Strengthening of shear deficient reinforced concrete T-beams using BFRP composites

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Abstract

Fiber-reinforced polymers (FRP) have emerged as the promising material for rehabilitation of existing reinforced concrete (RC) structures and strengthening of new civil engineering structures due to their well-known advantages like high strength-to-weight ratio, flexibility and excellent corrosion resistance. The rehabilitation of structures can be in the form of strengthening, repairing or retrofitting for seismic insufficiencies. The RC T-beams are stronger in shear, denotes the most realistic situation, and have more significance in the construction industry. The shear failure of RC flexural members is recognized as the utmost tragic failure mode since it does not show any prior warning. The present experimental study aims to explore the possible usage of Basalt fiber sheets, which is an eco-friendly fiber and comparatively newer to the world of fiber reinforced polymer (FRP) composites, as an external strengthening material for the shear deficient RC T-beams. Four RC T-beams were tested under the four-point loading system, and one of the four RC beams was considered as control beam without any external strengthening. The investigation parameters included the number of layers and the effect of the mechanical anchorage system. The experimental results revealed that the failure load of strengthened beams increased by 23-43% with respect to the control beam. In addition, it has been observed that the enhancement in shear capacity is not in the same proportion with the number of layers and the external anchorage system can enhance the shear contribution of BFRP composites as well as can change the failure mode.

Keywords: Shear strengthening, RC T-beam, Basalt Fiber, Anchorage.

1 Introduction

Civil engineering infrastructures such as buildings, offshore structures, bridge decks, girders, parking structures deteriorate due to poor maintenance, aging, defects in construction/design, damage in case of seismic events, and exposure to harmful environments. In the past, a large number of structures constructed according to the older design codes, and now, they are structurally unsafe as per the new design codes and hence need upgradations. As the complete replacement of such deficient structures leads to incurring a considerable amount of public money and time, retrofitting has become an acceptable way of improving their load-carrying capacity and extending their service lives. Fiber-reinforced polymers (FRP) have emerged as promising material for rehabilitation of existing reinforced concrete (RC) structures and strengthening of the new civil engineering structures because of their several advantages such as high strength-to-weight ratio, flexible nature, ease of handling, lower density and excellent corrosion resistance. FRPs are available in many forms i.e., bars, plates, and sheets; out of these sheets are more commonly used to strengthen the existing RC structures due to its greater flexibility compared to other types. The use of external FRP strengthening to beams may be classified as flexural and shear strengthening. The shear failure of an RC beam is distinctly different from the flexural one, which is ductile, whereas the shear one is brittle and catastrophic. When the RC beam is deficient in shear or when it’s shear capacity is less than the flexural capacity after flexural strengthening, shear enhancement of the beam must be considered. It is critically important to examine the shear capacity of RC beams, which are intended to be strengthened in flexure.

Ghazi et al. \cite{1} studied the shear strengthening of shear deficient reinforced concrete (RC) beams strengthened with epoxy bonded fiberglass plate. Li et al. \cite{2} studied the effect of FRP shear strengthening of RC beams on the stress distribution, initial cracks, crack propagation, and ultimate strength experimentally, and concluded that it is not necessary to strengthen the entire concrete beam surface. Khalifa and Nanni \cite{3} examined the shear performance, and modes of failure of the rectangular shear deficient RC beams with externally bonded carbon fiber reinforced polymer (CFRP) sheets and concluded that the externally bonded CFRP sheet can enhance the shear

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capacity significantly. Chen and Teng [4,5] investigated the shear capacity of FRP-strengthened RC beams and established that such strengthened beams fail in shear mainly in one of the two modes, i.e., FRP rupture and FRP de-bonding. Sundarraja and Rajamohan [6] examined the behavior of rectangular RC beams shear strengthened with inclined glass fiber reinforced polymer (GFRP) strips. Lee et al. [7] have investigated the behavior, and the performance of RC T-deep beams strengthened in shear with CFRP sheets by varying strengthening length, fiber direction, the combination of CFRP sheets, and an anchorage using U-wrapped CFRP sheets. Mofidi et al. [8] studied the performance of full-scale RC T-girders strengthened in shear using externally bonded FRP U-jackets, which were end-anchored with different systems. Koutas et al. [9] have experimentally investigated the effectiveness of various types of spike anchors in combination with U-shaped FRP jackets for shear strengthening of RC T-beams and concluded that anchors placed inside the slab are many times more effective than those placed horizontally. Panigrahi et al. [10] have experimentally investigated the effect of different FRP properties like amount, distribution, the number of layers, and orientations and anchorage schemes on the performance of shear deficient RC T-beams strengthened in shear using epoxy-bonded bi-directional GFRP fabrics. Li and Leung [11] considered shear span to effective depth ratio as a parameter to investigate the effect of epoxy bonded CFRP U-strips on the shear deficient reinforced concrete beams. Alam and Riyami [12] investigated the behavior of RC members strengthened with natural fiber reinforced plates (NFRP) made up of three different fibers i.e. kenaf, jute and jute ropes and compared with behavior of RC beam strengthened with CFRP laminates. Shomali et al. [13] experimentally studied the performance of RC beams shear strengthened with externally bonded reinforcement in grooves (EBRIG) CFRP laminates.

Basalt fiber is relatively newer to the world of FRP composites in comparison to the carbon, aramid and glass fibers. Basalt rocks are the single source of basalt fiber and are known for their durability and high resistance to temperature. Basalt fiber is made in a continuous process similar to that of the process used to produce glass fibers. Basalt fibers have higher tensile strength than the E-glass fibers, higher failure strain than the carbon fibers [14], and can be used in a wide range of temperatures [15]. Sim et al. [15] have carried out experimental studies on the durability and mechanical properties of basalt fiber and their applicability as flexural strengthening materials for the RC beams. Dong et al. [16] studied the stiffness and recoverability of the RC beam strengthened with basalt fiber-reinforced polymer sheets at the bottom face of the beams. Duic et al. [17] have conducted experiments on full-scale RC beams with or without BFRP composite as flexural strengthening materials. Chen et al. [18] studied the flexural behavior of RC beams strengthened with longitudinal and U-shaped basalt FRP sheets.

It is revealed from the literature that limited studies on flexural strengthening and no study on shear strengthening of RC beams with BFRP composite have been reported. Hence, an attempt has been made in the present study to examine the applicability of epoxy-bonded basalt fiber sheets for shear strengthening of RC beams. The strengthening schemes include U-wrap with or without the mechanical anchorage system. In the present study, a simple mechanical anchorage system is introduced after the curing of the epoxy. The present anchorage system can be applied to the RC beams, which are already strengthened with un-anchored U-wrap. In the present study, the effect of the number of layers and the mechanical anchorage system on the behavior of RC beams externally shear strengthened with BFRP sheets are studied.

2 Experimental program

The purpose of the present research work is to study the effect of the externally bonded basalt fiber reinforced polymer sheets on the shear capacity of the RC T-beams under static loading conditions. In this experimental program, four RC T-beams were cast and tested by applying a symmetrical four-point static loading system up to failure. Fig. 1 represents the geometrical details of the RC beams. Out of four beams, one is not strengthened with FRP and considered as the control beam, whereas other beams are strengthened with externally bonded BFRP sheets in the shear zone of the beams. The variables selected for the experimental works are the number of BFRP layers and the presence of end anchorage system (i.e., U-wrap with and without end anchor).

2.1 Material properties

2.1.1 Concrete

The Portland slag cement (PSC) with specific gravity 2.92 was used in the preparation of specimens. The river sand with specific gravity 2.65 was used as fine aggregates (FA) in this experimental study. The grading zone of fine
aggregate was zone III as per Indian standard specifications. The machine crushed granite stone (angular in shape) was used as the coarse aggregate. The maximum size and specific gravity of coarse aggregate were found to be 20 mm and 2.83, respectively. Ordinary clean portable tap water, free from suspended particles, was used for both concrete mixing and curing of the RC beams. Besides the test beam specimens, three cubes of 150 mm × 150 mm × 150 mm were cast and tested at the age of 28 days to determine the compressive strength of concrete. The average compressive strength of the concrete was found to be 20.44 MPa.

2.1.2 Steel reinforcement

High-Yield Strength Deformed (HYSD) bars confirming to IS 1786:1985 were used as reinforcing bars. Two 16 mm diameter and one 12 mm diameter bars were used as tension reinforcement, whereas 10 mm diameter bars were used for hang-up bars. Fig. 1 represents the reinforcement details. It should be noted that the specimens do not have any transverse steel reinforcements in the test span except at the loading and support points to avoid localized failures.

2.1.3 Fiber reinforced polymer (FRP) and epoxy resin

Basalt fiber composites are the newest and not too expensive of all composites. In this study, BFRP sheets having fiber oriented in both longitudinal and transverse directions were used. The epoxy was used to attach the BFRP sheets to the beam surface. The epoxy was a mixture of resin Araldite LY 556 and Hardener HY 951 in 10:1 parts by weight. For, tensile test, three test coupons (length = 250 mm and width = 25 mm) of two layers with thickness 0.65 mm were prepared and subjected to unidirectional tensile tests under displacement rate of 0.01 mm per second in an universal testing machine. The average values of the ultimate stress, ultimate strain and Young’s modulus of the mean values of three identical samples are found to be 340.42 MPa, 2.84% and 16.65 GPa, respectively.

![Diagram](image)

Fig. 1. (a) Schematic test set-up (b) Cross-section (dimensions in mm).

2.2 Strengthening of Beams with FRP fabrics

During the process of strengthening, the fibre-reinforced polymer fabrics are bonded to the concrete surface using a suitable resin and hardener. The concrete surface of the shear zone was made rough by chipping, and then filling work was done by a double-cut flat file to remove loose material from the concrete beam. Then, the coarse sandpaper used to make the surface rougher, and finally, all the dirt and debris particles were removed with an air blower. The epoxy resin was mixed and applied to the required part of the concrete surface after the preparation of the concrete surface. The mixing was done in a plastic container by taking 10 percent of hardener (HY 951) to the epoxy resin (Araldite LY 556) and was continued for some time to obtain a uniform mixture. Then, the epoxy was applied to the concrete surface. After the application of epoxy coating, the previously cut basalt fibre sheet was
placed at the top of the coating, and a steel roller was used to eliminate the entrapped air bubbles at the interface of concrete/epoxy or fabric/epoxy for perfect bonding. Then over the first layer of BFRP, the second layer of epoxy was applied, and BFRP fabric was employed over the epoxy coating. Again, the steel roller was used for eliminating the entrapped air, and the above process was repeated until the targeted number of BFRP layers is achieved. The excess epoxy was extruded by applying a constant uniform pressure on the composite fabric surface to achieve a good adherence between the concrete, the epoxy, and the fabric.

The operation was carried out at room temperature, cured for a minimum of 72 hours before testing. After being cured at room temperature, two BFRP plates (made up of nine layers), one on each face of the web were placed over free ends of U-jacket, and the anchor bolts passed through the holes made in the U-jacket, web and BFRP plates. Nuts were fixed to the bolts and tightened. By this process, the free ends of the U-jacket were anchored. The BFRP plates were 35 mm wide, 500 mm long and 3.2 mm thick. The holes in the webs of solid beams were made by placing plastic-coated mild steel bars (10 mm diameter) during the time of casting and removing them after seven days of the casting of the specimen. The bolts were 175 mm in length and 8 mm diameter.

3 Experimental Set-up for Testing of Beams

All the beams were tested in flexure under two symmetrical point loads with a shear span-to-effective depth ratio (a/d) equals to 3.5. A universal testing machine with 500 kN capacity was used to apply a concentrated load on a spreader beam, which generated two concentrated loads on the test specimen. The specimen was placed on the two steel rollers bearing at a distance of 150 mm from the ends of the beam. The remaining 1500 mm was divided into three equal parts of 500 mm each, as shown in Fig 1. The beam to be tested was marked with lines at L/3, L/2, and 2L/3 locations from the left support (L = 1500 mm), and three dial gauges were used for recording of the deflection of the beams. One dial gauge was placed just below the center of the beam, i.e., at the L/2 distance, and the remaining two dial gauges were placed just below the point loads, i.e., at L/3 and 2L/3 to measure the deflections. The experimental setup of the test is shown in Fig. 2.

4 Test results and discussions

The effects of the number of BFRP layers and the effect of the mechanical anchorage system on the ultimate shear capacity, failure patterns, and cracking characteristics of BFRP strengthened RC beams are investigated and compared with the corresponding control beams.
4.1 Cracking pattern and failure modes

The cracking pattern and modes of failure of the control beam and strengthened RC T-beams are shown in Fig. 3 (a-d). The propagation of cracks was observed in the whole shear span of the control beam with the progress of the load. However, it was not possible to observe the propagation of cracks in the shear span of the strengthened specimens since the whole shear span was covered with basalt fiber sheets. The initial crack in the control beam (CB) occurred at 63 kN and enlarged with the increase in load and finally failed in shear at a load of 74 kN. The failure of the SB1 beam (strengthened with two layers of BFRP sheets without anchorage system) was initiated by the debonding of FRP sheets from the beam surface and finally failed in shear. The SB2 (strengthened with two layers of BFRP sheets with mechanical anchorage system) beam also failed in shear internally without debonding of FRP sheets and the SB3 (strengthened with four-layer of BFRP sheets with mechanical anchorage system) beam failed in flexure.

![Cracking pattern of specimens](image1)

(a) CB (b) SB1 (c) SB2 (d) SB3

4.2 Load deflection history.

The mid-span deflections were measured at different load steps for the control and the strengthened beams. Fig. 4 represents the load-deflection history for the control beam, and BFRP strengthened specimens. As it can be observed from Fig. 4, it is observed that the load-deflection profile of all the specimens were nearly identical up to 50 kN. Beyond this load, all the strengthened beams experienced less deflection than the control beam under the same applied load. It is noted that the SB1 and SB2 beams performed well in shear, and load-deflection behavior is nearly similar. The SB3 beam performed very well in shear and failed in flexure. The SB1, SB2, and SB3 failed at a load of 91 kN, 93 kN, and 106 kN, which denotes an enhancement of 23%, 25.7%, and 43%, respectively, as compared to CB.
5 Conclusions

In the present experimental study, the effects of the number of BFRP layers and the presence of a mechanical anchorage system on the failure modes, mid-span deflections, and ultimate load capacity are investigated. For the above-mentioned investigations, four RC T-beams with shear span to effective depth ratio equal to 3.5 was designed, and three out of four specimens were externally shear strengthened with epoxy-bonded basalt fiber sheets. The following conclusions can be drawn from the analysis of the experimental results:

1. The BFRP strengthening systems have increased the ultimate shear capacity of the RC T-beams
2. The enhancement in shear capacity is not in the same proportion with the number of layers.
3. The mechanical anchorage system prevented debonding of basalt fiber sheets and thus increased the shear contribution of basalt fiber sheets
4. The BFRP strengthening schemes can also change the failure modes from brittle shear failure to ductile flexural failure.

Based on the present experimental investigations, the basalt fiber sheets can be used as a potential alternative to the commonly used fibers for shear strengthening of shear deficient RC members.

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6 References