Size Effect of RC Beams Strengthened in Shear with EB CFRP L-Shape Laminates

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ABSTRACT: This study presents results of an experimental investigation on the influence of size on the shear behavior of reinforced concrete (RC) T-beams strengthened in shear with externally bonded (EB) carbon fiber-reinforced polymer (CFRP) L-shape laminates. Four series and two different effective depths (medium and large size) of geometrically similar beams with internal transverse steel reinforcement were considered. The tests were conducted on control (unstrengthened) beams and on shear-strengthened beams using EB CFRP L-shape laminates in U-wrap configurations around the web, with and without an anchorage system. The results revealed the presence of a size effect in all the series, where both concrete and the CFRP contributions to the shear resistance were affected, despite the presence of transverse steel. The EB CFRP strengthened specimens with an anchorage system achieved the highest shear resistance gain and shear strength, but were nevertheless the most affected by the size effect.

Keywords: Size effect; Shear; Strengthening; Externally bonded; CFRP L-shape laminates.

1 INTRODUCTION

Shear resistance of RC beams depends on several inter-related and complex mechanisms of which the size of the member has a major influence, known as the size effect. Numerous studies have shown that the size effect in conventional RC beams relatively reduced the shear strength at failure with increasing size. However, some studies have been dedicated to the size effect of RC beams strengthened in shear with EB FRP (Bae et al. 2012; Benzeguir et al. 2018; Deniaud et al. 2001; Foster et al. 2016; Leung et al. 2007; Nguyen-Minh et al. 2015; Qu et al. 2005). This represents only 6% of all studies on size effect on shear either for conventional or EB FRP strengthened RC beams (Benzeguir et al. 2017). Most of these research studies revealed a relatively reduced shear strength with increasing size for specimens either with or without internal transverse steel. In addition, all tested specimens were strengthened with EB FRP sheets using the wet lay-up process and, to date, no study has been performed to assess the size effect of shear-strengthened RC beams using the pultruded CFRP L-shape laminates. Furthermore, only one study was reported on size effect with an anchorage system (Foster et al. 2016).

The objective of the present study was to bridge that gap and examine the size effect on the shear behavior of RC T-section beams strengthened with EB CFRP L-shape laminates. To that end, 4 series of specimens were considered, each one consisting of geometrically similar RC T-beams with two different sizes, medium and large. Also, the impact of using an anchorage system on the size effect, where the L-shape laminates were embedded into the flange (slab) is also investigated.

2 EXPERIMENTAL PROGRAM

2.1 Specimens and materials

The experimental program involved 8 tests performed on geometrically similar RC T-beams with two different sizes: Medium size specimens with 406 mm height and 3110 mm length between supports (total length = 4520 mm), and large size specimens with 605 mm height and 4430 mm length between supports (total length = 6400 mm). Both series of specimens had a slenderness ratio of around 3. Figure 1 illustrates the details of cross section specimens, including the geometry, the internal longitudinal and transverse steel reinforcement, as well as the EB CFRP shear strengthening configurations with and without anchorage.

The concrete of the test specimens is made of 14 mm maximum aggregate, with 30 MPa specified concrete compressive strength. The longitudinal steel reinforcement consisted of 25M (diameter = 25.2 mm) and 30M (diameter = 29.9 mm) bars with 470 and 420 MPa yield strengths, respectively, with a ratio (ρ_w) of 3.6%. The transverse steel stirrups, spaced at $s = d/2$ with a ratio (ρ_{st}) of 0.4%, consisted of 8 and 10-mm-diameter bars with 650 and 440 MPa yield strengths, respectively. Similarly, to maintain an identical EB CFRP rigidity for all strengthened specimens, same FRP ratio (ρ_{FRP}) of 0.6% was considered between the L-shape laminates, leading to 175 mm and 100 mm spacing for medium and large size beams, respectively. The properties of CFRP L-shape laminates, as provided by the manufacturer, are as follows: 1350 MPa, 90 GPa and 1.3% for respectively ultimate tensile strength, modulus of elasticity and ultimate strain at break.

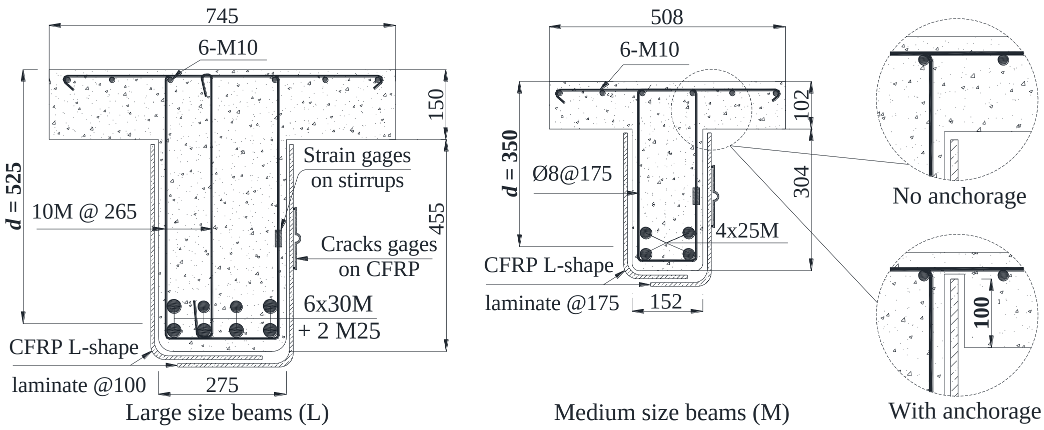


Figure 1. Cross section of specimen's and strengthening system (dimensions in *mm*).

2.2 EB CFRP procedure and test setup

Table 1 presents the experimental program matrix for the test specimens. The letters M and L refers to the medium and large size of beams, respectively. For each beam's size, 4 series of specimens were considered as presented in Table 1 (see also Fig. 1).

All beams were tested in three-point bending. The load was applied at a shear span of 3*d* from the nearest support to ensure a slender beam type of behavior, i.e., 1050 and 1575 mm for medium and large size specimen respectively. The tests were performed under displacement

Table 1. Experimental program

Series of specimens	Medium size (M)	Large size (L)
Control without stirrups	M.S0.Con	L.S0.Con
Control with stirrups	M.S1.Con	L.S1.Con
Strengthened without anchorage	M.S1.Str	L.S1.Str
Strengthened with anchorage	M.S1.Str-Anc	L.S1.Str-Anc

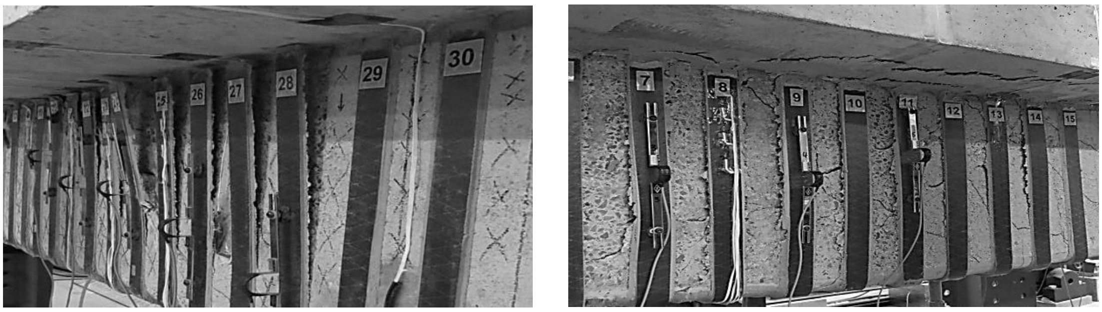
control conditions at a rate of 2 mm/min. Deflection of beams were measured using LVDT located under the applied load. Strains in internal transverse steel were measured using strain gauges affixed to steel stirrups along the anticipated theoretical plane of shear failure in the loading zone. The longitudinal steel bars were also instrumented with strain gauges at the location of applied load. To measure the strains experienced by the EB CFRP, crack gauges were installed vertically onto the L-shape laminate at the same position as the strain gauges affixed on internal transverse steel.

3 EXPERIMENTAL TEST RESULTS

The test results are presented in terms of (i) modes of failure; (ii) deflection response; and (iii) shear strength. The experimental test results are summarized in Table 2. It includes the ultimate load, P, the total shear resistance, V_T, the contribution to shear resistance due to CFRP laminate, V_{FRP}, the gain in shear capacity due to CFRP laminate, G_{FRP}, the maximum deflection under load, Δ, the shear strength at failure, v ($v = V_T / b_w d$), as well as the loss in shear strength in large size specimen with respect to medium one. The shear contributions of concrete and transverse steel were determined based on the test results on control specimens. The CFRP contribution V_{FRP} to the shear resistance is determined by subtracting the contributions of concrete and steel stirrups from total shear resistance.

3.1 Failure mode

All tested specimens failed by shear with diagonal tensile fracture. One major shear diagonal tension crack from support to applied load was revealed in control specimens without transverse steel, whereas distributed shear cracks along the shear span were observed in control and strengthened specimens with internal transverse steel. As the load increased, the shear cracks propagated upward through the flange towards the loading point. Although the ultimate failure was by shear, all strengthened specimens reached their elastic limit in flexure by yielding of longitudinal steel that was evident by the strain measurements. The failure of strengthened specimens with no anchorage occurred directly after debonding of the CFRP laminates that intercepted the diagonal shear cracks (Figure 2a). Note that specimens M.S1.Str and L.S1.Str exhibited yielding of steel stirrups before reaching their ultimate loads. In specimens M.S1.Str-Anc and L.S1.Str-Anc, the anchorage system helped the CFRP laminates to remain active despite the partial (local) debonding that occurred at the location of cracks (Figure 2b). The anchored specimens exhibited yielding of steel stirrups at ultimate loads. Therefore, yielding of steel stirrups was delayed under higher applied loads with respect to specimens without anchorage. In other terms, steel stirrups in anchored specimens exhibited a lower level of strains with greater CFRP contribution to the shear resistance, during the tests.



(a) (b)

Figure 2. Shear failure: (a) CFRP laminate debonding in L.S1.Str; and (b) CFRP laminate debonding in L.S1.Str-Anc without anchorage pullout.

Table 2. Experimental test results.

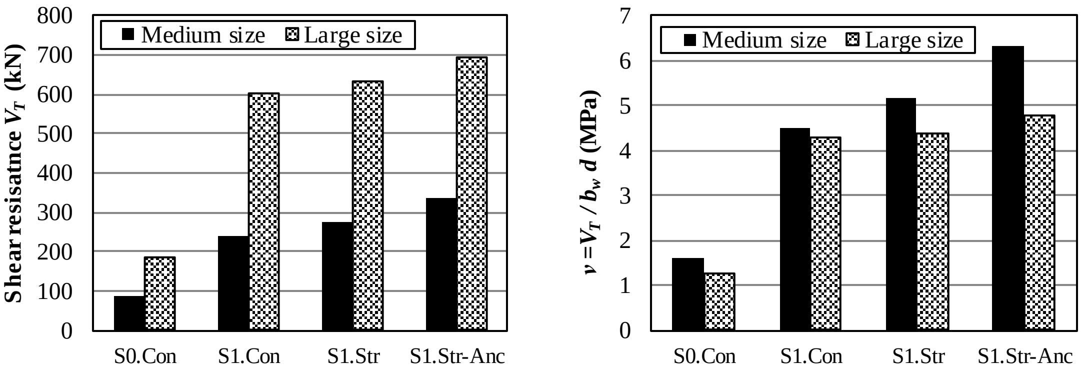
Specimens	P (kN)	V_T (kN)	V_{FRP} (kN)	G_{FRP} (%)	Δ (*mm*)	v (MPa)	Loss in v (%)
M.S0.Con	130	86	-	-	2.6	1.62	22
L.S0.Con	283	182	-	-	3.7	1.26	
M.S1.Con	360	238	-	-	11.9	4.47	7
L.S1.Con	931	600	-	-	18.8	4.16	
M.S1.Str	416	275	37	16	20.5	5.17	16
L.S1.Str	977	630	11	2	17.8	4.36	
M.S1.Str-Anc	507	336	98	41	44	6.32	24
L.S1.Str-Anc	1071	690	71	11	36	4.78	

3.2 *Deflection response*

The deflections (Δ) were obtained at the ultimate load P corresponding to the nominal shear resistance at failure (see Table 2). The control series showed an increase in the deflection with increasing the beams' size, i.e., 42% in L.S0.Con and 58% in L.S1.Con with respect to their corresponding medium specimens. This could be due to the increase in the beam span or to the higher ultimate loads. In contrast, in strengthened specimens, the size effect resulted in a decrease of the deflection by 13% in L.S1.Str and 18% in L.S1.Str-Anc with respect to their corresponding medium specimens. Also, the results revealed an increase in the beam's ductility in strengthened compared to control specimens, and particularly in anchored specimens. Furthermore, given the applied loads, the level of deflections was lower in large compared to medium specimens, indicating that the size effect may affect the beam's stiffness.

3.3 *Shear strength analysis*

The variation of the shear resistance, V_T, and the normalized shear strength at failure, ν, with increasing beam's size for the 4 series of specimens are illustrated in Figures 3a and 3b, respectively. The results showed a substantial increase in total shear resistance with effective



(a) (b)

Figure 3. Shear behavior with increasing beam's size: (a) Shear resistance and (b) Shear strength.

depth d for each series, although a decrease in shear strength, v, occurred. In fact, the gain in capacity was more than 100% when the beam's size increased from 350 mm to 525 mm (figure 3a), whereas a decrease in shear strength was observed in all series, as shown in figure 3b. This demonstrates that despite the significant gains in shear resistance, a presence of size effect on shear strength was observed in both conventional and EB CFRP strengthened specimens with L-shape laminates, with and without using anchorage.

Comparing the specimens of the same size, it can be seen that the presence of internal transverse steel significantly increased the shear resistance. For instance, the ratio of shear resistance between control specimens, with and without stirrups, increased from 2.8 to 3.3 times in medium to large specimens, respectively. However, the ratio of shear resistance between controls specimens and strengthened ones, with steel stirrups, decreased from 1.41 to 1.15 in anchored specimens, and from 1.16 to 1.05 in specimens without anchorage. This indicates the positive influence of size effect in the effectiveness of internal transverse steel, which results in an increase of the shear resistance with the beam's size. This contrasts with the effectiveness of strengthening using EB CFRP L-shape laminates where the size effect has a negative influence by decreasing the shear resistance as the beam's size increases. This change in behavior can be attributed to the interaction between the internal transverse steel and the EB CFRP that tends to decrease the effectiveness of the later as already demonstrated by other studies (Chaallal et al. 2002; Pellegrino et al. 2002; Bourget et al. 2017).

As shown in Figure 3b, the loss in shear strength at failure, v, with increasing the beam's size differs between the 4 series. In fact, the control series exhibited a decrease in shear strength loss from 22% between specimens without transverse steel (S0.Con) to 7% between specimens with steel stirrups (S1.Con). This clearly confirms the findings of other researchers observed in conventional RC beams, that the size effect decreases the normalized shear strength at failure in beams without steel stirrups (Bažant et al. 1991). On the other hand, the presence of transverse steel can mitigate the size effect by aggregate interlock enhancement, hence preventing the diagonal shear cracks to widen (Benzeguir et al. 2017). Also, the strengthened series with CFRP L-shape laminates exhibited an increase in shear strength loss at failure with beam's size, i.e., 16% between specimens with no anchorage (5.17 MPa in M.S1.Str to 4.36 MPa in L.S1.Str) and 24% between anchored specimens (6.32 MPa in M.S1.Str-Anc to 4.78 MPa in L.S1.Str-Anc). This result confirms the existence of an additional size effect attributed to the CFRP strengthening system with EB CFRP L-shape laminates, as already reported for strengthening with CFRP strips without an anchorage system (Leung et al. 2007).

4 CONCLUSIONS

This paper presented the influence of beam's size on the strength of RC T-beams shear strengthened in shear with EB CFRP L-shape laminates using a U-wrap configuration with and without anchorage system. The following conclusions can be drawn:

- Despite the partial CFRP debonding in anchored specimens, the CFRP laminates remained active due to the anchorage system.
- The anchored specimens exhibited lower level of strains in steel stirrups during the tests but greater CFRP contribution to the shear resistance.
- Given the applied load, the level of deflections was lower in large compared to the medium specimens, indicating that the size effect may increase the beam's stiffness.
- The results revealed the existence of an additional size effect due to the CFRP L-shape laminates, with increasing the effective depth d, and particularly in anchored specimens.

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