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Shear strength of FRP-Externally strengthened High Strength RC T-Beams

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Abstract. This paper presents preliminary results of an extensive experimental program on the behavior of high-strength (HS) reinforced concrete (RC) T-beams strengthened with Carbon Fiber Reinforced Polymer (CFRP) sheets. The test program involves the fabrication and testing of 56 RC beams and many objectives to achieve. The objective of this paper is to investigate the effect of the number of CFRP layers on the shear strength of HS RC beams. To this end, three full-scale specimens were prepared and instrumented with displacement transducers and strain gauges: one control beam, one single-layer of CFRP sheets, and one double-layer of CFRP sheets. All beams were simply supported and subjected to a monotonically increasing load until failure. Preliminary results showed that in the absence of transverse steel reinforcements, the number of CFRP layers does not affect the ultimate strength of the HSC beams.

1. Introduction

Generally, RC beams may undergo two types of failure: flexural and shear. The flexural type of failure is ductile as it occurs gradually, giving a warning before the failure occurs. Contrarily, the shear failure is brittle and catastrophic since it does not provide any kind of warning before it happens. Shear failure of concrete beams is commonly attributed to the insufficient shear reinforcement. However, it can be prevented by using different strengthening techniques. Different shear strengthening or repairing of concrete structures are available depending on the type of structural element, material, etc., these include: prestressing, shotcreting, and steel plate bonding. An alternative to these methods is the Externally Bonded Fiber Reinforced Polymers (EB-FRP). EB-FRP has been the subject of many studies [1-5].

The EB-FRP composites are used as shear reinforcements to improve the load-bearing capacity of beams and to control the deflection at the failure by constraining the growth of concrete cracks and delaying the loss of the aggregate interlock. The FRP can be bonded in S, U, or W configurations. It's called S configuration when the FRP is bonded only to the sides of the beam. When the FRP is bonded to both sides and the tension face of the beam, it's called U configuration. The W configuration, is the case where the FRP is fully wrapped around the beam section [6].

The most significant two modes of failure of beams strengthened in shear by FRP are the debonding of FRP sheets and FRP rapture. There are other modes however, such as peeling-off of the concrete cover, shear failure of the beam without the FRP being raptured, anchorage failure, etc.

In the S and U configurations, the FRP usually fail by debonding or peeling off of the concrete cover. The adhesive layer between the concrete surface and FRP sheets transmits the stress from the concrete to the FRP, thus, producing in-plane shearing between them. Therefore, debonding, which is mainly the loss of adhesion, is the main control of the ultimate strength in the S and U configurations.

Many studies on the use of FRP in shear strengthening of RC beams were carried out in recent years [1-3,7-9, among others). Although numerous studies were performed on the behavior of the bond between the concrete and the FRP, it still not well investigated yet and needs more research. The main objective of this work is to report preliminary results of a test program to study the effect of the number of CFRP layers in the absence of transverse steel reinforcements on HS RC beams.

2 Experimental Program

2.1 Material Properties

Three high strength (HS) concrete beams were casted with a concrete mix having an average of 70 MPa compressive strength (f'_c) at 28th day according to ASTM C39. The longitudinal bars used for the flexural reinforcement of the beams had a yield strength (f_y) of 560 MPa.

The EB-CFRP discrete strips used in this study are unidirectional woven carbon fiber flexible sheets. The CFRP sheets have a thickness (t_{frp}) of 0.168 mm, an ultimate elongation of 1.8%, a tensile modulus and tensile strength of 230 GPa and 4.8 GPa respectively. The CFRP sheets were applied to each beam specimen using a polymeric encapsulation resin.

2.2 Test specimens

All the three beams are large scale, HS RC T-beams without transverse reinforcement. The control specimen (Specimen 1) is virgin (i.e., without EB-CFRP). Specimen 2 is a beam that is strengthened with a layer of EB-CFRP strips in U-jacketing configuration placed at 90 mm from center to center. Specimen 3 similar to Specimen 2 except that the CFRP sheets are applied twice (double-layer). Table 1 summarizes the geometry and material properties of test specimens. Figure 1 shows the beams' section properties and Figure 2 illustrates the geometry of the beams and test setup.

As shown in Table 1, the beams have a T-section with a web width of 150mm (b_w), flange width of 450mm (b_f), flange height of 100mm (h_f), total height of 420mm (h), effective depth of 340mm (d), length of 3700mm and test span of 3300mm. The effective depth d_{frp} and the thickness t_{frp} of the CFRP are 240 mm and 0.166 mm/layer, respectively. All the 3 beams are designed to fail in shear. The longitudinal reinforcements consist of 4 25mm diameter bars as tensile reinforcements and 4 12mm diameter bars as compression reinforcements. Figure 1 shows the section details of the beams.

Table 1. Geometry and material properties of test specimens.

beam	h	h_f	b_w	b_f	Span	a/d	f'_c	ρ_s	d_{frp}	t_{frp}	w_{frp}	S_{frp}	ρ_{frp}
Units	mm	mm	mm	mm	m	-	MPa	-	mm	mm	mm	mm	-
1	420	100	150	450	3.3	3.2	70	0.0385	0	0	0	0	0
2	420	100	150	450	3.3	3.2	70	0.0385	240	0.166	50	90	0.0012
3	420	100	150	450	3.3	3.2	70	0.0385	240	0.332	50	90	0.0049

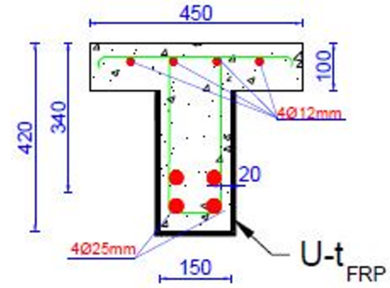

Figure 1. Beams section details.

2.3 Test setup and instrumentation

As shown in Figure 2 below, the test setup consisted of a simply supported condition using rollers. To control the shear failure location to be in the shorter span, the load has been applied at 1/3 of the beam's span. Thus the strain gauges were assigned at the expected shear failure location. Each beam specimen was tested under monotonically increasing point load in a displacement-controlled manner with a rate of 0.01mm/sec. along the test, beams deflection and cracking sequence were monitored during testing. Linear voltage displacement transducers (LVDTs) at three different locations along the span were used to recorded the beams deflection as shown in the figure.

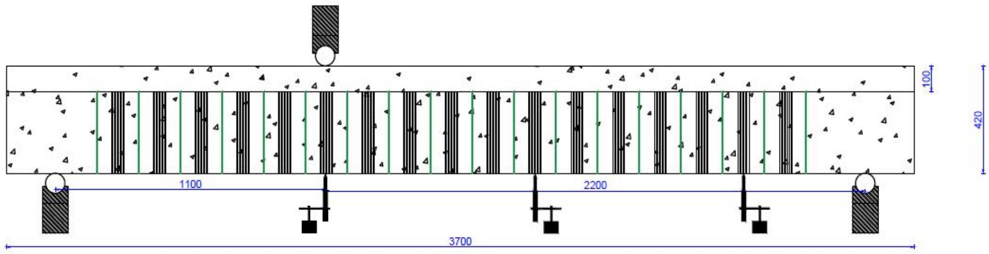

Figure 2. Geometry of the beam and test setup.

3. Results and discussion

As discussed previously, all 3 beams were designed to fail in shear. In what follows we discuss the preliminary results obtained from testing these beams.

3.1 Control Beam

Specimen 1 failed due to shear as shown in Figure 3. After the appearance of flexural cracks in the tension zone of the beam at a load level of 70 kN, the shear cracks started to appear at a load level of 130 kN in the shear span from the point of loading until the support, and since there's no transverse reinforcement to control the shear cracks, the cracks widened until the sudden failure at a load level of 196 kN.

Figure 3. Control beam after failure.

3.2 Single-Layer

The behavior of this beam, as shown in Figure 4, was not much different from the control beam. In the beginning, shear cracks appeared, at a similar load level of 130 kN in the shear span after the formation of flexural cracks. The shear cracks started to get wider from the point of load application until the support level at a load of 170 kN. After the beam reached its ultimate load capacity of 220 kN, the main shear crack increased abruptly. The contribution of the CFRP strips in resisting the shear cracks started beyond the load capacity of the beam then dropped sharply. Subsequently, the CFRP strips started to debond from the concrete surface without reaching the rupture of the fibers.

Figure 4. Single layer beam after failure.

3.3 Double-Layer

The performance of this beam was actually close to the behavior of the single layer. In the absence of the transverse steel reinforcement, adding another layer of CFRP strips was not effective as anticipated, which was mainly due to the debonding failure without rupture of the CFRP sheets (Figure 5).

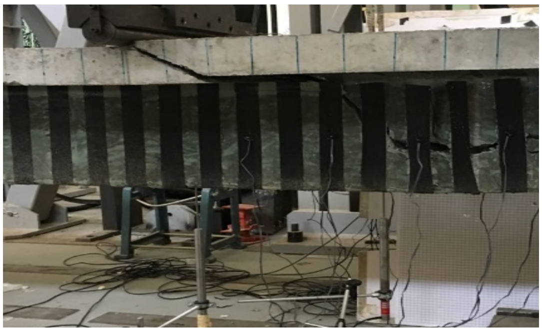

Figure 5. Double layers beam after failure.

Figure 6 shows the load-mid-span deflection curves of the three beam specimens. Clearly, the CFRP had the effect of enhancing the post failure behavior of the strengthened beams. However, the CFRP layers had a negligible influence on the overall load-carrying capacity of Specimens 2 and 3; CFRP shear reinforcement increased the load capacity of the beams by around 20 kN only, shown in Table 2 below, which represents about 10% of the capacity of the control beam (i.e., Specimen 1). A noticeable effect of EB-CFRP was the residual strength which was about 23% of the ultimate load-capacity of the beams. The control beam failed without recording any residual strength.

The observed debonding failure of the EB-CFRP in both, Specimen 2 and 3, suggests that the performance of the single-layer and double-layer specimens are no different, which means adding more layer was not effective in enhancing the shear behavior of the HS RC beam in the absence of transverse steel reinforcements.

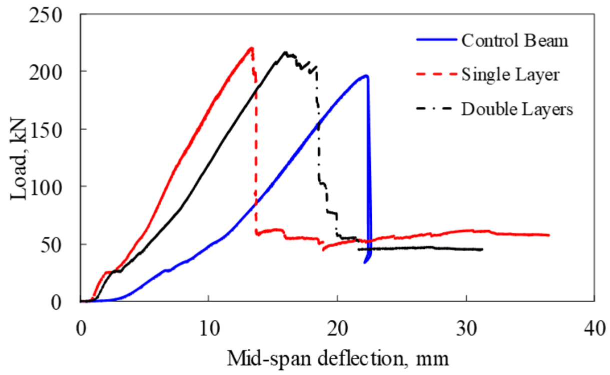

Figure 6. Load-Deflection curve.

Table 2. FRP contribution of the shear load capacity.

Beam	**Shear capacity load (kN)**	**FRP Contribution (kN)**
Control	196.60	-
Single Layer	220.95	24.35
Double Layers	216.97	20.37

4. Conclusion

The aim of this study was to investigate the behavior of the HS RC beams strengthened with single and double layers of EB-CFRP. This paper reported preliminary results pertaining to 3 specimens. Based on test results, the following conclusions were drawn:

- The shear failure of the externally U-bonded CFRP sheets to the T-section HS RC beams was of the debonding type, where the CFRP strips debonded before reaching rupture of CFRP sheets;
- The CFRP shear reinforcement enhanced the post-failure behavior of the HS RC beams. However, it increased the load capacity by no more than 10% of its control capacity only;
- CFRP sheets (be it single or double-layer) provided a residual strength of about 23% of the load-capacity of strengthened beams;
- Adding another layer of CFRP sheets to the HS RC beams was not efficient in the absence of the transverse steel reinforcement due to the debonding failure behavior.

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