Interaction between internal steel stirrups and externally bonded CFRP U-strips for shear strengthening of concrete T-beams

Jimenez-Vicaria, J.D.[1] and Paulotto, C.[1]

[1] *Technology Centre, ACCIONA Construction, Spain*

Abstract
To postpone or prevent premature debonding of CFRP U-strips for the shear-strengthening of T-section RC beams, guidelines suggest the use of additional anchorage systems, but no design provisions are available to evaluate the increased contribution of anchored CFRP strips to shear resistance. To achieve a better understanding of the shear resistance mechanism, 11 full-scale concrete T-section beams with different internal steel and external CFRP ratios (both with and without anchors) are tested. All beams are instrumented with strain gauges on the steel stirrups, CFRP U-strips and CFRP anchors to evaluate the shear contribution of each material, the interaction between the internal transverse steel reinforcement and externally bonded CFRP shear strengthening, and the effectiveness of CFRP anchors. Based on the results of tested beams, it is clear that both the steel stirrups reinforcing ratio and the CFRP strips strengthening ratio influence the efficiency of CFRP U-strips anchorages.

Keywords: shear strengthening, CFRP U-strip, spike anchorage, RC T-beams, strain gauges

Corresponding author's email: josedavid.jimenez.vicaria@acciona.com

Introduction

Anchorage systems can postpone or prevent end debonding failure of CFRP U-strips used for shear strengthening of RC T-beams [1], [2] and [3]; nevertheless, no design provisions are currently available. To achieve a better understanding of the shear resistance mechanism, 11 full-scale beams with different transverse steel reinforcement ratios, and strengthened with different CFRP U-strips ratios, both with and without anchors, are tested. The aim is to evaluate the interaction between the internal transverse steel reinforcement and externally bonded CFRP shear strengthening at shear failure, and the shear contribution of each material, when anchors are used.

Experimental program

Test specimens

Eleven T-section concrete beams, each one with a total length of 4.27 m, are manufactured with the same cross-section shown in Figure 1, using a concrete with an average compressive strength f_{cm} = 47.5 MPa. The clear span (distance between supports during tests) is 3.75 m, being the tested shear span (distance between the applied load and the closest support) *a* = 0.90 m. The effective depth *d* is 327 mm, so the shear span to depth ratio (*a/d*) is 2.75. With this configuration, the shear span is subjected to a constant shear force equal to $V = 0.75\ P$, being *P* the applied load.

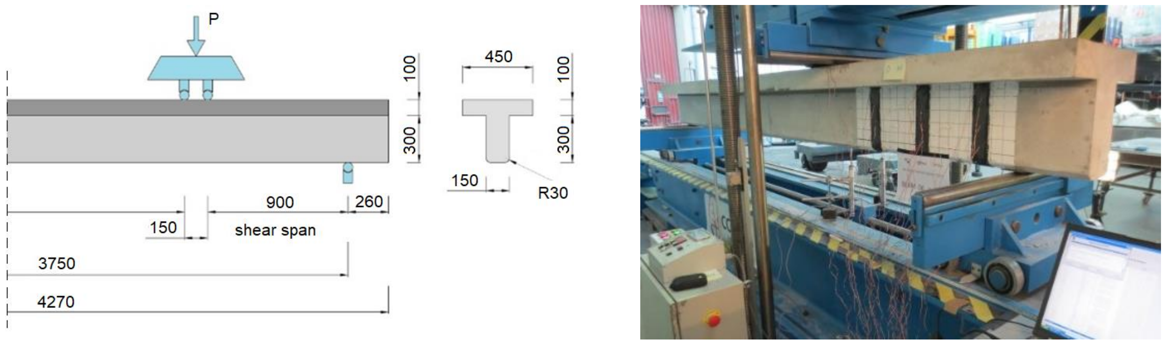


Figure 1: Details of beam specimens (units: length in mm)

The beams are reinforced in bending with four longitudinal 25 mm diameter steel rebar at the bottom and six longitudinal 10 mm diameter steel rebar at the top. As internal shear reinforcement, 8 mm diameter steel stirrups are used. They are separated 300 mm (centre-to-centre) in the shear span and 100 mm outside it. Depending on the value of the transverse reinforcing ratio in the shear span, tests can be divided into three series: a) one beam with no steel stirrups (series 1); b) five beams with 8 mm diameter steel stirrups (series 2); c) five beams with 10 mm diameter steel stirrups (series 3). The test matrix is shown in Table 1. Transverse steel stirrups are made with B500SD with a measured yield stress, tensile strength and ultimate strain of 544 MPa, 667 MPa and 0.25, respectively, for φ8 mm, and 522 MPa, 637 MPa and 0.25 for φ10 mm.
Except for the control beams (B01, B02 and B07), the other 8 beams are strengthened in shear by externally applying three CFRP transversally wrapped strips 70 mm wide and spaced at 300 mm centre-to-centre, with two different thicknesses: 0.5 mm and 2.0 mm

(Table 1), and with tensile modulus of elasticity E_f = 103.5 GPa. The strips are installed by wet lay-up with epoxy resin. In four beams, CFRP strips are also anchored using CFRP spike anchors inserted almost vertically just below the top flange of the T-beams. The anchor is fabricated with a 70 mm fan length and an embedment length of 80 mm (anchor bar), and inserted into a hole with a diameter of 12 mm and an inclination of 15°, filled with HIT-HY 200 injection mortar. The anchor fan, impregnated with the same epoxy resin used for CFRP strips, is spread with an angle of 60° to overlap with the CFRP strip previously installed (Figure 2).

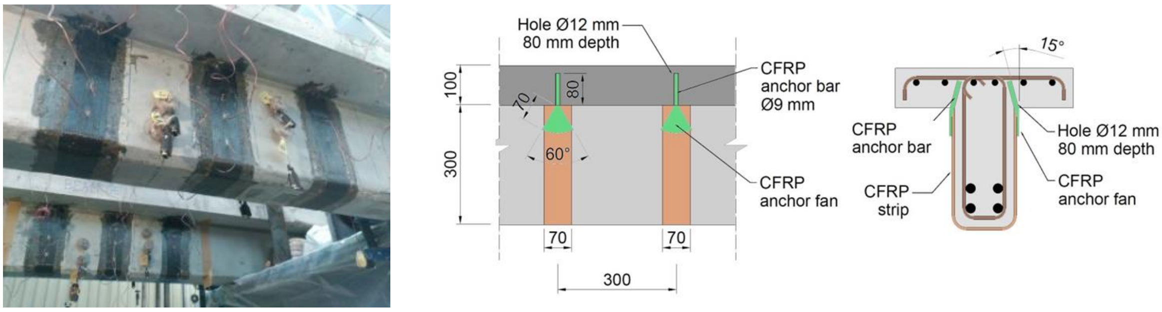


Figure 2: CFRP spike anchors

Test set-up

Beams are previously precracked to simulate the real state of damage that may exist in RC concrete beams of an in-service bridge before shear strengthening. The applied preload is computed based on the load level at which first steel stirrup attained an 80% of yield strain in control beams ($\varepsilon_s \approx 0.0020$). A precracking load of 160 kN and 200 kN is used for beams steel-reinforced with 8 mm and 10 mm stirrups in the shear span, respectively. After precracking, beams are completely unloaded, CFRP shear-strengthened and finally loaded up to failure with the same test set-up as used during precracking.
Beams are tested under three-point bending using a testing machine with a maximum load capacity of 500 kN. The load is applied at 6 kN/min and is stopped every 20 kN during 2 min to allow mapping the cracks on the beams. The internal steel stirrups and the external CFRP strengthening strips are monitored by strain gauges positioned at those sections along the beams where the critical inclined shear cracks are expected to appear.

Results

To gain insight into the interaction between the internal transverse steel reinforcement and externally bonded CFRP shear strengthening, the readings of the strain gauges applied on the steel stirrups and CFRP strips are analysed to evaluate the shear contribution of each material (Figure 3). The shear contributions of the steel stirrups V_s and the CFRP strips V_f shown in Table 1 are computed using the strains of the steel stirrups and CFRP strips intercepted by the critical shear crack that causes the beam failure, using conventional design equation (1). The shear contribution of concrete V_c is assumed as the difference between the total shear applied force V and the summation of FRP and steel shear contribution ($V_f + V_s$).

$$V_s = (0.9d/s_t \tan\theta)\ 2A_s f_y \quad (\text{for } \varepsilon_s > \varepsilon_y);\ V_f = (0.9d/s_t \tan\theta)\ 2A_f E_f \varepsilon_f \qquad (1)$$

Where d = effective depth [mm]; s_t = distance between stirrups [mm]; θ = critical shear crack inclination [°]; A_s = cross-section of steel stirrup bar [mm^2]; f_y = yield stress of steel stirrup [N/mm^2]; ε_s = measured strain in steel stirrup [mm/mm]; ε_y = yield strain of steel stirrup [N/mm^2]; A_f = cross-section of CFRP strip [mm^2]; E_f = CFRP modulus of elasticity [N/mm^2]; and ε_f = measured strain in CFRP [mm/mm].

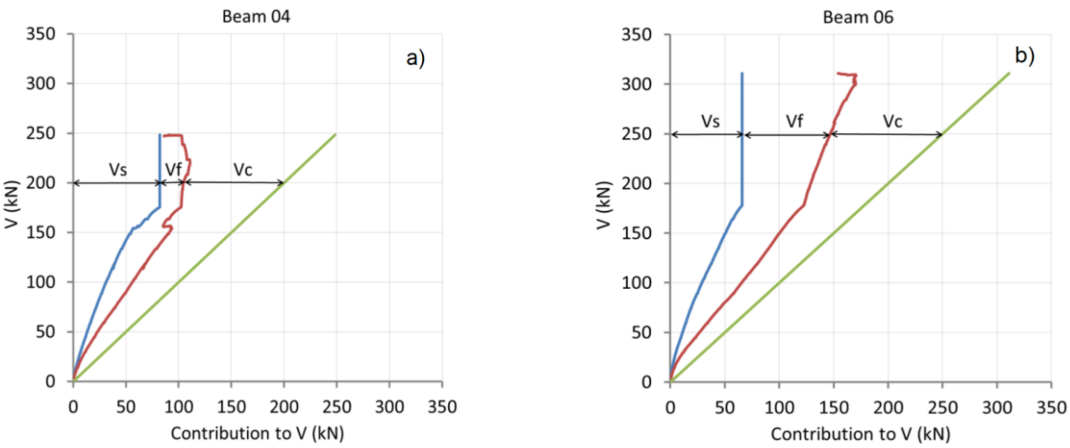


Figure 3: Shear contribution of each material: a) non-anchored B04; b) anchored B06

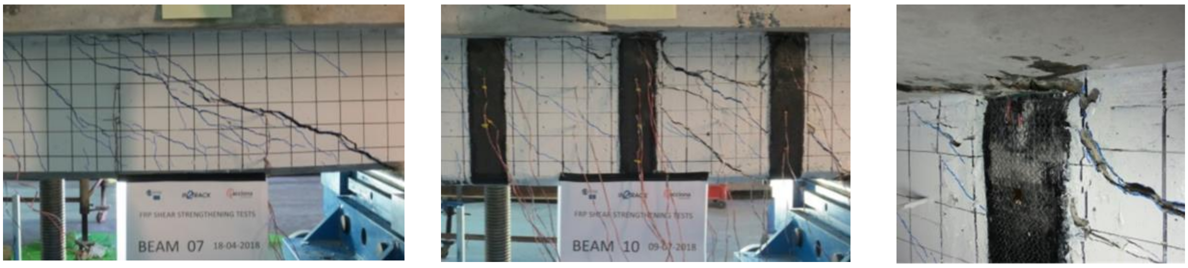
Table 1: Summary of test results

Beam	Steel stirrups	CFRP t_f	Anchor	V_s	ΔV_s (1)	$\varepsilon_{f,max}$	V_f	ΔV_f (2)	$V_{fail.}$	$\Delta V_{fail.}$ (1)
		[mm]		[kN]	[%]	[mm/mm]	[kN]	[%]	[kN]	[%]
B01	-	-	-	0.00	-	-	-	-	150.35	-
B02	Φ8	-	-	82.11	-	-	-	-	243.09	-
B03	Φ8	0.5	-	82.11	0.0	0.0037	39.74	-	284.62	17.1
B04	Φ8	2.0	-	82.11	0.0	0.0008	36.94	-	248.37	2.2
B05	Φ8	0.5	spike	68.25	-16.9	0.0067	60.45	52,1	296.18	21.8
B06	Φ8	2.0	spike	65.85	-19.8	0.0030	104.70	183,4	310.88	27.9
B07	Φ10	-	-	138.47	-	-	-	-	320.45	-
B08	Φ10	0.5	-	102.33	-26.1	0.0038	34.63	-	285.99	-10.8
B09	Φ10	2.0	-	98.72	-28.7	0.0019	67.67	-	289.25	-9.7
B10	Φ10	2.0	spike	102.33	-26.1	0.0029	105.42	55,8	337.68	5.4
B11	Φ10	0.5	spike	102.33	-26.1	0.0059	53.58	54,7	314.10	-2.00

(1)Increments in shear contribution of steel and shear failure load compared to control beams B02 or B07, depending on diameter of steel stirrups (8 mm or 10 mm, respectively).
(2)Increments in shear contribution of FRP when strips are anchored (compared to non-anchored).

For beams reinforced with 10 mm steel stirrups, the shear contribution of steel stirrups V_s reduces when CFRP strips are applied (a reduction up to 28.7% is registered in beam B09 compared to control beam B07). Even if a large shear contribution of CFRP strips V_f is obtained (beam B10), especially when using anchors, the contribution V_s is lowered in a 26.1%. This could be mainly because the shear crack angle θ measured from the horizontal axis of the beams is larger when FRP strengthening is used (Figure 4).
All tested beams have failed in shear (Figure 4). In all anchored specimens, anchors have failed before CFRP strip rupture, which can be attributed to an insufficient anchoring to take advantage of the full capacity of the CFRP strip. Increasing the diameter of the anchor to avoid anchor rupture and/or increasing the anchorage length inserted into the concrete to

avoid pull-out failure (Figure 4c) could have result in a higher shear contribution of CFRP strips.



a) b) c)

Figure 4: Shear failure mode of tested beams: a) non-strengthened B07; b) FRP-strengthened and anchored B10; c) anchor failure in B10 (pull-out).

Conclusions

1) The efficiency of CFRP strips for beam shear strengthening decreases as the transversal steel reinforcing ratio ρ_s increases.
2) The contribution of both steel stirrups and concrete may reduce when CFRP strengthening is applied compared to non-strengthened beam. This could be mainly because the crack angle θ measured from the horizontal axis of the beams is larger when FRP strengthening is used, so the number of stirrups intercepted by the critical crack becomes smaller. This can be a reason why the failure shear load in FRP-strengthened beams with 10 mm steel stirrups is generally lower than that of the non-strengthened beam B07, even with a large shear contribution of CFRP strips.
3) The efficiency of anchoring CFRP strips used for shear strengthening of T-section RC beams is influenced by both the steel stirrups reinforcing ratio ρ_s and the CFRP strips strengthening ratio ρ_f. The highest efficiency in the use of anchors is obtained for beams reinforced with 8 mm steel stirrups and strengthened with 2.0 mm thickness CFRP strips ($E_f\rho_f > E_s\rho_s$), resulting in a 183% increase in shear contribution V_f of CFRP strips when compared to non-anchored beam (B04).

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