFRP fabrics, which were impregnated with the primer by rolling, must be trimmed to the proper lengths. Additionally, a primer and epoxy layer were brushed onto the beam surfaces, and then the CFRP fabrics were attached to the bottom as publicized in Figure 2. The same process must be followed to prepare three further sets of beams, and CFRP fabrics must be fastened to all three sides of the beam.

(a) (b)

(c)

(d)

**Figure 2.** Strengthening procedure. (a) External preparation (b) Applying epoxy on beam surface (c) Applied CFRP fabrics on the 3 sides of the beam (d) Wrapped beam under loading machine

### 2.4. Test Setup

A two-point loading method was applied in the experimental study. The test was set up within a loading frame to allow a hydraulic jack to place the load on the beam specimen. A spreader beam which is I-Section shaped receives the load from the jack and transfers it onto the beam specimen. The beam specimens were named based on the strengthening materials used. At the beams center and at the supports, the digital dial gauges were fixed to quantify the deflection. The load was added incrementally using a handheld lever on the hydraulic jack. The load was manually added equally until the beam reached the failure. The variation in strain and the deflection interpretations were recorded for every 2kN load increment. The experimental setup of the specimen is publicized in Figure 3.

The outline of the beam laboratory is publicized in Figure 4. A Universal Testing Machine (UTM) with a capacity of 2000 kN was employed to apply loads to all beams using a two-point loading method at a displacement rate of 2 mm per minute, in accordance with IS516:2018. Furthermore, the five strain gauges were attached to the beam to measure its deflection.

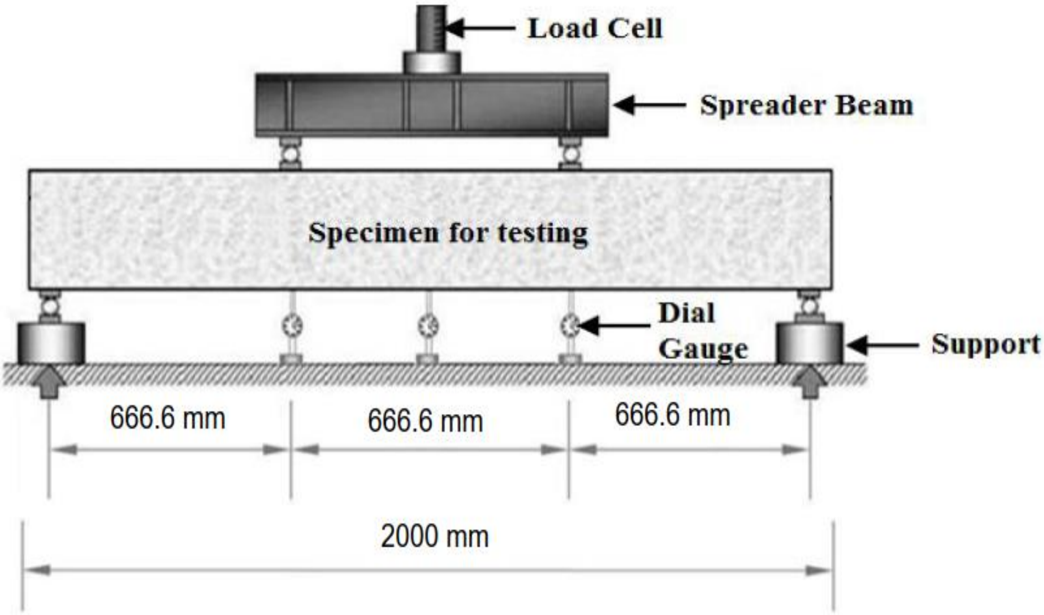

**Figure 3.** Experimental arrangement for two-point loading

**Figure 4.** Actual laboratory setup for testing

# 3. Test Results

This section dives into the experimental observations and results from analyzing the load-deflection of M40 grade RC beams under two-point loading.

## 3.1. Control Beam

The standard experimental procedure was followed. Initially, a load of 2kN was applied to the beam, and at this early stage, the concrete held up well under the pressure.

As the load increased, the first crack appeared at 22kN, measuring 0.56mm in width and causing a deflection of 3.73mm. The second crack was observed at 28kN, with a width of 0.73mm and a deflection of 5.177mm. Then, a third crack pattern emerged, showing a width of 0.79mm and a deflection of 5.646mm. The fourth crack was noted with a width of 0.85mm and a deflection of about 6.227mm, and as the load continued to vary, it eventually reached the failure limit. The crack patterns observed on the beam are shown in Figure 5, while the corresponding load versus deflection is depicted in Figure 6 below. The load versus deflection curves give a brief about how the beam responds to increasing loads, showcasing its transition from elastic deformation to ultimate failure. This illustrates the nonlinear flexural performance of the RC beam as the load gradually increases. As the load rises, the curve shifts into a nonlinear phase due to the formation and growth of flexural cracks, which leads to a decrease in stiffness. Ultimately, the beam reaches a peak load of 103kN, with a crack width of 0.96mm and a maximum deflection of 11.088mm.

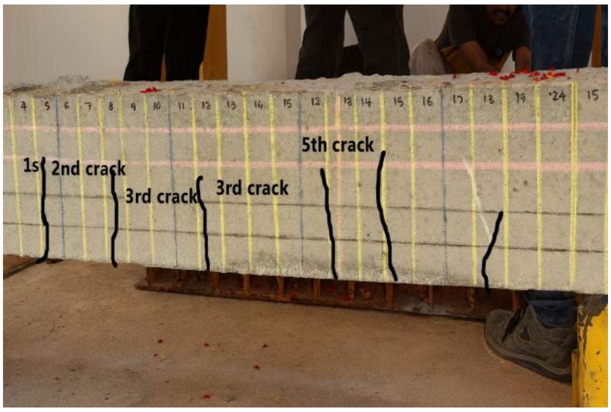

**Figure 5.** Crack patterns of control beam

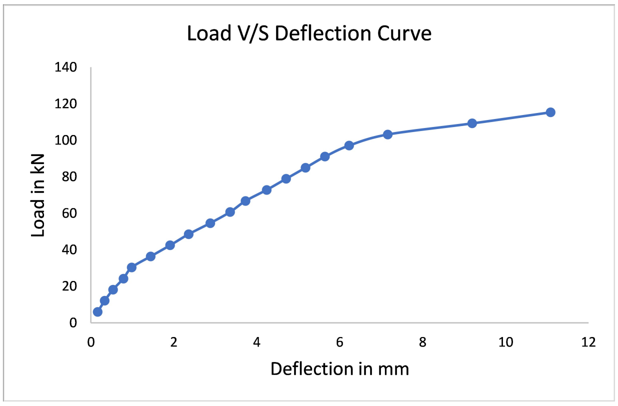

**Figure 6.** Load V/S Deflection of Control beam

## 3.2. Beam Strengthened with CFRP Fabrics at Bottom

The standard experimental procedure was adhered to throughout the process. In the initial phases of loading, the concrete seemed to hold up well under the applied weight.

As the load increased, the first crack was noticed on the beam at 28kN, which measured 0.29mm in width and a deflection of 1.076mm. The second crack appeared at 32kN, with a width of 0.34mm and a deflection of 2.187mm. Then, at 38kN, we observed a third crack pattern, which had a width of 0.35mm and caused a deflection of 5.817mm. The fourth crack was noted with a width of 0.38mm and a deflection of about 6.227mm, and as we continued to apply load, the cracks evolved until reaching the failure limit. The crack patterns noticed on the beam are illustrated in Figure 7, and the corresponding load versus deflection is represented in Figure 8. The load V/S deflection curve, which is publicized in Figure 8, illustrates the complex flexural behaviour of an RC beam as it undergoes progressive loading, which is crucial for grasping structural behavior in advanced research. At first, the beam displays a steep linear slope, reflecting uncracked elastic behavior and high stiffness. However, as the loading increases, it starts to indicate the tensile cracking in the concrete and a decrease in the flexural stiffness.

After 7mm deflection, it starts to notice an increase in resistance, with the wrapping of the CFRP fabrics to the beam. The ultimate load attains 157.87kN, with a maximum deflection of 8.532mm.

**Figure 7.** Crack patterns of Beam strengthened with CFRP Fabrics at bottom

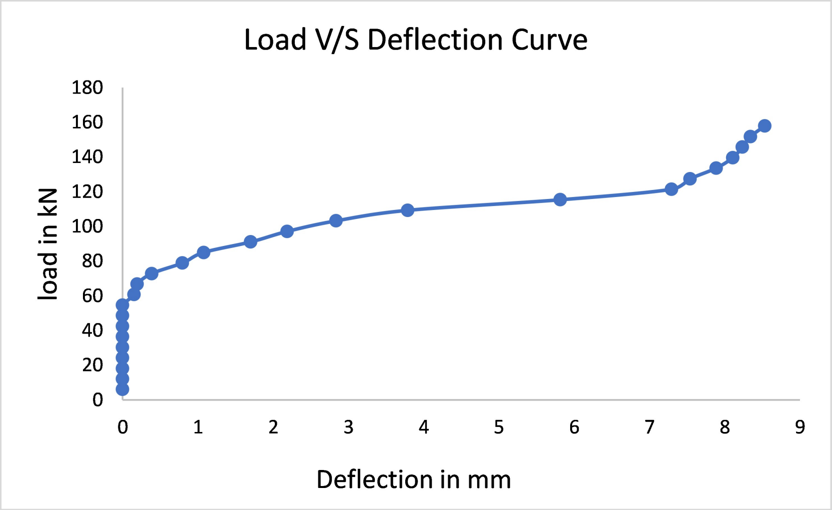

**Figure 8.** Load V/S Deflection of Beam strengthened with CFRP Fabrics at bottom

### 3.3. Beam Strengthened with CFRP Fabrics along Three Sides of the Beam

The standard experimental procedure was adhered to throughout the process. In the early stages of loading, the concrete demonstrated impressive strength, successfully bearing the applied load. As the load increased, the first crack appeared on the surface at 46kN, measuring 0.45mm in width and resulting in a deflection of 7.628mm. The second crack was observed at 52kN, with a width of 0.51mm and a deflection of 8.442mm. A third crack pattern emerged at 58kN, showing a width of 0.54mm and a deflection of 9.296mm. The fourth crack was noted with a width of 0.59mm and a deflection of approximately 9.859mm, and further variations in the cracks were observed as the load approached the failure limit. The crack patterns on the beam are illustrated in Figure 9, while the corresponding load versus deflection data are presented in Figure 10. The load V/S deflection curve shown in the below figure illustrates the typical nonlinear flexural behavior of a reinforced concrete beam as it bears an increasing load. At first, the beam shows a linear elastic response up to about 3 mm of deflection, which indicates that it remains uncracked and maintains maximum stiffness. As the load continues to increase, the curve shifts into a nonlinear phase, marked by the onset and growth of flexural cracks, which leads to a decrease in stiffness. Once the deflection reaches around 6 mm, the reinforcement takes over as the main load-bearing element, and the curve displays a steady, gradual increase, reflecting ductile behavior and energy absorption. The ultimate load attains 200.376kN, with a maximum deflection of 10.482mm.

### 3.4. Flexural Tensile Strength

The flexural tensile strength of the control beam obtained 18.45 MPa, the strength of a beam wrapped with CFRP Fabrics on base obtained as 25.25MPa and the beam wrapped with CFRP fabrics on base & on sides obtained 32.0MPa. The results indicate a significant enhancement in flexural performance due to wrapping. The beam wrapped with the CFRP Fabrics at the base has improved flexural strength associated with the control beam. The increased flexural strength is about 36.85% higher than that of the control beam. The beam that is wrapped with CFRP fabrics at the base and both longer sides is 73% higher than the control beam. This means that wrapping the beam with CFRP fabrics helps to control cracking and increase ductility. Furthermore, it fulfills the role of external reinforcement, confining the tensile zone and increasing load-carrying capacity.

### 3.5. Discussion of Findings

The findings also include the ultimate strain in the CFRP wraps (εfrp), mid-span deflection at ultimate load (δu), and the % of increase in ultimate load (Pu) associated to the normal specimen. Table 2 displays the results summary. Figure 11 displays the load against mid-span deflection responses of the beam.

Figure 11 illustrates the mid span load deflection behaviour of three different beams that are control beam, beam wrapped with CFRP fabrics on base (BCFRPFB) and beam wrapped with CFRP fabrics along three sides of the beam (BCFRPFBS). The BCFRPFB and BCFRPFBS beams display suggestively more load carrying capacity associated with the CB beam as indicated in the graph, as the curve extends to higher load values before significant failure. Table 2 indicates that the control beam's ultimate load carrying capability is much lower than that of the beams reinforced with CFRP fabrics along the three sides. It is clear that when comparing the ultimate load with the control beam, the % of increase in Pu is 62% higher, and when comparing the BCFRPFBS with the BCFRPFB, the % increase in load is approximately 32% higher. The experimental outcomes specify that the ultimate load and the % increase in Pu are higher when compared with the control beams. The values of ultimate strain obtained in Table 2 show that the BCFRPFBS utilized the strain more (0.0057). Strain describes the relative deformation produced by a material under load, defined as the change in length based on unit length. For flexural and shear strengthened members, distributions of strain, depict relative deformation capacity and ductility at failure. Beam BCFRPFBS reached 28.66 % of its ultimate strain capacity at failure and beam BCFRPFB reached 23.21 % of its ultimate strain capacity at failure. The beam BCFRPFBS was able to undergo a greater proportion of its ultimate strain capacity compared to BCFRPFB before failure occurred. This higher strain utilization implies the beam could deform more under load without experiencing brittle failure, allowing better energy absorption and redistribution of stresses.

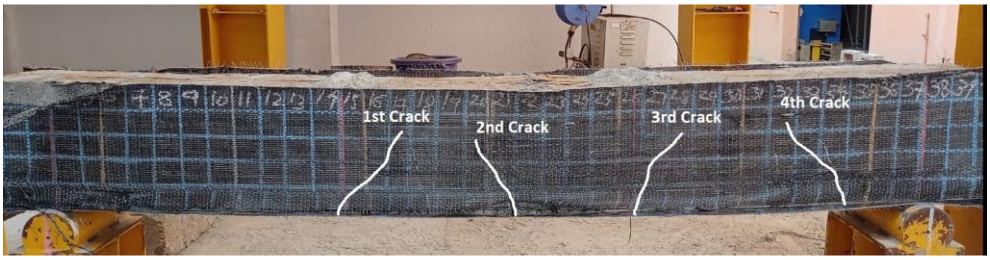

**Figure 9.** Crack patterns of Beam Strengthened with CFRP Fabrics along three sides of the beam

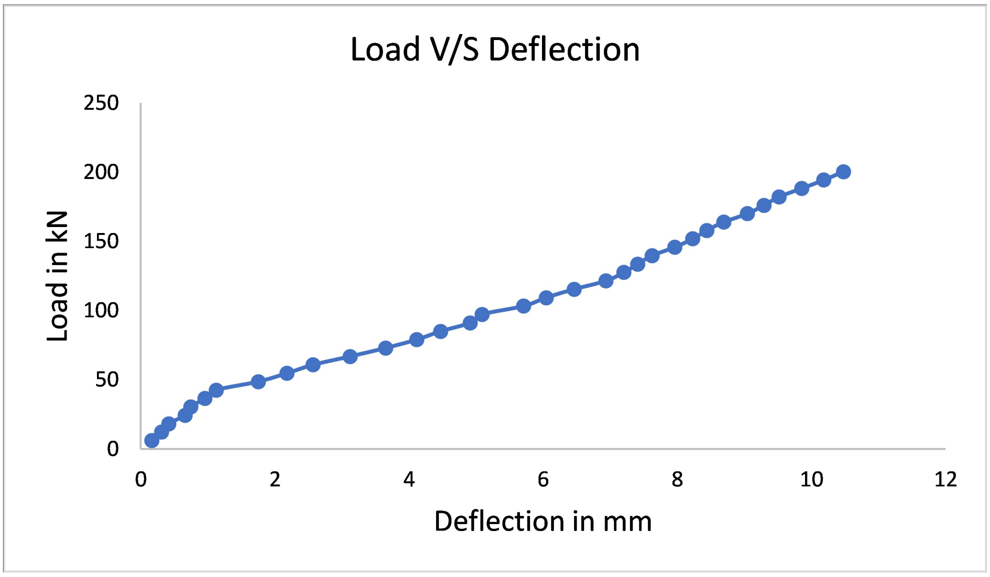

**Figure 10.** Load V/S Deflection of Beam Strengthened with CFRP Fabrics along three sides of the beam

**Table 2.** Discussion of findings

| Beam | Pu(KN) | δu (mm) | εfrp (με) | % Increase in Pu | % Increase in δu |
|---|---|---|---|---|---|
| CB | 115.368 | 14.191 | - | - | - |
| CB1 | 115.368 | 9.647 | - | - | - |
| CB2 | 109.296 | 9.426 | - | - | - |
| BCFRPFB | 151.800 | 8.974 | 4400 | - | - |
| BCFRPFB1 | 157.872 | 8.247 | 4100 | 37 | 23.21 |
| BCFRPFB2 | 157.872 | 8.452 | 4200 | - | - |
| BCFRPFBS | 200.31 | 11.546 | 5700 | 74 | 28.66 |
| BCFRPFBS1 | 200.31 | 10.045 | 5000 | - | - |
| BCFRPFBS2 | 200.31 | 9.854 | 4900 | - | - |

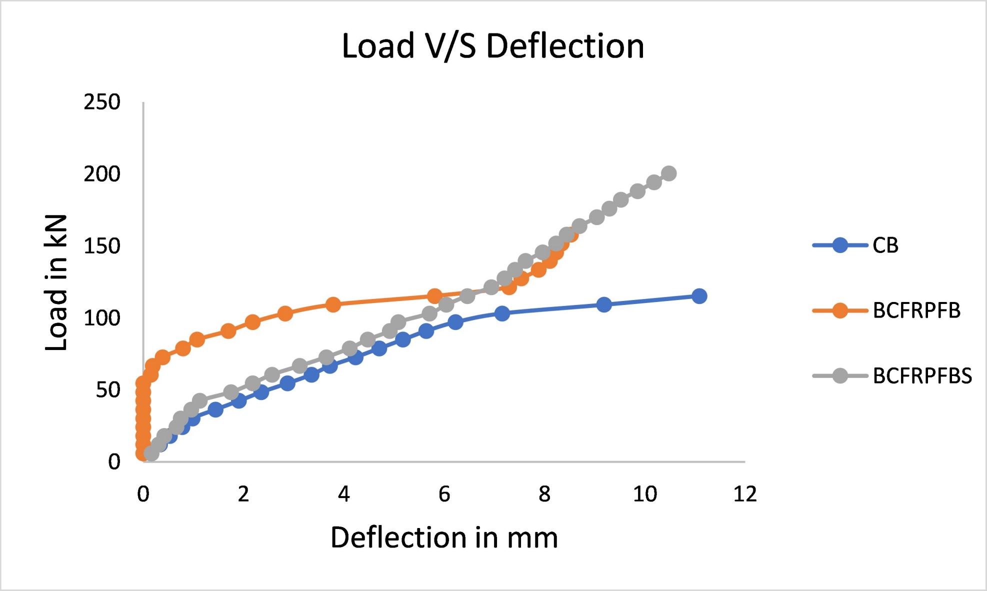

**Figure 11.** Mid span load deflection curves

## 4. Conclusions

The implementation of CFRP fabrics in concrete enhances the flexural strength. This study examined the flexural strengthening of RC beams, wrapped with CFRP fabrics on one side of the beam (bottom) and three sides (bottom and along two longer sides).

All beam specimens underwent two-point bending tests, and response curves for the mid-span load displacement were plotted. The experimental findings led to the following conclusions,

- The beam reinforced with CFRP fabrics at the base demonstrates an average ultimate load capacity of 155.848 kN and a working load of 60.72 kN, which is 57% higher than the control beam.
- A beam applying CFRP fabrics along the three sides of the beam, achieved an average ultimate load of (200.31 kN) and working load (42.504 kN) of 143% greater than the control beam. The ultimate load reached is nearly double when the beams are wrapped with CFRP fabrics along the three sides of the beam. This change implies that the CFRP is directly combating tensile stresses from bending and thus greatly augmenting the flexural capacity. The side wrap adds confining shear stress and lateral support, which provides constraints to crack widening and assists in delaying shear failure.
- When the beam is wrapped with CFRP fabrics placed at its base, a considerable rise in flexural strength is noted, as is also the case with the beam wrapped with CFRP fabrics at its base and on the two longer sides. The flexural strength of the beam wrapped with CFRP fabrics only at its base is 36.85% larger than the control beam, while the flexural strength of the beam wrapped with CFRP fabrics along the three sides of the beam is improved by 73% compared to the control beam. This arrangement has also been publicized to be optimal for increasing the load capacity of the beam and significantly increasing the ductility of the RC beams.
- The maximum load-bearing capacity of the beam encased with CFRP fabrics on three sides is greater than both the control beams and the beam that was wrapped with CFRP fabrics on one side. The three-side wrapping plan is a good option when beams can't be fully wrapped. The three-side CFRP wrapping strategy is effective because it simultaneously improves flexural capacity, shear resistance, and ductility, while providing lateral confinement to concrete and ensuring better strain utilization.

Compared to one-side wrapping, it addresses more failure modes, and compared to full wrapping, it remains practical for retrofitting existing beams without major structural alterations.

## 5. Scope for Further Research

- Future work can be built on investigating alternative and hybrid strengthening schemes to enhance the performance-to-cost ratio. Full wrapping systems, partial wrapping at critical zones, or the use of CFRP and other composite materials like GFRP, BFRP, or steel plates may provide ways to optimize the balance between stiffness, ductility, and economic feasibility.
- The effects of anchorage enhancement methods can also be studied (e.g., mechanical fasteners, U-wraps, or fan-shapes ends, etc.) to minimize the risk of debonding and improve the competence of load transfer.

- Research studies under cyclic and fluctuating stress conditions will also assist in understanding the behavior of strengthened beams when subjected to repeated traffic load (for example, vehicles, railcars, and pedestrians) or seismic loading.
- CFRPs' contribution to impact resistance, blast protection, and post-fire residual capacity should be researched, especially for use in critical infrastructure and defense facilities.

## 6. Limitations

- The experimental effort is limited to monatomic static loading situations, and does not consider the cyclic or fatigue effects characteristic of structures subjected to repeated or dynamic loading conditions, as in bridges or buildings in seismic zones.
- This study includes only the specific configuration of CFRP with a fixed thickness, fiber orientation and the bond length. Variation of these parameters and the inclusion of other types of FRP are not included.
- Conducting experiments on beams that are strengthened with CFRP and cast using high-strength concrete and reinforcement demonstrates controllability and repeatability, but has some constraints relative to more common RC members that might need retrofitting. High-strength materials experience fewer cracks and experience stiffer behavior, which may limit the identification of early tensile failure, and lead to non-representative bond behavior or crack patterns with existing low-grade concrete in aged concrete structures. The bond-slip interface between CFRP and high-strength concrete usually behaves more linearly, and exhibits a sudden final failure, which may understate energy dissipation and ductility.

## REFERENCES

[1] Ali Jahami, Camille A. Issa, “An Updated Review on the Effect of CFRP on Flexural Performance of Reinforced Concrete Beams”, International Journal of Concrete Structures and Materials, Vol. 8, article number 14, 2023. DOI: https://doi.org/10.1186/s40069-023-00651-y

[2] Ashour, A. F., El-Refaie, S. A., Garrity, S. W., “Flexural strengthening of RC continuous beams using CFRP laminates,”, Cement and Concrete Composites, Vol. 27, No. 7. pp. 765–775, 2005. DOI: https://doi.org/10.1016/j.cemconcomp.2003.07.002.

[3] Attari, N., Amziane, S., Chemrouk, M., “Flexural strengthening of concrete beams using CFRP, GFRP and hybrid FRP sheets”, Construction and Building Materials, Vol. 37, pp. 746–757, 2012. DOI: https://doi.org/10.1016/j.conbuildmat.2012.07.052.

[4] Ayesha Siddika, Krishno Saha, Md. Sumodro Mahmud, Sumon Chandra Roy, Md. Abdullah Al Mamun, Rayed Alyousef, “Performance and failure analysis of carbon fiber-reinforced polymer (CFRP) strengthened reinforced concrete (RC) beams”, SN Applied Sciences, Vol. 1, article number 1617, 2019. DOI: https://doi.org/10.1007/s42452-019-1675-x.

[5] Siddika A, Al Mamun MA, Alyousef R, Amran YHM, “Strengthening of reinforcedconcrete beams by using fiber-reinforced polymer composites: a review”, Journal of Build Engineering, Vol. 25, p. 100798, 2019. DOI: https://doi.org/10.1016/j.jobe.2019.100798.

[6] Haya H. Mhannaa, Rami A. Hawileh, Jamal A. Abdalla, “Shear Strengthening of Reinforced Concrete Beams Using CFRP Wraps”, Procedia Structural Integrity, Vol. 17, pp. 214–221, 2019. DOI: https://doi.org/10.1016/j.prostr.2019.08.029.

[7] Meyyada Y. Alabdulhady, Mohammed F. Ojaim, Aqeel H. Chkheiwer, “The efficiency of CFRP strengthening and repair system on the flexural behavior of RC beams constructed with different concrete compressive strength”, Results in Engineering, Vol. 16, p. 100763, 2022. DOI: https://doi.org/10.1016/j.rineng.2022.100763.

[8] R. Al-Shamayleh, H. Al-Saoud, M. Alqam, “Shear and flexural strengthening of reinforced concrete beams with variable compressive strength values using externally bonded carbon fiber plates”, Results in Engineering, Vol. 14, p. 100427, 2022. DOI: https://doi.org/10.1016/j.rineng.2022.100427.

[9] R.J. Abed, M.A. Mashrei, A.A. Sultan, “Flexural behavior of reinforced concrete beams strengthened by carbon fiber reinforced polymer using different strengthening techniques”, Advances in Structural Engineering, Vol. 25, No. 2, pp. 355–373, 2022. DOI: https://doi.org/10.1177/13694332211049992.

[10] Kim, Y. J., & Alqurashi, A., “Effectiveness of carbon fiber-reinforced polymer sheets for torsional strengthening of reinforced concrete beams,” ACI Structural Journal, Vol. 121, No. 5, pp. 203–215, 2024. DOI: https://doi.org/10.14359/51740867.

[11] A. T. John1, S. O. Osuji, E. Nwankwo, “Effect of bond surface area on the shear strength of Carbon fibre reinforced polymer (CFRP) strengthened Reinforced concrete beams”, Nigerian Journal of Technology (NIJOTECH), Vol. 41, No. 6, pp. 955–963, 2022. DOI: https://doi.org/10.4314/njt.v41i6.5.

[12] S. N. Mat Saliah and N. Md Nor, “Assessment of the Integrity of Reinforced Concrete Beams Strengthened with Carbon Fibre Reinforced Polymer Using the Acoustic Emission Technique”, Frontiers in Mechanical Engineering, Original Research, Vol. 8, Article number 885645, 2022. DOI: https://doi.org/10.3389/fmech.2022.885645.

[13] Xinzhe Min, Jiwen Zhang, Yongming Tu, Xing Li, Chao Wang, Gabriel Sas, Lennart Elfgren, “A full-range fatigue life prediction model for RC beams strengthened with prestressed CFRP plates accounting for the impact of FRP debonding”, Engineering Structures, Vol. 301, p. 117305, 2024. DOI: https://doi.org/10.1016/j.engstruct.2023.117305.

[14] Guo D, Zhou H, Wang HP, Jian-Guo Dai, “Effect of

temperature variation on the plate-end debonding of FRP-strengthened steel beams: Coupled mixed-mode cohesive zone modeling", Engineering Fracture Mechanics, Vol. 270, p. 108583, 2022. DOI: https://doi.org/10.1016/j.engfracmech.2022.108583.

[15] Li K, Zhao D, Wang X, Hu Feng, and Xuyan Zou, "Investigation of crack growth in CFRP-concrete interface under fatigue loading", Structures, Vol. 34, pp. 356–367, 2021. DOI: https://doi.org/10.1016/j.istruc.2021.07.088.

[16] Cheng J, "Study on the fatigue behavior of reinforced concrete continuous beams prestressed with external CFRP tendons", China, Doctoral Dissertation, Southeast University, 2017.

[17] Dia Alwash, Robin Kalfat, and Riadh Al-Mahaidi, "Numerical modelling of RC beams strengthened in shear using NSM FRP and cement-based adhesives", Structures, Vol. 57, p. 105217, 2023. DOI: https://doi.org/10.1016/j.istruc.2023.105217.

[18] Hebah Al-zu'bi, Mu'tasim Abdel-Jaber, and Hasan Katkhuda, "Flexural Strengthening of Reinforced Concrete Beams with Variable Compressive Strength Using Near-Surface Mounted Carbon-Fiber-Reinforced Polymer Strips [NSM-CFRP]", Fibers, Vol. 10, No. 10, p. 86, 2022. DOI: https://doi.org/10.3390/fib10100086.

[19] Ibrahim M, Wakjira T, Ebead U, "Shear strengthening of reinforced concrete deep beams using near-surface mounted hybrid carbon/glass fibre reinforced polymer strips", Engineering Structures, Vol 210, p. 110412, 2020. DOI: https://doi.org/10.1016/j.engstruct.2020.110412.

[20] Abdel-Jaber M, "Influence of Externally Bonded CFRP on the Shear Behavior of Strengthened and Rehabilitated Reinforced Concrete T-Beams Containing Shear Stirrups", Fibers, Vol. 9, No. 12, p. 87, 2021. DOI: https://doi.org/10.3390/fib9120087.

[21] Jincheng Yang, Reza Haghani, Thomas Blanksvärd, Karin Lundgren, "Experimental study of FRP-strengthened concrete beams with corroded reinforcement", Construction and Building Materials, Vol. 301, Article number 124076, 2021. DOI: 10.1016/j.conbuildmat.2021.124076.

[22] Ali A. Mohammed, Allan C. Manalo, Wahid Ferdous, Yan Zhuge, P. V. Vijay, Ashraf Q. Alkinani, Amir Fam, "State-of-the-art of prefabricated FRP composite jackets for structural repair", Engineering Science and Technology, an International Journal, Vol. 23, No. 5, pp. 1244–1258, 2020. https://doi.org/10.1016/j.jestch.2020.02.006.

[23] P. Manibalan a, S. Kesavan, G. Abirami; R. Baskar, "Fatigue response of RC beam strengthened by BFRP laminate", Case Studies in Construction Materials, Vol. 18, p. e01707, ISSN: 2214-5095, 2023. DOI: https://doi.org/10.1016/j.cscm.2022.e01707.

[24] Shrestha, S., Pantelides, C.P. Seismic repair of severely corroded precast RC columns with FRP shell and headed steel bars. J Infrastruct Preserv Resil 5, 17 (2024). https://doi.org/10.1186/s43065-024-00106-yF. A. Megahed, M. H. Seleem, A. A. M. Badawy, I. A. Sharaky, "The flexural response of RC beams strengthened by EB/NSM techniques using FRP and metal materials: a state-of-the-art review", Innovative Infrastructure Solutions, Vol. 8, article number 289, 2023. DOI: https://doi.org/10.1007/s41062-023-01245-z.

[25] Parshwa Composites, An Iso 9001:2015 Certified Company.

[26] IS: 456-2000, Indian standard "Plain and reinforced concrete"- code of practice. 33.IS: 10262-2009, Indian standards "Recommended guidelines for concrete mix design proportioning"- code of practice.

[27] IS: 383-1970, "Specifications for coarse and fine aggregates from natural source of concrete", (second revision), Bureau of Indian standards, New Delhi, India.

[28] IS:518-2018, part 1, section 2, testing of strengthened hardened concrete as per the Bureau of Indian Standards.