TESTS ON WEB CRIPLING STRENGTHENING OF PULTRUDED GLASS FIBRE REINFORCED POLYMER SECTIONS

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ABSTRACT

Web crippling failure is critical for pultruded glass fibre reinforced polymer (GFRP) sections under concentrated bearing load due to their low material strength in transverse direction. This paper examined two approaches to enhance the web crippling strength of pultruded GFRP sections, through CFRP strengthening or steel tube strengthening. Experimental studies were conducted on the strengthened GFRP square hollow sections (SHS) of two different dimensions. Two loading conditions, end-two-flange (ETF) and interior-two-flange (ITF), were applied to investigate the effect of loading position on the web crippling behaviour. It was found that the web crippling capacity of GFRP section was effectively improved by up to about 85% using CFRP strengthening, and by up to about 4 times using steel tube strengthening.

KEYWORDS

Fibre-reinforced composite; Strengthening; Pultrusion; Web crippling; Web-flange junction; Shear failure.

INTRODUCTION

Pultruded glass fibre reinforced polymer (GFRP) composite has emerged as a new structural material for construction of civil infrastructure and has attracted extensive research attentions (Keller 2003; Bank 2006). Pultruded GFRP sections have advantages over conventional construction material (i.e. steel, concrete), such as lightweight, ease of installation, low maintenance, and high resistance to harsh environmental conditions (Hollaway 1993; Hollaway 2009). Despite of these benefits, pultruded GFRP does have some limitations due to its inherent orthotropic material characteristics. For example, it was reported in a recent study (Wu and Bai 2013) that the web crippling capacity of pultruded GFRP section under concentrated bearing load was low because of the premature failure at web-flange junction. This largely impedes full utilization of the material strength of pultruded GFRP sections, especially when transverse concentrated loading is applied (Borowicz and Bank 2011; Bai et al. 2013), i.e. reaction force and load from support or other structural members like joists, purlins and rafters. This highlights the necessity of the development of suitable approaches to improve the web crippling capacity of pultruded GFRP sections.

This paper examines two approaches to enhance the web crippling strength of pultruded GFRP sections. One was to bond carbon fibre sheets on the external web surfaces of GFRP section. The other method was to use steel plates externally wrapping the whole GFRP section. The strengthened GFRP square hollow sections were tested under two loading conditions: ETF and ITF. The load displacement response was recorded and analysed with relation to the observed progressive failure modes. The web crippling capacity of strengthened GFRP sections was identified and compared to the capacity of unstrengthened sections, and improvement in web crippling capacity was quantified by both strengthening methods.

EXPERIMENTAL PROGRAM

Materials

The pultruded GFRP square hollow sections (S1 and S2) examined in the experimental program were 102×102×10 mm (height×width×thickness) for S1 and 50×50×6 mm for S2. The measured tensile modulus and strength in pultrusion direction are 25 GPa and 283 MPa, respectively. The modulus and strength in transverse direction are 5 GPa and 22 MPa, respectively. The interlaminar shear strength is 28 MPa.
High modulus CFRP sheeting, MBrace CF 530, was adopted for web crippling strengthening. It is a unidirectional tow sheet carbon fibre of 0.19 mm thick. The tensile modulus and tensile strength from manufacturer in the fibre direction is 640 GPa and 2650 MPa, respectively. In the second strengthening scenario, 2 mm thick mild steel plates were used. The steel yielding stress is 275 MPa. Araldite 420 was used as adhesive for bonding strengthening materials (CFRP sheeting or steel plates) to GFRP sections. The reported tensile modulus and tensile strength of the adhesive were 1.9 GPa and 28.6 MPa, respectively (Wu et al. 2012a).

**Specimens**

The schematic view of the two strengthening configurations under both ETF and ITF conditions is shown in Fig. 1. A coordinate system is also included in Fig. 1 for the definition of directions, i.e. x for transverse direction, y for vertical direction, and z for pultrusion direction. For the first configuration, three layers of CFRP sheets were externally bonded on each web of the GFRP section. CFRP sheets were oriented with the fibre direction perpendicular to the z axis. Similar CFRP strengthening configuration was also adopted for strengthening metallic sections in (Wu et al. 2012b). For the second configuration, three steel plates were fillet welded into a C section. Two C sections were bonded outside of the GFRP section. The fillet welds were placed on the web side of the steel C section (see Fig. 1d) to insure the top and bottom bearing surfaces smooth and flat. The specimen length and strengthening length depended on the loading conditions. When the bearing load is applied at the end of specimen (ETF condition), the specimen length was of 300 mm for those with S1 section and 200 mm for those with S2. When the load is applied in the middle of the specimen (ITF condition), such lengths were doubled, i.e. 600 mm for S1 section and 400 mm for S2. The strengthening lengths for specimens with S1 section was 200 mm and 125 mm for those with S2 section under ETF, and again doubled for ITF loading condition.

![Fig 1. Strengthening configurations](image)

Regarding the specimen preparation, the first step was surface preparation of GFRP sections for subsequent strengthening. The strengthening area was sand blasted until the mat layer was exposed. Then the surfaces were cleaned using acetone before applying adhesive. Parts A and B of Araldite 420 were mixed by a weight ratio of 4:1, and a thin adhesive layer was uniformly applied on the surface using a paint brush. For CFRP strengthened specimens, one layer of CFRP sheet was attached on the webs of GFRP section and a roller was used along the fibre direction to apply uniform pressure until the sheet was immersed in the resin and extra epoxy and air pockets were forced to bleed out. In the same way, another two layers of CFRP sheets were applied. For steel strengthened specimens, a large amount of adhesive was applied inside of the two steel C sections, as well as on the GFRP strengthening surfaces. Then the two steel C sections were put together to form a tube and bonded outside GFRP section. Extra adhesive was squeezed out and cleaned. All strengthened specimens were kept in room temperature for curing for at least one week.

A total of 16 strengthened specimens were prepared as listed in Table 1. The first part of the specimen label refers to the GFRP section, i.e. S1 or S2. The second part of the label is the loading condition, i.e. ETF for end-two-flange, ITF for interior-two-flange (see details in the following section). The third part stands for the strengthening material used, i.e. CFRP or steel. The final number is the ID of repeating specimens.

**Experimental Setup and Instrumentation**

Two loading conditions, ETF and ITF, were adopted as shown in Fig. 2. The concentrated bearing load was applied on both top and bottom flanges of the specimen through two rigid steel bearing plates. The bearing plates were 10 mm thick, 50 mm in z direction and 200 mm in x direction.

Baldwin universal testing machine was used to conduct all the tests. The compressive load was applied through displacement control and the loading speed was 0.5 mm/min. All specimens were tested until the bearing plate displacement exceeded at least 15% the depth of the section. The progressive failure of each specimen was
monitored by a video camera. Five strain gauges, G1 to G5, were attached in the longitudinal direction along the neutral axis of the other web.

Table 1. Specimens and results

<table>
<thead>
<tr>
<th>Specimen label</th>
<th>Web crippling capacity $P_i$ (kN)</th>
<th>Capacity of control specimens $P_i$ (kN)</th>
<th>Increase in $P_i$ (%)</th>
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<tr>
<td>S1-ETF-CFRP-1</td>
<td>30.50</td>
<td>22.87</td>
<td>33.4</td>
</tr>
<tr>
<td>S1-ETF-CFRP-2</td>
<td>35.43</td>
<td>41.47</td>
<td>59.2</td>
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<tr>
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<td></td>
<td></td>
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<td>S1-ITF-CFRP-2</td>
<td>66.95</td>
<td></td>
<td></td>
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<tr>
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<td>20.74</td>
<td>56.9</td>
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<tr>
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<td>358.3</td>
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</table>

Fig 2. Loading conditions: (a) ETF; and (b) ITF

EXPERIMENTAL RESULTS

The major experimental results are listed in Table 1 for all the specimens, with relation to the failure modes, load-displacement responses as discussed in this section.

Failure Modes

The typical failure modes of section S1 under ETF condition are presented in Fig. 3, whereas those of S1 under ITF condition are shown in Fig. 4. Similarly, the failure modes of section S2 are also grouped according to the loading conditions, with failure modes under ETF given in Fig. 5, and those under ITF are depicted in Fig. 6. Under ETF, unstrengthened S1 section experienced an initial failure at the web-flange junction with a 45° interlaminar shear crack at each corner of the GFRP sections as shown in Fig. 3a, d. When strengthened by CFRP sheets, initial failure with 45° shear cracks at web-flange junctions was also observed for sections S1 (see Fig. 3b, e). At the same time, the CFRP reinforcement was locally crushed in compression (see Fig. 3b, e). When strengthened with steel plates, the initial crack at the web-flange junction was not as obvious as previous ones. Instead, steel yielding and GFRP web crushing were observed as shown in Fig. 3c, f.
When S1 was loaded under ITF, the damage seemed to be restrained within a limited web area, regardless of strengthening methods. For unstrengthened S1, the web-flange separated before the bearing plate punched into the webs (see Fig. 4a). When strengthened with CFRP sheets (Fig. 4b) and steel plates (Fig. 4c), the local damage of the reinforcing materials were observed indicating that the strengthening materials effectively engaged in the load carrying mechanism.

For S2 under ETF loading condition as in Fig. 5, clear 45° shear crack was observed for unstrengthened sections (Fig. 5a, d), as well as for CFRP sheets strengthened sections (Fig. 5b, e). The CFRP sheets were locally crushed close to the top and bottom corners whereas no debonding between CFRP sheets and GFRP webs was observed. For steel strengthened section, the GFRP was crushed with steel plate yielding (Fig. 5c, f). The yielded steel plate separated from GFRP web with a thin layer of GFRP rovings attached, indicating good bond between steel and GFRP web.
Fig 6. Typical failure modes of S2 under ITF: (a) S2-ITF-2; (b) S2-ITF-CFRP-2; and (c) S2-ITF-Steel-1

Load-Vertical Displacement Curves

The curves of applied concentrated load versus the vertical displacement of the bearing plate are presented in Fig. 7 for S1 and in Fig. 8 for S2. For the same section, S1 or S2, the load-displacement curves are grouped according to the loading conditions of ETF and ITF.

Firstly, the overall developments of load-displacement responses of CFRP strengthened specimens are very similar to those of unstrengthened specimens. According to the observed progressive failure processes, the elastic stage ended when the web-flange junction failure occurred and non-linear stage was associated with the subsequent web failure modes. Since the section lost its integrity due to the web-flange junction failure, the load at the end of elastic stage is defined as the load bearing capacity. It is clear in Fig. 7 that the web crippling capacity of GFRP section has been effectively improved due to CFRP strengthening, by 44.1%/60.4% under ETF/ITF for S1 and by 68.0%/69.8% under ETF/ITF for S2.

Secondly, a different load-displacement response was identified for the steel tube strengthened specimens, i.e. the load decreased immediately after the elastic stage because of the failure of GFRP-steel composite section. Then the load drops and sustains at a lower level which is due to the yielded steel section sustaining the loading.
The improvement in load bearing capacity is much higher by steel strengthening, by 389% and 273% for S1 under ETF and ITF conditions respectively, and by 230% and 370% for S2 under ETF/ITF conditions respectively.

Thirdly, the effect of loading position on the load-displacement curves is obvious for both S1 and S2 specimens. Higher elastic limit load (for both CFRP and steel tube strengthened specimens) and ultimate load (only for CFRP strengthened specimens) were achieved by specimens under ITF condition than those under ETF condition. This is because the ITF loaded specimens can have the bearing load sustained by a larger web area comparing to the corresponding ETF specimens.

CONCLUSION

This paper proposed two strengthening methods to improve the web crippling capacity of pultruded GFRP sections. An experimental study was carried out on two GFRP SHS sections subjected to end-two-flange (ETF) and interior-two-flange (ITF) loading conditions. A total of 16 strengthened specimens were tested and the experimental results showed that the two strengthening schemes, CFRP strengthening and steel tube strengthening, were able to considerably improve the web crippling capacities of GFRP sections.

1) The GFRP sections strengthened by CFRP failed in a two-stage process which was similarly to the unstrengthened specimens, with initial 45° shear failure at web-flange junction followed by the web failure. However, the failure modes of GFRP sections strengthened by steel tubes were very different, as steel plate yielding along with GFRP section crushing.

2) Both CFRP and steel tube strengthening configurations demonstrated considerable enhancement of web crippling capacity for GFRP sections. Particularly, the maximum increase in web crippling capacity achieved by CFRP strengthening was about 85%. The steel tube strengthening performed much better and generated a maximum improvement in web crippling capacity by about 400%.

The theoretical analysis is being carried out to predict the web crippling behaviour of pultruded GFRP strengthened by CFRP and steel.

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REFERENCES


