INVERTED T-SECTION RC BEAMS SHEAR STRENGTHENED WITH ANCHORED FRP STRIPS: SHEAR INTERACTION

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ABSTRACT

This paper presents the test results of six T-section beams shear-strengthened with anchored FRP U-strips in the negative moment region. The six full-scale T-section beams can be divided into two groups: beams with and without steel stirrup. In each group, one control beam without any strengthening, another beam was strengthened with CFRP U-strips for comparison, the third was strengthened with CFRP U-strips anchored with a new patented end anchor. To investigate the shear behavior of T-section beams shear-strengthened in negative moment region as in practice (e.g. cantilever beams and continuous beams), the T-section beams were tested inverted under four-point bending so that the flange was in tension. The test results showed that the end anchors used in this study changed the failure mode of the strengthened beam from FRP debonding failure to FRP rupture failure, and significantly enhanced the shear strengthening effect of the strengthened beam. From the large number of strain values measured in this study, it was shown that apparent adverse shear interaction exists between FRP and concrete.

1 INTRODUCTION

In the past decade, structural strengthening using externally bonded (EB) fiber reinforced polymer (FRP) composites has become a widely adopted method, with shear strengthening of RC beams using EB FRP one of such applications [1]. When using EB FRP in shear strengthening of RC beams, one of the following strengthening configurations is usually adopted: full wraps, U-strips and FRP side strips. Existing studies have shown that beams shear strengthened with FRP full wraps usually fail by FRP rupture and the vast majority of beams strengthened using FRP U-strips and all those strengthened with side strips fail by FRP debonding [2]. When debonding failure occurs, the FRP stress is controlled by the debonding stress (or strain) which is mainly determined by the bond strength of FRP-to-concrete bonded interface and the high strength of FRP is not fully utilize. In practical applications such as strengthening of T-section beams, FRP U-strips are widely adopted because FRP full-wraps can not be easily implemented. This has necessitated the development of different types of anchors to avoid the detrimental effects of FRP debonding. When T-section beams are shear-strengthened with anchored FRP U-strips, the failure mode as well as the shear-resistance mechanism of the strengthened beam can be quite different from rectangular beams shear-strengthened with FRP full-wraps due to the different configurations of both FRP and beam sections. As a result, some of the recent research efforts have been directed at addressing the issues related to the behavior of T-section RC beams shear-strengthened with anchored FRPs (e.g. [3]). This paper presents an experimental study of six T-section beams shear-strengthened with anchored FRP U-strips in negative moment region. A newly
patented end anchor (China Patent No. ZL201520085446.9) as schematically shown in Fig. 1(b) was used to anchor the FRP U-strips. The merits of applying the anchor were demonstrated in terms of the enhanced shear capacity as well as the change of failure mode from FRP debonding to FRP rupture failure. From the large number of strain values measured in this study, the apparent adverse shear interaction existing between FRP and concrete was evident.

2 EXPERIMENTAL PROGRAM

The experimental program included six T-beam specimens in two groups: one with and another without steel stirrups, as shown in Table 1. Each group consists of one control beam without strengthening, one beam strengthened by FRP U-strips only and the third strengthened with anchored FRP U-strips in the test shear span. The beams were over-reinforced in flexure to ensure that shear failure dominates the failure mode. In the untested shear-span, the beams were over-reinforced in shear with 10 mm diameter deformed steel stirrups at a center-to-center spacing of 50 mm and continuous CFRP sheets with the same material as the CFRP U-strips to ensure that shear failure occurred in the test span. The tensile strength and modulus of elasticity of the CFRP were 4406 MPa and 211GPa respectively. The yield strength of the stirrups was 308 MPa. Other details of the beams can be found in Chen et al. [4].

The T-section beams were tested inverted under four-point bending so that the beam flange was in tension, as schematically shown in Fig. 1. The test set-up is similar to that used by Higgins et al. [5] and Luo [6].

To measure the strain distributions in the CFRP U-strips, three strain gauges were bonded at each side of the U-strips (i.e. six strain gauges for each U-stripe). The locations of the strain gauges are shown in Fig. 2

![Dimensions of beam specimens](image1)

![Schematic diagram of the anchoring device](image2)

Figure 1  Details of beam specimens (units: length in mm; area in mm$^2$)
3 TEST RESULTS AND DISCUSSIONS

3.1 Failure mode and shear capacity

Of the six beams, the control beams S0-C and S6-C failed in shear featured by shear compression failure near the loading point, the strengthened beams S0-U and S8-U failed in shear due to FRP debonding, and the strengthened beams S0-UA and S6-UA with anchors failed in shear by FRP rupture. The use of the end anchor significantly increased the shear enhancement as shown in Table 1: for beams without steel stirrups, the shear capacity of strengthened beam with anchored U-strips (S0-UA) was 330.0 kN, which is 80% and 42% higher than the control beam (S0-C) and the FRP U-stripe strengthened beam without anchors (S0-U) respectively; for beams with steel stirrups, the FRP U-stripe strengthened beam with anchors (S6-UA) was 379.6 kN, 26% and 58% higher than the control beam (S6-C) and the FRP U-stripe strengthened beam without anchors (S6-U) respectively. Apart from the effects on failure mode and shear capacity of the strengthened beam, the use of anchors has a significant effect on the crack pattern: the angle of the critical shear crack (with respect to the longitudinal axis of the beam) became steeper compared to the corresponding control beam and the FRP U-strips strengthened beam without anchors (see details in Chen et al. [4]), probably due to the stronger constrain effect of anchored FRP U-strips.

Table 1 Details and failure modes of beam specimens.

<table>
<thead>
<tr>
<th>Beam No.</th>
<th>h (mm)</th>
<th>d (mm)</th>
<th>b (mm)</th>
<th>l0 (mm)</th>
<th>a (mm)</th>
<th>CFRP U-strips</th>
<th>Steel stirrups</th>
<th>Failure load (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S0-C</td>
<td>400</td>
<td>313</td>
<td>200</td>
<td>2640</td>
<td>945</td>
<td>—</td>
<td>—</td>
<td>183.8</td>
</tr>
<tr>
<td>S0-U</td>
<td>400</td>
<td>313</td>
<td>200</td>
<td>2640</td>
<td>945</td>
<td>0.167</td>
<td>50</td>
<td>100</td>
</tr>
<tr>
<td>S0-UA</td>
<td>400</td>
<td>313</td>
<td>200</td>
<td>2640</td>
<td>945</td>
<td>0.167</td>
<td>50</td>
<td>100</td>
</tr>
<tr>
<td>S6-C</td>
<td>400</td>
<td>313</td>
<td>200</td>
<td>2640</td>
<td>945</td>
<td>—</td>
<td>—</td>
<td>ø 6@200</td>
</tr>
<tr>
<td>S6-U</td>
<td>400</td>
<td>313</td>
<td>200</td>
<td>2640</td>
<td>945</td>
<td>0.167</td>
<td>50</td>
<td>100</td>
</tr>
<tr>
<td>S6-UA</td>
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<td>313</td>
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<td>2640</td>
<td>945</td>
<td>0.167</td>
<td>50</td>
<td>ø 6@200</td>
</tr>
</tbody>
</table>

Note: h = beam depth; d = effective beam depth; b = width of beam web; l0 = clear span; a = shear span; t_f = CFRP thickness; w_f = strip width; s_f = centre-to-centre strip spacing
3.2 Shear interaction between FRP and concrete

Based on the measured FRP strain data, the shear contribution of CFRP U-strips \( V_f \) intersected by the critical shear crack can be determined using the approach adopted by Teng et al. [7]; the shear contribution of concrete \( V_c \) or concrete and steel stirrups \( (V_c + V_f) \) can be derived by subtracting \( V_f \) from the total shear force. The development of shear contributions of CFRP strips and concrete for strengthened beam (S0-UA) obtained using this method is shown in Figure 3. For comparison, the shear force versus displacement curve of the corresponding control beam (S0-C) is also shown. It can be clearly seen that before the load approached 100 kN, which was the cracking loading of the control beam at which the critical shear crack could be seen by naked eyes, the shear contribution of FRP was nearly zero but the load-displacement response of the strengthened beam was slightly stiffer than the control beam. The cracking load of the strengthened beam was also slightly higher than that of the control beam due to the beneficial effects of FRP (i.e. the restraint effect of FRP on crack initiation and development). After the appearance of the critical shear crack, the shear contribution of FRP increased quickly, as a result, the shear contribution of concrete in the strengthened beam was lower than that in control beam until the ultimate state of the control beam (point M in Fig. 3). It is worth noting that shortly after point M, the shear contribution of concrete \( V_c \) in the control beam dropped quickly associated with the shear compression failure of the beam, while that of strengthened beam was well maintained until the displacement reaches about 13.4 mm where \( V_c \) in the strengthened beam peaked. At the ultimate state of the strengthened beam (point N in Fig. 3), \( V_c \) of the strengthened beam has been reduced from its peak value by 7.4%, while the shear contribution of CFRP U-strips \( V_f \) was still increasing. It should be noted that only a small part of the test results were presented/interpreted herein due to space limitation. A similar phenomenon can be observed for strengthened with stirrups (S6-UA) as demonstrated in Chen et al. [4]. According to experimental data not shown here (see Ref.[14] for details), the average effective strains of anchored CFRP U-strips are 5439 \( \mu \varepsilon \) and 9276 \( \mu \varepsilon \) for the points M and N respectively, with the former being slightly larger and the latter being significantly larger than 4000 \( \mu \varepsilon \) recommend by ACI 440.2R [8] for preventing significant loss of concrete shear resistance mechanism (e.g. aggregate interlock).

4 CONCLUSIONS

This paper has presented the preliminary results of an experimental study on the shear behavior of T-section RC beams shear-strengthening with anchored CFRP U-strips in the negative moment zone. From the test data, comparisons and discussions presented in this paper, the following conclusions can be drawn:

1. The new end anchor changed the failure mode of the strengthened beam from FRP debonding failure to FRP rupture failure, significantly enhancing the shear capacities of the strengthened beams.

2. Adverse shear interaction exists between concrete and the anchored CFRP U-strips, namely at
The ultimate state of the strengthened beam. The shear contribution of concrete was reduced while that of the anchored CFRP U-strip was still increasing.

3. The average effective strains of anchored CFRP U-strips at the ultimate state of strengthened beam was 9276 με, significantly higher than the ACI. 440.2R recommended value of 4000 με for preventing significant loss of concrete shear resistance mechanism (e.g. aggregate interlock), but this strain level cannot be used as the recommendation for effective strain limit of FRP due to the adverse shear interaction between concrete and FRP.

Further studies are required to quantify the effects of the adverse shear interaction and to development a reasonable design approach capable of considering the effects of shear interaction.

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REFERENCES

[6] Y.L. Luo, T-section RC beams shear-strengthened with FRP U-strips anchored through anchoring bars: an investigation on affecting factors, Changsha: Central South University (MSc Thesis); 2010