Use of Anchors in Shear Strengthening of Reinforced Concrete T-Beams with FRP

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Abstract: This paper presents an experimental investigation on the effectiveness of various types of spike anchors in combination with U-shaped fiber-reinforced polymer (FRP) jackets for shear strengthening of reinforced concrete T-beams. The parameters examined include the orientation, the number and spacing of anchors, and the role of carbon versus glass fibers in the anchors. It is concluded that anchors placed inside the slab are many times more effective than those placed horizontally inside the web, and anchors of similar geometrical characteristics (e.g., embedment length) display similar effectiveness despite the difference in fiber type. **DOI: 10.1061/(ASCE)CC.1943-5614.0000316.** © *2013 American Society of Civil Engineers.*

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Introduction and Background

The use of fiber-reinforced polymers (FRP) as shear strengthening materials for RC elements has become quite popular because of the outstanding combination of properties (low weight, easy handling and application, high strength, immunity to corrosion, minimal disruption) offered by FRP. A common field of application is that of externally applied jacketing in RC beams to enhance shear resistance. Investigations on shear strengthening of RC with FRP started in the 1990s (e.g., Triantafillou 1998; Khalifa et al. 1998) and have been numerous since then. Shear strengthening projects in RC beams are typically realized through the use of three-sided (U-shaped) jackets comprising unidirectional sheets (with fibers in the direction perpendicular to the member axis) wrapped around the web of T-beams. The primary advantage of this configuration is simplicity of application, whereas the key disadvantage is premature debonding of the FRP sheets as forces are transferred from the concrete member into the FRP through interface bond.

The effectiveness of externally applied FRP in shear strengthening of T-beams may be improved by providing anchorage at the two ends of the U-shaped jacket. Anchorage systems typically involve the use of metallic elements (e.g., plates and bolts) or FRP anchors. Metallic anchorages have been investigated by Sato et al. (1997a, b) and Galal and Mofidi (2010). Despite their effectiveness, these anchors are rather heavy, incompatible with jacket materials, and require protection against corrosion. FRP anchors comprise either near-surface mounted (NSM) bars placed at the reentrant corners between slab and web (e.g., Eshwar et al. 2008) or resin-impregnated fiber rovings, often referred to as spike anchors. Spike anchors are more practical to use and have received the attention of some investigators in a few studies related to tensile properties (Ozbakkaloglu and Saatcioglu 2009; Kim and Smith 2010), bond aspects (Eshwar et al. 2008; Niemitz et al. 2010; Ceroni and Pecce 2010; Huaco et al. 2011), confinement of columns (Karantzikis et al. 2005; Kim et al. 2011a), flexural strengthening of beams or slabs (Ekenel et al. 2006; Orton et al. 2008; Smith et al. 2011), flexural strengthening of columns (Vrettos et al. 2013), and shear strengthening of columns (Nagai et al. 1999; Kobayashi et al. 2001).

Studies on the use of spike anchors in shear strengthening of beams are limited to Jinno et al. (2001) and Kim et al. (2011b). Jinno et al. (2001) presented test results on T-beams strengthened with U-shaped CFRP sheets combined with spike anchors placed vertically inside the slab and reported that this method is quite promising in shear strengthening. In a similar study, Kim et al. (2011b) placed spike anchors horizontally inside the web and, on the basis of five experiments, they reported a 40–45% increase in shear strength when anchored CFRP strips were installed on the webs of T-beams.

From the preceding literature survey, it is clear that studies on FRP shear strengthening of T-beams in combination with spike anchors have been extremely limited. In this paper, the authors investigate this problem experimentally in further detail by examining parameters not studied before: the relative performance of anchors placed horizontally (in the web) versus vertically (in the slab); the number and spacing of anchors; and the role of carbon versus glass fibers in the anchors. Details are provided in the following sections.

Experimental Program

Test Specimens and Experimental Parameters

The experimental program aimed to study the role of spike anchors in three-sided jacketing (U-jackets) of reinforced concrete T-beams strengthened in shear and to compare the effectiveness of different anchor schemes. A total of six beams with the same geometry were constructed and tested as simply supported in monotonic nonsymmetric three-point bending (Fig. 1). All beams had a flexural resistance well above their shear resistance at the short shear span;

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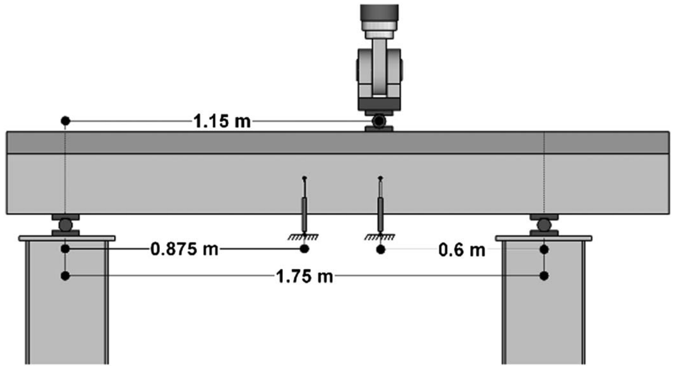

Fig. 1. Test setup

hence, only shear failures could develop and be examined accordingly. Details of beam geometry and reinforcement are given in Fig. 2.

The specimens were designed such that the role of three basic parameters on the effectiveness of shear strengthening schemes could be investigated, namely, the orientation of anchors, the number of anchors in the shear span, and the type of fibers used both for the FRP jackets and for the anchors. The following description of the specimens is supported by Figs. 3 and 4:

- One beam (CON) was tested without shear strengthening, as control (Fig. 3a).
- Specimen U2C was strengthened with two layers of epoxy-impregnated unidirectional carbon fiber sheets wrapped around the web at the shear-critical span without any anchors [Fig. 3(b)]. Each layer had a nominal thickness (corresponding to dry fibers) of 0.115 mm.
- Specimen U2C-AN3Ch was strengthened with the same materials as U2C and combined with three carbon fiber spike anchors at each side of the shear span at a spacing of 167 mm. The part of the anchors placed inside the concrete was horizontal [Fig. 3(c)].
- Specimen U2C-AN3Cin was strengthened as U2C-AN3Ch except that the part of the anchors placed inside the concrete was inclined at an angle approximately equal to 25° with respect to the vertical [Fig. 3(d)]. Note that this angle was chosen for practical reasons because it is extremely difficult and expensive to drill vertical holes inside slabs exactly at the corners where they meet the web.
- Specimen U2C-AN5Cin was strengthened as U2C-AN3Cin except that the number of anchors at each side of the shear span was five instead of three at a spacing of 100 mm [Fig. 3(e)].
- Specimen U2G-AN3Gin was strengthened as U2C-AN3Cin [Fig. 3(f)] except that the fibers in both the U-shaped sheets and the anchors were made of glass instead of carbon.

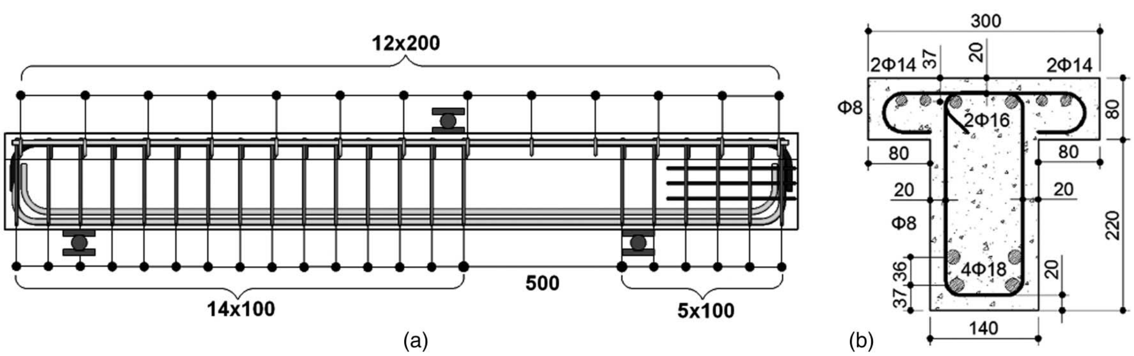

Fig. 2. (a) Beam geometry and reinforcement; (b) cross section (dimensions in mm)

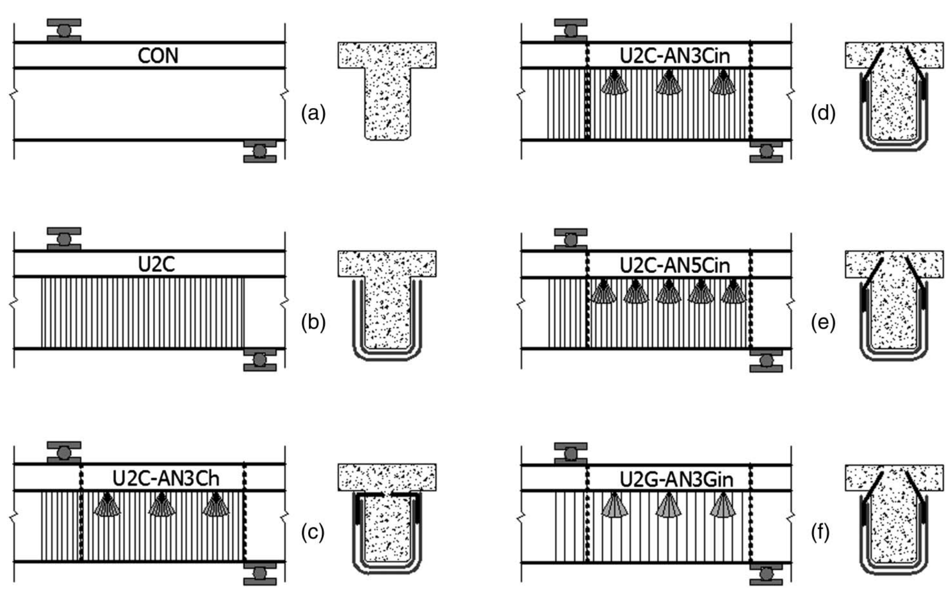

Fig. 3. Strengthening configuration for the six beams tested

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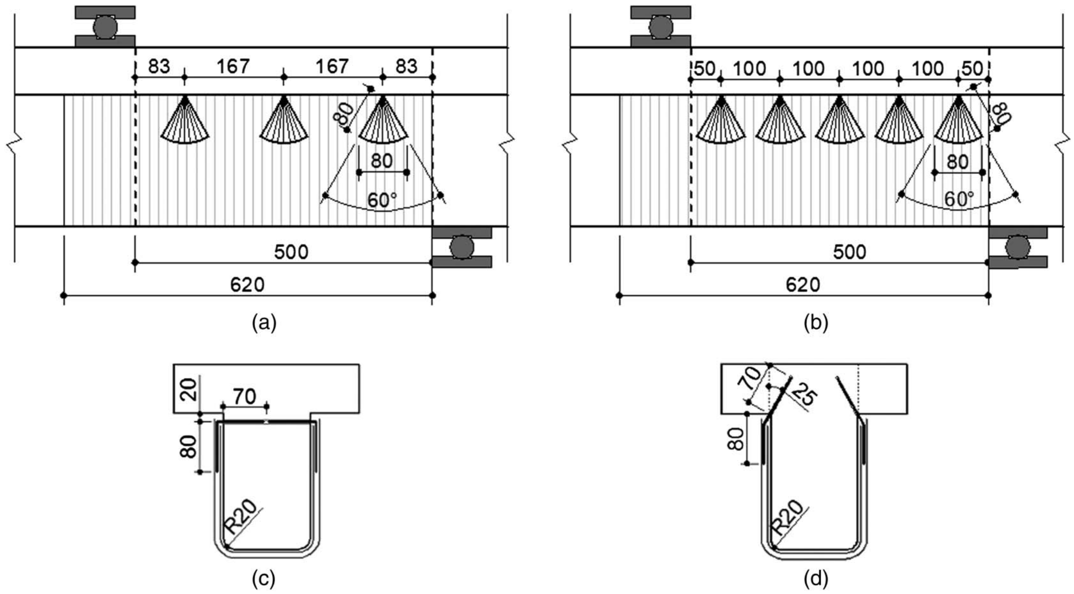

Fig. 4. Configuration of anchors for beams (a) U2C-AN3Ch, U2C-AN3Cin, U2G-AN3Gin; (b) U2C-AN5Cin; (c) U2C-AN3Ch; (d) U2C-AN3Cin, U2C-AN5Cin, U2G-AN3Gin (dimensions in mm)

The sheets had a nominal thickness of 0.36 mm and the anchors were identical to the ones made of carbon except for the type of fiber and the nominal diameter, which, in the case of glass anchors, was higher by approximately 15%.

Materials and Strengthening Procedures

Casting of the beams was made with the same batch of ready-mix concrete. The average compressive strength on the day of testing the beams, measured on 150×150 mm cubes (average values from three specimens), is given in Table 1. Cylinders with a diameter of 150 mm and a height of 300 mm were also used to obtain the splitting tensile strength of the concrete; the average tensile strength which was obtained from six specimens on the day of testing the beams is given in Table 1. Strength properties (average values from three specimens) for all the different diameter steel used for longitudinal and transverse reinforcement are listed in Table 2.

The carbon fiber sheet used for shear strengthening was a commercial unidirectional fiber product with a weight of 200 $\mathrm{g/m^2}$ and a nominal thickness (based on the equivalent smeared distribution of fibers) of 0.115 mm. The mean tensile strength and elastic modulus of the fibers (as well as of the sheet when the nominal thickness is used) was taken from manufacturer data sheets equal to 3,790 MPa and 230 GPa, respectively. The carbon fiber sheet was impregnated with a commercial low viscosity structural adhesive (two-part epoxy resin with a mixing ratio 3:1 by weight) with tensile strength of 72.4 MPa and an elastic modulus of 3.2 GPa (cured three days at 60°C). Values of tensile strength and elastic modulus for the epoxy-impregnated carbon sheet were taken from manufacturer data sheets equal to 1,062 MPa and 102 GPa, respectively, corresponding to a thickness equal to 0.18 mm.

Table 1. Strength of Concrete on the Day of Testing the Beams

Specimen notation	Concrete strength f_c (MPa)	Concrete splitting strength $f_{ct,sp}$ (MPa)
CON	22.5	2.50
U2C	22.7	2.52
U2C-AN3Ch	22.3	2.48
U2C-AN3Cin	22.2	2.45
U2C-AN5Cin	22.9	2.54
U2G-AN3Gin	22.9	2.58

Table 2. Strength Properties of Steel Reinforcement

Diameter (mm)	Yield stress f_y (MPa)	Tensile strength f_u (MPa)
8	548	664
14	509	608
16	543	654
18	546	661

The glass fiber sheet used in specimen U2G-AN3Gin was a commercial unidirectional fiber product with a weight of 915 $\mathrm{g/m^2}$ and a nominal thickness of 0.36 mm. The mean tensile strength and elastic modulus of the fibers (as well as of the sheet when the nominal thickness is used) was taken from manufacturer data sheets equal to 3,240 MPa and 72.4 GPa, respectively. The same adhesive used for the carbon fiber sheets was also used for the glass fiber sheet. Values of tensile strength and elastic modulus for the epoxy-impregnated glass sheet were taken from manufacturer data sheets equal to 575 MPa and 26.1 GPa, respectively, corresponding to a thickness equal to 1.17 mm. The glass fiber sheet had an axial stiffness (calculated as the product of elastic modulus times nominal thickness of dry fibers) equal to that of the carbon sheet.

Each anchor comprised a tow of fibers of the same type used in the unidirectional sheets. The length of anchors was 150 mm and their weight was 34 g/m and 59 g/m for carbon and glass fiber anchors, respectively. Impregnation and bonding of fiber anchors was done using the same epoxy adhesive used for the impregnation of the carbon sheets.

The fiber sheets were bonded on the properly prepared concrete surface of the web in a U-shaped configuration. Preparation of the concrete surface was made through the use of a grinding machine. The sheets were placed with the fibers vertical and covered the shear span where shear failure was expected to develop. To avoid stress concentrations in the jacket, the two edges of each beam were rounded to a radius equal to 20 mm.

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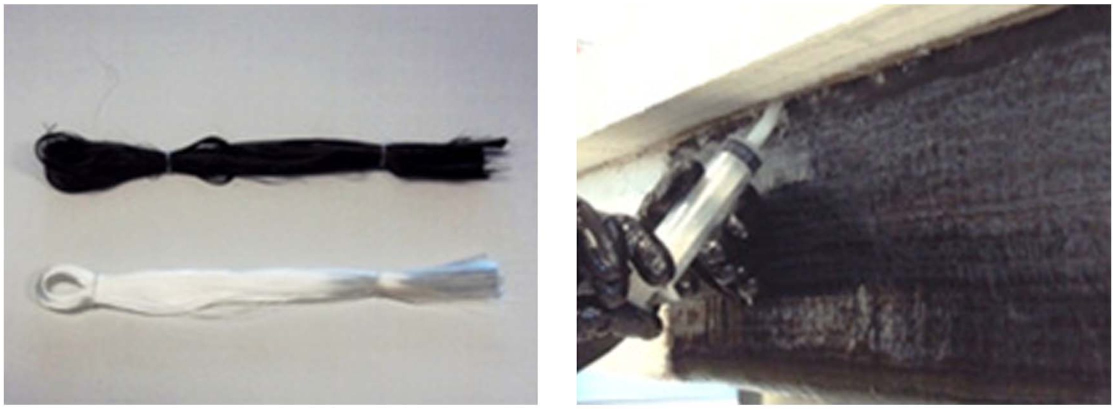

(a) (b)

Fig. 5. (a) Anchors; (b) filling of hole with epoxy resin

Fiber anchor spikes were formed by impregnating dry fibers [Fig. 5(a)] with epoxy. Holes were drilled into the beam with the dimensions of 70 mm in depth and 12 mm in diameter. The holes were filled with epoxy [Fig. 5(b)] to half of their depths. Each anchor spike was inserted into the holes after applying the first layer of the FRP sheet around the web, and the protruding dry fibers were fanned out over the first layer of the sheet at an angle of 60° [Figs. 4(a and b)]. This method of anchoring was selected on the basis of transferring the tension forces from the FRP sheet terminating below the concrete slab into the web for specimen U2C-AN3Ch or into the slab for all other specimens with anchors.

Experimental Setup and Procedure

The beams were subjected to monotonic transverse loading using a stiff steel frame (Fig. 1) at a total span of 1.75 m and a shear span of 0.60 m. The load was applied using a vertically positioned 500 kN MTS actuator at a displacement rate of 0.01 mm/s. Displacements were measured at the position of load application and at midspan by using external variable differential transducers (LVDT) mounted on the side of each beam. To record strains in the strengthening jackets, a set of nine electrical strain gauges was applied at the short shear span on the outside of the FRP. The exact position of the strain gauges is illustrated in Fig. 6. A point of concern is that strains in the FRP may not be uniform across its thickness, especially near the vicinity of fanned out anchor fibers (G1, G2, and G3). However, because the number of layers (two), the nominal thickness of each fiber sheet, and the thickness of the fanned out anchors are all minimal, the assumption is made that strains across the FRP thickness are not too different; hence, those recorded by the strain gauges may be considered to be average across the thickness.

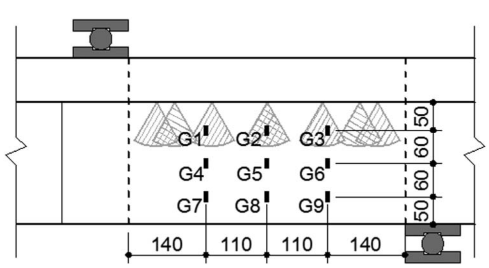

Fig. 6. Position of strain gauges in shear span (dimensions in mm)

Additional strain gauges were attached to the longitudinal rebars, both in tension and compression, at the cross section of maximum moment. Data from the load cell, the actuator's displacement transducer, the external LVDTs, and the strain gauges were recorded using a fully computerized data acquisition system.

Experimental Results

Fig. 7 shows the load versus displacement at the section of load application of the six beams tested. The control beam (CON) failed in shear, as expected, through the formation of shear cracks in the shear span [Fig. 8(a)], at an ultimate load of 113 kN. An interesting observation during this test was that no sudden drop in the load was recorded after diagonal cracking owing to the considerable contribution to shear resistance provided by the strong dowel action of the longitudinal reinforcement.

Beam U2C failed in a similar way but at a higher load, equal to 157 kN, owing to contribution of the jacket to the shear resistance. As expected, the formation of diagonal cracking resulted in debonding of the jacket at the part crossed by the shear crack [Fig. 8(b)]. According to strain measurements provided by the strain gauges just before debonding, the jacket was most highly stressed at its part above the diagonal crack and near the support, where the bond length above the crack is maximum. The average strain in this part (mean value obtained from gauges G3, G6,

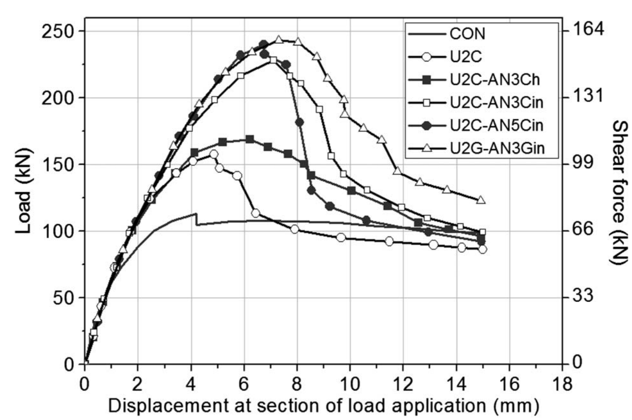

Fig. 7. Load versus displacement (at section of load application) curves

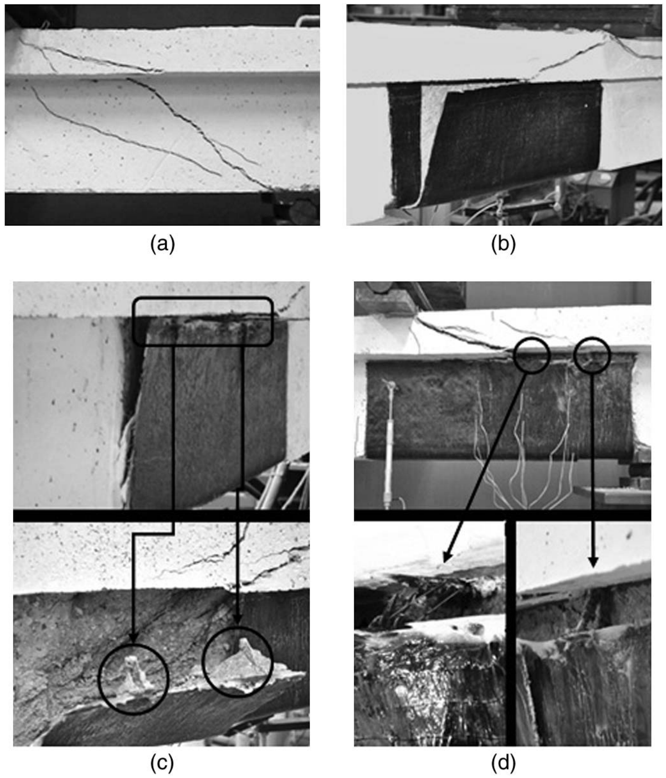

Fig. 8. (a) Shear cracking in beam CON; (b) shear cracking and debonding of the jacket in beam U2C; (c) pullout of anchors and debonding of the jacket in beam U2C-AN3Ch; (d) rupture of one anchor (left) and pullout of another (right) in beam U2C-AN3Cin

and G9) corresponding to debonding was equal to 0.0022, whereas the average strain obtained from all gauges was equal to 0.0014.

Beam U2C-AN3Ch failed in shear at a higher load, equal to 169 kN, as a result of improved bond conditions of the FRP owing to the horizontal anchors. Failure of the specimen was accompanied by pullout of two anchors on each side of the beam and debonding of the jacket [Fig. 8(c)]. The anchors that pulled out at peak load were the ones above the diagonal crack (closest to the support) because these were the most highly stressed. The average recorded FRP strain at debonding obtained from all gauges was equal to 0.0016.

Beam U2C-AN3Cin failed in shear at an even higher load, equal to 228.5 kN, owing to the favorable anchorage conditions provided by the inclined anchors. Failure of the specimen was accompanied by rupture of the middle anchor on one side of the beam followed by pullout of the symmetric anchor on the opposite side and of the two anchors (one on each side) near the support [Fig. 8(d)]. In this case also, the anchors that failed were the ones above the diagonal crack. The average strain recorded at debonding by all gauges in the FRP was equal to 0.0025.

Beam U2C-AN5Cin, with five anchors on each side of the shear span instead of three, failed in shear at a load equal to 240 kN. The maximum load was reached when three central anchors on one side of the jacket ruptured and the jacket debonded; this was followed by pullout of the symmetric anchors on the opposite side. As illustrated in Fig. 9, the development of strains in the FRP jacket is nonuniform despite the relatively large number of anchors; strains are higher in the part of the jacket near the support. The average recorded strain in the FRP at debonding was equal to 0.0026.

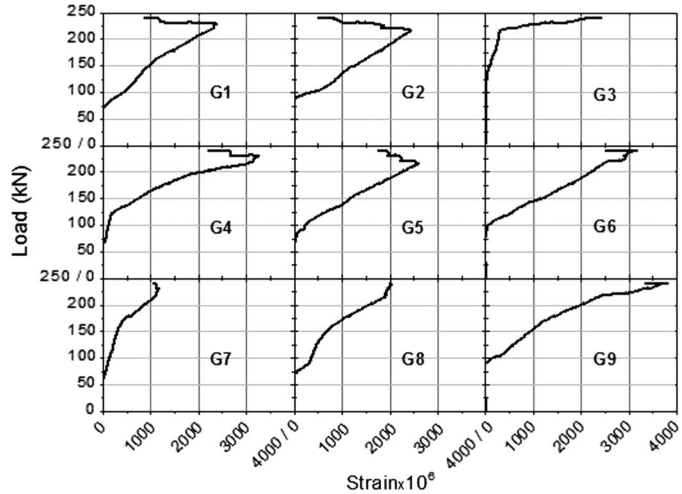

Fig. 9. Strains recorded by the strain gauges as a function of the applied load for beam U2C-AN5Cin

Finally, beam U2G-AN3Gin, with glass fibers instead of carbon, failed in shear at a load equal to 244 kN. Peak load was reached when the central anchors on each side of the beam pulled out and the jacket debonded. The average strain recorded at debonding by all gauges in the FRP was equal to 0.0029.

Discussion

Effectiveness of Different Anchor Schemes

The test results are summarized in Table 3, which also gives the experimental shear resistance for each specimen, calculated as the shear force in the shear span at failure. In agreement with nearly all analytical models for the contribution of FRP jackets to the shear resistance, one may assume that the shear resistance of a strengthened specimen minus the resistance of the control gives the contribution of the strengthening system to the total resistance. This value is given in Table 3 as a percentage of the control specimen's resistance. It was demonstrated that the CFRP jacket without anchors increased the strength by 39%, the same jacket with three horizontal anchors (on each side) by 50%, with three inclined anchors by 103%, and with five inclined anchors by 114%; the GFRP jacket with three glass fiber anchors increased the resistance by 116%.

A comparison of the results for specimens U2C and U2C-AN3Ch shows that use of three horizontal carbon anchors on each side of the beam increases the effectiveness of the jacket by only 28% [$= (50 - 39)/39$]. However, if the same anchors are used in a nearly vertical configuration (specimen U2C-AN3Cin), the increase becomes equal to 164%, which is quite substantial. Hence, (nearly) vertical anchors were found to be approximately six times more effective in comparison with their horizontal counterparts. This result is not surprising because, unlike nearly vertical anchors, fibers in horizontal anchors are hardly activated in tension.

A comparison of the results for specimens U2C-AN3Cin and U2C-AN5Cin shows that increasing the number of anchors provides a nonproportional increase in their effectiveness. With five anchors on each side of the shear span instead of three, the increase in effectiveness of the jacket was 192% instead of 164%. A possible explanation for this may be seen in Fig. 10, which illustrates that only those anchors above the shear crack are fully active in carrying

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Table 3. Summary of Test Results and Comparison of Strengthening Schemes

Specimen notation	Strengthening scheme	Peak force (kN)	Failure mode	Shear resistance (kN)	Increase in shear resistance owing to strengthening (%)	Effectiveness of anchors
CON	—	113.0	DC[a]	74	—	—
U2C	2 layers of CFRP, no anchors	157.0	DC, D[b]	103	39	—
U2C-AN3Ch	2 layers of CFRP, 3 horizontal CFRP anchors per side of shear span	169.0	DC, D, P[c]	111	50	1.28
U2C-AN3Cin	2 layers of CFRP, 3 inclined CFRP anchors per side of shear span	228.5	DC, D, R[d]+P	150	103	2.64
U2C-AN5Cin	2 layers of CFRP, 5 inclined CFRP anchors per side of shear span	240.0	DC, D, R+P	158	114	2.92
U2G-AN3Gin	2 layers of GFRP, 3 inclined GFRP anchors per side of shear span	244.0	DC, D, P	160	116	Not applicable

[a]Diagonal cracking.
[b]Debonding of FRP.
[c]Anchor pullout.
[d]Anchor rupture.

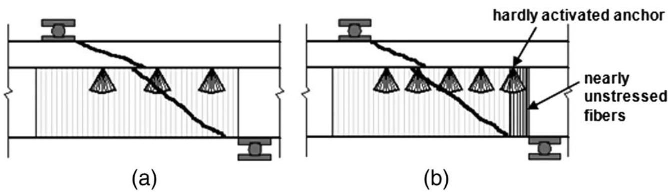

Fig. 10. Anchors fully activated in beams (a) U2C-AN3Cin and U2G-AN3Gin; (b) U2C-AN5Cin

tension. Those anchors are two (on each side) for specimen U2C-AN3Cin [Fig. 10(a)] and slightly more than three (on each side) for specimen U2C-AN5Cin: the anchor near the support was hardly activated because many of the fibers in the jacket below this anchor were outside the cracked zone of the beam [Fig. 10(b)].

Finally, the results are compared for specimens U2C-AN3Cin and U2G-AN3Gin, which were different only with respect to the type of fibers used in both the jacket and the anchors. The two jackets in these specimens had the same axial stiffness; hence, in view of the fact that none of the jackets failed, it may be assumed that any difference in the response may be attributed to the anchors. This difference is minimal, which may be explained by the fact that nearly all anchors which failed in beam U2C-AN3Cin and all anchors which failed in beam U2G-AN3Gin pulled out according to the classical concrete cone failure mode; hence, pullout forces were independent of anchor materials. In conclusion, the two different fiber systems displayed a similar performance.

Force Carried by the Inclined Anchors

On the simplifying assumption that a total of four anchors were equally activated in specimen U2C-AN3Cin (see the preceding discussion), one may estimate the force carried by each anchor at shear failure as the difference in shear resistance between specimens U2C-AN3Cin and U2C divided by four, that is $(150 - 103)/4 = 11.75$ kN. The same exercise may be repeated for specimen U2C-AN5Cin, assuming that the anchor on each side of the beam near the support was activated very little. This implies that a total of six anchors were equally activated in this specimen; hence, the force carried by each anchor is estimated as $(158 - 103)/6 = 9.17$ kN, a value 20% lower but not much different from the value obtained for U2C-AN3Cin. These values, which have been obtained on the basis of simplifying assumptions, could be different in the case of anchor embedment lengths different from those used in this study (70 mm) because failure of some anchors was attributable to pullout.

Conclusions

This paper presents an experimental investigation on the effectiveness of various types of spike anchors in combination with U-shaped FRP jackets for shear strengthening of RC beams. The design of specimens allowed for an investigation of the orientation, the number and spacing of anchors, and the type of fibers. The primary conclusions are summarized as follows:

- Spike anchors increase substantially the effective strains in U-shaped jackets, thereby providing a viable solution towards enhancing the shear resistance of RC T-beams.
- Anchors placed inside the slab (that is, nearly vertical) are many times more effective than those placed horizontally inside the web.
- Increasing the number of anchors in the shear span results in nonproportional increase in shear resistance because those anchors not above shear cracks are not activated.
- Anchors of similar geometrical characteristics (e.g., embedment length) display similar effectiveness despite the difference in the type of fiber.

In view of the limited number of tests performed in this study, the aforementioned results should be considered as rather preliminary. Future research should be directed toward providing a better understanding of parameters including anchor embedment length, amount of fibers in the anchors, and different beam dimensions.

Acknowledgments

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