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A Review on Strengthening of Reinforced Concrete using Rectangular Beams, Tee Beams, and Rectangular and T- Beams with Web Opening

Chandan Kumar[1], Ankita Singhai[2], Rahul Kumar Satbhaiya[3]
[1]M.Tech Scholar, Civil department, Infinity Management & Engineering College, Sagar (MP)
[2]Asst. professor and Guide, Infinity Management & Engineering College, Sagar (MP)
[3]HOD, Infinity Management & Engineering College, Sagar (MP)

Abstract: In this study focuses on the review of strengthening structurally deficient reinforced concrete (RC) T-beams using externally bonded glass fiber reinforced polymer (GFRP) sheets. Rehabilitation of RC structures is essential due to aging, corrosion, construction defects, increased service demands, and seismic vulnerabilities. Among various beam configurations, T-beams are widely used in buildings and bridges, with shear failure being particularly catastrophic due to its sudden nature. Externally bonded FRP has emerged as a promising strengthening solution due to its high strength-to-weight ratio, corrosion resistance, and ease of installation. This research involved testing eleven full-scale RC T-beams under symmetrical four-point static loading to assess shear performance and failure modes. Key variables included the presence of steel stirrups, shear span-to-depth ratios, and the quantity of GFRP used. The results demonstrated a notable improvement in shear capacity with GFRP application. However, failure typically began with debonding of the FRP sheets, followed by brittle shear collapse. To address this issue and ensure full utilization of FRP strength, an innovative anchorage technique using GFRP plates was introduced, effectively preventing premature debonding. This method offers a more efficient, cost-effective alternative to traditional strengthening approaches and highlights the potential of FRP composites in structural rehabilitation.
Keywords: Glass Fiber Reinforced Polymer, T-Beams, Reinforced Concrete, Frp, Structural Rehabilitation.

I. INTRODUCTION

To meet up the requirements of advance infrastructure new innovative materials/ technologies in civil engineering industry has started to make its way. Any technology or material has its limitations and to meet the new requirements new technologies have to be invented and used. With structures becoming old and the increasing bar for the constructed buildings the old buildings have started to show a serious need of additional retrofits to increase their durability and life. The retrofitting is one of the best options to make an existing inadequate building safe against future probable earthquake or other environmental forces. There are many other factors, considered in decision making for any retrofitting strategy. This proves to be a better option catering to the economic considerations and immediate shelter problems rather than replacement of buildings. Because replacement is very costly and structural behavior also may change and it may cause inconvenience also. There are several situations in which a civil structure would require retrofitting or rehabilitation.

II. LITERATURE REVIEW

This literature review aims to fill these existing gaps by providing a comprehensive analysis of the state of deterioration of the existing civil engineering concrete structures is one of the greatest concerns to the structural engineers worldwide. The renewal strategies applied to existing structures comprise of rehabilitation and complete replacement. The latter involves a huge expenditure and time; hence the rehabilitation is the only option available. Fiber reinforced polymers (FRP) are the promising materials in rehabilitation of the existing structures and strengthening of the new civil engineering structures.

This chapter presents a brief review of the existing literature in the area of reinforced concrete (RC) beams strengthened with epoxy-bonded FRP. The major achievements and results reported in the literature are highlighted. The review of the literature is presented in the following three groups:

- Strengthening of Reinforced Concrete (RC) Rectangular Beams.
- Strengthening of Reinforced Concrete (RC) T-Beams.
- Strengthening of RC Rectangular and T- Beams with web opening.

A. Strengthening of Reinforced Concrete (RC) Rectangular Beams.

Author	Year	Title	Inside	Findings
Mahmood Y. Alkhateeb, Farzad Hejazi	2024	Strengthening Reinforced Concrete Beams through Integration of CFRP Bars, Mechanical Anchorage System, and Concrete Jacketing	The study proposes strengthening RC rectangular beams using carbon-fiber-reinforced polymer (CFRP) bars, mechanical anchorage systems, and concrete jacketing, enhancing beam capacity significantly from 44 kN to 83 kN, while preventing premature debonding under cyclic loads.	Beam capacity increased from 44 kN to 83 kN. Proposed system prevents premature debonding effectively.
Tao Yu, Quansheng Sun, Chunwei Li, Yancheng Liu	2021	Experimental Research on the Flexural Performance of RC Rectangular Beams Strengthened by Reverse-Arch Method	The paper discusses strengthening reinforced concrete rectangular beams using the reverse-arch method with CFRP boards, which enhances load-bearing capacity and stiffness by 56% and 63% for cracking and ultimate loads, respectively, while reducing ductility..	CFRP reinforcement improves RC beam performance using reverse-arch method. Load-bearing capacity increased by 56% and stiffness enhanced.
Jaime Xavier Nieto-Cárdenas, Paúl Illescas-Cárdenas	2024	Reinforcement concrete beams with external steel elements	The paper investigates strengthening reinforced concrete beams using external steel elements, specifically comparing cold-formed angle sections and steel plates. The addition of steel elements enhances strength and flexibility, while angled sections unexpectedly reduce load-carrying capacity and ductility.	nvestigates strengthening RC beams with external steel elements. Compares two types of beams under monotonic and cyclic loading.

Ghazi et al. (1994) studied the shear repair of reinforced concrete (RC) beams strengthened with fiber glass plate bonding (FGPB) for structural and non-structural cracking behavior due to a variety of reasons. Results from a study on strengthening of RC beams having deficient shear strength and showing major diagonal tension cracks have been presented. The beams with deficient shear strength were damaged to a predetermined level (the appearance of the first shear crack) and then repaired by fiber glass plate bonding (FGPB) techniques. Different shear repair schemes using FGPB to upgrade the beams shear capacity were used, i.e., FGPB repair by shear strips, by shear wings, and by U-jackets in the shear span of the beams. The study results also show that the increase in shear capacity by FGPB was almost identical for both strip and wing shear repairs. However, this increase was not adequate to cause beams repaired by these two schemes to fail in flexure.

Chaallal et al. (1998) investigated a comprehensive design approach for reinforce concrete Flexural beams and unidirectional slabs strengthened with externally bonded fiber. Reinforced plastic (FRP) plates. The approach complied with the Canadian Concrete Standard. This was divided into two parts, namely flexural strengthening and shear strengthening. In the first part, analytical models were presented for two families of failure modes: classical modes such as crushing of concrete in compression and tensile failure of the laminate, and premature modes such as debonding of the plate and ripping off of the concrete cover. These models were based on the common principles of compatibility of deformations and equilibrium of forces. In the Second part, design equations were derived to enable calculation of the required cross-sectional area of shear lateral FRP plates or strips for four number of plating patterns: vertical strips, inclined strips, wings, and U-sheet jackets.

Khalifa et al. (2000) studied the shear performance and the modes of failure of reinforced concrete (RC) beams strengthened with externally bonded carbon fiber reinforced polymer (CFRP) wraps experimentally. The experimental program consisted of testing twenty-seven, full- scale, RC beams. The variables investigated in this research study included steel stirrups (i.e., beams with and without steel stirrups), shear span-to depth ratio (i.e., a/d ratio 3 versus 4), CFRP Amount and distribution (i.e., Continuous wrap versus strips), bonded surface (i.e., lateral sides versus U-wrap), fiber orientation (i.e., 90°/0° fiber combination versus 90° direction), and end anchor (i.e., U-wrap with and without end anchor). The experimental results indicated that the contribution of externally bonded CFRP to the shear capacity is significant and dependent upon the variable investigated. For all beams, results show that an increase in shear strength of 22 to 145% was achieve.

Alex et al. (2001) studied experimentally the effect of shear strengthening of RC beams on the stress distribution, initial cracks, crack propagation, and ultimate strength. Five types of beams with different strengthening carbon-fiber–reinforced plastic sheets are often strengthened in flexure. The experimental results show that it is not necessary to strengthen the entire concrete beam surface. The general and regional behaviors of concrete beams with bonded carbon-fiber– reinforced plastic sheets are studied with the help of strain gauges. The appearance of the first cracks and the crack propagation in the structure up to the failure is monitored and discussed for five different strengthened beams. In particular, for one of the strengthened RC beams, the failure mode and the failure mechanism are fully analyzed.

B. Strengthening of Reinforced Concrete (RC) T-Beams.

Author	Year	Title	Inside	Findings
Mallikarjuna K, Parkhe Ravindra, Muhmmad Daniyal, Mohammad Amir Khan, Saiful Islam	2023	Employing Carbon Fiber Reinforced Polymer Composites toward the Flexural Strengthening of Reinforced Concrete T-Beams.	Reinforced concrete T-beams are strengthened using carbon fiber reinforced polymer (CFRP) composites through externally bonded (EB) and near surface mounted (NSM) techniques. NSM laminates demonstrated superior performance in ultimate load capacity compared to EB laminates in experimental tests.	Reinforced concrete structures are strengthened using CFRP composites. NSM laminates outperformed EB laminates in ultimate load.
Adamantis G. Zapris, Violetta K. Kytinou, Ioannis Xynopoulos, Viktor Gribniak, Constantin E. Chalioris	2024	Innovative torsional strengthening of rc t-beams using nsm frp ropes	The study introduces a novel strengthening technique for RC T-beams using fiber-reinforced polymer (FRP) ropes configured as closed stirrups, effectively enhancing torsional capacity and addressing challenges of conventional methods, thus contributing to improved design practices for torsional loading.	Novel FRP ropes enhance torsional capacity of T-beams. Findings inform design practices for torsional loading in RC structures.
Hasan Ehssan Alobaidi, Alaa Hussein Al-Zuhairi	2023	Structural Strengthening of Insufficiently Designed Reinforced Concrete T-Beams using CFRP Composites	Strengthening of RC T-beams using CFRP composites enhances their performance. The study shows that increasing CFRP laminate width improves ultimate strength by up to 41%, while reducing U-wrap sheet spacing increases shear strength by up to 23.5%.	Study compares CFRP-strengthened and non-strengthened RC T-beams. Experimental analysis on flexural and shear strengthening effects. Increased CFRP laminate width improves ultimate strength significantly. Decreased CFRP U-wrap spacing enhances shear strength.

Hamid et al. (1992) have investigated the static strength of reinforced concrete beams strengthened by gluing glass-fiber-reinforced-plastic (GFRP) plates to their tension flanges experimentally. Five rectangular beams and one T-beam were tested to failure under four-point bending. The results indicate that the flexural strength of RC beams can be significantly increased by gluing GFRP plates to the tension face. In addition, the epoxy bonded plates improved the cracking behavior of the beams by delaying the formation of visible cracks and reducing crack widths at higher load level.

Sayed et al. (1999) have investigated the behavior of reinforced concrete beams strengthened with various types of fiber reinforced polymer (FRP) laminates. The ratio of absorbed energy at failure to total energy, or energy ratio, was used as a measure of beam ductility. It is concluded that the presence of vertical FRP sheets along the entire span length eliminates the potential for rupture of the longitudinal sheets. The combination of vertical and horizontal sheets, together with a proper epoxy, can lead to a doubling of the ultimate load carrying capacity of the beam. However, all the strengthened beams experienced brittle failure, mandating a higher factor of safety in design.

Khalifa et al. (2000) has investigated the shear performance of reinforced concrete (RC) beams with T-section. The experimental program consisted of six full-scale, simply supported beams. The parameters investigated in this study included wrapping schemes, CFRP amount, 90°/0° ply combination, and CFRP end anchorage. The experimental results show that externally bonded CFRP can increase the shear capacity of the beam significantly. In addition, the results indicated that the most effective configuration was the U-wrap with end Anchorage Results showed that the proposed design approach is conservative and acceptable.

Khaled et al. (2009) have studied the feasibility and effectiveness of a new method of strengthening existing RC T-Beams in shear by using mechanically anchored unbounded dry carbon fiber (CF) sheets. This method eliminates the debonding of epoxy-bonded carbon-fiber- reinforced polymer (CFRP) sheets and utilizes the fully capacity of dry sheets. In this method, dry CF sheets are wrapped around and bonded to two steel rods. Then the rods are anchored to the corners of the web-flange intersection of the T-beam with mechanical bolts. The test results showed that the beam strengthened by the new mechanically anchored dry CF had about 48% increase in shear capacity as compared to the control beam and 16% increase in shear capacity as compared to the beam strengthened by CFRP epoxy-bonding method.

Tanarslan et al. (2009) have studied an experimental investigation on T- section reinforced concrete (RC) beams strengthened with externally bonded carbon fiber-reinforced polymer (CFRP) strips. Five shear deficient specimens were strengthened with side bonded and U- jacketed CFRP strips, remaining one tested with its virgin condition without strengthening. The main objective was to analyze the behavior and failure modes of T-section RC beams strengthened in shear with externally bonded CFRP strips. According to test results premature debonding was the dominant failure mode of externally strengthened RC beams so the effect of anchorage usage on behavior and strength was also investigate.

Heyden et al.(2010) have investigate the results of an experimental study to the behavior of structurally damaged full-scale reinforced concrete beams retrofitted with CFRP laminates in shear or in flexure. The experimental results, generally, indicate that beams retrofitted in shear and flexure by using CFRP laminates are structurally efficient and are restored to stiffness and strength values nearly equal to or greater than those of the control beams. It was found that the efficiency of the strengthening technique by CFRP in flexure varied depending on the length. The main failure mode in the experimental work was plate debonding in retrofitted beams.

Panda et al. (2011) have investigated the performance of 2500mm long reinforced concrete (RC)T-beams strengthened in shear using epoxy bonded glass fiber fabric. The experimental program consisted of testing of 18 full scale simply supported RC T-beams. The experimental result indicates that RC T-beams strengthened in shear with side-bonded GFRP sheet increases the effectiveness by 12.5% to 50%.

Deifalla et al. (2012) investigated on several cases of loading and geometrical configurations, flexure beams, and girders are subjected to combined shear and torsion.. Four strengthening techniques using carbon FRPs were tested. The experimental results were reported and analyzed to assess the effectiveness of the proposed strengthening techniques. An innovative strengthening technique namely the extended U-jacket showed promising results in terms of strength and ductility while being quite feasible for strengthening.

C. *Strengthening of RC Rectangular and T- Beams with web opening.*

Author	**Year**	**Title**	**Inside**	**Findings**
Ahmed Khalil, Mohamed Elkafrawy, Rami A. Hawileh, Mohammad AlHamaydeh	2024	Numerical Investigation on Improving Shear Strength of RC Beams with Various Web Opening Shapes Using Pre-Stressed Fe-SMA Bars	The paper focuses on strengthening web openings in RC beams, specifically diamond, circular, and square shapes, using pre-stressed Fe-SMA bars. It does not address the strengthening of rectangular or T-beams with web openings.	Web openings reduce shear capacity of RC beams significantly. Pre-stressed Fe-SMA bars enhance shear strength and control cracking.

Shanmugamt et al. (1988) have studied the strength of fiber reinforced concrete deep beams with openings. In this study, nine beams were tested to failure, all the beams were of the same dimensions having a length of 1550 mm, overall depth of 650 mm and width of 80 mm. Steel fiber content in all the beams was kept the same equal to 1% by volume. Two rectangular openings, one in each shear span, were placed symmetrically about the vertical axis in each of the beams. The beams were simply supported on a clear span of 1300 mm, and are tested under two point loading.

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The experimental results presented here confirm previous findings, i.e., the effect of opening on the behaviour and ultimate shear strength of deep beams depends primarily on the extent to which it intercepts the natural load path and the location at which this interception occurs. Mansur (1998) has studied effect of openings on the behaviour and strength of reinforced concrete (RC) beams in shear. In this study, the behaviour and design of a beam containing a transverse opening and subjected to a predominant shear are briefly reviewed. Based on the observed structural response of the beam, suitable guidelines are proposed for classifying an opening as small or large. For small openings, a design method compatible with the current design philosophy for shear is proposed and illustrated by a numerical design example. In the method proposed, the maximum shear allowed in the section to avoid diagonal compression failure has been assumed to be the same as that for solid beam except for considering the net section through the opening. Mansur (2006) has studied the design of reinforced concrete beams with web openings. To investigate the problem of openings in beams, the author initiated a research program in the early 1980s. Since then extensive research has been carried out giving a comprehensive coverage on both circular and large rectangular openings under various combinations of bending, shear and torsion.

III.CONCLUSIONS

The following critical observations are made from the review of existing literature in the area of reinforced concrete (RC) beams strengthened with epoxy-bonded FRP

1) Most of the research efforts have been made to study the flexural and shear behaviour of RC rectangular beams strengthened with fiber reinforced polymer (FRP) composites.
2) Despite the growing number of field applications, there is limited number of reports on shear behaviour of strengthened RC T-beams using externally bonded FRP composites
3) A limited works have been reported on strengthening of RC T-beams with web openings.
4) There is a gain in shear capacity of RC beams when strengthened with FRP composites, peeling of FRP sheets from main concrete has been reported due to improper anchorage.
5) The study on anchorage system used for the prevention of debonding of FRP and concrete on shear behavior of RC beams is limited.
6) Many researchers are of the opinion that the previous design provisions do not have comprehensive understanding of the shear behavior.

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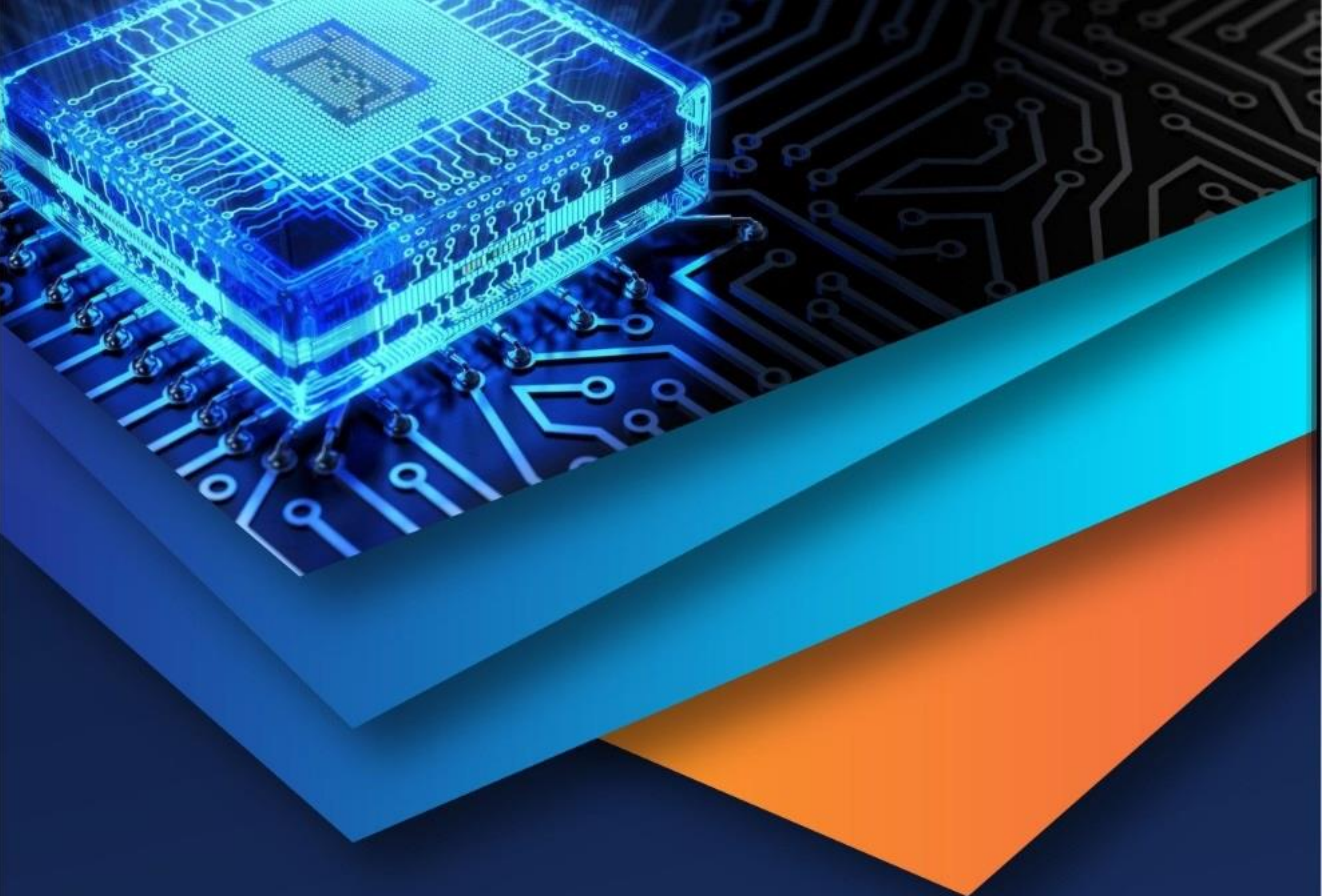

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