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RC T-BEAMS SHEAR-STRENGTHENED WITH CFRP U-STRAPS AROUND BARS PASSING EYE BOLTS PENETRATING FLANGE

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ABSTRACT

Some new strengthening schemes with fibre-reinforced polymer (FRP) sheets have been developed to improve shear behaviour of reinforced concrete (RC) beams. The current work focuses on one of them, which is suitable for RC T-shaped beams when penetration of flange is allowed. In this scheme, U-shaped straps of carbon fibre-reinforced polymer (CFRP) were wrapped around two bars, one of which passes a series of eye bolts penetrating flanges. The scheme can achieve reliable end-anchorage for U-straps and prevent premature debonding. The test results showed the dominant failure mode changed from the delamination of CFRP to CFRP fracture. In comparison with the control specimens, the shear capacities of the strengthened T-beams were promoted to different degrees, depending on the amount of straps and their distribution. The ductility and stiffness of the upgraded beams were also found enhanced to some extent.

KEYWORDS

beam, reinforced concrete, FRP, shear, strengthening.

1. INTRODUCTION

Nowadays carbon fiber-reinforced polymer (CFRP) fabrics are widely used in the rehabilitation of RC structures due to excellent corrosion resistance, high strength-to-weight ratio and ease of installation. Generally, CFRP sheets, when used for shear strengthening; have three configurations, i.e., side bonding, U-jacketing and fully wrapping, respectively. Different configurations can result in different failure modes and thus shear capacities. Almost all beams upgraded by side bonding and a vast majority of those by U-jacketing failed by FRP debonding with limited enhancement of shear capacity and low efficiency of material usage [Error! Reference source not found.]. This is especially true for continuous T-beams because the extensible FRP-strap length is shortened by the flange and the strap end is located at the shear-tensioned area. Longitudinal FRP straps attached laterally to two sides of a retrofitted beam might be the simplest solution to improving anchorage of the U-shaped straps, but proved nearly insignificant to increasing shear resistance [2]. Fully wrapping may achieve reliable anchorage, however, the straps are inconvenient to install for beams with T-shape or/and beneath a wall. Hence a novel series of techniques using CFRP for shear strengthening has been developed and patented, in which CFRP U-straps are wound around additional bars attached to beam surfaces (CUSAB). The specific scheme can vary with different field conditions, and thus form the SAB series [3]. Among them is the CFRP U-straps wound around steel bars passing eye bolts penetrating flanges (CUSABbpf), which is suitable for T-beams of floors or decks when penetrating flanges is allowed (Fig.1). It may work effectively against FRP end-debonding that usually occurred in beams strengthened with U-straps conventionally bonded, and thus achieve nearly the same effect as fully wrapping without excavating holes in the wall above and penetrating floors or decks on a large scale. The paper reports the findings from the tests of RC continuous T-beams shear-strengthened with CUSABbpf.

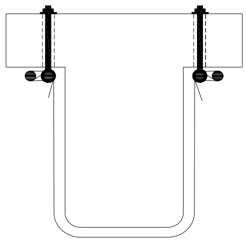
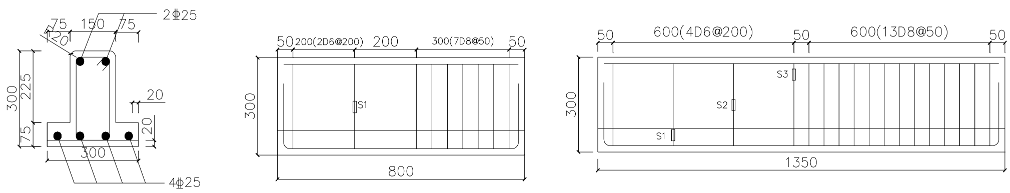


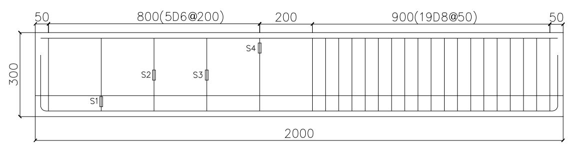
Figure 1.Schematic diagram of CUSABbpf

2. SPECIMENS

Figure 2 shows the dimensions of the specimens and steel reinforcement distribution. The cover was 20 mm thick. The longitudinal bars were designed to preclude flexural failure. Stirrups with a diameter of 6.5 mm and a spacing of 200 mm were distributed in the FRP-strengthened zone (stirrups radio is 0.221%) and those with 8 mm-diameter of and 50 mm-spacing arranged in the rest zone (see Fig.2).



(a) Section (b) Tc_1 (Tc_1C_{121}) (c) Tb_2 (Tb_2C_{121})



(d) Tc_3 (Tc_3C_{121})

Figure 2.Details of the specimens and strain gauges for stirrups (unit in mm)

Table 1 lists the concrete compressive strength for each specimen. And the shear span-to-depth ratio λ is 1.1, 2.2 and 3.4, respectively. For stirrups used in the strengthened zone and the rest zone, the tested yeilding strength were 341.6Mpa and 332.2Mpa, respectively. The yeilding strength for longitudinal rebars was 433.7Mpa. The manufacturer provides the physical properties for CFRP (i.e., 0.167mm thick, with a tensile strength of 3450MPa, a Young's modulus of 230 GPa and a ultimate tensile strain of 0.015).

3. LOADING PROCEDURE AND MEASUREMENT

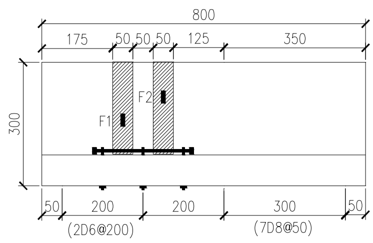
All T-beams were inverted, simply supported and loaded at mid-span to experimentally simulate the shear behavior within the zone of negative moment in continuous T-beams. Specimens of T2 series were tested by a program called "one beam twice tested" which was designed to investigate the effect of various factors on shear resistance under constant concrete strength.

Table 1.Parameters of each specimen shear-strengthened with CUSABbpf plus test results

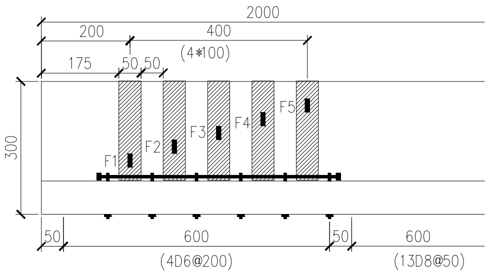
Beam	Original conditions		CFRP		Results			
	Concrete cubic compressive strength(MPa)	λ	Layer×width(mm) @spacing(mm)	ρ_{fv}（%）	Cracking load（kN）	Ultimate load（kN）	Enhancement of ultimate load （%）	Failure modes
Tc_1	28.1	1.1	——	——	170	557	——	S
Tc_1C_{121}	28.1	1.1	1×50@100	0.111	190	640	15	S
Tb_2	21.6	2.2	——	——	105	230	——	S
Tb_2C_{121}	21.6	2.2	1×50@100	0.111	120	380	65	S
Tc_3	28.1	3.4	——	——	115	220	——	S
Tc_3C_{121}	28.1	3.4	1×50@100	0.111	120	340	55	S

Note: S in the last column represents the shear failure characterized by crushing of compression concrete

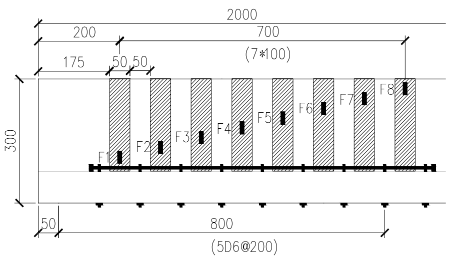
A jack was used to exert load manually at an increment of 10kN and the load was kept 3-5 minutes each step. Fig.2 shows the locations of strain gauges for stirrups and Fig.3 for CFRP straps. Mid-span deflection and crack width was observed.. For convenience of presentation below, FRP straps were numbered F1 to F8 from the support to the load point (or F1, F2, F3 in the case of three straps only) and steel stirrups S1 to S4 as shown in Fig.2 and Fig.3.



(a) Tc_1C_{121}



(b) Tb_2C_{121}



(c) Tc_3C_{121}

Figure 3.Arrangement of CFRP straps and strain gauges (unit in mm)

4. TEST RESULTS AND DISCUSSION

4.1 Experimental phenomenon and failure modes

Fig.4 shows the crack patterns and failure modes of the strengthened specimens. With different shear span-to-depth ratios, they displayed different behaviors during the test process.

(a) Tc_1C_{121} (b) Tb_2C_{121} (c) Tc_3C_{121}

Figure 4. Crack patterns and failure elevations

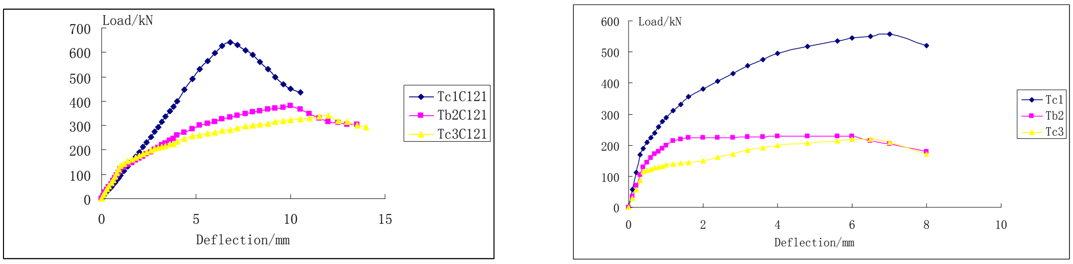
For specimen Tc_1C_{121}, initial cracks of members appeared at the mid shear-span, near the web/flange conjunction. The cracking load for Tc_1C_{121} (190kN) was much higher than that for Tb_2C_{121} and Tc_3C_{121} (120kN), whereas the enhancement was not obvious for all the strengthened beams, compared to the corresponding referrence beams (i.e., 11.8%、14.3%、4.3%, respectively). As load increased, new cracks emerged and the old ones extended upwards and downwards. Some straps intersecting shear cracks started to peel off at 260kN. For RC beams strenghthened with FRP U-straps conventionally bonded, shear failure typically came soon after fibre peeling-off with a rapid drop in load. By contrast, the specimens strengthened with CUSABbpf system could be further loaded after FRP-strap debonding for the reliable anchorage. With load further increasing, the number of inclined cracks grew and their width gradually increased. Several straps intersected by the critical shear crack peeled off completely. Up to 640kN，compression concrete between adjacent parallel diagonal cracks crushed and partly scaled off, the cover at bottom of the flanges even exfoliated. The shear resistance reached its extreme, with strap F1 completely ruptured and F2 partially torn. The major inclined crack had extended from the load point to the support.

Specimen Tb_2C_{121} and Tc_3C_{121}， with λ value larger than Tc_1C_{121}, had an inclination of critical shear crack flatter than that for Tc_1C_{121}. They experienced a process of strap debonding as did $Tc_1C_{121.}$ The ultimate failure occurred when concrete in shear-compression zone beneath the concentrated load reached its ultimate strength or crushed, which is different from $Tc_1C_{121.}$

The test results in table 1 indicate that there has been a noticeable increase in shear capacity for all members strengthened with CUSABbpf. Comparing to the reference beams, the shear capacity for Tb_2C_{121} and Tc_3C_{121} increased by 65% and 55%, respectively. Such a noticeable rise justified the use of CUSABbpf as an end-anchorage system assisting T-beams in resisting shear. Tc_1C_{121}. with a smaller shear span-to-depth ratio λ had a much lower increase (15%) though. The main reason might be that for a small λ or deep beam, arch action is the dominant mechanism against shear failure, i.e., concrete arch between load point and supports is supposedly undertake most shear, therefore, FRP plays a less important role than compressive concrete itself in shear-resisting. Almost all the specimens failed by crushing of the compression concrete instead of strap rupture, which may be partially ascribed to the relatively low compressive strength of concrete.

4.2 Load-deflection curves

Figure 5 showed the stiffness of specimens gradually declined with the increase of the applied load and a rapid growth of deflection is distinct when approaching the ultimate load. Prior to concrete cracking, FRP played little role in improving beam stiffness since the shear-strengthened and the reference beam had almost an equal slope. After cracking, the deflection for the strengthened grew fast at a higher load, demonstrating that FRP-straps helped to make the beams stiffer. Herein the CUSABbpf strengthening system played an important role. In addition, FRP-straps, in CUSABbpf system, restrained the development of inclined cracks, which mitigated the lose of aggregate interlock action and thus enhanced the stiffness indirectly. Interestingly, for Tb_2C_{121} and Tc_3C_{121} ($\lambda > 2$), with a slowly upward value of load yet a rapid increasing deflection, the curves start a relatively long plateau at about 300kN, exhibiting a more ductile behavior. What's more, the area curve covered below (between the curve and the x-axis) is larger than that of their references. The facts showed that they had an emerge-dissipation capacity bigger than the corresponding references.

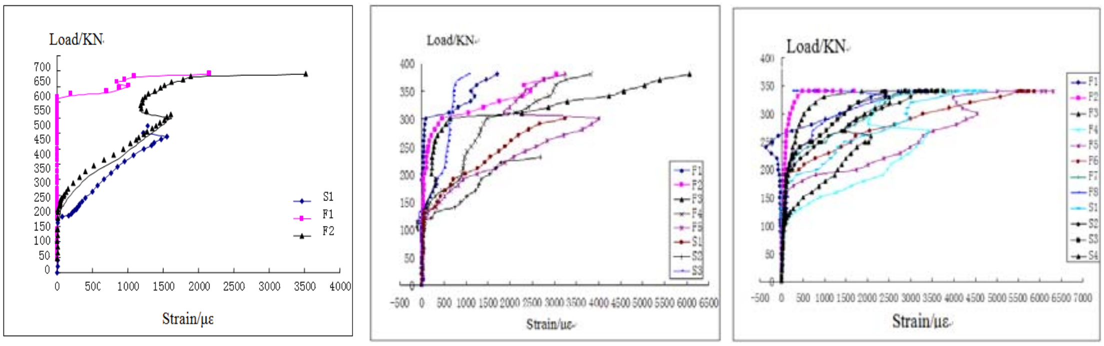


(a) The strengthened beams (b) The reference beams

Figure 5.Load-deflection curves

4.3 Load-Strain curves of steel stirrups and CFRP straps

Presumably steel stirrups and CFRP straps share shear force in a similar way within a beam. With regard to strains in stirrups and straps, what deserved more attention was the progress of those located at mid shear-span but gauged in crack-intensive elevation (such as F3, F4 in Tb_2C_{121} and Tc_3C_{121}, S1in Tc_1C_{121}, or S2 in other beams, etc.). Before concrete cracking their strains stayed low and the concrete undertook most shear. The stirrups and straps experienced a sudden increase in strain when cracks emerged, subsequently, their strain grew rapidly. With the load rising up, cracks further extended and broadened, which greatly activated the stirrups and CFRP straps in resisting shear.

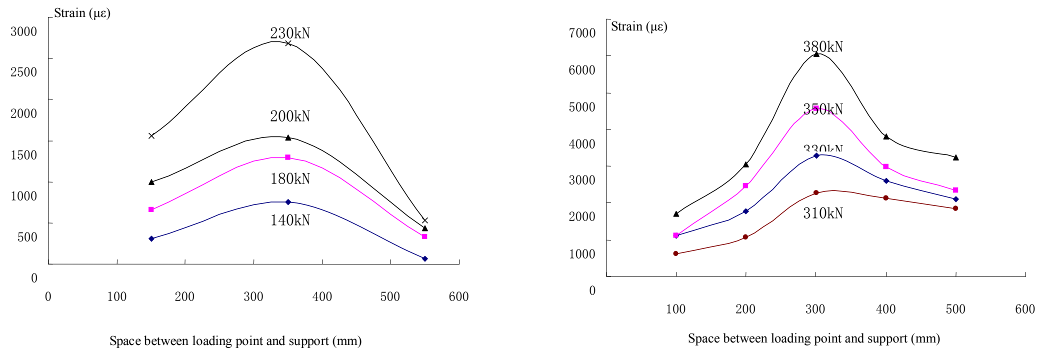


(a) Tc_1C_{121} (b) Tb_2C_{121} (c) Tc_3C_{121}

Figure 6.Load-strain curves

By comparison, the strains of S2 for all the strengthened beams are lower than that for the unstrengthened under the same load, implying that CFRP does carry partial shear. With the help of CFRP straps, the stress of the stirrups reduced and their yielding process got delayed. As to FRP strain distribution, the straps crossed by the diagonal cracks have developed a much larger strain than not. For instance, few inclined cracks intersected strap F5, whereas several extended across strap F3 at mid shear-span. Fig. 6b showed a larger strain in F3 but a smaller in F5. Also in Fig.6c, the strains in F3 to F6 were greater than in F1, F2, F7, and F8.

4.4 Strain distributions



(a) Steel stirrups (b) CFRP

Figure 7.Distribution of strain of Tb_2C_{121}

Strains in steel stirrups and CFRP straps both distributed unevenly along the shear span. This was related to the uneven distribution of crack width. Overall the cracks opened wider in the middle of the shear span than at the support and load point. Consequently, for steel stirrups, the strain curves displays a higher value in the zone of mid shear-span and it grew lower towards both ends. The strains in CFRP straps also attained the peak near the mid shear-span.

CONCLUSIONS

An innovative scheme for strengthening with CFRP has been proposed. The test justified that wrapping CFRP U-straps around steel bars passing eye bolts penetrating flanges (CUSABbpf) is a practical and effective technique in anchoring U-shaped strips. For all T-beams strengthened with CUSABbpf, the shear capacities increased by an average of nearly 60% and up to a maximum of nearly 75% as compared to the control specimen. Premature debonding was avoided and even if debonding happened loads can be further risen until other factors caused shear failure. The stiffness for the strengthened members has been enhanced to some extent and the ductility has also been improved especially for those specimens with higher content and denser distribution of CFRP straps.

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