Performance of RC Beams Strengthened in Shear with Embedded Through-Section FRP Rods

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ABSTRACT: Embedded through-section technique (ETS) is a recently developed method to increase the shear capacity of reinforced concrete (RC) using fiber reinforced polymer (FRP) rods. For some applications, the ETS method may present advantages over existing methods such as externally bonded FRP sheets (EB FRP) and near surface mounted FRP rods (NSM FRP). The objective of this paper is to present results of an experimental investigation which studies the feasibility of the ETS method and compares the performance of the ETS method with both EB and NSM methods.

Twelve tests are performed on full-scale RC T-beams. The studied parameters are: (1) the performance of the FRP using the ETS method compared to EB FRP sheet and NSM FRP rod methods, (2) the effect of the existence of the internal transverse steel and (3) the effect of internal transverse steel reinforcement ratio (spacing). The test results confirmed the feasibility of the ETS method and revealed that the performance of the beams strengthened in shear using this method is superior compared with that of the beams strengthened with EB and NSM methods.

1 INTRODUCTION

In the last few years the use of externally-bonded (EB) fiber-reinforced polymer (FRP) composites has gained acceptance in the construction engineering community, particularly for strengthening and rehabilitation of reinforced concrete (RC) structures. For shear strengthening, externally bonded (EB) method is generally used, whereby FRP sheets are applied on the side surface of the beams to be strengthened. However, some would argue that the EB method presents shortcomings such as: (i) quality of the concrete strata; (ii) surface preparation; (iii) lack of protection (vandalism /fire); and (iv) debonding. The near surface mounted (NSM) FRP rebar method is another technique successfully used to increase the shear resistance of RC beams. In the NSM method, FRP rods are embedded into grooves intentionally prepared on the concrete cover of the side faces of RC beams. In this method debonding of FRP rods is still inevitable. Recently, a new shear strengthening method (ETS) for RC beams has been developed, where FRP bars (or steel bars) can be epoxy-bonded to vertical holes drilled into concrete to strengthen RC beams in shear (Valerio and Ibell 2003). The proposed technique was shown to be feasible, successful and potentially more effective than other shear strengthening approaches (Valerio et al. 2009).

2 TEST PROGRAM

2.1 *Description of specimens*

The experimental program (Table 1) involves 12 tests performed on 6 full-scale RC T-beams. The T-beams are 4520 mm long. The T-section has overall dimensions of 508 mm (width of flange) by 406 mm (total depth). The width of the web and the thickness of the flange are 152 and 102 mm, respectively. The longitudinal steel reinforcement consists of four 25M bars (diameter of 25.2 mm, area of 500 mm^2) laid in two layers at the bottom and six 10M bars (diameter of 10.3 mm, area of 100 mm^2) laid in one layer at the top. The internal steel stirrups (where applicable) are 8 mm in diameter (area of 50 mm^2).

Table 1. Experimental program matrix

Series / Beam name	Control beam	EB FRP method	NSM FRP	ETS FRP
S0 Series	S0-CON	S0-EB	S0-NSM	S0-ETS
S1 Series	S1-CON	S1-EB	S1-NSM	S1-ETS
S3 Series	S3-CON	S3-EB	S3-NSM	S3-ETS

2.2 *Materials*

The average concrete strength on three 152 mm diameter by 305 mm concrete cylinders is 25 MPa for S0 and S1 series and 35 MPa on average for S3 series. The internal flexural steel have a nominal yield strength of 470 MPa for S0 and S1 series and 650 MPa for S3 series. The shear reinforcement has a nominal yield strength of 540 MPa for S0 and S1 and 650 MPa for S3 series. Sand coated CFRP rods with a nominal diameter of 9.5 mm (area: 71 mm^2) and 12.7 mm (area: 127 mm^2), are used for NSM and ETS strengthening methods, respectively. The average tensile strength and modulus of elasticity of the CFRP rods are 1870 MPa and 143.9 GPa, respectively. The epoxy mechanical properties, as specified by the manufacturer, are: 21 MPa bond strength, 1% elongation at break, 75 MPa compressive strength and 3656 MPa compressive modulus. The CFRP sheet used for EB series is a unidirectional carbon fiber fabric. Table 2 provides the mechanical and elastic properties of the CFRP fabric and rods as provided by the manufacturers.

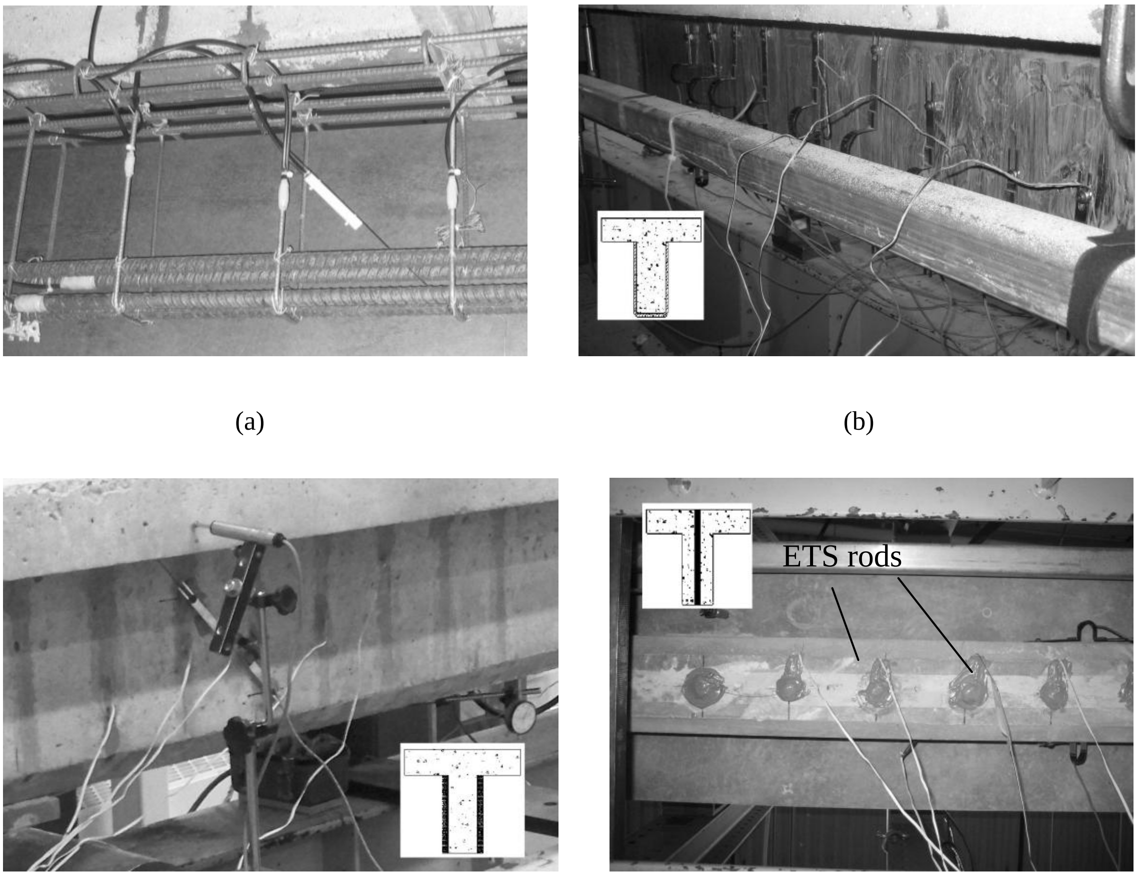
Table 2. Mechanical properties of CFRP sheets and rods used

Property	Modulus of elasticity, GPa	Ultimate elongation, %	Ultimate stress, MPa
Dry fiber sheet	231	1.40	3650
9.5 mm diameter CFRP rod	148	1.27	1885
12.7 mm diameter CFRP rod	140	1.33	1855

2.3 Test setup and procedure

The beams are tested in three-point load flexure. A carefully engineered measuring scheme is adopted for the project (Fig. 1 a-d). The vertical displacement is measured using linear displacement sensors located under the load point and at mid-span, as well as at each side of the supports perpendicular to the flange plan. Strain gauges are glued on the transverse steel and CFRP rods to measure stirrup deformations during the different loading stages and to monitor any yielding in steel and measure the CFRP rod maximum strain. The deformations experienced by the CFRP U-jacket are measured using displacement sensors known as crack gauges.

Three different strengthening systems are used in this research study. The EB FRP, NSM FRP and ETS FRP strengthening techniques are illustrated in Fig. 1 b-d.



(a) (b)

(c) (d)

Figure 1. (a) Strain gauges on transverse steel and embedded in concrete; (b) EB CFRP sheets and crack gauges on CFRP sheets; (c) NSM rods and strain gauges on the rods (side view); (d) ETS rods epoxy-bonded to RC beam's holes (bottom view).

3 PRESENTATION OF RESULTS

Table 3 summarizes the average experimental results obtained from the tests for all the test series.

Table 3. Experimental results

Specimen	Load at rupture kN	Total shear resistance kN	Resistance due to concrete kN	Resistance due to steel kN	Resistance due to CFRP kN	Gain due to CFRP %
S0-CON	122.7	81.3	81.3	0.0	0.0	0
S1-CON	350.6	232.2	81.3	150.9	0.0	0
S3-CON	294.0	194.7	96.2	98.5	0.0	0
S0-EB	181.2	120.0	81.3	0.0	38.7	48
S1-EB	378.5	250.7	81.3	150.9	18.5	8
S3-EB	335.2	222.0	96.2	98.5	27.3	14
S0-NSM	198.0	131.1	81.3	0.0	49.8	61
S1-NSM	365.0	241.7	81.3	150.9	9.5	4
S3-NSM	380.0	251.6	96.2	98.5	56.9	29
S0-ETS	273.0	180.8	81.3	0.0	99.5	122
S1-ETS	397.0	262.9	81.3	150.9	30.7	13
S3-ETS	425.5	281.8	96.2	98.5	87.1	45

4 DISCUSSION OF RESULTS

Performance of RC beams strengthened with ETS method - Table 3 shows that the strengthened beams experienced significant increase in capacity with respect to the control beams. In average, the beams strengthened with EB CFRP U-jacket sheet and NSM were about 23% and 31% stronger than the corresponding control beams, respectively. For the beams strengthened with ETS method, these numbers jump to 60% over the control beam in average. This confirms that ETS FRP outperformed the other two retrofitting techniques and can be a cost-effective method for strengthening RC beams deficient in shear.

Effect of transverse steel - As previously established (Chaallal et al. 2002; Pellegrino and Modena 2002 and Bousselham and Chaallal 2004), the presence of transverse steel resulted in a significant gain decrease for the beams strengthened with EB FRP method. Thus, the gain in the specimen S0-EB with no transverse steel is 48%, compared to 8% and 14.0% for beams S1-EB (spacing = 175 mm) and S3-EB (spacing = 260 mm). In the beams strengthened with the NSM method the gain drops from 61% for S0-NSM to 4% and 29% for beams S1-NSM and S3-NSM, respectively.

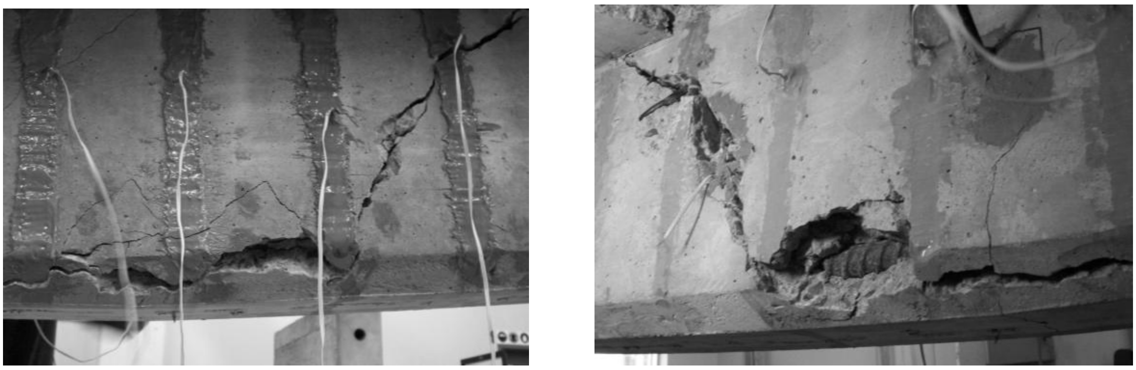

(a) (b)

Figure 2. Common failure mode in beams strengthened with NSM method: (a) Cracking pattern; and (b) detachment of concrete cover.

Finally, in the beams strengthened with the ETS method the gain due to FRP attained 122% in beam S0-ETS, compared to 13% and 45% for beams S1-ETS and S3-ETS, respectively. However, it should be noted that beams S1-ETS and S3-ETS reached their ultimate. Therefore, the gain due to ETS strengthening method in the beams with stirrups would have been higher, had failure did not occur by flexure or concrete cross section limitations. In addition, it should be noted that the resistance due to FRP has not significantly changed in the specimens with transverse steel strengthened with ETS method. This shows that the effect of transverse steel in inhibiting the effectiveness of FRP is less pronounced in the ETS method in comparison to EB method and NSM method.

Internal transverse steel reinforcement ratio (spacing) - Series S1 and S3 differed by the spacing of the transverse steel reinforcement: *d/2* for S1 and *3d/4* for S3 series, where *d* is he effective depth of the beams cross-section. In EB specimens, the gain due to FRP decreases as the spacing of the transverse steel reinforcement is reduced,. This is attributed to the fact that the cracking pattern became more distributed as the spacing of the steel striups was reduced resulting thereby in a decrease in the bond force in the FRP fibers. Therefore, the specimen S1-EB started debonding at a lower FRP strain than S3-EB. It follows that the gain in S1-EB is lower than that of S3-EB specimen.

In NSM strengthened specimens, decreasing the spacing of the transverse steel reinforcement resulted in a lower gain for the S1-NSM compared to S3-NSM specimen. As the spacing of the steel stirrups was reduced, the effect of steel stirrup vertical legs, causing the side concrete of RC beam to detach, increased. Therefore, the specimen S1-NSM started debonding at a lower FRP strain than S3-NSM. It follows that, the gain in the S1-NSM is lower than that of S3-NSM specimen. Similar failure effect has been reported by De Lorenzis and Nanni (2001).

In the specimens strengthened using ETS method, it seems that decreasing the spacing of the transverse steel resulted in a lower resistance gain due to FRP. However, the failure modes of S1-ETS and S3-ETS beams were governed by flexure. Therefore, S1-ETS and S3-ETS beams did not reach their maximum shear capacity and hence the effect of transverse steel for these specimens could not be analyzed.

5 CONCLUSIONS

Based on results of the present investigation, the following main conclusions can be drawn:

- FRP systems and, in particular, ETS FRP strengthening system can significantly enhance the shear capacity of RC beams even in presence of a limited amount of transverse steel reinforcement. In this study, the average increase in shear capacity reached 23% for the beam strengthened with EB U-jacket sheet, 31% for the beams strengthened with NSM FRP rods and 60% for the beams strengthened with ETS FRP rods. The ETS technique was more efficient in terms of developing FRP tensile strength potential before the final failure happens;
- Beams strengthened with EB failed by FRP sheet debonding, whereas beams strengthened with NSM failed by separation of the side concrete covers at the internal steel stirrups. The failure in the beams strengthened with ETS FRP rods was mainly in flexure (S1 and S3 series).
- The presence of the transverse steel resulted in a decrease of the contribution of FRP to the shear resistance for the beams strengthened with EB and NSM methods. The contribution of FRP did not significantly decrease with the presence of transverse steel reinforcement in the specimens strengthened with the ETS method.
- Given the load, the strain in the transverse steel was significantly greater in specimens with no CFRP. Nevertheless, the transverse steel yielded in most cases, as assumed by design codes and standards.

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