Experimental Investigation for Enhancing the Shear Capacity of Reinforced Concrete (RC) T-Beams

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Abstract— Deterioration in reinforced concrete structures is a major issue faced by the infrastructures and bridge industries all over the world. Since complete replacement of these structures requires high investment, strengthening has become the suitable solution to modify and improve the performance of the structures. Previously steel plates were used as external reinforcement to strengthen deficient RC structures, but in the last fifteen years or so on, FRP composites have been used to replace steel because of their superior properties. RC T-section is the most common shape of beams and girders in buildings and bridges. Shear failure of RC T-beams is identified as the most disastrous failure mode as it does not give any advance warning before failure. The shear strengthening of RC T-beams using externally bonded (EB) FRP composites has become a popular structural strengthening technique, due to the well-known advantages of FRP composites such as their high strength-to-weight ratio and excellent corrosion resistance. This study explores the result of an experimental investigation for enhancing the shear capacity of reinforced concrete (RC) T-beams with shear deficiencies, strengthened with Basalt Fiber Reinforced Polymer (BFRP) sheets which are a relatively new and economic alternative to more expensive fibers commonly used in strengthening of RC beams. A total of 22 numbers of concrete T-beams are tested and various sheet configurations and layouts are studied to determine their effects on the shear capacity of the beams. One beam of the beams is considered as control beam, while other beams are strengthened with externally bonded BFRP sheets/strips. To accommodate essential services like electricity cables, natural gas pipes, water and drainage pipes, air-conditioning, telephone lines, and computer network transverse web opening are necessary in modern building construction. Hence, the present study investigates the shear behavior of RC T-beams with different types of transverse web openings. The various parameters investigated in this study included BFRP amount and distribution, bonded surface, number of layers of BFRP, fiber orientation, transverse web openings of different shape (i.e., circular versus square versus rectangular) and end anchor. The experimental results demonstrated that the use of the new mechanical anchorage scheme comprising of laminated composite plates increases the shear capacity of the beams significantly by preventing the deboning of BFRP sheets, so that the full strength of the BFRP sheets get utilized. An analytical study is also carried out to validate the experimental findings.

Key words: RC Structure, FRP, T-beam, BFRP, Bonded Surface, Composite Plates

I. Introduction

A. Preamble

The rapid deterioration of the infrastructures is one of the major issues facing concrete and bridge industry worldwide. The deterioration of these structures are mainly due to ageing, poor maintenance, corrosion, aggressive environmental conditions, poor initial design or construction errors and accidental situations like earthquakes. In the past a large number of structures were constructed using the older design codes which are structurally unsafe according to today's design standards. Since the complete replacement of such deficient structures requires enormous amount of money and time, strengthening has become the suitable way of improving their load carrying capacity and extending their service lives.

The conventional design approaches available are concrete-jacketing and steel-jacketing. The concrete-jacketing makes the existing section large and thus improves the load carrying capacity of the structure. But these techniques have several demerits such as construction of new formworks, additional weight due to enlargement of section, high installation cost etc. The steel-jacketing has proven to be an effective technique to enhance the performance of structures, but this method requires difficult welding work in the field and have potential problem of corrosion which increases the cost of maintenance. Now-a-days, FRP composite materials are an excellent option to be used as external reinforcement because of their high specific stiffness, high specific weight, high tensile strength, light weight, resistance to corrosion, high durability and ease of installation.

B. Fiber Reinforced Polymer (FRP)

FRP composites are, as the name proposes, a composition of two or more materials which, when suitably united, form a different material with properties not available from the individual ingredients.

Fiber reinforced composite materials consist of fibers of high tensile strength and adhesive that binds the fibers together to produce the structural material. Commonly used fibers are aramid, basalt, carbon and glass in the civil engineering industry. The adhesive that is commonly used is epoxy which protects the fibers, providing durability and under the loading

C. Objective

The main objectives of the present research work may be summarized as follows:

- To analyses the structural behavior of T-section RC beams under static loading condition.

- To investigate the shear behavior and modes of failure of shear deficient RC T-beams strengthened with FRP composite sheets.
- To examine the effect of different parameters such as number of layers, bonding surface, different fiber orientation etc. on the shear capacity of the RC T-beams.
- To study the effect of strengthening with externally bonded FRP on the enhancement of strength in RC T-beams with web openings of different cross-section.
- To investigate the effect of an anchorage scheme on the improvement of shear capacity of the RC T-beams.

II. REVIEW OF LITERATURE

Panda et al. (2011, 2012) carried out an experimental investigation to study the shear behavior of RC T-beams strengthened in shear using epoxy bonded GFRP fabric. Nine beams were treated as control beams with three different stirrup spacing and the remaining beams were strengthened in shear using one, two and three layers of GFRP sheets bonded to the side of the web and in the form of U-jacket around the web of T-beams for each type of stirrup spacing. The effectiveness, shear behavior, cracking pattern and modes of failures of the strengthened RC T-beams were evaluated and the test results illustrated that RC T-beams strengthened with side bonded and U-jacketed GFRP sheets in shear enhances the load carrying capacity of the beams significantly and the design approach proposed by ACI guidelines shows conservative results as compared with the experimental data. Panigrahi et al. (2014) studied the behavior of shear deficient RC T-beams strengthened with epoxy bonded bi-directional GFRP fabrics. Test results indicated that the external strengthening with GFRP composites can be used to increase the shear capacity of RC T-beams, but the efficiency varies depending on the test variables considered.

Rendy Thamrin et al (2016) experiment studied shear capacity show that all of equations conservatively estimate the occurrence of shear failure with the values of the test results 10 to 90% higher than the theoretical values. It was confirmed from the test that the shear capacity of T-beams were higher than for rectangular beams, with the values ranging from 5 to 25%, depending on the ratio of longitudinal reinforcement. Also, it was observed that ratio of longitudinal reinforcement influences the shear capacity of the beam as well as the angle of diagonal shear crack. In addition, based on the test results, a simple model for predicting the contribution of flange to shear capacity in T-beam was presented.

Aadil mansuri et al (2017) investigated carried out wherein 5 beams were casted of 2000 mm length, 200 mm width & 270 mm depth followed by testing after strengthening. In the current experiment, materials used for strengthening are weaved mesh and welded mesh, using mechanism of Ferro-cement & Micro-Concrete. Further loads and deflections were measured and the results show improvement in load carrying capacity of strengthened beam as compared to non-strengthened beam.

– Many researchers are of the opinion that the previous design approaches do not have comprehensive understanding of the shear behavior of RC T-beams.

A. *Scope of the Present Investigation*

Based on the critical observations made from the survey of existing literatures and to achieve the objective outlined in the previous chapter, the scope of the present research study is summarized as follows:

– To analyses the shear behavior of T-section RC beams under static loading condition.
– To examine the shear behavior and modes of failure of RC shear deficient T-beams externally strengthened with basalt fiber reinforced polymer (BFRP) sheets.
– To investigate the effect of different test parameters such as fiber amount and distribution, bonded surface, number of layers, fiber orientation and end anchorage system on the shear capacity of RC T-beams strengthened with externally bonded BFRP composites.
– To study the behavior of shear deficient RC T-beams with transverse openings of circular, square and rectangular shapes in web portion.
– To investigate the effect of a new anchorage scheme on the shear behavior of the RC T-beams.
– To compute analytically the shear capacity of the RC T-beams

III. EXPERIMENTAL PROGRAMME

A. *General*

The purpose of the present research work is to study the effect of the externally bonded fiber reinforced polymer sheets on the shear capacity of the RC T-beams with and without transverse openings under static loading conditions. In this experimental program me a total of twenty two numbers of beams are cast and tested by applying symmetrical four point static loading system up to failure. The beams are grouped into two series designated as A and B. The first series of tests, series A, dealt with the shear strengthening of the RC beams with T-shaped cross-section without transverse openings. The second series B, focused on the shear strengthening of the RC T-beams with transverse openings of different shapes. In each series, one of the beams is not strengthened with FRP and considered as control beam whereas other beams are strengthened with externally bonded unidirectional BFRP sheets in the shear zone of the beams.

The variables selected for the experimental works are BFRP amount and distribution (i.e., continuous wrap versus strips), bonded surface (i.e., lateral sides versus U-wrap), number of layers of BFRP, fiber orientation (i.e., 0° direction versus 90° direction versus 45^0 direction), Transverse web openings of different shape (i.e., circular versus square versus rectangular) and end anchor (i.e., U-wrap with and without end anchor).

B. *Test Specimens*

Twenty two reinforced concrete T-beams are considered in this study with dimensions as follows:

– Span= 1300mm
– Width of web= 150mm
– Depth of web= 125mm
– Depth of flange= 50mm
– Effective depth= 125mm

Specimen Name	Specimen ID	Average Cube Compressive

		Strength (MPa)
Control Beam	CB	23.11
Strengthened Beam 1	SB1	25.25
Strengthened Beam 2	SB2	24.65
Strengthened Beam 3	SB3	24.35
Strengthened Beam 4	SB4	23.36
Strengthened Beam 5	SB5	28
Strengthened Beam 6	SB6	26.89
Strengthened Beam 7	SB7	26.07
Strengthened Beam 8	SB8	24.47
Strengthened Beam 9	SB9	26.36
Strengthened Beam 10	SB10	28.30
Strengthened Beam 11	SB11	28.90
Strengthened Beam 12	SB12	28
Control Beam 1	CB1	23.51
Strengthened Beam 13	SB13	26.18
Strengthened Beam 14	SB14	28.34
Control Beam 2	CB2	26.20
Strengthened Beam 15	SB15	28.12
Strengthened Beam 16	SB16	27.21
Control Beam 3	CB3	23.23
Strengthened Beam 17	SB17	29.04

Table 1: Test Results of Cubes after 28 days of curing

Sl. no. of Sample	Diameter of Bar Tested (mm)	0.2% Proof Stress (N/mm^2)	Avg. Proof Stress (N/mm^2)
1	16	507	
2	16	490	494
3	16	485	
4	12	590	
5	12	562	574
6	12	571	
7	10	531	
8	10	524	529
9	10	533	
10	8	522	
11	8	520	522
12	8	523	

Table 2: Tensile Yield Strength of Reinforcing Steel bars

Beam ID	(MPa)	Tension Reinforcement	Yield Stress (MPa)	FRP Thickness (mm)	Strengthening Scheme using BFRP sheet
CB	22.1	2-16mmφ, 1-12mmφ	494, 578	-	Control Beam (without FRP sheets)
SB1	26.27	2-16mmφ, 1-12mmφ	494, 578	0.56	Two layers continuous bonded horizontally to the bottom and sides of shear span of beam (U-wrap)
SB2	25.67	2-16mmφ, 1-12mmφ	494, 578	0.56	Two layers continuous bonded horizontally only to the sides of shear span of beam (Side wrap)
SB3	24.30	2-16mmφ, 1-12mmφ	494, 578	0.56	Two layers strip bonded horizontally to the bottom and sides of shear span of beam (U-strip)
SB4	23.36	2-16mmφ, 1-12mmφ	494, 578	0.56	Two layers strip bonded horizontally only to the sides of shear span of beam (Side strip)
SB5	28	2-16mmφ, 1-12mmφ	494, 578	0.56	Two layers continuous bonded vertically to the bottom and sides of shear span of beam (U-wrap)
SB6	26.81	2-16mmφ, 1-12mmφ	494, 578	0.56	Two layers continuous bonded vertically only to the sides of shear span of beam (Side wrap)
SB7	26.07	2-16mmφ, 1-12mmφ	494, 578	0.56	Two layers strip bonded vertically to the bottom and sides of shear span of beam (U-strip)

C. Detailing of Reinforcement in RC T-beams

The arrangement of reinforcement is same for all the beams. Two numbers of 16 mm φ and one number of 12 mm φ HYSD bars are provided as tension reinforcements and four numbers of 10 mm φ steel bars are used as hang-up bars. The cross-section and reinforcement details of the control beam are depicted in Figure 1. All the strengthened beams have same cross-section and reinforcement details as that of the control beam.

The tensile strength and modulus of elasticity of the specimens are determined in the Production Engineering Lab, PIES, Bhopal using INSTRON 100kN. First, specimens are gripped in the fixed upper jaw and then gripped in the movable lower jaw. To prevent the slippage, gripping of the specimen should be proper. In this study, the gripping is taken as 50mm from each side. The load, as well as the extension, is recorded digitally with the help of a load cell and an extensometer respectively. The stress versus strain graph is plotted from the results obtained and the initial slope of it gives the modulus of elasticity. The ultimate stress and ultimate load are obtained at the failure of the specimen. The mean value of the three specimens of each layer of 0^0 and 90^0 orientations is given in Table 3.

Orientation	No. of layers	Ultimate Stress (MPa)	Ultimate Load (N)	Young's Modulus (MPa)
0^0 Orientation	2 Layers	13.80	202	4588
	4 Layers	14.09	578	5561
	6 Layers	19.45	883	5607
	8 Layers	23.31	1011	6395
90^0 Orientation	2 Layers	329	5808	11920
	4 Layers	390	11870	12870
	6 Layers	421	22110	13130
	8 Layers	465	25482	13920

Table 3: Result of the specimens from tensile test

D. Summary

In this experimental program, twenty two numbers of beams are investigated which are separated into two series (A and B). The detail descriptions of all the beams of two series (A and B) are presented in Table 4.

SB8	24.45	2-16mmφ, 1-12mmφ	494, 578	0.56	Two layers strip bonded vertically only to the sides of shear span of beam (Side strip)
SB9	28.01	2-16mmφ, 1-12mmφ	494, 578	0.56	Two layers strip bonded vertically only to the sides of shear span of beam (Side strip)
SB10	28.33	2-16mmφ, 1-12mmφ	494,578	0.56	vertically to the bottom and sides with composite plate bolt arrangement i.e., anchoring system only in shear span of beam (U-wrap)
SB11	28.89	2-16mmφ, 1-12mmφ	494, 578	1.07	Four layers continuous bonded vertically to the bottom and sides with composite plate bolt arrangement i.e., anchoring system only in shear span of beam (U-wrap)
SB12	28	2-16mmφ, 1-12mmφ	494, 578	0.56	Two layers strip bonded vertically to the bottom and sides with composite plate bolt arrangement i.e., anchoring system only in shear span of beam (U-strip)
CB1	23.55	2-16mmφ, 1-12mmφ	494, 578	-	Control Beam with circular hole (without FRP sheets)
SB13	25.20	2-16mmφ, 1-12mmφ	494, 578	1.07	Four layers continuous bonded vertically to the bottom and sides of shear span excluding the circular hole part of beam (U-wrap)
SB14	27.62	2-16mmφ, 1-12mmφ	494, 578	1.07	Four layers continuous bonded vertically to the bottom and sides of shear span excluding the circular hole part with composite plate bolt arrangement i.e., anchoring system of beam (U-wrap)
CB2	26.14	2-16mmφ, 1-12mmφ	494, 578	-	Control Beam with rectangular hole (without FRP sheets)
SB15	28.14	2-16mmφ, 1-12mmφ	494, 578	1.07	Four layers continuous bonded vertically to the bottom and sides of shear span excluding the rectangular hole part of beam (U-wrap)
SB16	27.26	2-16mmφ, 1-12mmφ	494, 578	1.07	Four layers continuous bonded vertically to the bottom and sides of shear span excluding the rectangular hole part with composite plate bolt arrangement i.e., anchoring system of beam (U-wrap)
CB3	23.26	2-16mmφ, 1-12mmφ	494, 578	-	Control Beam with square hole (without FRP sheets)
SB17	28.04	2-16mmφ, 1-12mmφ	494, 578	1.07	Four layers continuous bonded vertically to the bottom and sides of shear span excluding the square hole part of beam (U-wrap)
SB18	25.18	2-16mmφ, 1-12mmφ	494, 578	1.07	Four layers continuous bonded vertically to the bottom and sides of shear span excluding the square hole part with composite plate bolt arrangement i.e., anchoring system of beam (U-wrap)

Table 4: Beam material properties and test parameters

IV. TEST RESULTS AND DISCUSSIONS

A. *Series A*

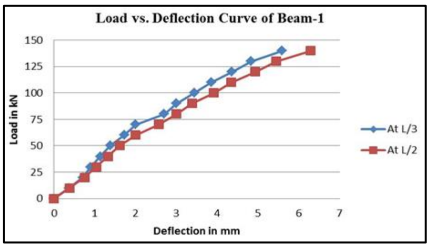

Fig. 1: Load vs. Deflection Curve for CB

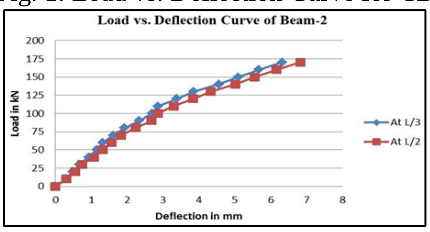

Fig. 2: Load vs. Deflection Curve for SB1

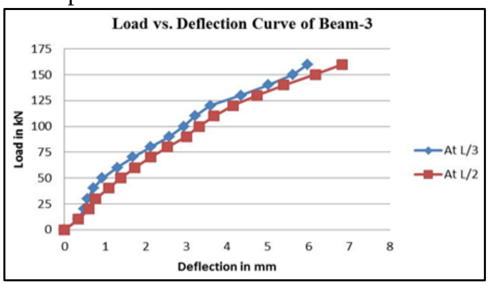

Fig. 3: Load vs. Deflection Curve for SB2

The deflection profile for the control beam CB and beams SB1 (strengthened with continuous U-wrap with 0^0 fiber direction) and SB2 (strengthened with continuous side wrap with 0^0 fiber direction) and SB3 (strengthened with strip U-wrap with 0^0 fiber direction) and SB4 (strengthened with strip side wrap with 0^0 fiber direction) are shown in Figure 4.23. It is observed that the strengthen beams experienced less mid-span deflection as compared to the control beam under the same loading condition. The percentage reduction in mid-span deflection of SB1, SB2, SB3 and SB4 compared to CB are 20.19, 14.31, 13.99 and 11.76 respectively.

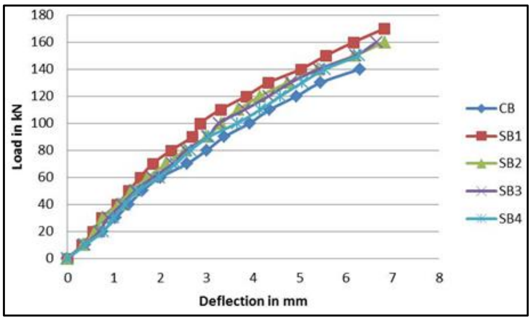

Fig. 4: Load vs. Deflection Curve for CB vs. SB1 & SB2 & SB3 & SB4

The deflection profile for the control beam CB and beams SB5 (strengthened with continuous U-wrap with 90^0 fiber direction) and SB6 (strengthened with continuous side wrap with 90^0 fiber direction) and SB7 (strengthened with strip U-wrap with 90^0 fiber direction) and SB8 (strengthened with strip side wrap with 90^0 fiber direction) are given in Figure 4.24. It is revealed that the percentage decrease in the central deflection of SB5, SB6, SB7 and SB8 compared to CB are 27.03, 23.53, 21.62 and 16.85 respectively under the same loading condition.

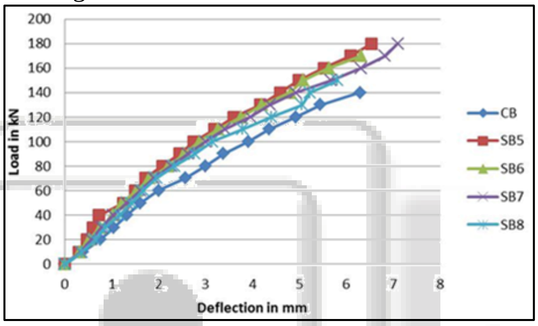

Fig. 5: Load vs. Deflection Curve for CB vs. SB5 & SB6 & SB7 & SB8

The deflection profile for the control beam CB and beams SB3 (strengthened with strip U-wrap with 0^0 fiber direction) and SB7 (strengthened with strip U-wrap with 90^0 fiber direction) and SB9 (strengthened with strip U-wrap with 45^0 fiber direction) are shown in Figure 4.25. It is observed that all the strengthened beams experienced less deflection than the control beam under the same loading condition. The beam strengthened with inclined strips (SB9) performs better in shear than that with the horizontal (SB3) and vertical strips (SB7). The percentage reduction in mid-span deflection of SB9, SB7 and SB3 compared to CB are reported to be 34.82, 21.62 and 13.99 respectively.

B. *Load at Initial Crack*

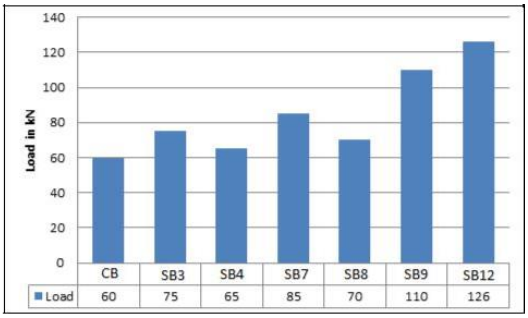

Fig. 6: Load at initial crack of beams CB, SB3, SB4, SB7, SB8, SB9 and SB12

The crack patterns of the beams are visualized with the progress of the load. The initial cracks are visualized for the beams which are not fully wrapped with BFRP sheets. The load corresponding to initial crack of the beams is recorded and depicted in Figure 4.33. It is observed that the initial cracks in the strengthened RC T-beams are developed at a higher load than the control beam. From Figure 4.33, it is noticed that the load at first crack of SB12 is the highest among all the strengthen beams and is 110% higher than the control beam.

C. *Ultimate Load Carrying Capacity*

1) *Series A*

A comparison in ultimate load carrying capacity is made among the control beam CB, SB1 (strengthened with continuous U-wrap with 0^0 fiber direction) and SB5 (strengthened with continuous U-wrap with 90^0 fiber direction) and presented in Figure 4.35. It is observed that the ultimate load carrying capacity of SB5 is 26.58% higher than the control beam and is 12.36% higher than the beam SB1.

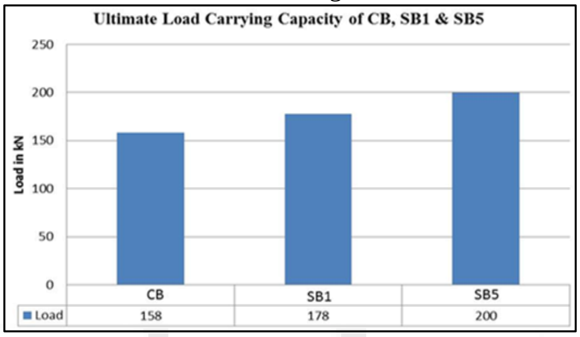

Fig. 7: Ultimate load carrying capacity of beams CB, SB1 and SB5

The ultimate load carrying capacity of the control beam CB, SB3 (strengthened with strip U-wrap with 0^0 fiber direction) and SB7 (strengthened with strip U-wrap with 90^0 fiber direction) beams are compared and shown in Figure 4.36. It is revealed that the ultimate load carrying capacity of SB7 is 17.08% higher than the control beam and is 8.82% higher than the beam SB3.

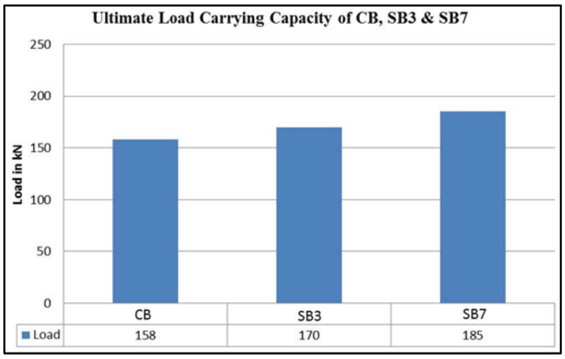

Fig. 8: Ultimate load carrying capacity of beams CB, SB3 and SB7

Beam ID	Nature of Failure	(kN)	
CB	Shear failure	158	-
SB1	Splitting and Deboning of BFRP + Shear failure	178	1.08
SB2	Splitting and Deboning of BFRP + Shear failure	167	1.04
SB3	Deboning of BFRP + Shear failure	170	1.09
SB4	Deboning of BFRP + Shear failure	163	1.03
SB5	Splitting and Deboning	200	1.26

	of BFRP + Shear failure		
SB6	Splitting and Deboning of BFRP + Shear failure	175	1.15
SB7	Deboning of BFRP + Shear failure	185	1.13
SB8	Deboning of BFRP + Shear failure	166	1.07
SB9	Deboning of BFRP + Shear failure	192	1.20
SB10	Tearing of BFRP + Shear failure	219	1.35
SB11	Tearing of BFRP + Shear failure	232	1.44
SB12	Tearing of BFRP + Shear failure	200	1.20
CB1	Shear failure	100	-
SB13	Deboning of BFRP + Shear failure	132	1.31
SB14	Tearing of BFRP + Shear failure	162	1.60
CB2	Shear failure	114	-
SB15	Splitting and Deboning of BFRP + Shear failure	135	1.15
SB16	Tearing of BFRP + Shear failure	154	1.30
CB3	Shear failure	120	-
SB17	Splitting and Deboning of BFRP + Shear failure	144	1.21
SB18	Tearing of BFRP + Shear failure	164	1.33

Table 5: Ultimate load and nature of failure for various beams

V. Conclusions

Based on the experimental investigation and analytical study of shear strengthening of RC T-beams with externally bonded unidirectional BFRP composites, the following conclusions are drawn:

- The shear capacity of RC beams with T-shaped cross-section can be enhanced significantly by using BFRP composites as an external reinforcement.
- The initial cracks in the strengthened beams are formed at a higher load compared to the ones in the control beams.
- Strengthening with BFRP composites bonded to webs only are most susceptible to deboning with premature failure.
- The beam strengthened with BFRP sheets is found to have more shear capacity than the beam strengthened with BFRP strips.
- Strengthening of beams using U-wrap configuration is found to be more effective than the side-wrap configuration.
- Among all the BFRP strip configurations (i.e., horizontal strips, vertical strips and strips inclined at 45^0), the U-strip with 45^0 fiber orientations is more effective.
- The performance of externally bonded BFRP composites can be improved significantly by using adequate anchoring system.
- A proportional increase in the shear capacity with the increasing BFRP amount cannot be achieved when deboning is not prevented.
- Anchorage system prevents the deboning of BFRP sheets/strips from the concrete surface, eliminating the premature failure, which consequently results in a better utilization of the full strength of the BFRP sheet/strip.
- Formation of crack gets delayed due to the use of BFRP sheets and also by introduction of end anchorage.
- U-wrap with end anchorage is found to be the most effective configuration among all the configurations.
- The load carrying capacity of the strengthened beams are found to be greater than that of the control beams, thus the externally bonded BFRP composites enhances the load carrying capacity.
- The shear strength of the T-beam strengthened with the U - wrap is found to be more in case of the beam without transverse web openings.
- The T-beam with transverse web openings strengthened with anchored U-wrap performs superior than the beam without anchorage.
- Among different shapes of transverse web openings, square hole is found to be more effective as compared to other ones.
- The analytical model based on ACI guidelines and Chen and Tang's model predicts conservative results compared to experimental ones.
- Finally, BFRP composite is proven to be a promising material for shear strengthening of RC T-beams with or without opening.

VI. Recommendations for Future Studies

Based on the finding and conclusions of the present study, the following recommendations are made for further research in FRP shear strengthening:

- Study of the bond mechanism between BFRP composite and concrete substrate.
- FRP strengthening of RC T-beams using carbon and aramid composites.
- Strengthening of RC T-beams using woven basalt fiber.
- Strengthening of RC L-section beams with FRP composites.
- Strengthening of RC L-section beams with transverse web openings.
- Effect of transverse web openings of different shape and size on the shear behavior of RC L-section beams.
- Effects of shear span to effective depth ratio on the shear capacity of beams.
- Numerical modeling of RC T & L-beams strengthened with FRP sheets with end anchorage.

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