FLEXURAL STRENGTHENING OF RC "T" BEAMS WITH NEAR SURFACE MOUNTED (NSM) FRP REINFORCEMENTS

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1 INTRODUCTION

The use of fiber-reinforced plastics has grown steadily for strengthening reinforced concrete structures. Research on the Near Surface Mounted (NSM) technique for reinforced concrete structures strengthening has being done, among others places, in North Caroline – USA [1] and in Missouri – USA [2 and 3]. The tests reported at this paper are part of a Ph.D. thesis [4]. Three series of eight "T" beams (each) of the same dimensions, but strengthened in shear were tested previously [5 to 7].

2 EXPERIMENTAL STUDY

2.1 Test Program

Tests were made on twelve "T" reinforced concrete beams, simply supported, with 4400 mm (overall length); 4000 mm (clear span); 150 mm (width of the web); 400 mm (overall height); 550 mm (flange width) and 100 mm (flange thickness). The shear span was 1500 mm and the shear span / effective depth (d) was 4.26. Details of the beams are given in Figure 1. The flexural reinforcement for all beams was 2 bars of 20 mm diameter (fy = 558 MPa; εy = 4.63‰), while the shear reinforcement for all beams was rectangular stirrups of 8.0 mm (diameter) (fy = 531 MPa; εy = 4.4‰) positioned at each 160 mm. At the flanges the stirrups were of 6.3 mm (diameter) (fy = 552 MPa; εy = 4.58‰) positioned at each 100 mm.

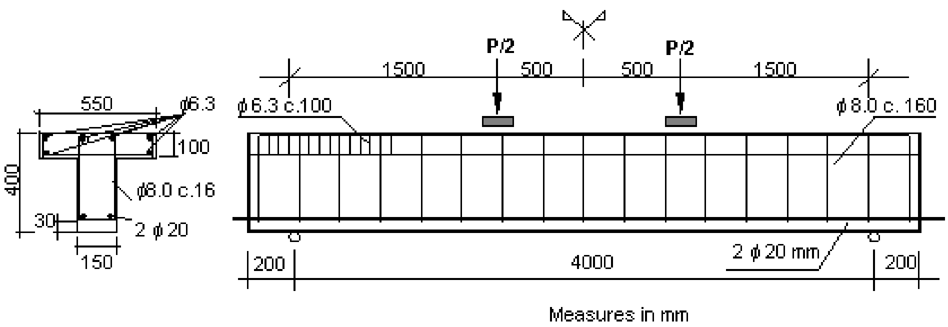

Fig. 1 Transversal section, reinforcement details and loading scheme

The anchorage of the longitudinal bars was assured by 12.5 mm thick welded steel plates, positioned outside the beam. The concrete cover was 30 mm for the bottom bars and 15 mm elsewhere. Five types of strengthening were used (Tables 1, 2 and 3 and Figure 2): Beams B.1 and B.2 (Group B) were strengthened with NSM (near surface mounted): 3 CFRP (2 x 16 mm) strips. The beams from Group C (C.1 and C.2) were strengthened with NSM (near surface mounted): 1 CFRP (ϕ 10 mm) bar. Beams D.1 and D.2 (Group D) were strengthened with NSM (near surface mounted): 2 GFRP (ϕ 12,7 mm) bars. The beams from Group E (E.1 and E.2) were strengthened with externally bonded 2 layers of (0,165 x 150 mm) CFRP unidirectional laminate while beams F.1 and F.2 (Group F) were strengthened with NSM (near surface mounted): 1 steel (ϕ 8 mm) bar. The slots (Figure 3) for the NSM strips and bars were 5 x 18 mm (Group B beams), 20 x 20 mm (Group C beams), 25 x 25 mm (Group D beams) and 16 x 16 mm (Group F beams).

Table 1 Flexural strengthening type utilized

Group	Beam	Flexural Strengthening Type Utilized
A	A.1	Reference
	A.2	
B	B.1	NSM (near surface mounted): 3 CFRP (2 x 16 mm) strips
	B.2	
C	C.1	NSM (near surface mounted): 1 CFRP (ϕ 10 mm) bar
	C.2	
D	D.1	NSM (near surface mounted): 2 GFRP (ϕ 12,7 mm) bars
	D.2	
E	E.1	Externally bonded: 2 layers of (0,165 x 150 mm) CFRP unidirectional laminate
	E.2	
F	F.1	NSM (near surface mounted): 1 steel (ϕ 8 mm) bar
	F.2	

Table 2 Strengthening details

Group	Strengthening material	Measures or diameter (mm)	Quantity	E (GPa)	Area (mm^2)	A x E
B	CFRP strips	2 x 16	3 strips	131	96	12.576
C	CFRP bars	ϕ 10	1 bar	147	78.54	11.545
D	GFRP bars	ϕ 12.7	2 bars	40.8	289.7	11.820
E	CFRP unidirectional laminates	0.165 x 150	2 layers	228	49.5	11.286
F	Steel bar	ϕ 8	1 bar	221	50.26	11.107

Table 3 Strengthening material characteristics (by makers)

Strengthening material	Producer	ε^*_{fu} (‰)	f^*_{fu} (MPa)	E (GPa)
CFRP strips	Aslan 500	17	2068	131
CFRP bars	Leadline	13.4	1970	147
GFRP bars	Aslan 100	17	690	40,8
CFRP unidirectional laminates	MBT CF 130	16.6	3790	228
Steel bar	CA 50	> 10	500	210

Loading was applied in steps of 10 kN up to cracking and then in steps of 20 kN, and at the end of which readings were taken. The behaviour of the beams tested was analyzed through the strains of the flexural and shear reinforcement and of the concrete, the strains of the composites strengthening material, the vertical and horizontal deflections, the developing and widths of the cracks, and by the ultimate load and mechanism of rupture. Figure 4 shows the strengthened beam D.2 before being tested.

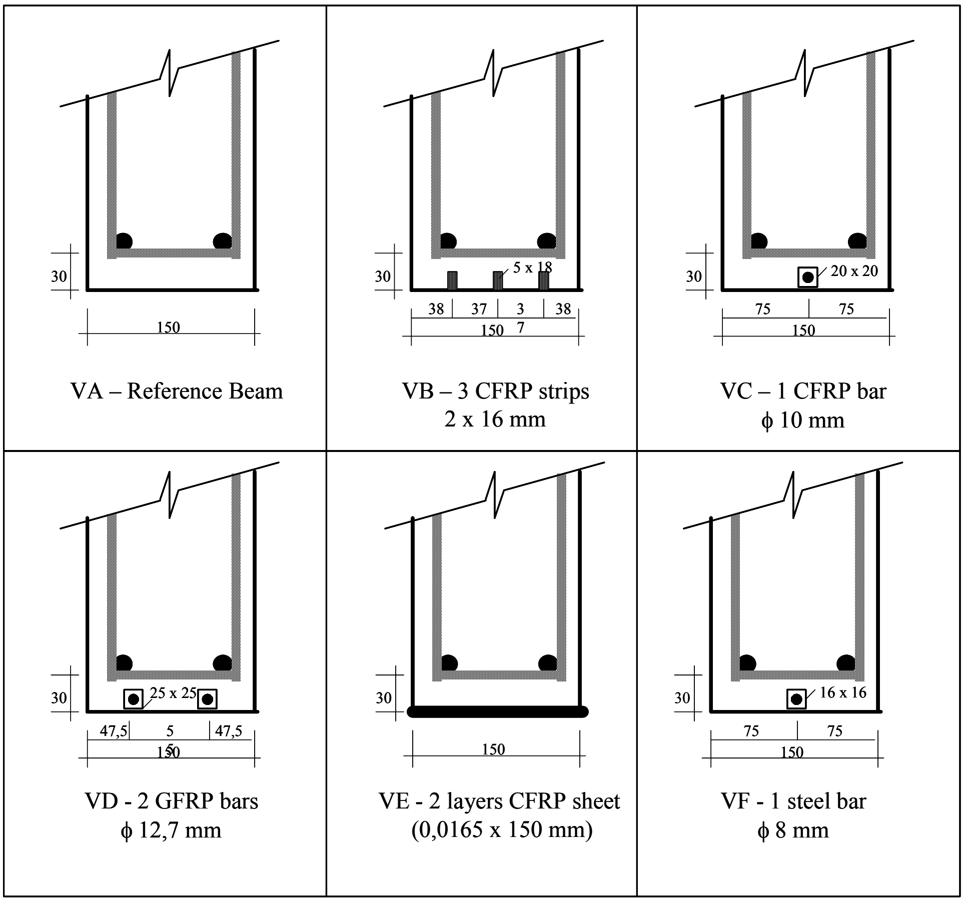

Fig. 2 Details of the strengthened beams

Fig. 3 Details of the slots made at the beams

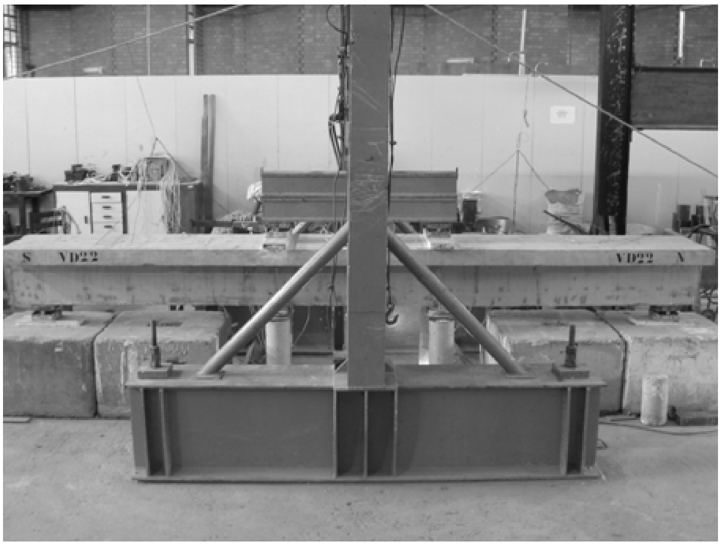

Fig. 4 Strengthened beam D.2 before being tested

2.2 Discussion of test results

Table 4 presents, for each beam, the strength of the concrete, the estimated flexural ultimate load (Pflex), the experimental ultimate load (Pu), and the rupture type obtained. Beams A.1 and A.2 (reference beams without strengthening) failed in flexure, presenting a tension failure: Beams A.1 and A.2 deflected extensively and developed wide cracks, and beam A.2 produced crushing of the concrete much deflection. Test of beam A.1 was stopped as the deformations were increasing and the load could not go up. As is going to be seen later the deflections of beam A.2 (maximum 171.5 mm) were much bigger than beam A.1 (37.6 mm) and this was attributed to the concrete (concrete resistance < 40 MPa).

Table 4 Experimental results

Beam	Strength. Type	f_c (MPa	$P_{u,exp}$ (kN)	$P_{u,teor}$ (kN)	$P_{u,exp}$/ $P_{u,teor}$	Rupture type
A.1	Refer.	46.3	162.6	160	1.01	Reinforcement yielding
A.2		36.5	185.1	156	1.19	Reinforcement yielding followed by concrete crushing
B.1	CFRP strips	49.5	245.6	232	1.06	Peeling off of the CFRP strengthening together with the concrete cover
B.2		52.8	250.0	240	1.05	
C.1	CFRP bars	52.7	253.4	225	1.12	Slipping of the CFRP followed by the rupture of the CFRP bar
C.2		50.1	249.6	237	1.05	
D.1	GFRP bars	50.1	250.0	234	1.07	Peeling off of the GFRP strengthening together with the concrete cover
D.2		35.2	226.7	219	1.04	
E.1	CFRP Lamina-te	40.0	205.7	196	1.05	Debonding of the CFRP strengthening near the support after extensive cracking of the concrete cover below the load points
E.2		47.7	215.0	203	1.06	
F.1	Steel bar	35.2	198.5	169	1.18	Reinforcement yielding followed by concrete crushing
F.2		36.4	195.4	168	1.16	

Beams from Group B (B.1 and B.2) and Group D (D.1 and D.2), strengthened respectively with CFRP strips and with GFRP bars, failed by peeling off of the composite strengthening (CFRP strips or GFRP bars) together with the concrete cover. However, it could be seen that the failure happened actually at the interface between the epoxy mortar and the concrete, as can be seen in Figures 5 and 6.

Fig. 5 Detail of the CFRP strips strengthening peeling off - Beam B.2

Fig. 6 Peeling off of the GFRP strengthening - Beam D.2

Beams C.1 and C.2 (Group C), strengthened with CFRP bars failed by slipping of the CFRP bar inside followed by the rupture of the CFRP bar (Figure 7). Besides this there was cracking at the concrete along the bar, but there was no peeling off of the concrete cover.

Beams from Group E (E.1 and E.2), strengthened with externally bonded layers of CFRP unidirectional laminate, and failed by debonding of the CFRP laminate near the support after extensive cracking of the concrete cover below the load points. Figure 8 shows details of the debonding of beam E.2.

Beams F.1 and F.2 (Group F), strengthened with 1 ϕ 8 mm steel bar failed in flexure, presenting a tension failure, deflecting extensively and developing wide cracks, and eventually crushing the concrete was obtained.

The ultimate test load was above (overall average of 1.09) the estimated flexural failure load for all beams, despite the premature failures happened for the beams of Groups B to E. It can be said then that all the used strengthening procedures worked well in terms of ultimate load.

Fig. 7 Detail of the rupture of the CFRP bar in Beam C.2

Fig. 8 Detail of the debonding of the CFRP laminate - Beam E.2

For the reference beams (A.1 and A.2) the ultimate test load was 10% in average above the estimated flexural failure load, and beam A.2, which had crushing of the concrete reached an ultimate test load 19% above the estimated flexural failure load.

Among the strengthened beams, the highest ratio (in average 1.17) ultimate test load over estimated flexural failure load was reached by the beams from Group F (strengthened with a steel bar), which had crushing of concrete. As the epoxy mortar was the same for all the NSM strengthened beams this could be attributed to the capability of the steel to produce big strains after yielding. It should not be forgotten that the concrete of these beams had a lower strength (35.2 and 36.4 MPa) and was more deformable as will be seen. Of course the estimated flexural failure loads for these beams (F.1 and F.2), in average 168 kN were not so high as the estimated flexural failure load for the

FRP strengthened beams - Groups B to E, in average 224 kN. Looking from the other side, ultimate loads 32% higher were obtained with almost the same Area x E (modulus) for the FRP strengthened beams (Groups B to E), in comparison with steel strengthened beams (Group F) as can be seen also in Figure 9, that the increase of the ultimate test loads for the beams are compared.

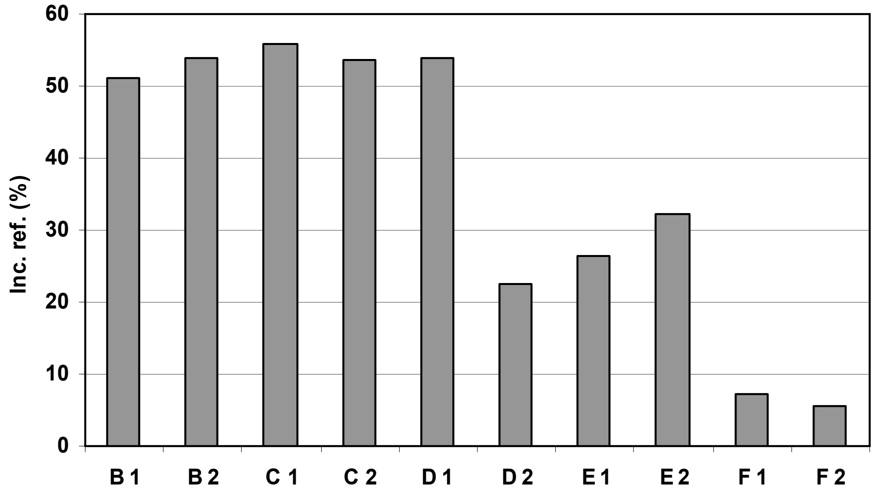

Fig. 9 Load increase in percentage in relation to the reference beam

The best single result among the FRP strengthened beams (Groups B to E) was reached by beam C.1, strengthened with the CFRP bar, which reached an ultimate test load 12% higher than the estimated flexural failure load, and the strains obtained for the concrete suggest that crushing of the concrete was not so close, as will be seen. Of course there are only a few results and the difference is small but the results suggest that the CFRP bar strengthening is the one with best performance among the FRP strengthening procedures tested.

Table 5 Experimental results Concrete and main reinforcement strains

Beam	Streen	Load (kN)	ε_c (‰)	Load (kN)	ε_s (‰)
A.1	Refer.	162.6	1.60	160.0	14.60
A.2		185.1	3.04	--	*
B.1	CFRP strips	240.0	1.62	240.0	15.77
B.2		250.0	1.76	250.0	14.90
C.1	CFRP bar	250.0	1.85	250.0	15.39
C.2		245.0	1.86	245.0	5.99
D.1	GFRP bar	250.0	1.80	250.0	11.32
D.2		220.0	1.89	170.0	3.50
E.1	CFRP laminate	205.0	1.12	205.0	10.43
E.2		215.0	1.22	215.0	11.50
F.1	Steel Bar	198.5	2.77	--	*
F.2		190.0	3.98	--	*
* strain gauge had not worked properly after yielding					

Table 5 presents the maximum concrete and main reinforcement strains registered at the tests, together with the corresponding load step. For the concrete it can be seen that only beams A.2, F.1 and F.2, in which the concrete crushed reached big strains (respectively 3.04, 2.77 and 3.98‰). It can be said that the remaining beams were quite far apart from having crushing at the concrete. For the main reinforcement (Figure 10 left) can be seen that the reinforcement yielded ($\varepsilon y > 4.63‰$) in almost all beams that the strain were registered (Group A to E). In beams A.2, F.1 and F.2 the strain gauges had not worked properly after much yielding.

The strains registered for the composite (Groups B to E) and steel (Group F) strengthening is shown in Table 6 and in Figure 10 right, together with the corresponding load step and the ultimate strains given by the producers. For the beams of Group B the CFRP strips reached in average 71.3% of the ultimate strain given by the producer while for the beams of Group D the GFRP bars reached in average 70% of the ultimate strain given by the producer. For the beams of Group C, in which the CFRP bars were broken at the end of the tests, the registered strains reached before ultimate load was 84.8% of the ultimate strain given by the producer for beam C.1 and 7% higher than the ultimate strain given by the producer for beam C.2. Beams from Group E (externally bonded CFRP laminate) reached in average only 43.2% of the ultimate strain given by the producer.

For the beams of Group F (steel bars) in which there was crushing of the concrete the recorded strains indicating that the reinforcement was quite far from fracturing.

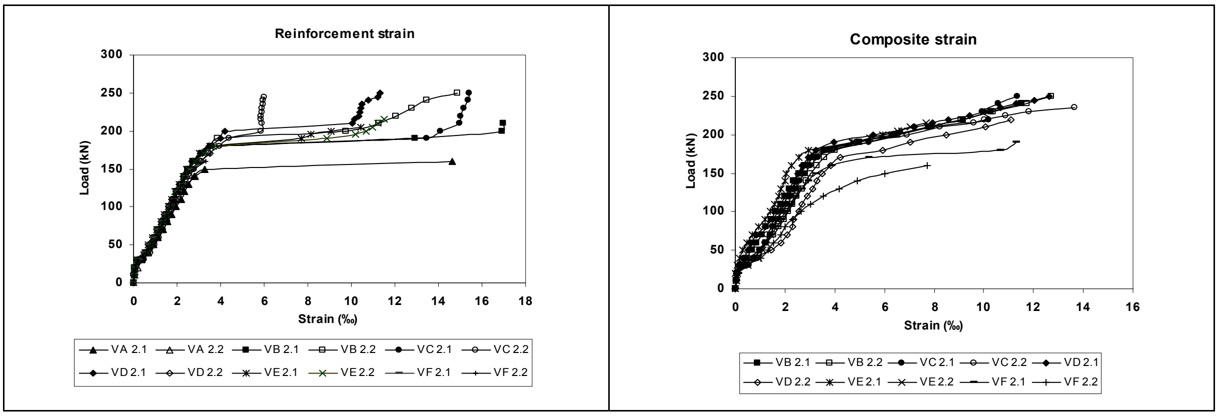

Fig. 10 Steel reinforcement load x strain (left) and composite strengthening load x strain (right)

Table 6 Strengthening strains

Beam	Streng. Type	Load (kN)	ε_f (‰)	ε_{fu} (‰) Maker	ε_{fu} / ε_{fu}
B.1	CFRP strips	240.0	11.52	17.0	0.68
B.2		250.0	12.73	17.0	0.75
C.1	CFRP bar	250.0	11.37	13.4	0.85
C.2		240.0	14.36	13.4	1.07
D.1	GFRP bar	250.0	12.64	17.0	0.74
D.2		220.0	11.08	17.0	0.65
E.1	CFRP laminate	205.0	6.68	16.6	0.40
E.2		215.0	7.66	16.6	0.46
F.1	Steel Bar	190.0	11.30	> 10.0	1.13
F.2		160.0	7.72	> 10.0	0.77

Table 7 shows the maximum vertical displacements registered for the beams with concrete strength ≥ 40 MPa while Table 8 shows the maximum vertical displacements for the with concrete strength < 40 MPa.

Table 7 Maximum vertical displacements – Beams with concrete strength ≥ 40 MPa

Beam	Strength. Type	f_c MPa	Load (kN)	δ_u (mm)	$\delta_u / \delta_{u\ ref}$
A.1	Refer.	46.3	162.4	37.60	-
B.1	CFRP strips	49.5	240.0	56.39	1.50
B.2		52.8	250.0	67.30	1.79
C.1	CFRP bar	52.7	250.0	70.26	1.87
C.2		50.1	245.0	77.83	2.07
D.1	GFRP bar	50.1	210.0	40.56	1.08
E.1	CFRP laminate	40.0	205.0	36.00	0.96
E.2		47.7	215.0	38.77	1.03

Table 8 Maximum vertical displacements – Beams with concrete strength < 40 MPa

Beam	Streng. Type	Load (kN)	δ_u (mm)	$\delta_u / \delta_{u\ ref}$
A.2	Refer.	185.0	171.50	-
D.2	GFRP bar	220.0	65.57	0.38
F.1	Steel Bar	195.0	155.28	0.91
F.2		190.0	158.76	0.93

Beams with concrete strength ≥ 40 MPa (Table 7 and Figure 11 left) from Groups B (B.1 and B.2) and C (C.1 and C.2) reached ultimate vertical displacements at least 50% higher than the reference beam A.1, while beams from Groups D (D.1) and E (E.1 and E.2) reached ultimate displacements about the same of the reference beam A.1, even for much higher ultimate loads.

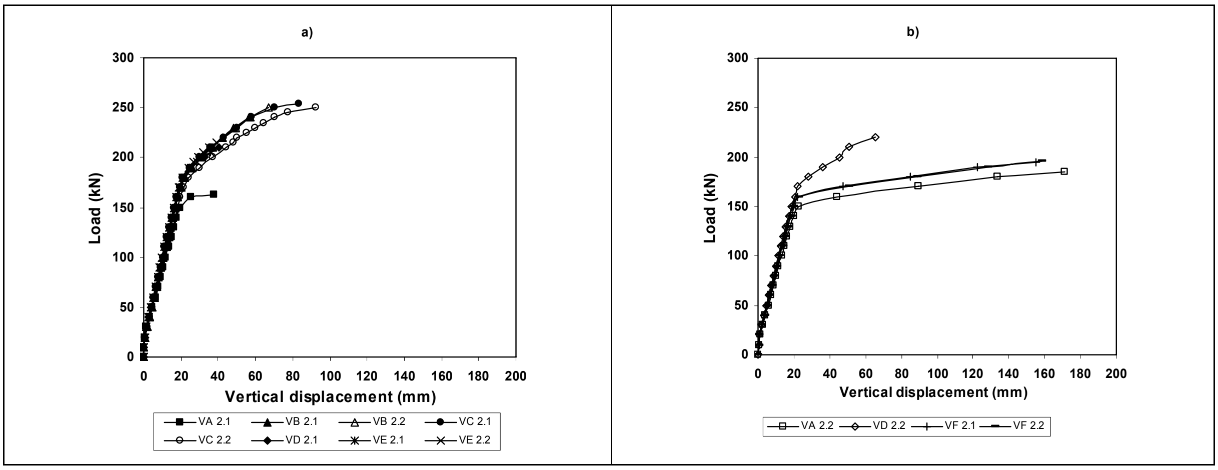

Fig. 11 Load x vertical displacement – Concrete strength ≥ 40 MPa (left) and concrete strength < 40 MPa (right)

For the concrete strength < 40 MPa (Table 8 and Figure 11 right) all beams reached ultimate vertical displacements lower than the reference beam A.2. Beam D.2 reached only 38% of the ultimate load while beams from Group F (F.1 and F.2) reached in average 92% of the ultimate load of the reference beam A.2.

3 CONCLUSIONS

All the strengthening procedures studied at this research worked in terms of ultimate load. The ultimate test load was above the estimated flexural failure load for all beams, despite the premature failures happened for the beams of Groups B (strengthened respectively with CFRP strips) to E strengthened with externally bonded layers of CFRP unidirectional laminate.

Ultimate loads 32% higher were obtained with almost the same Area x E (modulus) for the FRP strengthened beams (Groups B to E), in comparison with steel strengthened beams (Group F).

The best single result among the FRP strengthened beams (Groups B to E) was reached by beam C.1, strengthened with the CFRP bar, which reached an ultimate test load 12% higher than the estimated flexural failure load, and the strains obtained for the concrete suggested that crushing of the concrete was not so close.

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