

EFFECT OF EMBEDMENT LENGTH ON THE PERFORMANCE OF SHEAR-STRENGTHENED RC BEAMS WITH L-SHAPED CFRP PLATES

A. Mofidi^{1*}, S. Thivierge², O. Chaallal³, Y. Shao⁴

¹ Department of Civil Engineering and Applied Mechanics, McGill University, Postdoctoral Fellow, Montreal, Canada.

² Department of Construction Engineering, University of Quebec, École de Technologie Supérieure, Montreal, Canada.

³ Department of Construction Engineering, University of Quebec, École de Technologie Supérieure, Professor of Structural Engineering, Montreal, Canada.

⁴ Department of Civil Engineering and Applied Mechanics, McGill University, Associate Professor, Montreal, Canada.

* Corresponding author (amir.mofidi@mail.mcgill.ca).

Keywords: *Concrete beam; Fibre-reinforced polymer; Strengthening; Shear; Epoxy bonded; Embedment; L-Shaped Plates.*

Abstract

This paper presents results of an experimental investigation on reinforced concrete (RC) T-beams retrofitted in shear with prefabricated L-shaped carbon fibre-reinforced polymer (CFRP) plates. Shear-strengthening of RC beams with L-shaped fibre-reinforced polymer (FRP) plates proved to be an effective method. In this method, holes are drilled throughout the beam's flange to fully embed the vertical (perpendicular to the longitudinal axis of the RC beam and in the RC beam's web surface) leg of the L-shaped CFRP plate (Fig. 1). However, in some cases drilling holes in the concrete flange might not be applicable due to presence of obstacles such as longitudinal steel in the flange of the RC beams. Therefore, in this study, the effect of the embedment length of the L-shaped FRP plates in the RC beam's flange to the behaviour of the shear-strengthened RC beams with L-shaped plates is investigated.

In total, 6 tests were performed on 2100 mm-long T-beams. Three specimens were strengthened in shear using epoxy bonded L-shaped CFRP plates with different embedment lengths of the plates in the RC

beam's flange. One specimen was shear-strengthened with fully-embedded CFRP plates in



Fig. 1. Reinforced-concrete beam strengthened in shear using epoxy-bonded CFRP L-shaped plates.

the concrete beams' flange. One specimen was strengthened with partial embedment of the L-shaped CFRP plate. This specimen is representative of the case that full penetration of the CFRP plate is not feasible due to the presence of an obstacle. In this specimen the embedment length was set equal to 25 mm to simulate the minimum concrete cover thickness in RC beams. One specimen was shear-strengthened with L-shaped plates CFRP with no embedment of the CFRP plate in the concrete beams' flange.

For all the specimens strengthened with CFRP L-shaped plates, a set of two L-shaped CFRP plates formed a U-shaped configuration in one cross-section of the strengthened RC beams. One leg of the two L-shaped plates was overlapped and bonded to the soffit of the beams (Fig. 2). The vertical ending of the L-shaped CFRP plate was epoxy bonded to the hole in the RC beam's flange. In addition, the performance of the strengthened beams with L-shaped CFRP plate was compared with similar specimen strengthened with externally-bonded FRP sheets.



Fig. 2. The overlapped and bonded leg of the L-shaped plates to the soffit of the RC beams.

Overall, the efficiency of the strengthening method used to retrofit the test specimens was investigated. The experimental shear resistance of each specimen due to FRP divided by the ultimate tensile capacity per unit length of the FRP was calculated to evaluate

the efficiency factor of all the strengthened specimens.

An analytical model was proposed considering different failure modes of RC beams strengthened with L-shaped CFRP plates such as: FRP pull-out, concrete break-out in the flange, FRP plate debonding and FRP lap-splice failure at the soffit of the beam. The proposed analytical model showed reasonable correlation with the experimental results. The results of this study revealed that RC beams retrofitted with fully-embedded L-shaped FRP plates was the most effective method amongst other strengthening methods in this study. Moreover, partial embedment of the L-shaped CFRP plates was the most effective alternative to the full embedment of the L-shaped CFRP plates when full embedment of L-shaped plates is not feasible. In addition, RC beams strengthened with partially-embedded L-shaped plates showed a superior behaviour compared to those strengthened with externally bonded CFRP plates and sheets.

1 Introduction

Prefabricated L-shaped FRP plates present a potential to EB FRP sheet, Near-surface mounted (NSM) FRP rod and Embedded through-section (ETS) FRP rod for shear strengthening of Reinforced Concrete (RC) beams. Meier (1998) conducted a series of pull-out tests on L-shaped Carbon-FRP (CFRP) plates bonded to concrete blocks. In addition, a series of tests on Adhesively Post-installed Embedded (APE) CFRP plates bonded to concrete blocks were also implemented by Meier (1998). Czaderski (1998) investigated the effectiveness of the L-shaped CFRP plates in shear-strengthening of RC beams. The test matrix of his investigation study included three RC beams with different concrete cross-sectional properties and loading configurations. In 2002, an experimental investigation was conducted at EMPA (Eidgenössische Materialprüfungs und Forschungsanstalt) laboratories on retrofitting RC beams with L-shaped CFRP plates as follows: (i) Two shear-strengthened specimens using L-shaped CFRP plates with different internal transverse steel

ratio were tested under static load; (ii) one test was implemented on a pre-cracked RC beam strengthened in shear using L-shaped FRP plates, and finally (iii) one strengthened specimen was tested under cyclic loads. The results of this experimental investigation were published in EMPA Report No. 116/7 (2002). Later, Czaderski and Motavalli (2004) focused on the fatigue behavior of RC beams strengthened with L-shaped CFRP plates using the results of their tests in EMPA (2002). Chen and Robertson (2004) tested a pre-cracked prestressed concrete T-beam retrofitted in shear using L-shaped CFRP plates. Later, Robertson et al. (2007) conducted a cyclic loading test on an AASHTO type RC beam strengthened with L-shaped CFRP plates.

Clearly, there are very few tests worldwide performed on RC beams strengthened in shear with L-shaped FRP plates and the need for more related data is clearly demonstrated. Of all the tests implemented on retrofitted RC beams with L-shaped plates few were tested under static load and none considered partial embedment of RC beams in the flange in case of presence of an obstacle that inhibit full penetration into the flange.

2 Experimental Investigation

The RC beams were tested in three-point load flexure. Overall, the experimental program (Table 1) involved 6 tests performed on half-scale RC T-beams. The control specimen, not strengthened with Carbon FRP (CFRP), was labeled CON, whereas the specimens retrofitted with L-shaped CFRP plates were labeled LS. The single specimen strengthened with a layer of EB CFRP sheet was labeled EB. In the specimens strengthened with the L-shaped CFRP plates the depth of plates embedment into the RC beams flange was denominated as follows: the beam strengthened with CFRP L-shaped plates with no embedment was labeled NE; the specimen strengthened with CFRP L-

shaped plates with partial embedment (25 mm embedment) of the CFRP plates into the RC beam's flange was labeled PE and the beam strengthened with fully embedded (102 mm embedment) CFRP L-shaped plates into the beam's flange was labeled FE.

All the beams tested in this study were labeled S1, except the beam S0-CON which had no transverse steel reinforcement. Series S1 correspond to specimens with internal transverse steel stirrups spaced at $s = d/2$, where $d = 350$ mm and represents the effective depth of the cross-section of the beam (Fig. 3). Thus, for example, specimen S1-LS-PE features the beam with internal steel stirrups spaced at $s = d/2$, which was retrofitted with the L-shaped plates that were embedded one inch into the RC beam's flange. The labels used for each beam are provided in Table 1.

2.1 Specimens

The cross-section of the specimens and dimensions are presented in Fig. 3. The tested specimens consisted of a T-beam with a web width of 152 mm and a flange depth of 102 mm. The RC beams had an overall length of 2500 mm and span of 2100 mm. The load was applied to the mid-span of the RC beam. The longitudinal steel reinforcement at the bottom of the RC beam was laid in two layers of four 25M bars (diameter of 25.2 mm, area of 500 mm²). At the top of the cross-section, the longitudinal steel reinforcement consisted of six 10M bars laid in one layer (diameter of 10.3 mm, area of 100 mm²). The transverse steel reinforcement was 8 mm in diameter (area of 50 mm²). The spacing between the steel stirrups was equal to 175 mm ($d/2$) for all the specimens with internal transverse steel (see Fig. 3). The specimens had chamfered outer corners at the sides of the soffit of the beam to match the curved shaped of corner of the CFRP L-shaped plates (Fig. 2). The strengthening L-shaped FRP plates were epoxy-bonded mid-way between the steel stirrup locations.

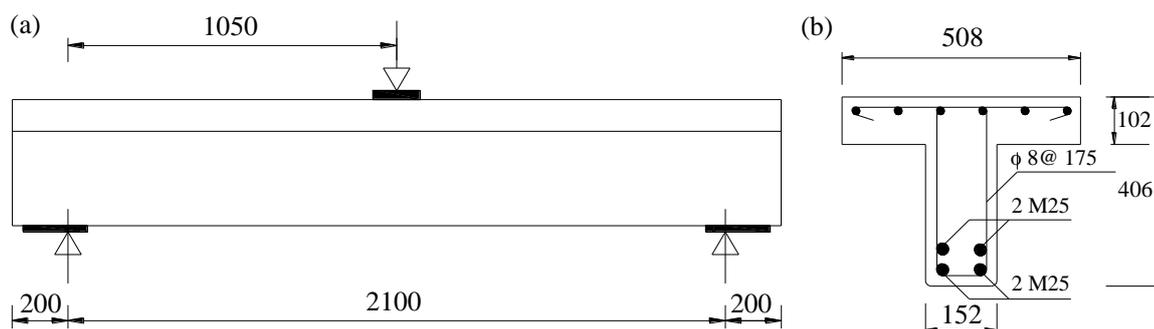


Fig. 3. Details of RC beams: (a) elevation; (b) cross section.

The internal longitudinal and transverse steel had nominal yielding strengths of 540 and 650 MPa, respectively. A commercially available concrete was delivered to the laboratory by a local supplier. The average concrete strength of 152 mm diameter by 305 mm concrete cylinders at 28 days was 29.6 MPa, whereas it was 33.7 MPa during the RC beam tests. The scatter between the results of compression tests of the cylinder specimens 28th days after pouring of concrete or on the test day was negligible.

The CFRP L-shaped plates used for strengthening of RC beams were unidirectional. The L-shaped plates originally consisted of 500 mm × 200 mm legs. However, the legs of the plates had to be shortened to properly fit the corresponding strengthening configuration of each strengthened specimen, including the embedment lengths. The L-shaped plates were 40 mm wide and 2 mm thick. The modulus of elasticity of the plates was equal to 90 GPa according to the manufacturer datasheet. The ultimate tensile strength and the ultimate strain of the L-shaped plates were set equal to 1350 MPa and 1.3%, respectively. The L-shaped plates were epoxy-bonded to the test zone in a U-shape envelope around the web, i.e., the short legs of two L-shaped plates at one cross-section overlapped on the soffit of the specimens. The

L-shaped CFRP plates were bonded to the beam surface with a two-component adhesive made of a resin and a hardener, both of which are mainly engineered for structural applications and supplied by the manufacturer. The epoxy's mechanical properties, as specified by the manufacturer, were: 24.8 MPa bond strength, 1% elongation at break and 4.5 GPa tensile modulus of elasticity. The CFRP sheet used for the specimen strengthened with EB FRP sheet was a unidirectional carbon fiber fabric. It was applied continuously over the test zone in a U-shape envelope around the web. The continuous composite material was selected as it can be an appropriate bench mark to evaluate the effectiveness of the L-shaped FRP plates in shear strengthening of RC beams. The mechanical properties of the CFRP sheet according to the manufacturer datasheet were as follows: 3450 MPa tensile strength, 230 GPa tensile E-modulus, 1.5% elongation at break, 1.8 g/cm³ density and 230 g/m² area weight. The CFRP fabric was bonded to the beam surface with a two component epoxy paste made of a resin and a hardener. The mechanical properties of the epoxy paste as specified by the manufacturer were as follows: 30 MPa tensile strength, 1.5% elongation at break and 3.8 GPa flexural modulus of elasticity.

Table 1. Experimental results

Specimen	Load at rupture	Total shear resistance	Resistance due to concrete	Resistance due to steel	Resistance due to CFRP	Gain due to CFRP	Deflection at load point	Failure mode
	kN	kN	kN	kN	kN	%	mm	
S0-CON	162.4	81.2	81.2	0.0	0.0	0	2.6	Shear
S1-CON	432.4	216.2	81.2	135.0	0.0	0	11.9	Shear
S1-LS-NE	550.7	275.4	81.2	135.0	59.2	27	19.8	Shear
S1-LS-PE	600.5	300.3	81.2	135.0	84.1	39	19.2	Shear
S1-LS-FE	671.4	335.7	81.2	135.0	119.5	55	42.9	Flexure
S1-EB-NA	587.9	294.0	81.2	135.0	77.8	36	21.3	Shear

3. Presentation of Results

The experimental results obtained from the tests for all the test specimens are summarized in Table 1. The results are presented in terms of the loads attained at failure; the experimental shear resistance due to concrete, due to the transverse steel, and due to the CFRP; as well as the shear capacity gain ($\text{gain} = V_f / (V_c + V_s)$) due to the CFRP. The results reveal that the shear capacity gain due to the CFRP for the specimen strengthened with fully-embedded L-shaped plates is 55%, compared to 39%, 36% and 27% for the corresponding specimens strengthened with partially-embedded L-shaped plates, EB sheet and L-shaped plates with no embedment respectively.

This clearly confirms the effectiveness of all the strengthening method used in this research study especially the shear strengthening method of RC beams with L-shaped CFRP plates with full or partial embedment (specimens S1-LS-FE and S1-LS-PE).

Table 1 reveals that the beams strengthened using fully-embedded CFRP L-shaped plates (S1-LS-FE) and partially-embedded CFRP L-shaped plates (S1-LS-PE) reached the highest shear resistance due to FRP strengthening compared to other two strengthened specimens (S1-LS-NE and S1-EB-NA). Specimens S1-LS-

FE and S1-LS-PE reached 119.5 kN and 84.1 kN shear resistance due to FRP, respectively. Whereas, Specimens S1-LS-NE and S1-EB-NA reached 59.2 kN and 77.8 kN shear resistance due to FRP, correspondingly.

It should be noted that the shear contribution of the concrete (V_c) and the steel (V_s) are calculated based on the results achieved from the control test specimens, i.e., S0-CON and S1-CON. Some of the values provided in Table 1 are calculated based on the following assumptions implicitly admitted in the design guidelines: a) the shear resistance due to concrete is the same whether the beam is reinforced with transverse steel reinforcement or not and whether the beam is strengthened with CFRP or not; and b) the shear resistance due to steel is the same whether the beam is strengthened with CFRP or not.

4. Conclusions

Prefabricated L-shaped CFRP plates can significantly enhance the shear capacity of RC beams. In this study, the average increase in shear capacity reached 40% for the beam retrofitted with epoxy-bonded L-shaped CFRP plates. Within the experimental scope of this

research study, the following conclusions can be drawn:

- The effective application of partially embedded L-shaped CFRP plates to shear-strengthen RC beams was verified based on experimental investigations.
- Among the tested specimens, partial embedment of the L-shaped CFRP plates was the most effective alternative to the full embedment of the L-shaped CFRP plates when full embedment of L-shaped plates is not feasible.
- Specimens strengthened with partially and fully embedded L-shaped FRP plates (S1-LS-PE and S1-LS-FE) reached the highest gain in shear resistance due to FRP strengthening and outperformed the other strengthened specimens with no embedment or anchorage (S1-LS-NE and S1-LS-NA).

5. References

- [1] Chen, J., and Robertson, I., 2004. Test of cracked prestressed concrete T-beam retrofitted for shear using CFRP L-shaped plates. *Uni.of Hawaii Research Report, UHM/CEE/04-06*.
- [2] Czaderski, C. 1998. Nachträgliche schubverstärkung mit CFK-Winkeln. *Schweizer ingenieur und architekt SI + A*, 43(22). 822–26. (in German).
- [3] Czaderski, C. and Motavalli, M. 2004. Fatigue behaviour of CFRP L-shaped plates for shear strengthening of RC T-beams. *Composites: Part B*. 35. 279-290.
- [4] EMPA Test Report 116/7. 2002. Shear strengthening with prefabricated CFRP L-shaped plates, Test beams S1 to S6. *Eidgenössische Materialprüfungs- und Forschungsanstalt*. 79 pages.
- [5] Meier, H., 1998. CFK-Schubverstärkungselemente. *Schweizer ingenieur und architekt SI + A*, 43(22). 819–21. (in German).
- [6] Robertson, I., Johnson, G. P., Sharma, B. 2007. Shear retrofit of concrete t-beams using CFRP. *Proc. of the 8rd Int. Symp. on Fiber Reinforced Polymers in reinforced concrete structures*. Patras. Greece.