



EXPERIMENTAL STUDY: STRENGTHENING OF REINFORCED CONCRETE MEMBERS USING EXTERNALLY BONDED FRP COMPOSITES

Vikrant Dhoke¹, Monika Jain²

Student, Department of Civil Engineering, G.H. Raisoni College of Engineering & Management, Nagpur, Maharashtra,
India¹

Assistant Professor, Department of Civil Engineering, G.H. Raisoni College of Engineering & Management, Nagpur,
Maharashtra, India²

Abstract: The rapid deterioration of reinforced concrete (RC) infrastructure due to corrosion, increased service loads and environmental exposure has created a strong demand for efficient strengthening and retrofitting techniques. Fiber reinforced polymer (FRP) composites have emerged as a promising alternative to conventional steel plate bonding because of their high strength-to-weight ratio, corrosion resistance and ease of installation. This paper presents a concise review of the application of externally bonded FRP systems for the flexural and shear strengthening of RC beams and for the confinement of RC columns.

Key experimental and analytical studies are discussed to highlight improvements in strength, stiffness and ductility, as well as changes in failure modes associated with FRP retrofitting. Particular attention is given to bond and debonding behaviour, the role of structural adhesives, and practical aspects such as constructability and durability.

Existing international guidelines and design provisions for FRP-strengthened RC members are briefly outlined, together with current limitations and gaps. The review shows that externally bonded FRP systems can significantly enhance the performance of deficient RC members, but design is often governed by brittle debonding or FRP rupture, and long-term durability data and unified standards are still evolving.

Keywords: Fiber reinforced polymer (FRP); Reinforced concrete (RC); Retrofitting; Flexural strengthening; Shear strengthening; Column confinement; Structural adhesives.

I. INTRODUCTION

Reinforced concrete remains the most widely used construction material for buildings, bridges and other infrastructure; however, many existing RC structures suffer from distress due to reinforcement corrosion, poor quality control, design or detailing deficiencies, changes in loading and environmental actions. The need to upgrade such structures in a cost-effective manner, often without significant interruption to service, has led to extensive research on strengthening and retrofitting techniques.

Traditionally, strengthening has been achieved using steel plate bonding, concrete or steel jacketing and the addition of new structural members or supports. Although effective, steel-based solutions are associated with issues such as corrosion, high self-weight, cumbersome installation and the need for heavy lifting equipment. Fiber reinforced polymer (FRP) composites, typically based on carbon, glass or aramid fibres in a polymer matrix, offer an attractive alternative due to their low density, high tensile strength and excellent corrosion resistance.

Externally bonded FRP systems can be applied as plates, laminates or fabrics, and are now used for flexural and shear strengthening of beams, slabs and girders, as well as for confinement of columns and bridge piers. Despite thousands of successful applications worldwide, the widespread acceptance of FRP in design practice is still constrained by limited long-term field data, variability in design recommendations and concerns about bond behaviour and fire resistance.



The main objective of this paper is to synthesize key findings from experimental, analytical and field investigations on FRP-strengthened RC members and to identify critical issues related to behaviour, design and implementation. The focus is on externally bonded systems for beams and columns, with emphasis on strength enhancement, ductility, failure mechanisms, bond behaviour and the role of structural adhesives.

II. FRP STRENGTHENING OF RC STRUCTURES

A. Need for Retrofitting with FRP

RC structures often require strengthening when actual loads exceed the original design values, when deterioration reduces capacity or when performance requirements change, as in seismic retrofitting or widening of bridges. Common causes include corrosion of reinforcement, increased traffic intensity, modifications in structural configuration, and changes in code provisions leading to higher design forces.

Externally bonded FRP systems provide a means of upgrading load-carrying capacity and serviceability with minimal addition of dead load and without substantial enlargement of member dimensions. In many cases, FRP retrofitting can be executed while the facility remains in partial operation, which is a major advantage for bridges, industrial plants and transportation structures.

In comparison with traditional jacketing or steel plate bonding, FRP systems require less surface preparation, can be installed with relatively simple equipment and are well suited for confined or difficult-to-access locations such as soffits of bridge decks, tunnels and basements. These practical advantages have accelerated the adoption of FRP in rehabilitation projects worldwide.

B. Advantages of FRP Composites

FRP materials have a high tensile strength and low density, resulting in a strength-to-weight ratio that can exceed steel in many applications. The low self-weight reduces additional demands on foundations and supporting elements and simplifies transport and handling on site. In plate or sheet form, FRP can be rolled, cut to length and applied in long continuous strips, which reduces the number of joints and simplifies detailing around irregular geometries.

Externally bonded FRP systems are particularly suited to situations where access is limited and heavy lifting equipment is impractical; application is often comparable to placing “structural wallpaper,” where the FRP sheet is bonded to a properly prepared concrete surface using epoxy adhesive and rolled to expel entrapped air. No mechanical fasteners are required, avoiding damage to existing reinforcement and eliminating drilling-related weaknesses.

From a durability perspective, appropriately specified FRP systems exhibit good resistance to corrosion, chemicals and environmental exposure, and their installation does not significantly increase the cross-sectional dimensions of strengthened members. This is important for bridges with clearance limitations, tunnels and structures where architectural constraints do not permit bulky strengthening solutions. Life-cycle assessments have also indicated potential environmental benefits due to reduced material usage and lower transportation demands.

C. Limitations and Practical Concerns

Despite these advantages, externally bonded FRP systems present certain limitations that must be considered in design. One key concern is performance under fire and elevated temperatures; the polymer matrix softens well below the glass transition temperature, leading to loss of bond and strength unless suitable fire protection measures are provided. For bridge soffits and other exposed locations, accidental impact or vandalism may damage the FRP layer, partially reducing the strengthening effect.

Another limitation is the relative novelty of FRP in civil infrastructure compared with steel and concrete; long-term field performance data over several decades are still limited, and many asset owners remain cautious. Material costs are generally higher than for steel, although total project costs may be comparable or lower when reduced installation time, limited traffic closures and minimal demolition are considered.

Designers must also account for the lack of globally unified design standards; various national and international recommendations exist, but differences remain in the treatment of bond behaviour, reduction factors and safety formats. Consequently, engineering judgment and careful interpretation of available guidelines are essential.



III. LITERATURE REVIEW

Meier [1] first demonstrated flexural strengthening of RC beams using externally bonded CFRP plates, reporting significant gains in ultimate moment and stiffness but highlighting brittle plate-end debonding as a governing failure mode.

Meier [1] & Kaiser [2] extended CFRP plate retrofitting to in-service bridges, confirming field feasibility under traffic loads and aggressive exposure while stressing the need for reliable anchorage and surface preparation.

Saadatmanesh [3] & Ehsani [4] strengthened under-reinforced beams with CFRP laminates, observing roughly 20–60% increases in flexural capacity and reduced deflection/crack widths, though failures often shifted from steel yielding to sudden FRP rupture.

Chajes et al. [5] investigated composite plates bonded to concrete prisms and beams, showing that bond strength and failure mode depend strongly on concrete surface preparation, adhesive type and substrate strength.

Nanni et al. [6] retrofitted pre-damaged beams using CFRP sheets on soffit and web, demonstrating effective recovery of stiffness and strength but also local cover splitting near plate terminations when bonded length was insufficient.

Malek et al. [7] developed analytical predictions for FRP-strengthened beam capacity, validating that ultimate load is frequently governed by concrete cover failure or interfacial debonding rather than FRP tensile rupture.

Grace et al. [8] compared beams strengthened with CFRP and GFRP laminates, reporting appreciable enhancements in strength and fatigue performance while noting brittle failures that necessitate higher safety margins in design.

Ross et al. [9] and Sebastian [10] evaluated stiffness evolution of CFRP-strengthened beams at pre-cracking, post-cracking and post-yield stages, confirming substantial deflection control under service loads but bond-controlled behaviour at ultimate.

Saadatmanesh et al. [3] and Chaallal [11] & Shahawy [12] tested FRP-wrapped RC columns under axial and combined axial–flexural loading, demonstrating significant gains in strength and ductility, particularly for circular sections where confinement is more uniform.

IV. METHODOLOGY

A. Materials

Concrete for all specimens was designed to achieve a characteristic compressive strength in the range typically used for structural beams (e.g., 20–30 MPa at 28 days), with mix proportions selected to ensure adequate workability and strength. Ordinary Portland cement, natural sand and crushed coarse aggregate were used, and standard cube/cylinder tests were conducted to confirm the target strength. Reinforcement consisted of high-yield deformed bars with specified yield strength (Fe 415/Fe 500), used for both longitudinal and transverse reinforcement in the T-beams.

Externally bonded strengthening was provided using unidirectional GFRP sheets/laminates with manufacturer-specified tensile strength, modulus of elasticity and thickness. A two-component epoxy adhesive compatible with concrete substrates and ambient-temperature curing was employed for surface priming and bonding of GFRP; the adhesive was mixed in the prescribed ratio and applied in a thin, uniform layer.

Concrete mix proportions refer to the relative quantities of cement, water, fine aggregate, and coarse aggregate used to produce concrete with the required strength, workability, and durability. The material properties of concrete, such as compressive strength, workability, density, permeability, and durability, depend strongly on these proportions, especially the water-cement ratio

Table 1: Concrete Mix Proportions and Material Properties

Material / Property	Value / Description
Concrete grade (design)	M20 (characteristic strength 20 N/mm ²)
Cement type	Konark Portland Slag Cement
Cement specific gravity	2.96
Normal consistency of cement	32%
Initial setting time	105 minutes
Final setting time	535 minutes
Soundness of cement	2 mm expansion
Fineness (90 μm sieve)	1 g retained
Fine aggregate grading	Zone III
Fine aggregate specific gravity	2.67
Fine aggregate water absorption	0.8%
Coarse aggregate specific gravity	2.72
Coarse aggregate water absorption	0.5%
Concrete mix proportion (C: FA:CA: W, by weight)	1: 1.56: 3.30: 0.50
Quantities per m ³ (cement: sand: coarse agg.: water)	372 kg: 580 kg: 1228 kg: 186 kg
Steel yield strength (Fe500)	500 N/mm ²
Steel modulus of elasticity	200 GPa

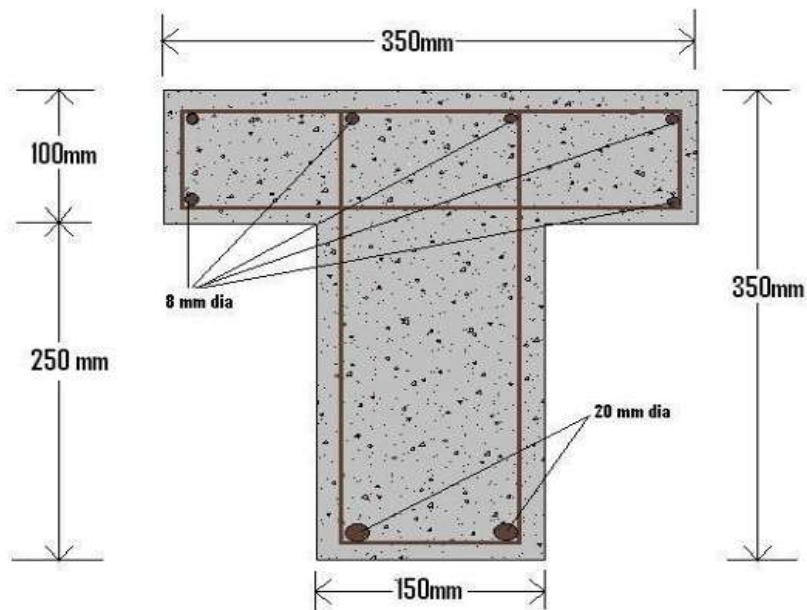


Fig. 3.1 Front view of reinforcement detailing of T- beam



Table 3: Beam specimen dimensions and reinforcement

Parameter	Value
Number of specimens	7
Beam type	Reinforced concrete T-beam
Total length	2000 mm
Flange width	350 mm
Web width	150 mm
Flange thickness	100 mm
Overall depth	350 mm
Support condition during test	Simply supported
Clear distance from beam end to support	150 mm
Effective span between supports	1700 mm
Reinforcement arrangement	Same for all seven beams
Main flexural reinforcement	2 Nos. 20 mm HYSD bars
Hanger reinforcement	4 Nos. 8 mm HYSD bars
Shear reinforcement	8 mm, 2-legged stirrups @ 100 mm c/c

D. Comparison and Evaluation

The response of the control beam and the six strengthened beams was systematically compared to quantify the effect of externally bonded GFRP on flexural performance. The comparison was based on percentage increase in ultimate load, reduction in deflection, and observed failure characteristics such as debonding, tearing of GFRP, and flexural cracking. Summary tables and comparison graphs were prepared to identify the most effective strengthening configuration in terms of structural efficiency and practical applicability

IV. RESULTS & DISCUSSION

The experimental investigation was carried out on reinforced concrete T-beams under two-point static loading to study the flexural behavior of the control beam and the GFRP-strengthened beam. For the present paper, only Beam 1 and Beam 2 are considered. Beam 1 was taken as the control specimen without any strengthening, while Beam 3 was strengthened with a single layer of GFRP sheet at the soffit from L3 to 2L3.

4.1 Beam 1 Result

Beam 1 was tested as the unstrengthened control specimen. The first hairline crack appeared at 120 kN, and the beam finally failed in flexure at an ultimate load of 290 kN. The load-deflection curve showed comparatively larger deflections, indicating lower stiffness and weaker flexural resistance than the strengthened beam. The crack pattern of Beam 1 showed visible flexural cracks concentrated in the high-moment region near the center and support zone. resistance to cracking and crack propagation. The crack pattern was observed near the center and right support region, which is typical of a flexure-dominated failure in an unstrengthened beam.

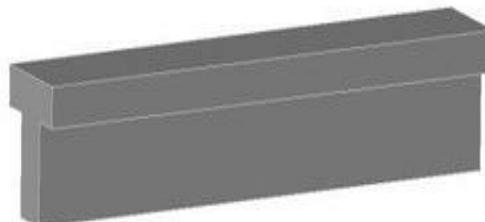




Fig 4.1: Experimental setup for Beam 1



Fig 4.2: Control beam after cracking

In Fig 4.1 and 4.2 shows tht Beam 1, being the control beam, exhibited normal flexural behavior without external strengthening. Initial hairline cracks appeared at 120 kN, and the beam failed completely in flexure at an ultimate load of 290 kN. The load–deflection response of Beam 1 showed comparatively higher deflections than the strengthened specimen, indicating lower stiffness and lower resistance to cracking and crack propagation. The crack pattern was observed near the center and right support region, which is typical of a flexure-dominated failure in an unstrengthened beam.

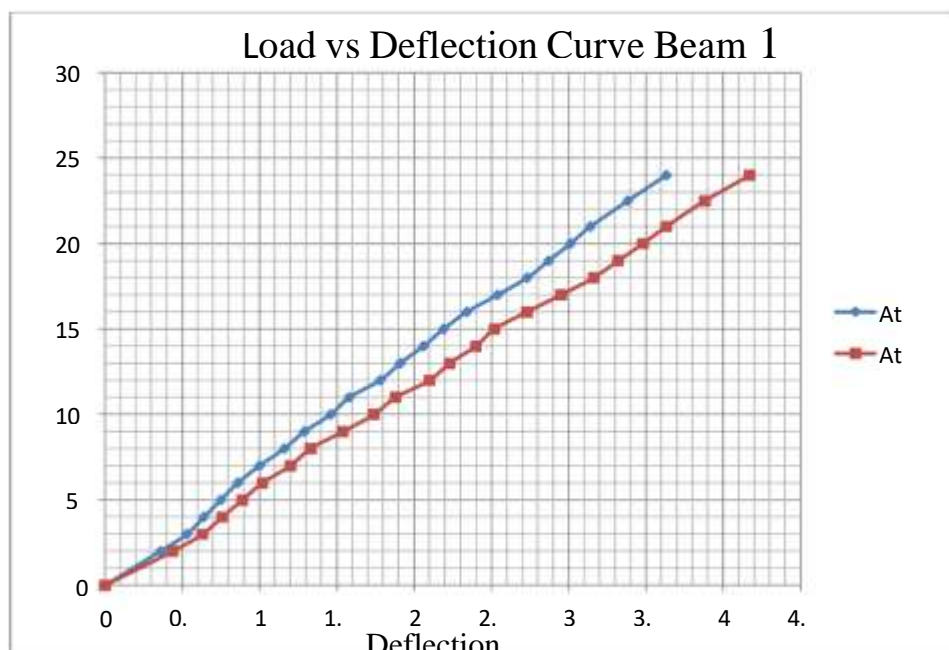


Fig 4.3: Load deflection curve of beam 1

Fig 4.3: Beam 1 exhibited a gradual increase in deflection as the load increased, which is typical of an unstrengthened RC beam under flexural loading. The curve indicates lower stiffness and earlier cracking compared to the strengthened beam, and the beam finally failed at **290 kN**. The initial crack appeared at **120 kN**, after which deflection increased more rapidly as the beam approached failure.

4.2 Beam 2 Result

Beam 2 was strengthened with a single layer of GFRP sheet at the soffit only in the central region from $L/3$ to $2L/3$. The first crack appeared at **125 kN**, which is slightly higher than Beam 1. Beam 2 carried a higher ultimate load of **325 kN**, and its failure occurred due to **debonding of the GFRP sheet followed by flexural failure**. The load–deflection response shows improved load-carrying capacity and better flexural performance compared to the control beam.

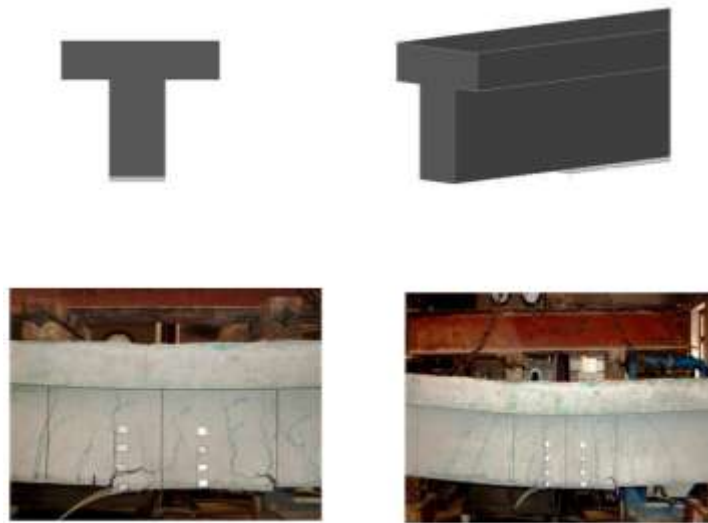


Fig. 4.4: Debonding of fibre and Cracks in beam 2

Fig. 4.4: Debonding of fiber and cracks in Beam 2 shows that the GFRP sheet started separating from the concrete surface after load was increased, and flexural cracks developed in the critical region. This indicates that Beam 2 had reached a higher stress level, where the bond between the fiber and concrete became insufficient and failure progressed through debonding followed by cracking.

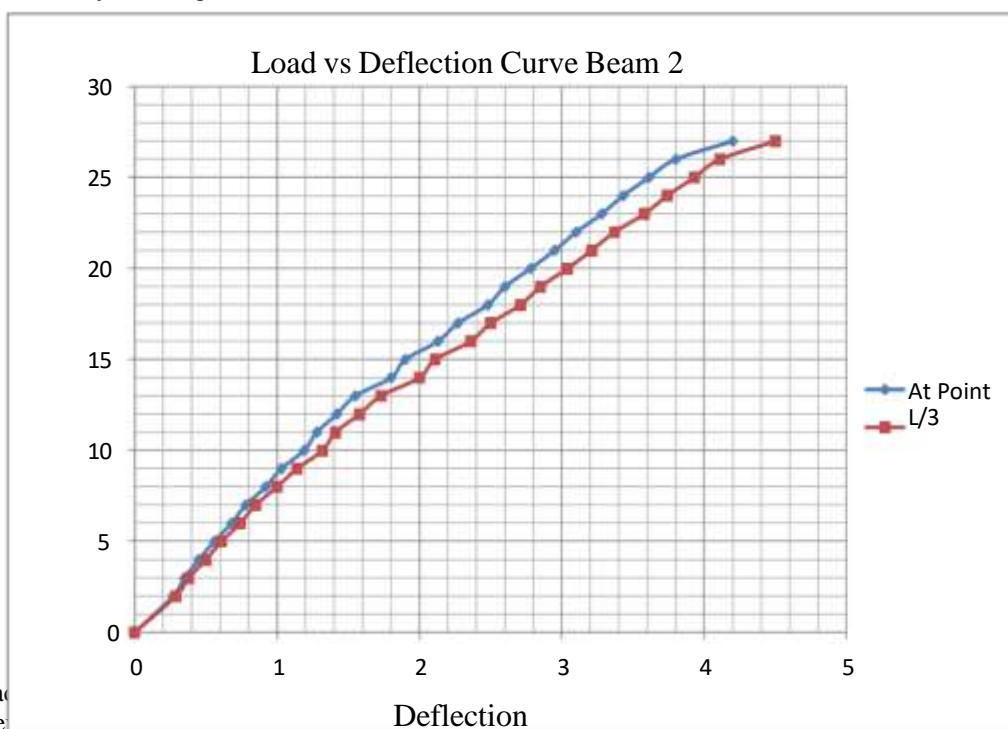


Fig. 4.3: Load and better fle

ed stiffness
tion for the



same load level, which means the GFRP sheet helped Beam 3 resist bending more effectively. Beam 2 also reached a higher ultimate load of 325 kN, confirming that the strengthening arrangement increased the beam’s load-carrying capacity. Overall, the graph demonstrates that Beam 2 performed better in both strength and serviceability than Beam 1.

4.3 Comparison of Beams

The comparison clearly shows that Beam 2 performed better than Beam 1. Beam 2 sustained 35 kN more load than Beam 1, which corresponds to an increase of about 12.07% in ultimate load capacity. The delayed crack initiation and higher failure load indicate that the GFRP strengthening improved the flexural behaviour of the beam. Therefore, Beam 2 is the better specimen in terms of strength and structural performance.

4.4 Comparison Table

Table 4. Comparison of Beam 1 and Beam 2 results.

Parameter	Beam 1	Beam 2
Beam type	Control beam	Strengthened beam
Strengthening detail	None	Single-layer GFRP at soffit from $L/3$ to $2L/3$
First crack load	120 kN	125 kN
Ultimate load	290 kN	325 kN
Increase over Beam 1	—	12.07%
Failure mode	Flexural failure	GFRP debonding followed by flexural failure
Performance	Lower	Better

The literature clearly demonstrates that externally bonded FRP systems are effective in enhancing the flexural and shear capacities of RC beams and the confinement and ductility of RC columns, often with relatively small additions of material and minimal disruption to the structure. As a result, FRP retrofitting has become a practical option for extending the life of bridges, buildings and waterfront structures.

However, the change in failure mode from ductile steel yielding to brittle FRP rupture or sudden debonding requires careful consideration in design. To maintain an adequate level of ductility, many guidelines recommend limiting FRP strain and ensuring that yielding of internal steel reinforcement precedes FRP failure, wherever feasible. Anchorage devices, such as FRP U-wraps or mechanical anchors, may also be used to delay debonding.

Durability and long-term performance remain active areas of research. While laboratory studies and medium-term field observations generally indicate good resistance to corrosion and environmental effects, uncertainty remains regarding behaviour under combined actions such as sustained load, temperature cycles, moisture ingress and freeze–thaw over decades. Monitoring systems and periodic inspections are therefore important for critical structures.

From a practical standpoint, success of FRP strengthening projects strongly depends on quality control during surface preparation, adhesive mixing and application, and curing. Inadequate workmanship can lead to voids, poor bond and premature failure. Training of contractors, clear specifications and appropriate site supervision are essential to realize the full benefits of FRP systems. From a practical standpoint, the success of FRP strengthening projects depends heavily on careful workmanship at every stage of installation. Proper surface preparation is especially important because the concrete must be clean, dry, and roughened enough to ensure strong adhesion between the FRP sheet and the substrate.

Likewise, adhesive mixing and application must be done accurately. If the resin and hardener are not mixed in the correct proportion, or if the adhesive is applied unevenly, the bond quality may reduce significantly. During installation, air voids, trapped bubbles, or incomplete wetting of the fibers can create weak zones that may later initiate debonding.

VII. CONCLUSION



The experimental results confirm that GFRP strengthening improves the flexural performance of RC T-beams. Beam 2 performed better than Beam 1 in terms of higher load-carrying capacity, delayed cracking, improved stiffness, and better overall resistance to bending.

Beam 1, as the control specimen, showed normal flexural failure at a lower ultimate load, while Beam 2 carried a higher load before failure and showed debonding of fiber followed by flexural cracking. This proves that the externally bonded GFRP sheet was effective in enhancing the behavior of the beam under two-point loading.

Based on the comparison, Beam 2 is the better specimen because it achieved an ultimate load of 325 kN compared to 290 kN for Beam 1. The increase in capacity shows that GFRP retrofitting is a useful strengthening technique for improving deteriorated or under-strength RC T-beams.

The study also indicates that the bond between the GFRP sheet and concrete plays an important role in the final behavior of the beam. Although Beam 2 showed better performance, debonding occurred at higher load, so proper surface preparation and bonding quality are essential for effective strengthening.

Overall, the findings support the use of externally bonded GFRP sheets as a practical and efficient method for flexural strengthening of RC T-beams.

REFERENCES

- [1]. ACI Committee 440. *Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures*. ACI 440.2R-17, American Concrete Institute, Farmington Hills, MI.
- [2]. ACI Committee 440. *Guide for the Design and Construction of Structural Concrete Reinforced with FRP Bars*. ACI 440.1R-15, American Concrete Institute, Farmington Hills, MI.
- [3]. Nanni, A., Tumialan, G., and others. Research on externally bonded FRP strengthening of RC beams and T-beams, including flexural response and bond behavior.
- [4]. Rehabilitation of Reinforced Concrete T-Beam Structures Using Externally Bonded FRP Composites. Proceedings of the ASCE study on T-beam bridge rehabilitation and FRP repair design.
- [5]. Experimental and numerical studies on externally bonded GFRP-strengthened RC beams, including flexural performance and failure behavior.
- [6]. Strengthening reinforced concrete beams with GFRP plates: experimental studies on load-carrying capacity and crack control.
- [7]. Flexural strengthening of RC beams using GFRP grid bonded with epoxy-based adhesive systems.
- [8]. New code provisions and design considerations for GFRP-reinforced concrete and repair applications.
- [9]. Genedy, M. *A New CFRP-UHPC System for Strengthening Reinforced Concrete T-Beams*. University of New Mexico, 2014.
- [10]. Bank, L. C. *Composites for Construction: Structural Design with FRP Materials*. Wiley, 2006.
- [11]. Hollaway, L. C., and Teng, J. G. *Strengthening and Rehabilitation of Civil Infrastructures Using Fibre-Reinforced Polymer (FRP) Composites*. Woodhead Publishing, 2008.
- [12]. fib Task Group. *Design of FRP Systems for Strengthening Concrete Structures*. fib Bulletin, relevant guideline document.