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A Review on Strengthening Techniques of RC Beams with Various FRP Sheets

M. Sushma swaraj, P. Jagadeesh, P. Rohit, S. Pallavi, A. Priyatham

Department of Civil Engineering, GMR Institute of Technology, Rajam,532127, INDIA.

ABSTRACT

This paper provides an in-depth review of the techniques used to strengthen reinforced concrete (RC) beams through the application of fibre-reinforced polymer (FRP) sheets. Traditionally, steel reinforcement has been the primary choice for enhancing the strength of RC beams, but its susceptibility to corrosion, especially in humid or moist environments, leads to significant durability issues and higher maintenance costs. Over the past two decades, FRP composites have emerged as a viable alternative due to their lightweight nature, high strength-to-weight ratio, and superior resistance to both corrosion and heat. These characteristics make FRP an attractive option for long-term structural strengthening, offering potential cost reductions of up to 25% compared to traditional steel reinforcement, along with improved structural performance. The review examines a range of experimental studies that investigate the effectiveness of FRP in improving the behaviour of RC beams, focusing on the use of epoxy adhesives for bonding FRP sheets to concrete surfaces. Key aspects such as load-deflection characteristics, failure patterns, and ductility improvements are analysed in detail. One notable observation is that the application of multiple layers of carbon fibre-reinforced polymer (CFRP) sheets increases the shear strength of RC beams, although the relationship between the number of layers and load-carrying capacity is not linear. This suggests that merely adding more layers may not always result in proportional gains in strength. The study also underscores the critical importance of proper anchorage and the strategic placement of FRP sheets to maximize their strengthening potential. Inadequate bonding or improper anchorage can lead to premature failures, negating the benefits of FRP application. Overall, this review highlights FRP as a promising, cost-effective alternative to traditional steel reinforcement, offering significant advantages in enhancing the performance, durability, and lifespan of RC structures, particularly in the field of civil engineering.

Keywords: FRP strengthening, Different FRP schemes, Shear strengthening, Flexure strengthening, Load-deflection responses.

1. INTRODUCTION

1.1 General

A modern and convenient way to strengthen reinforced concrete (RC) beams is by using fibre-reinforced polymer (FRP) sheets/strips/plates. Fibre-reinforced polymers are composite materials of polymer matrix reinforced with fibres. Fibres like carbon, glass, basalt, hybrid, aramid, natural, ceramic, metal, silica etc. polymer matrices such as thermoset and thermoplastic. The Use of Fibre-Reinforced Polymer for RC Beams Started in the year 1960. The adoption of FRP Composites for RC beam strengthening was widely Spread In the year 2000. Over the past several years, many investigations and experiments have been conducted on RC beams with different FRP schemes and methods to know the various applications of FRP in the case of RC beams. For strengthening the RC beams, initially, steel is used but its lifespan is less and not durable because of the corrosion if the steel is faced by moisture and after several observations, steel has more limitations. Further, the researchers were attracted by the FRP properties like cost efficiency (if we replace steel with FRP the cost will be reduced to 25%) lightweight, cost efficiency, feasibility, high strength-to-weight ratio, high stiffness, high resistance to corrosion and heat, high tensile strength, low density, highly durable, ease of application, efficiency and effectiveness. So due to the above properties of FRP, they are tested experimentally by taking different strengthening schemes for RC beams. Flexure and shear modes of failure are the two prime failure modes for RC beams. Flexural failure is generally preferred as ductile failure i.e. it occurs when a material is loaded beyond its yield strength and begins to plastically deform for a period before ultimately failing. The shear failure is preferred as brittle failure i.e. without any indication fails suddenly and thus is catastrophic. If the beams are deficient in shear or flexure, strong and enough strengthening is required. Moreover, FRP has more reliable bond line strength as compared to steel where corrosion at the interface is unavoidable in the presence of moisture.

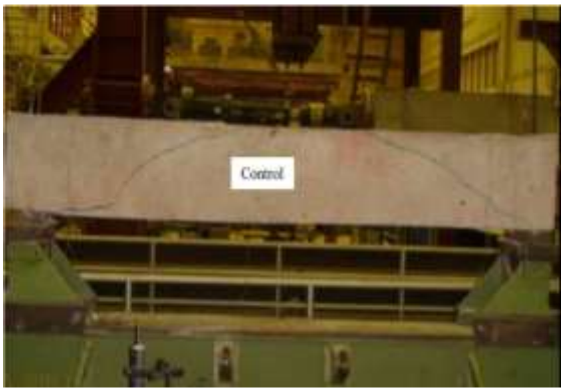

Fig.1.1: Flexural failure **Fig.1.2: Shear failure**

The first application of FRP sheets to beams involves the external bonding of FRP sheets on the tension face of beams using epoxy. Epoxy is an additive resin used to improve properties like adhesion and resistance or which is used as a glue to combine RC beam to FRP sheet with 1mm thickness. Beam strengthening using externally bonded composite sheets/plates/strips has been studied widely over the years. The behaviour was presented in terms of load deflection, load-strain, failure patterns and structural ductility.

Fig.1.3: Externally bonded (EB) FRP

The second method is embedded through section (ETS), a new technique for enhancing the capacity of RC beams with FRP materials instead of bonding FRP strips on the external face of the element but in this case, the beam in the web section involves perforated holes and inserting FRP into the holes and filling the holes with grout. Hence the experimental results show the beam reinforced with the proposed technique performs similar to or better than those with externally bonded FRP.

The third method is the near-surface mounted (NSM) method. In this method, grooves are first cut into the concrete cover of an RC element and the FRP reinforcement is bonded therein with an appropriate groove filler typically epoxy paste or cement grout. This method is also known as grouted reinforcement or embedded reinforcement. Hence from the three methods, the advantage of the embedded through section (ETS) method in comparison with the externally bonded (EB) and near-surface mounted (NSM) method, is that using the ETS method which consumes less time and doesn't require surface preparation.

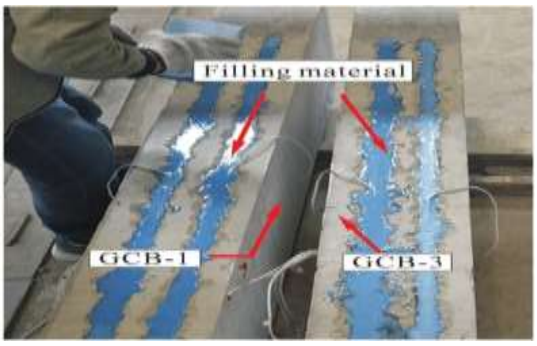

Fig.1.4: Near surface mounted method

In addition to those methods, different anchorage systems were considered. So by providing anchorage at the ends after providing FRP sheets in the tension zone, it will give support to the sheets and beam and hence it may protect it from a failure called debonding. It means after the load is applied to the beam, the separation of the beam and the sheet is known as debonding. This type of failure occurs for externally bonded (EB) FRP systems. Although substantial research has been conducted on the FRP strengthening of RC beams, the behaviour of FRP-strengthened beams under different schemes of strengthening is still not well established. The failure patterns are shown in figures 6 and 7.

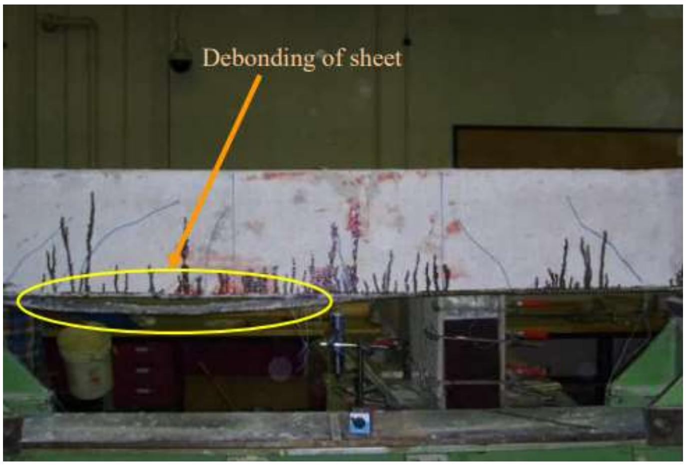

Fig.1.5: Debonding of sheet failure

Fig.1.6: FRP Rupture

From the past several years, studies on FRP have been done through an experimental program, and efforts have been made to study the efficiency and effectiveness of two different FRP schemes for flexure and shear strengthening of RC beams. The different schemes that are implemented on the externally bonded FRP system are u wrap, w wrap, different layers of FRP sheets, partial and full depth of FRP strips, and 90 degrees vertically and 30, 60, and 45 degrees inclined FRP sheets.

Fig.1.7: vertical strip system

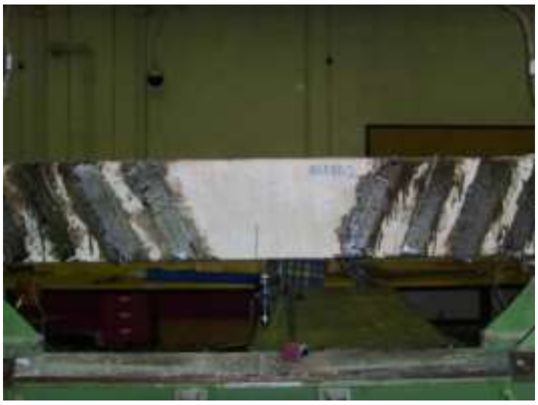

Fig.1.8: Inclined strip system

Fig.1.9: Fully depth FRP strip

Fig.1.10: Partial depth FRP strip

1.2 ANSYS Modelling

The software ANSYS (analysis system) is the solution to the engineering industry where finite element analysis is performed by engineers by hand. An accurate method that analyses a wide range of problems related to structure design by using numerical techniques these design models can be further tested for strength, elasticity, and toughness. It saves both time and manufacturing costs and reduces the risks involved in the process from designing to manufacturing. In this software solid65 represents concrete, link180 represents steel or FRP bars, solid45 or solid185 represents loading plate, shell65 represents FRP sheet, and combine49 represents bond [].

The experiments are done and investigated to know the applications like structural performance, to understand the behaviour and failure mechanisms, and to optimise design parameters. The modes of failures are debonding, rupture, concrete crushing, delamination shear and flexure failures in the RC beams strengthened with FRP composites for all the methods mentioned above. After gathering experimental results and confirming the effectiveness of FRP sheets, they are primarily used in retrofitting and repairs of various types of structures.

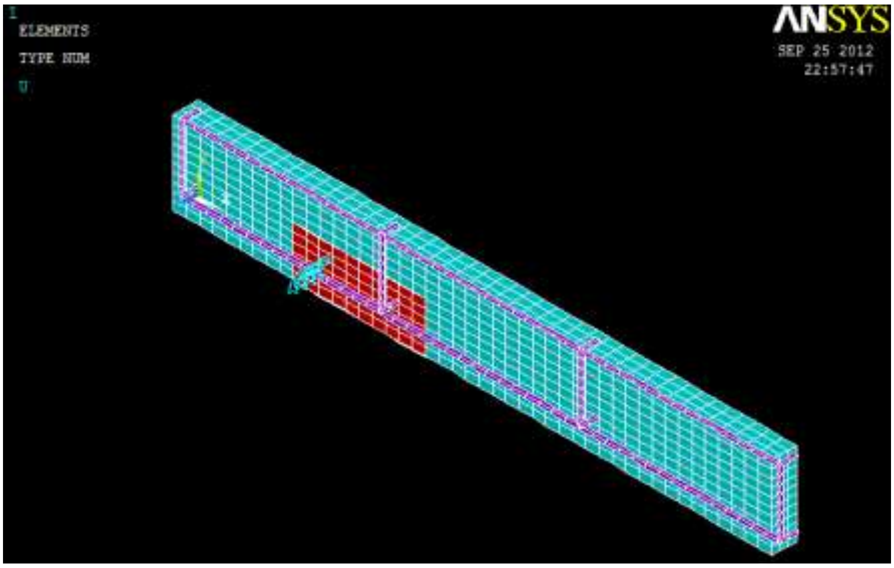

Fig.1.11: ANSYS model for FRP strengthened RC beam

1.3 Shear & Flexure Deficient RC Beams

a) **Shear-deficient RC beams:** Shear-deficient reinforced concrete (RC) beams fail primarily due to their inability to resist shear forces acting perpendicular to the beam's longitudinal axis. This type of failure is brittle and occurs suddenly, often without significant warning, making it dangerous for structural safety. Shear deficiencies are typically caused by insufficient shear reinforcement (stirrups), poor concrete quality, inadequate cross-sectional dimensions, or unexpected high loads. When shear failure occurs, diagonal cracks form near the support or load points and propagate toward the compression zone. To strengthen shear-deficient beams, various techniques can be employed. Fiber-reinforced polymers (FRPs) are commonly used as externally bonded sheets or wraps to enhance shear capacity. Steel plate jacketing, increasing the number of stirrups, or using concrete jacketing to increase the cross-sectional size and improve the beam's ability to resist shear forces and prevent sudden brittle failure.

b) **Flexure-deficient RC beams:** Flexure-deficient RC beams fail due to insufficient capacity to resist bending (flexural) stresses. Unlike shear failure, flexural failure is ductile and provides visible warning signs, such as extensive cracking or large deflections, before ultimate collapse. Causes of flexural deficiencies include inadequate tensile reinforcement, poor-quality concrete, improper detailing, or overloading. Failure typically begins with the yielding of tension reinforcement, followed by crushing of the concrete in the compression zone.To address flexure deficiencies, strengthening methods focus on enhancing the beam's tensile capacity. Externally bonded FRP strips or plates are widely used to increase flexural strength. Steel plate bonding, post-tensioning with external cables, and concrete jacketing to enlarge the beam's section are also effective strategies. These techniques ensure the beam can withstand higher flexural loads and extend its service life.

c) **Key Differences between Shear and flexure deficient RC Beams:** Shear failure in RC beams is sudden and brittle, requiring prompt strengthening with methods like FRPs or additional shear reinforcement. Flexural failure, on the other hand, is gradual and ductile, often addressed by increasing tensile reinforcement or applying external strengthening techniques. Understanding these deficiencies and their solutions is critical for maintaining structural integrity and safety.

LITERATURE REVIEW

- Shalif et al., (2022), the shear strengthening of RC beams with various FRP schemes has been studied. For this purpose, 9 shear-deficient reinforced concrete slender beams were taken to test, and 3 different FRPs, i.e., Carbon fibre reinforced polymer, glass fibre reinforced polymer, and fibre-reinforced cement matrix, were used to determine the higher shear strength and ductility among all these three different FRP's by comparing all these three schemes with control beams i.e. un-strengthened beam. The first beam is a control beam with no strengthening, the second beam is strengthened with Carbon Fiber Reinforced Polymer (CFRP) with anchorage, and the third beam is a CFRP-strengthened beam without anchorage the fourth Beam is reinforced with Fabric-Reinforced Cementitious Matrix (FRCM) and anchored and the fifth beam is FRCM-reinforced beam without anchorage. The sixth beam is a Full-depth Glass Fiber Reinforced Polymer (GFRP) strengthened beam without anchorage. The seventh beam is a partial-depth GFRP-strengthened beam without anchorage. The eighth beam is Partial-depth with carbon anchorage and the ninth is a Partial-depth beam glass anchorage. All nine beams are tested under 4-point bending. After testing three modes of failure are observed. The first failure is the shear failure for the control beam, the second failure is a shear failure with debonding of FRP sheet for GFRP and FRCM (diagonal tension shear failure) and the third failure is a flexure failure with crushing of concrete for CFRP. All the beams exhibited similar flexural stiffness. Shear capacity is greater for the CFRP without anchorage and deflection is greater for CFRP sheets with anchorage as compared to other schemes and control beam.
- Hawileh et al., (2015), the effect of flexural CFRP sheets on the shear resistance of RC beams have been studied. For that purpose, 13 reinforced concrete beams were tested which are categorized into 3 groups. Group 1 contains 5 beams, group 2 contains 4 beams, and group 3 contains 4 beams. Group 1 consists of a control beam with no strengthening, and another four beams strengthened with Carbon Fiber Reinforced Polymer (CFRP) in different layers such as 2, 3, 4, and 5 layers. Group 2 included a control beam with no strengthening and CFRP-strengthened beams with 2, 3, and 4 layers. Group 3 consists of a control beam with 2 layers of no strengthening, and un-strengthened beams with 3, 4, and 5 layers. They were tested under four-point bending. The deflection is greater for the 3 layered beams among the average of all the different groups. The tested specimens failed in shear as a result of a diagonal-tension crack. All strengthened specimens in each group showed an increase in the shear capacity over the control specimens. The increase was in the range of 10–70% over the control specimens. As the number of layers of CFRP sheets increased, the shear strength of the tested RC beams also increased. This concludes that the flexural longitudinal reinforcement ratio has a significant effect on the shear strength of RC beams.
- Ahmed et al., (2011), the RC beams strengthened with CFRP layers are tested experimentally using different strengthening schemes. For this test purpose, six RC beams are taken and strengthened as follows. The first beam is a control beam and the second third and fourth beams are strengthened with CFRP laminates consisting of one layer for the second beam, two layers for the third beam and three layers for the fourth beam. The fifth beam consists of 1 layer of U-shaped wrapping end strip and the sixth beam consists of 1 layer of W-shaped wrapping end strip. Due to transverse CFRP laminates, which provide anchorage for the longitudinal plate and prevent the beam from debonding failure from CFRP laminates. The beams were tested under four-point bending and the observations are if there is an increase in layers, the ultimate load and stiffness increase but if these layers are compared with edge wrapping strips, the use of transverse edge strips increased the flexural capacity of strengthened beams by 33%. It was also observed that the ultimate load-carrying capacity cannot be increased simply by adding

the number of CFRP layers. From the experimental results, it is clear that a minimum of one layer of CFRP sheets with end anchorage can give the desired results.

- Murad (2018), the shear behaviour of RC beams strengthened with CFRP sheets under different orientation angles including 0,45,60,90 degrees to the longitudinal axis of the beam. For this purpose, five simply supported beams were used for experimental purpose. Out of five beams, the first beam is a control beam which is not strengthened(S-C), the second beam (S-0) is strengthened with CFRP sheets oriented parallel to the beam and was fully wrapped from its three sides. The third beam (S-45) is strengthened with CFRP sheets inducing 45 degrees to the beam's longitudinal axis rather than being side-wrapped. The fourth beam (S-60) is strengthened with CFRP sheets by wrapping from its three sides. The beam five(S-90) is strengthened with CFRP sheets perpendicular to the beam's longitudinal axis from its three sides. The beams are tested under two-point bending. After the test, the results are observed as the ultimate load; shear strength and deflection are greater for S-60 than others, and ductility is greater for S-45. Therefore, the 45 and 60-degree inclined CFRP sheets are recommended as the most effective schemes for strengthening RC beams.

- Saribiyik et al., (2021), investigated the effectiveness of using Basalt Fiber-Reinforced Polymer (BFRP) composites to strengthen reinforced concrete (RC) beams with low strength concrete. The procedure involved designing and producing 18 RC beams, with 15 beams strengthened with BFRP composite and 3 control beams. The beams were designed according to with varying strengthening configurations using BFRP composite. The BFRP composite was applied using different fiber angles, confinement methods, and widths. The beams were then prepared for testing by rounding the corners, cleaning the surfaces, and applying epoxy. The BFRP strips were bonded to the beam surfaces in various configurations, including U-shape, full confinement, side confinement, and anchor U confinement. The beams were then tested in a flexural test frame to examine shear failure forms of FRP-reinforced beams. The test setup included a reaction beam, hydraulic cylinder pump, electronic load cells, displacement meters, and data loggers to record load, displacement, and crack width data. results showed that BFRP composites significantly increased the shear strength of RC beams, with gains ranging from 43% to 100% compared to control beams. The study found that full confinement methods with continuous wraps and strips were most effective, while U-wrapping strips with anchors were less effective due to uneven stress distribution. The use of BFRP composites also improved flexural stiffness, reduced crack opening, and decreased displacement values. Analytical models, such as the FIB-TG 9.3 regulation and the Chen-Teng model, generally predicted the shear strength contribution of BFRP composites accurately. Overall, the study concludes that BFRP composites are a promising alternative material for RC beam shear strengthening, particularly when used with head strips and anchors in U-shaped and side wrapping methods.Finally, BFRP composites increased the shear strength of RC beams by 43% to 100%. Full confinement methods with continuous wraps and strips were most effective. U-wrapping strips with anchors were less effective due to uneven stress distribution. BFRP composites improved flexural stiffness, reduced crack opening, and decreased displacement values. Analytical models accurately predicted the shear strength contribution of BFRP composites. BFRP composites are a promising alternative material for RC beam shear strengthening.

- Attari et al., (2012), investigated the efficiency of external strengthening systems for reinforced concrete beams using FRP fabric (Glass-Carbon). Seven beams were tested, including a control reference beam (PC) and six strengthened beams with different configurations (A serial beams). The failure modes observed included flexural failure, such as compression failure before and after yielding of steel, rupture of FRP strips, and shear failure, as well as local failure, including peeling of the composite off the concrete beam. The results showed that the strengthened beams exhibited higher strength and ductility compared to the reference beam, with a maximum strength gain of 114% for beam PA1 (strengthened with two layers of carbon fiber CFRP). The use of a twin layer Glass-Carbon fibers composite material was found to be very efficient, and the U-anchorage strengthening configuration improved flexural strength and contributed to the redistribution of internal forces. The study also found that a strengthening composite material in glass fibers alone or as a single-layered hybrid composite improved ductility, refuting the idea that FRP strengthened beams are prone to brittle and sudden failure. The analytical model developed to predict flexural failure of strengthened concrete elements accurately correlated with the experimental results. Finally, HFRP glass carbon fibre reinforcement polymer fabric offers a cost effective and efficient solution for flexural strengthening. Reinforced concrete beams and high strengthening with increase and 138 percent and therefore ductility decreased by 26 percent. This test says that ductility decrease and increases ultimate strength. occurred failure is rupture and cracks can be seen at mid span of the beam.

CONCLUSION

The review on strengthening reinforced concrete (RC) beams using fiber-reinforced polymer (FRP) sheets highlights both the technological progress and the practical significance of adopting FRP as a modern reinforcement material in civil engineering. FRP materials, especially carbon fiber-reinforced polymers (CFRP), have proven to be superior to traditional steel reinforcement due to their lightweight nature, high strength-to-weight ratio, and exceptional resistance to corrosion, moisture, and other environmental factors. These qualities make FRP an attractive solution for both new construction and the rehabilitation of aging structures. Experimental studies have shown that the use of CFRP sheets can lead to remarkable improvements in the structural performance of RC beams, with some configurations yielding up to 114% increases in strength and significant improvements in ductility. The review also emphasizes the critical importance of correct application procedures to fully realize the benefits of FRP. Techniques such as using epoxy adhesives for bonding, ensuring proper surface preparation, and strategically layering CFRP sheets are essential for achieving the desired strengthening outcomes. While adding more CFRP layers can increase shear strength, the relationship is not always linear, and improper design or inadequate anchorage can lead to premature failures like debonding or peeling, which can compromise the structural integrity of the beam. Therefore, attention to detail in application, particularly in anchorage and bonding techniques, is paramount to ensuring the effectiveness of FRP reinforcement. In conclusion, the integration of FRP sheets in strengthening RC beams represents a forward-thinking approach that addresses the challenges of durability and longevity in modern construction. FRP provides an effective alternative to steel, particularly in structures exposed to harsh environmental conditions. Looking ahead, further research should focus on the long-term performance of FRP-reinforced structures, including their behaviour under sustained loads and environmental stressors. Additionally, comprehensive cost-benefit analyses are needed to assess the economic feasibility of widespread FRP adoption in diverse structural applications.