TENSILE TESTS ON BONDED DOUBLE-STRAP JOINTS BETWEEN PULTRUDED GFRP PROFILES

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ABSTRACT

In this paper the results of a series of tensile tests on bonded double-strap joints between pultruded GFRP flat profiles with different geometry are presented. For every kind of joint the ultimate failure load, the stress-strain curve and the mechanism of failure is indicated. The behaviour of these joints typically is elastic-brittle. The ultimate failure load is basically influenced by the thickness-length ratio of the outer adherents. Other important parameters are the ratio between the inner and the outer thickness and stiffness of the adherents as well as the adhesive stiffness. In most of the cases failure is initiated in the mat layer situated in the outer part of the adherents. No cohesive failure in the adhesive or adhesive failure between adherent and adhesive has been observed.

KEYWORDS

Double-strap bonded joints, GFRP profile, pultrusion, failure load, mechanism of failure.

INTRODUCTION

The efficiency of a structure made of FRP elements is largely influenced by the performance of the joints. The bonded joints appears to be the most suitable option in connecting elements, because of no breaking the fibres is needed and a more uniform load transfer is guaranteed. Otherwise an appropriate surface preparation is needed prior to bonding as well as a controlled environment during the adhesive curing process.

The load transfer in a bonded joint is not completely uniform along the bond line and many studies have been carried to develop a correlation between the applied loads and the stresses inside the joint. Such studies varies from closed form analytical solution for simple joints configurations, such as single-lap joints (e.g. Volkersen 1938; Goland and Reissner 1944; Renton and Vinson 1975; Greenwood 1968) including evaluation of the influence of local geometry on the joint strength (e.g. Adams and Harris 1987; Lang and Mallik 1998; Crocombe and Adams 1981; Adams et al. 1998), and for double-lap joints (e.g. Harth-Smith 1973; Harth-Smith 1974, Harth-Smith 1987; Weitsman 1981; Ikegami et al. 1996; Tong et al. 1996), for such kind of joints and for more complex geometry FE methods can be used to predict stress concentration. However, results can be sensitive to the method of meshing, the materials model may lack accuracy and there are problems interpreting the results at interfaces between materials and singularities.

The most of these studies have been carried out for the aerospace-automotive fields, investigating the behaviour of elements with dimensions of an order of magnitude of the millimetre, and produced basically with lay-up and mould techniques.

For the buildings and constructions fields the researches are still at the beginning and test on elements with thickness of an order of magnitude of the centimetre, produced with pultrusion or filament winding techniques must be accomplished.

In these paper will be presented the results of a series of tests on bonded double strap joints between pultruded flat profiles. The full scale specimens tested vary in some geometry parameters

• Ratio of overlap length-outer adherent thickness (25 and 12.5).
• Different thickness of the adherents (10mm inner and 6mm outer, 5mm inner and 3mm outer).
• Squared edges without spew fillet and tapered edges with spew fillet.
ADHERENTS AND ADHESIVE PROPERTIES

Different GFRP pultruded profile, with flat rectangular sections of 50mm width, was used to assemble the specimen: the profiles used are of 3, 5, 6, 10 millimetres thick, with the same kind of reinforcement. The reinforcement is made of glass fibres unidirectional rovings in the centre of the profile and of a chopped strand mat (CSM) layer as well as a woven fabrics 0°/90° layer in the outside. An exterior polyester surface veil protects the fibres. The matrix is an isophthalic polyester resin. The properties provided by the manufacturer’s design manual are listed in Table 1. A two-component epoxy adhesive (Sikadur 30) was used. The properties provided by the producer are listed in Table 2.

<table>
<thead>
<tr>
<th>Failure Tensile Stress 0° (MPa)</th>
<th>Failure Tensile Stress 90° (MPa)</th>
<th>Failure Compressive Stress 0° (MPa)</th>
<th>Failure Compressive Stress 90° (MPa)</th>
<th>E-Modulus 0° (GPa)</th>
<th>E-Modulus 90° (GPa)</th>
<th>Failure Shear Stress (MPa)</th>
<th>G-Modulus (GPa)</th>
<th>Poisson Ratio</th>
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<td>240</td>
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<td>240</td>
<td>70</td>
<td>23</td>
<td>8,5</td>
<td>25</td>
<td>3</td>
<td>0,23</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>E-Modulus (GPa)</th>
<th>Failure shear stress (MPa)</th>
<th>α_T (%/°C°)</th>
<th>Curing temperature (°C)</th>
<th>Curing time (h)</th>
</tr>
</thead>
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<tr>
<td>12,8</td>
<td>15</td>
<td>9x10^-5</td>
<td>25</td>
<td>24</td>
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</tbody>
</table>

EXPERIMENTAL TESTS

Specimen configuration

A double-strap configuration has been selected to realize the specimen (Figure 1). The double-strap joints attempts to eliminate the eccentric loads that occur in the single-strap configuration using a symmetric disposition of the outer adherents. Although bending is reduced, peel stresses at the outer adherents is unavoidable, since the load is applied to the outer adherents via the adhesive, away from the neutral axis. This kind of joint offers, in any case, better performances than the single-strap joint, even utilizing the same amount of material (Brander 1994).

Rectangular flat sections profile with 50mm width was used to minimize the eccentricities in load transfer. The four kinds of joints that have been assembled are listed in Table 3.

<table>
<thead>
<tr>
<th>Specimen designation (N° of tests)</th>
<th>Tapered edges &amp; spew fillet</th>
<th>t_o</th>
<th>t_i</th>
<th>L/t_o</th>
<th>E_o</th>
<th>E_i</th>
<th>width</th>
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<tr>
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<td>no</td>
<td>6</td>
<td>10</td>
<td>12,5</td>
<td>23000</td>
<td>23000</td>
<td>50</td>
</tr>
<tr>
<td>ABIS (2)</td>
<td>no</td>
<td>3</td>
<td>5</td>
<td>12,5</td>
<td>23000</td>
<td>23000</td>
<td>47</td>
</tr>
<tr>
<td>B (3)</td>
<td>no</td>
<td>3</td>
<td>5</td>
<td>25</td>
<td>23000</td>
<td>23000</td>
<td>47</td>
</tr>
<tr>
<td>C (3)</td>
<td>yes</td>
<td>3</td>
<td>5</td>
<td>12,5</td>
<td>23000</td>
<td>23000</td>
<td>47</td>
</tr>
</tbody>
</table>

The specimens are assembled following the standard procedure indicated by the adhesive’s producer. First the surface is prepared abrading the polyester surface veil with a coarse-grained sand-paper, cleaned and degreased
with acetone (Figure 2), and then the epoxy adhesive is prepared and applied on the surfaces of the inner and outer adherents and on the butt ends. Some copper wires 1mm thick are positioned between the adherent to guarantee the adhesive thickness (Figure 3), than the two adherents are gently pressed together to let the excess adhesive to flow out and to be removed (Figure 4). The A, Abis and B (Figure 5) type specimen were manufactured with a 0.5mm radius fillet; the C type specimen (Figure 6) was assembled with a spew fillet and with outer adherents with tapered edges. The double-strap joints specimens were cured for 48h at laboratory temperature.

Figure 2: Surface preparation of the specimen

Figure 3: Application of the adhesive and copper wires for thickness control

Figure 4: A specimen assembled

Figure 5: B-type specimen

Figure 6: C-type specimen
**Instrumentation**

On the external surface of the outer adherent and on the inner adherent 20mm away from the end of the outer adherent had been placed two strain gauges 30mm long, to measure local displacements (Figure 7); a transducer had been placed over the butt-end only in the A-type specimen (Figure 8).

![Figure 7: Strain gauges on inner and outer adherents](image)

![Figure 8: Transducer over butt-end in A-type specimen](image)

A MTS 810 servo-hydraulic testing machine with a capacity of 500kN in tension and compression and a maximum displacement of 500mm was used. The load had been applied in quasi-static manner and displacement-controlled at a rate of 1.3mm/min. The specimen had been clamped in the machine with a surface of 50mm x 100mm. Figure 9 shows an A-type specimen clamped in the testing machine before test starts.

![Figure 9: A-type specimen clamped in the testing machine before test starts](image)

**RESULTS**

**Stress-Strain behaviour**

The four different kind of specimen tested present at the beginning a similar behaviour changing in stiffness and in ultimate failure load only after the failure of the central butt joint. The four curves presented in Figure 10 are
referred to the four kind of joints showing the relationship between the elongation (‰) of the strain gauge positioned on the centre of the outer adherent and the stress in the inner adherent (Load/Area of the inner adherent).

In the first part of the curve the four kinds of joints show similar linear-elastic behaviour, then at different levels of stress, it is possible to observe a knee due to the separation of the butt-ends of the inner adherents; the same kind of behaviour is observed also in single strap joints (Brander 1994). After the separation of the butt-end it is possible to notice different reductions in stiffness, depending of the type of joint considered. The B-type (3mm/5mm adherents, L/to = 25) shows the highest failure load, due to the longer overlap length, this is appreciable also observing that the separation of the butt-end happens at a higher level of stress than in the other cases. The A-type (6mm/10mm adherents, L/to =12, 5) shows the greatest reduction in stiffness and the greatest elongation. This is due to the thicker adherents that can better absorb the peel stresses with greater deformations before failure. The separation of the butt end is influenced by the ultimate failure load in tension at the adhesive-adherent interface; the separation in the four kinds of joints happens at various values of load, maybe for the influence of size effect and quality of the adhesion on different surfaces. The Abis-type (3mm/5mm adherents, L/ t₀ = 12,5) and the C-type (3mm/5mm adherents, L/ t₀ = 12,5, spew fillet & tapered edges) show a similar behaviour until failure, the C-type has a better resistance due to the presence of spew fillet and of tapered edges that reduce the peel stresses at the edges.

Mechanisms of failure

The classification of the mechanism of failure has been performed in accordance with ASTM D5573. No cohesive failure in the adhesive or adhesive failure between adherent and adhesive were observed. In all the specimens tested failure is localized in the adherent, corresponding to a light-fibre-tear and a fibre-tear failure mode. In most of the cases the ultimate failure is located in the outer mat layer that surrounds the profile.
After the creaking due to the separation of the central butt end, failure is typically brittle and occurs in a sudden manner after a few seconds. The A-type specimen shows a light-fibre-tear failure mode, Figure 11, as well as a fibre-tear mode as secondary failure mode, Figure 12, due to the greater thickness of the adherents.

The other kind of joints tested show only a light-fibre-tear mode; in the B-type (Figure 13) failure occurs at higher loads than in the other cases, for the greater capacity of the long overlap (L/t₀ = 25). In the C-type joint failure occurs after the sudden separation of one or more spew fillet (Figure 14).

Ultimate failure loads

The ultimate failure loads Fₘ of the specimens tested are listed in Table 4. In the table are listed also the value of tension in the inner profile σᵢ (ultimate failure load / Section’s area of the inner profile) and the joint efficiency Φ (joint strength/inner profile strength) calculated with the profiles (conservatives) producer’s data.

DISCUSSION

The four kind of specimen tested present a mechanism of failure characteristic of the joints made with pultruded profile with a mat layer and woven fabrics as external reinforcement. Also other studies (Keller and Vallée 2005a) have shown that the failure is, in most of the cases, located at the level of the mat layer approximately at 0.5mm from the profile’s surface.

The behaviour of the joints tested is typically brittle, linear-elastic at the beginning and with a reduction in stiffness after the separation of the central butt end. The separation of the butt end always occurs before failure and a similar behaviour has been observed also by Brander (1994) for single and double strap joints. A longer overlap gives to the joint a higher ultimate failure load and greater deformation before failure, for similar joints (Abis-type and B-type) doubling the overlap length gives a 55% increased ultimate failure load.
The reduction of the peak stresses at the edges of the overlap as well as the increased resistance that FRP profiles show when local instead of distributed stresses are applied (Keller and Vallée 2005b) determine the influence of a longer overlap on the overall joint strength. The tapered edges and the presence of a spew fillet increase the joint strength thanks to reduced peel stresses (Hart-Smith 1974b, Adams and Harris 1987).

The performance of the joints with such variation in the local geometry is influenced by the quality of the adhesion between the spew fillet and the adherents. A simple surface preparation, such as the one performed for this series of tests, and a controlled environment for the assembly, guarantees a good quality of adhesion: no failure due to bad surface preparation had been observed.

<table>
<thead>
<tr>
<th>Specimen designation (N° of tests)</th>
<th>Tapered edges &amp; spew fillet</th>
<th>( t_0 )</th>
<th>( t_i )</th>
<th>L/( t_0 )</th>
<th>width</th>
<th>( F_u )</th>
<th>( \sigma_i )</th>
<th>( \Phi )</th>
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<td>±1,1</td>
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<td>12,5</td>
<td>47</td>
<td>26,1</td>
<td>±1,5</td>
<td>111</td>
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<td>178,2</td>
<td>0,74</td>
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<tr>
<td>C (3) yes</td>
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<td>12,5</td>
<td>47</td>
<td>31,2</td>
<td>±1,8</td>
<td>132,7</td>
<td>0,55</td>
</tr>
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</table>

**CONCLUSIONS**

The results and the consideration presented in this paper can be summarized in the following conclusions:

1. The typical mechanism of failure for a bonded double-strap joint assembled with pultruded GFRP profiles is a light-fibre-tear mode. This behaviour is influenced by the presence of an external mat layer: the interface between the mat layer and the inner unidirectional fibre rovings is the weakest part of the joint.
2. First degreasing, then abrading the polyester surface veil with a coarse-grained sand-paper and then cleaning and degreasing again with acetone the surface in a controlled environment is a simple procedure that guarantees good quality adhesion. No cohesive failure in the adhesive or adhesive failure between adherent and adhesive had been observed.
3. The behaviour of the joints at the beginning is linear-elastic; after the separation of the central butt end is appreciable a small reduction in stiffness until the brittle failure that occurs in a sudden manner.
4. The overlap length (in the range considered) is the parameter that more influences the joint strength.
5. The increased resistance that the joints with tapered ends showed, suggest the use of outer adherents with this modified shape.

**ACKNOWLEDGMENTS**

For the support given in the realization of this paper the authors wish to acknowledge the Structures and Soil Mechanic Laboratory of the Università degli Studi “Roma Tre”, Sika Italia (supplier of the adhesives) and Saimex, Italian distributor of Fiberline Composites A/S Denmark (supplier of the GFRP pultruded profiles).

**REFERENCES**


