International Journal of Multidisciplinary Research and Technology
ISSN 2582-7359, Peer Reviewed Journal, Impact Factor 6.325
www.ijmrtjournal.com

EXPERIMENTAL INVESTIGATION OF THE STRUCTURAL BEHAVIOR OF REINFORCED CONCRETE BEAMS STRENGTHENED WITH FIBER REINFORCED POLYMER (FRP) COMPOSITES

[1]Valvaikar Diptesh Devrai, [2]Prof. Naman Tripathi

[1]M.Tech Scholar, [2]Assistant Professor, Department of Civil Engineering
Vikrant University, Gwalior MP

ABSTRACT

Fiber reinforced polymer (FRP) composites have proven to be efficient materials for rehabilitation of existing reinforced concrete (RC) beams which are affected by aging, deteriorating, corrosion, inappropriate design, and excessive service loading. The current literature review is dedicated to the study of the experimental structural behavior of FRP reinforced RC beams and covers such aspects as flexure, shear resistance, load-deformation, crack, stiffness, ductility, bonding, and failure modes. The common types of strengthening methods, which include external reinforcement, near-surface mounted system, anchored FRP, and prestressed FRP, are considered in the work. From the experiments, it could be concluded that strengthening of RC beams by means of FRP results in an increase in the load-carrying ability, stiffness, crack control, and serviceability compared to the control sample. However, the efficiency of strengthening of RC beams by FRP depends on various factors such as FRP type, thickness, number of layers, concrete compressive strength, length of bond, surface preparation, characteristics of adhesives used, strengthening method, and anchoring system. Premature debonding between FRP and concrete is one of the main problems in strengthening, since it prevents FRP from reaching their tensile strengths and leads to sudden failure of beams. The recent advances in NSM, mechanical anchorages, prestressed FRP and hybrid FRP-cementitious systems were introduced with the goal of overcoming these disadvantages.

Keywords: *Fiber reinforced polymer, CFRP, GFRP, flexural strengthening, shear strengthening.*

1. INTRODUCTION

Reinforced concrete is one of the most widely used materials in buildings, bridges, industrial structures and other infrastructure. Typically, RC structures are designed to have sufficient strength, stiffness, serviceability and durability for the intended service life. A large number of the buildings and structures in existence are, however, suffering from deterioration or are structurally inadequate due to ageing, corrosion, environmental exposure, poor construction methods, original design defects, accidental damage, change of usage, and/or change of service loads. This is why it's often cheaper and more environmentally friendly to enhance existing members than to replace them outright.

Concrete jacketing, steel plate bonding, section enlargement, external post-tensioning and additional reinforcement are the traditional strengthening methods. While these methods may enhance the structural ability, they can cause member sizes to grow, may introduce significant dead weight, may result in long construction operations, and may introduce durability issues. The high strength-to-weight ratio, corrosion resistance, and ease of installation of FRP composites has made it an alternative strengthening material.

In general, FRP composites are composed of high strength fibres in a polymer matrix. Typical fibers are carbon, glass, aramid or basalt. In this materials, CFRP is especially interesting to be used for structural strengthening due to its high tensile strength, high stiffness, low density and good durability. FRP systems can be installed on the concrete surface externally or near the concrete surface in the grooves as near surface mounted system.

Since the 1990s, the strengthening of RC members with externally bonded FRP has been the subject of extensive research. Some preliminary experimental studies confirmed that the flexural and shear capacity of deficient RC members could be significantly enhanced using externally bonded FRP. Khalifa et al. evaluated the ability of externally bonded FRP to contribute to the shear resistance of RC flexural members, and later research showed that debonding of the FRP is one of the significant issues that limit the strengthening effectiveness. Smith and Teng emphasized the significance of debonding from plates at end and intermediate cracks in FRP strengthened beams.

The structural reactions of an FRP strengthened beam are influenced by the interactions among the concrete, the internal steel reinforcement and the adhesive and the FRP. If the FRP is applied to the tension side, it can offer extra tensile resistance once the concrete cracks. This can provide higher flexural capacity, flexural stiffness and less deformations. However, the strengthening system may fail prematurely if the FRP is not attached to the concrete to the breaking point.

Research has thus evolved from the traditional externally bonded systems to more efficient ones including NSM FRP, mechanical anchorage, prestressed FRP and hybrid FRP-cementitious systems. They all try to enhance stress transfer, decrease debonding and maximize the use of the FRP strength.

This review aims at analyzing the experimental findings related to the structural performance of RC beams strengthened with the FRP composites. Flexural and shear performance, load deflection, cracking, stiffness, ductility, bond and failure mechanism are all addressed. The major parameters that have an impact on strengthening efficiency are also identified in the review and important research gaps are summarized.

2. FRP COMPOSITES FOR STRUCTURAL STRENGTHENING

FRP Composites mainly include the use of high strength fibers and a polymer matrix. The fibers give tensile strength while the matrix is responsible for binding the fibers.

The principal FRP types used in civil engineering are:

Table 1: Types of Fiber Reinforced Polymer (FRP) Composites and Their Characteristics

FRP Type	Main Characteristics	Typical Application
CFRP	Very high strength and stiffness, low weight	Flexural and shear strengthening
GFRP	Economical, corrosion resistant	General strengthening
AFRP	Good toughness and impact resistance	Specialized strengthening
BFRP	Good corrosion resistance and moderate cost	Emerging strengthening applications

CFRP is the most well-researched composite material used for strengthening reinforced concrete beams. CFRP's high elastic modulus makes it capable of making considerable contribution to tensile strength of the structure without its considerable mass increase.

FRP strengthening offers several advantages:

- high tensile strength;
- low additional dead load;
- corrosion resistance;
- relatively rapid installation;
- minimal increase in member dimensions;
- adaptability to irregular structural geometry;
- suitability for rehabilitation of existing structures.

Nevertheless, FRP also has certain limitations. For example, while the failure behavior of steel is nonlinear and has yielding properties, that of FRP is linear. As a result, FRP failure may be quite abrupt. Moreover, FRP systems rely greatly on the condition of the surface of the concrete and its bonding with the FRP.

2.1 Frp Strengthening Techniques

Fiber Reinforced Polymer (FRP) Strengthening Systems have been introduced as viable ways of enhancing the structure performance of existing concrete reinforced beams. Based on the nature of the structural deficiency, amount of strength required, the ease of accessing the beam, and the load transfer mode preferred, FRP composites may be attached through various methods. These commonly used FRP strengthening techniques include; externally bonded reinforcement (EBR), near surface mounted (NSM) reinforcement, anchored FRP systems and prestressed FRP systems.

Each technique has its own method of load transfer from the existing concrete member to the FRP and hence its own benefits, disadvantages, and failure modes. Thus selecting the best FRP strengthening system is one of the crucial factors that determine successful FRP strengthening process. The subsequent parts will analyze the main FRP strengthening techniques for reinforced concrete beams.

2.2 Externally Bonded Reinforcement

The external bonded reinforcement technique is one of the most common methods used for FRP strengthening. The FRP sheets, mats, or laminates are attached to the surface of the concrete through the use of an adhesive, mostly epoxy.

For flexural strengthening, FRP is typically attached to the tension side of the beam. This extra tensile reinforcement increases the resistance of the member to moments.

In shear strengthening, FRP sheets can be attached either at the sides or in a U-form. Fiber orientation can be decided based on the expected principal tensile stresses.

The biggest benefit of EBR is its ease of installation. Debonding, however, continues to be a problem. FRP could peel off the concrete surface before reaching its full tensile strength.

2.3 Near-Surface Mounted FRP

In NSM, the FRP strips or rods are embedded within grooves formed on the surface of the concrete cover. The grooves are filled with an adhesive material or some other appropriate bonding material.

The NSM system is able to give good mechanical protection to the FRP and usually provides better anchorage as compared to the externally bonded system. Experimental studies have shown that NSM CFRP strips can significantly enhance the load-carrying capacity and stiffness of RC beams.

Qaisi et al. studied the effect of NSM CFRP strips and ropes on RC beams and found enhancements in the load-carrying capacity and stiffness. The study also found that the strengthening behavior was dependent on the type of NSM reinforcement used.

2.4 Anchored FRP Systems

The mechanical/fiber anchors may be incorporated into the external FRP system to enhance the process of transferring load and postpone debonding.

Anchorages play a crucial role in cases when FRP of a high strength is used since the tensile strength of FRP may exceed the one of the concrete-adhesive interface. Experiments performed on CFRP sheets with anchorages have demonstrated the increased load and deformation capacity of FRP systems.

3. EXPERIMENTAL STRUCTURAL BEHAVIOR OF FRP-STRENGTHENED RC BEAMS

The results obtained from the experimental structural behavior of reinforced concrete beams strengthened with FRP indicate the strengths and weaknesses of different strengthening techniques. The laboratory tests are employed to determine the variations in load carrying capacity, bending resistance, shear resistance, stiffness, cracking, ductility, deflections, strains, and failure mode. The structural response of the strengthened beam is influenced by the properties of the FRP material used, its volume, the strength of the concrete, reinforcement, bonding, strengthening method, anchoring, and load application.

Comparing the responses of the strengthened beam to those of the control one gives an indication of the role of the FRP in structural response. The following sections give an outline of different experimental behaviors that include flexural strength, shear strength, load-deflection behavior, cracking, stiffness, ductility, bond behavior, and failure modes.

3.1 Flexural Strength

The primary goal of strengthening using flexural action is to enhance the bending resistance of reinforced concrete beams.

FRP is used in strengthening in the tension zone; it becomes effective after the cracking of concrete. The extra tensile stress is taken up by FRP, thus reducing the need for internal reinforcement.

In experimental studies, the results reveal that strengthened beams always have higher ultimate loads compared to control beams. This depends on several factors, including the type of FRP used, its thickness, width, number of layers, strength of concrete, bond properties, and the strengthening arrangement.

Studies conducted using CFRP sheets showed an increase in ultimate load capacity. In the case of NSM CFRP system, there is an increase in flexural strength, and at the same time, it offers increased protection to the strengthening materials.

However, with increased amounts of FRP, it does not necessarily lead to a proportional increase in structural capacity, and debonding may occur as a result of an increase in amount of FRP.

3.2 Shear Strength

Shear failure is normally more brittle than flexural failure. FRP may also be used in strengthening the shear capacity of RC beams through resistance to diagonal tensile forces.

FRP layers when attached vertically or diagonally in an RC beam can serve as external shear reinforcement. Experimental tests have shown considerable increase in shear capacity after strengthening with FRP.

The effectiveness of shear strengthening is influenced by:

- FRP orientation;
- FRP width and spacing;
- number of layers;
- concrete strength;
- internal stirrup ratio;
- effective bond length;
- anchorage arrangement.

However, the important point here is that increasing the flexural strength without taking into account the shear strength could lead to a change in the failure mode. Consequently, the evaluation of the shear strength becomes necessary when any flexural strengthening is done.

4. LOAD-DEFLECTION BEHAVIOR

Load-deflection behavior is one of the most critical parameters used to assess the behavior of reinforced beams.

A typical RC beam passes through three stages:

- uncracked elastic behavior;
- cracked behavior following concrete tensile cracking;
- post-yield and ultimate behavior.

FRP strengthening can improve the stiffness of the element and reduce the deflection especially after the concrete is cracked. The tensile stiffness of the CFRP gives it an important contribution to resisting the cracked elements.

The general load-deflection response of strengthened beams can be represented as:

- **Control Beam:** Lower cracking load → lower stiffness → earlier yielding → lower ultimate load.
- **FRP-Strengthened Beam:** Higher cracking load → greater post-cracking stiffness → higher yield load → higher ultimate load.

Nevertheless, increased strength can go hand in hand with a decrease in ductility when the strengthening system causes early failure or debonding of FRP. Hence, ultimate load cannot be taken as the sole criterion for structural enhancement.

4.1 CRACKING BEHAVIOR

Crack formation is an important factor associated with RC beam performance, since too many cracks will lead to serviceability and durability problems.

FRP reinforcement usually leads to the delay of flexural crack formation and reduces crack width. Post-cracking, the FRP acts to transfer tensile stresses and changes crack spacing.

The main parameters that should be monitored experimentally include:

- first-crack load;
- maximum crack width;
- crack spacing;
- crack propagation;
- crack location;
- final crack pattern.

Digital image correlation has been used more frequently for extracting complete field data on displacement and strain. The method can extract more data related to the initiation and growth of cracks than traditional point measurements.

The enhancement in crack control is especially pertinent to the case of structural reinforcement where serviceability rather than ultimate strength is controlling.

4.2 FRP–Concrete Bond Behavior

Adhesive bond is among the most crucial topics that are associated with reinforced concrete beams using FRPs.

The FRP needs to transfer its load to the concrete substrate via the adhesive and concrete surrounding the adhesive. Poor transfer of the stress can lead to early debonding.

The major forms of debonding include:

- plate-end debonding;
- intermediate crack debonding;
- concrete-cover separation;
- adhesive-concrete interface failure;
- adhesive-FRP interface failure.

Smith and Teng's work proved that debonding may happen before the flexural strength limit. The above information is very relevant in present day FRP strengthening.

Bond performance depends on:

- concrete surface condition;
- concrete tensile strength;

- adhesive properties;
- FRP stiffness;
- bond length;
- FRP width;
- crack distribution;
- anchorage;
- environmental conditions.

Consequently, surface preparation becomes a necessity. Dust, laitance, grease, loose concrete, and moisture have a considerable effect on the quality of adhesion.

Table 4.1: Comparative Summary of Selected Experimental Studies on FRP-Strengthened Reinforced Concrete Members

Author(s) & Year	Research Focus	Major Finding
Rodsin, K., Ejaz, A., Hussain, Q., & Parichatprecha, R. 2023	Experimental and analytical behavior of RC beams	Low-cost GFRP composites showed potential for improving the structural performance of RC beams
Kaya, T., Aras, M., Yilmaz, T., Çalişkan, Ö., Anil, Ö., & Erdem, R. T. 2021	Impact behavior of RC beam-column connections	CFRP strengthening improved impact resistance and structural response
Ferrier, E., Michel, L., & Ngo, M. D. 2021	Shear behavior of RC beams	Natural fiber composites demonstrated potential for improving shear performance
Kim, T. K., Park, J. S., Kim, S. H., & Jung, W. T. 2021	Structural behavior of reinforced concrete	FRP strengthening improved the overall structural performance of RC members
Huang, X., Wang, J., Zhang, F., Niu, S. S., & Ding, J. 2015	Failure behavior of notched concrete beams	CFRP strengthening modified the failure behavior and improved the resistance of notched beams

From Table 1 below, it is apparent that experimental studies have been carried out on different FRP materials and methods of strengthening. The general trend from the reviewed studies reveals that there were enhancements in load resistance, shear/impact performance, and failure mode among others.

5 FACTORS INFLUENCING STRENGTHENING EFFICIENCY

The main issues affecting the experimental behavior of FRP reinforced beams are outlined below.

Parameter	Influence on Structural Behavior
Concrete strength	Affects cracking and bond strength
FRP type	Controls tensile strength and stiffness
FRP thickness	Influences additional tensile capacity
Number of layers	Increases capacity but may increase debonding risk
Bond length	Influences stress transfer
Surface preparation	Directly affects bond quality
Adhesive properties	Controls interface strength
Anchorage	Delays premature debonding
Internal steel ratio	Influences yielding and failure mode
Loading configuration	Controls stress and crack distribution

In relation to these properties, the interface between the FRP and concrete plays a crucial role as the strength of the strengthened beam can be dependent on this interface and not the FRP itself.

6. CONCLUSIONS

In the reviewed experimental study, it was found that the use of FRP composites leads to significant enhancements in the structural properties of reinforced concrete beams, namely increased load-bearing capacity, flexural and shear strength, stiffness, and crack-resistance. At the same time, CFRP is considered one of the most extensively studied strengthening materials due to their high strength and stiffness, whereas NSM, anchored, and prestressed FRP systems serve as different alternatives for increasing efficiency of reinforcement. The performance of structures depends on various parameters like concrete properties, FRP system, bond length, adhesive properties, surface treatment, internal reinforcement, and anchorage. Of all those mentioned factors, the bond behavior between FRP and concrete plays a critical role in the structure as early debonding may impede the use of FRP and cause sudden failure. In addition, increasing the FRP content does not always lead to proportional enhancement of structures.

. REFERENCES

1. Solahuddin, B. A., & Yahaya, F. M. (2023). A state-of-the-art review on experimental investigation and finite element analysis on structural behaviour of fibre reinforced polymer reinforced concrete beams. *Heliyon*, *9*(3).
2. Hamrat, M., Bouziadi, F., Boulekbache, B., Daouadji, T. H., Chergui, S., Labed, A., & Amziane, S. (2020). Experimental and numerical investigation on the deflection behavior of pre-cracked and repaired reinforced concrete beams with fiber-reinforced polymer. *Construction and Building Materials*, *249*, 118745.
3. Makhlouf, M. H., Abdel-kareem, A. H., Mohamed, M. T., & El-Gamal, A. (2024). Experimental and numerical study of shear strengthening of reinforced concrete beams using jute fiber reinforced polymers (JFRP). *Journal of Building Engineering*, *86*, 108732.
4. Xue, Y. J., Wang, W. W., Wu, Z. H., Hu, S., & Tian, J. (2023). Experimental study on flexural behavior of RC beams strengthened with FRP/SMA composites. *Engineering Structures*, *289*, 116288.
5. G. Karayannis, C., K. Kosmidou, P. M., & E. Chalioris, C. (2018). Reinforced concrete beams with carbon-fiber-reinforced polymer bars—Experimental study. *Fibers*, *6*(4), 99.
6. Nematzadeh, M., & Fallah-Valukolaee, S. (2021). Experimental and analytical investigation on structural behavior of two-layer fiber-reinforced concrete beams reinforced with steel and GFRP rebars. *Construction and Building Materials*, *273*, 121933.
7. Akkaya, H. C., Aydemir, C., & Arslan, G. (2022). Investigation on shear behavior of reinforced concrete deep beams without shear reinforcement strengthened with fiber reinforced polymers. *Case Studies in Construction Materials*, *17*, e01392.
8. Effiong, J. U., & Ede, A. N. (2022). Experimental investigation on the strengthening of reinforced concrete beams using externally bonded and near-surface mounted natural fibre reinforced polymer composites—a review. *Materials*, *15*(17), 5848.
9. Junaid, M. T., Elbana, A., Altoubat, S., & Al-Sadoon, Z. (2019). Experimental study on the effect of matrix on the flexural behavior of beams reinforced with Glass Fiber Reinforced Polymer (GFRP) bars. *Composite Structures*, *222*, 110930.
10. Tedford, T., & Polak, M. A. (2022). Experimental investigation of concrete beams reinforced with glass Fiber–Reinforced polymer bars. *Journal of Composites for Construction*, *26*(5), 04022055.
11. Javed, M. A., Irfan, M., Khalid, S., Chen, Y., & Ahmed, S. (2016). An experimental study on the shear strengthening of reinforced concrete deep beams with carbon fiber reinforced polymers. *KSCE Journal of Civil Engineering*, *20*(7), 2802-2810.
12. Jirawattanasomkul, T., Likitlersuang, S., Wuttiwannasak, N., Ueda, T., Zhang, D., & Shono, M. (2020). Structural behaviour of pre-damaged reinforced concrete beams strengthened with natural fibre reinforced polymer composites. *Composite Structures*, *244*, 112309.
13. Abadel, A., Abbas, H., Almusallam, T., Alshaikh, I. M., Khawaji, M., Alghamdi, H., & Salah, A. A. (2022). Experimental study of shear behavior of CFRP strengthened ultra-high-performance fiber-reinforced concrete deep beams. *Case Studies in Construction Materials*, *16*, e01103.
14. Kaszubska, M., Kotynia, R., Barros, J. A., & Baghi, H. (2018). Shear behavior of concrete beams reinforced exclusively with longitudinal glass fiber reinforced polymer bars: Experimental research. *Structural Concrete*, *19*(1), 152-161.
15. Bywalski, C., Drzazga, M., Kaźmierowski, M., & Kamiński, M. (2020). Shear Behavior of Concrete Beams Reinforced with a New Type of Glass Fiber Reinforced Polymer Reinforcement: Experimental Study. *Materials*, *13*(5), 1159.
16. Fan, X., & Zhang, M. (2016). Experimental study on flexural behaviour of inorganic polymer concrete beams reinforced with basalt rebar. *Composites Part B: Engineering*, *93*, 174-183.
17. Sun, Y., Fu, W., Chen, X., Zhang, Z., Yu, W., & Li, S. (2023). Theoretical and experimental investigations into flexural behavior of existing reinforced concrete beams strengthened by CFRP bars. *Journal of Building Engineering*, *77*, 107528.
18. Wang, G., Yang, C., Meng, C., Xia, Z., Pan, Y., & Wang, M. (2020). Experimental study on the mechanical and self-sensing behaviors of prestressed carbon fiber–reinforced polymer reinforced concrete composite structures. *Advances in Structural Engineering*, *23*(8), 1507-1520.

19. Solahuddin, B. A., & Yahaya, F. M. (2023, June). A narrative review on strengthening of reinforced concrete beams using carbon fibre reinforced polymer composite material through experimental investigation and numerical modelling. In *Structures* (Vol. 52, pp. 666-710). Elsevier.

20. Shen, D., Li, M., Kang, J., Liu, C., & Li, C. (2021). Experimental studies on the seismic behavior of reinforced concrete beam-column joints strengthened with basalt fiber-reinforced polymer sheets. *Construction and Building Materials*, *287*, 122901.

21. Rodsin, K., Ejaz, A., Hussain, Q., & Parichatprecha, R. (2023). Experimental and analytical studies on low-cost glass-fiber-reinforced-polymer-composite-strengthened reinforced concrete beams: A comparison with carbon/sisal fiber-reinforced polymers. *Polymers*, *15*(19), 4027.

22. Kaya, T., Aras, M., Yilmaz, T., Çalişkan, Ö., Anil, Ö., & Erdem, R. T. (2021). Investigation of impact behavior of reinforced concrete beam to column connection strengthened with carbon fiber-reinforced polymer strips. *Structural Concrete*, *22*(4), 1977-2010.

23. Ferrier, E., Michel, L., & Ngo, M. D. (2021, October). Experimental study on the shear behavior of RC beams reinforced by natural composite materials (flax fibers). In *Structures* (Vol. 33, pp. 637-654). Elsevier.

24. Kim, T. K., Park, J. S., Kim, S. H., & Jung, W. T. (2021). Structural behavior evaluation of reinforced concrete using the fiber-reinforced polymer strengthening method. *Polymers*, *13*(5), 780.

25. Huang, X., Wang, J., Zhang, F., Niu, S. S., & Ding, J. (2015). An experimental investigation on the failure behavior of a notched concrete beam strengthened with carbon Fiber-Reinforced Polymer. *International Journal of Polymer Science*, *2015*(1), 729320.

26. Duarte, P., Correia, J. R., Ferreira, J. G., Nunes, F., & Arruda, M. R. T. (2014). Experimental and numerical study on the effect of repairing reinforced concrete cracked beams strengthened with carbon fibre reinforced polymer laminates. *Canadian Journal of Civil Engineering*, *41*(3), 222-231.

27. Liu, D., Qin, F., Di, J., & Zhang, Z. (2023). Flexural behavior of reinforced concrete (RC) beams strengthened with carbon fiber reinforced polymer (CFRP) and ECC. *Case Studies in Construction Materials*, *19*, e02270.

28. Cosgun, T. (2016). An experimental study of RC beams with varying concrete strength classes externally strengthened with CFRP composites. *Journal of Engineered Fibers and Fabrics*, *11*(3), 155892501601100302.

29. Zheng, Y. Z., Wang, W. W., Mosalam, K. M., Fang, Q., Chen, L., & Zhu, Z. F. (2020). Experimental investigation and numerical analysis of RC beams shear strengthened with FRP/ECC composite layer. *Composite Structures*, *246*, 112436.

30. Pathak, P., & Zhang, Y. X. (2019). Numerical study of structural behavior of fiber-reinforced polymer-strengthened reinforced concrete beams with bond-slip effect under cyclic loading. *Structural Concrete*, *20*(1), 97-107.