ACOUSTIC EMISSION ANALYSIS AND ACOUSTO-ULTRASONICS FOR DAMAGE DETECTION IN GFRP ADHESIVE JOINTS

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Keywords: Adhesive joints, GFRP, tensile load, damage accumulation

Abstract

Selected tensile tests on balanced, adhesively bonded double-lap joints (DLJ) made from pultruded glass-fibre-reinforced, polymer-matrix (GFRP) flat profiles have been monitored with acoustic emission (AE) for an assessment of damage initiation and accumulation. The thickness was 10 mm for the inner and 5 mm for the two outer profiles. Three different bond-line thicknesses of the adhesive bond (nominally 0.3, 0.5 and 1.0 mm), all with an overlap length of 100 mm, were tested. The usual AE signal parameter set was recorded with four AE sensors (either of type SE-45H or SE-150M) from three tests each per DLJ type. AE sensors were mounted above and below the adhesive bond with duct tape using a silicone-free coupling agent. Sensor coupling was checked before and after the tensile tests to stress levels around 70% to 97% of the effective ultimate tensile strength. Both, the auto-calibration function of the AE equipment and pencil-lead breaks (Hsu-Nielsen sources) applied at different locations on the joints were used for checking sensor coupling. Transient AE waveforms were recorded during the auto-calibration with 5 MHz sampling rate. This effectively constitutes acousto-ultrasonic (AU) testing of the DLJ before and after loading. AU results will be compared with the assessment of damage accumulation from AE analysis based on AE activity, intensity and source location.

Introduction

Previous experiments on the strength of adhesively bonded joints composed of glass-fibre reinforced polymer-matrix (GFRP) pultruded adherends [1-3] indicated that, even using enhanced mathematical methods on the basis of a fully linear mechanical model, a gap of around 10% between predicted and experimentally determined joint strengths remained. Reasons for this, invoked in [3], were either possible damage occurring by microscopic defect accumulation (e.g., micro-crack formation) and/or the resulting nonlinear behaviour of the GFRP material at higher stresses (beyond those obtained on the samples of limited size, i.e., 40 mm x 40 mm).

Acoustic emission (AE) monitoring is, in principle, capable of detecting microscopic damage accumulation in GFRP composites. AE was hence used to monitor the area of the adhesive bond during tensile tests on a series of nine full-size adhesively bonded double-lap joints (DLJ) up to a load of 140 kN, including subsequent unloading. The DLJ were then loaded to their ultimate tensile strength, i.e., to tensile failure without AE. The AE data are analysed with respect to damage accumulation under tensile load. AE sensor coupling was checked with the auto-calibration function of the AE equipment and the resulting AE waves, effectively constituting acousto-ultrasonics (AU) are analysed and compared with the AE monitoring results.

Experimental

The balanced double-lap joints (DLJ) consisted of pultruded glass-fibre reinforced polymer-matrix (GFRP) flat profiles of 500-mm length, 100-mm width, and 5-mm and 10-mm thickness for the inner and outer DLJ profiles, respectively. A polyester resin and E-glass fibres were used for the profiles, with mainly unidirectional rovings towards the centre and one and two combined
mats towards the outside for the 5-mm and 10-mm thick profiles, respectively. The combined mats consisted of chopped strand mats and 0°/90° woven fabrics, which were stitched together. For the adhesive bond, a two-component polyurethane adhesive (Sika S-Force 7851) was used, the nominal bond line thicknesses were 0.3, 0.5 and 1.0 mm. The specimens were cured under ambient laboratory conditions (23±1°C, 50±5% relative humidity) for one week, and then stored under comparable conditions before testing.

The tensile tests have been performed on a servo-hydraulic test machine (Instron 1346) under displacement control (0.5 mm/min). A metal plate has been inserted between the outer two profiles inside the hydraulic grips at the bottom.

AE equipment and software from Vallen Systeme GmbH (AMS-3 and VisualAE™) have been used for AE monitoring. At least one DLJ for each bond-line thickness has been equipped with four multi-purpose AE sensors (type SE-45H from Dunegan Engineering Corp.) while the remaining DLJ have been tested with 150-kHz resonant AE sensors (type SE-150M from the same supplier). Preamplifier gain was set at 34 dB, AE signal acquisition threshold at 50 dB\textsubscript{AE} except for two DLJ with 52 and 65 dB\textsubscript{AE} in order to eliminate excess noise from the hydraulic grips. The AE signals were band-pass filtered between 30 and 1000 kHz. Rearm time was set to 1.38 ms. Machine load and displacement (analog 10-V signals) were synchronously recorded with the AE data set via external parametric inputs at a rate around 4 Hz.

![Fig. 1. Photograph of (left) a double lap joint in the test machine with two AE sensors (above and below the adhesive bond) on either side of the joint; (right) a joint after tensile failure (top view and side view); the failure occurs inside the GFRP, not in the adhesive layer; note that one of the outer profiles is partially debonded, the second outer profile is not shown.](image)

**Results**

Table 1 summarizes the applied and observed tensile failure loads of the DLJ and the AE activity observed during the first loading to 140 kN. The number of AE signals (so-called “hits”) recorded up to the load of 140 kN monitored for all DLJ indicates that the two sensors mounted on the centre profile (10-mm thick) is always significantly higher (between a factor of 2 and about 14) than that recorded by the sensors on the outer profiles (5-mm thick). The only exception is DLJ031, but here it was observed that the coupling of one sensor on the centre profile became unsatisfactory during the test (loosening of the adhesive tape). There is also a trend for a higher number of recorded hits for those DLJ, which have been monitored with the 150-kHz resonant AE sensors (SE-150M) compared to those with the other type (SE-45H).
Table 1: Tensile load cycles and failure load (kN) for DLJ with different bond-line thickness and number of recorded AE signals per sensor up to 140 kN.

<table>
<thead>
<tr>
<th>DLJ No.</th>
<th>Load cycle(s) [kN]</th>
<th>Tensile failure load [kN]</th>
<th>AE sensor type</th>
<th>Number of AE hits up to 140 kN for centre / outer profile*</th>
</tr>
</thead>
<tbody>
<tr>
<td>031</td>
<td>0-141-0, 0 to failure</td>
<td>155.2</td>
<td>SE-45H</td>
<td>1580, 225 / 725, 1000</td>
</tr>
<tr>
<td>032</td>
<td>0 to failure</td>
<td>239.2</td>
<td>SE-45H</td>
<td>980, 670 / 125, 130</td>
</tr>
<tr>
<td>033</td>
<td>0-140-0, 0 to failure</td>
<td>202.2</td>
<td>SE-150M</td>
<td>3700, 6300 / 1000, 1250</td>
</tr>
<tr>
<td>051</td>
<td>0-140-0, 0 to failure</td>
<td>143.7</td>
<td>SE-45H</td>
<td>1350, 1940 / 650, 450</td>
</tr>
<tr>
<td>052</td>
<td>0-140-0, 0-100-0, 0 to failure</td>
<td>188.7</td>
<td>SE-150M</td>
<td>4600, 7000 / 480, 550</td>
</tr>
<tr>
<td>053</td>
<td>0-139-0, 0 to failure</td>
<td>177.4</td>
<td>SE-150M</td>
<td>4500, 7500 / 350, 800</td>
</tr>
<tr>
<td>101</td>
<td>0-140-0, 0 to failure</td>
<td>190.8</td>
<td>SE-45H</td>
<td>650, 820 / 360, 260</td>
</tr>
<tr>
<td>102</td>
<td>0-140-0, 0 to failure</td>
<td>170.8</td>
<td>SE-150M</td>
<td>2800, 3850 / 380, 300</td>
</tr>
<tr>
<td>103</td>
<td>0-140-0, 0 to failure</td>
<td>174.0</td>
<td>SE-150M</td>
<td>280, 1120 / 50, 40</td>
</tr>
</tbody>
</table>

* see text for details and discussion

The average tensile failure load for all DLJ, irrespective of their bond-line thickness is 182.4 ± 28 kN, and 199.1 ± 42 kN, 169.9 ± 23 kN and 178.5 ± 11 kN for 0.3, 0.5 and 1.0 mm bond-line thickness, respectively. Plotting machine load data versus time (not shown) indicated an overall non-linear behaviour of the DLJ, typically starting at tensile loads below 50% of the failure load.

The AE signal intensity, e.g., measured by AE signal energy, indicates that “bursts” of AE energy are emitted stochastically during loading. This is exemplified in Fig. 2 for two DLJ with nominal bond-line thickness of 0.5 mm and failure loads of 143.7 kN and 188.7 kN, respectively. Both, the number of significant AE energy bursts emitted and the amount of energy emitted per kN load increase are not much different for the two specimens. For the specimen with lower failure load (DLJ051), significant energy is not emitted until a load of about 100 kN (about 70% of the failure load), while for the other (DLJ052) the first significant emission occurs around 55 kN (about 30% of the failure load).

Fig. 2. Cumulative AE signal energy of all four sensors (per kN load increase) versus applied tensile load; (left) DLJ051 with failure load 143.7 kN, (right) DLJ052 with failure load 188.7 kN.

Linear AE signal source location between the sensors on one side of the DLJ is shown in Fig. 3. The first diagram (Fig. 3, left) shows the results up to the proof load level of 140 kN with a continuous cluster of locations around about 42 cm, once the load exceeds 100 kN. The second diagram (Fig. 3, right) shows that this cluster formation continues up to failure (at 239 kN) and clearly yields the most intense AE signals.
Fig. 3. Linear AE signal source location with AE energy per located event versus applied tensile load for DLJ032; (left) up to the proof load of 140 kN, (right) up to failure (at 239 kN).

Fig. 4. Distance ratio (logarithmic scale) determined from pattern recognition and classification of AU signals; (left) AU signals before and (right) after applying the proof load of 140 kN.

AU signals are analysed based on an approach described in detail in [4]. First, a pattern classification program (VisualClass™ from Vallen Systeme GmbH) was used to separate specified prototype signal classes each consisting of two or three signals recorded before applying the proof load. These classes correspond to four different emitter-sensor configurations. Then, all AU signals recorded by the four sensors before and after applying the proof load are classified according to the four specified classes, i.e., the emitter-sensor pairs. A so-called “distance ratio” indicates how well each signal fits the assigned class relative to the chosen prototype signals. The example (DLJ102, Fig. 4) shows that AU signals before proof loading are clearly distinguished from signals emitted and recorded by the same emitter-sensor pairs after proof loading to 140 kN.

Discussion

The AE proof load of 140 kN amounted to between 58% and 97% of the observed failure load. This indicates that damage accumulation due to the proof load ranges from low (e.g., DLJ032) to severe (e.g., DLJ051). The fact that a significantly higher AE activity is recorded for the sensors mounted on the centre profile compared to those mounted on the outer profiles is consistent with the observation that the delamination failure occurred in the centre profile (see Fig. 1, right) and not in the adhesive layer or at the interface between adhesive and GFRP profile. It can be noted that separate measurements of the mechanical properties of the adhesive yield a comparatively low value of the Young’s modulus (E) compared to the GFRP laminate. The sensors on the outer profiles, therefore, quite likely record a significantly lower number of AE hits because of signal attenuation in the adhesive. If the cumulative number of AE hits and the AE hit rates recorded by the sensors on the centre profile is plotted versus tensile load, a roughly expo-
nential curve could be fitted through the data for each DLJ (not shown). This behaviour is typical of damage accumulation in GFRP laminated parts under quasi-static tensile load [5]. The higher number of AE hits recorded with the 150-kHz resonant sensor (SE-150M) compared to that with the multi-purpose sensor (SE-45H) probably reflects the intrinsic higher sensitivity of the resonant sensor.

The analysis of the AE intensity (e.g., the AE signal energy shown in Fig. 2) indicates that with increasing load stochastic “bursts” of AE signal energy are recorded. The magnitude of these bursts and their distribution vs. the applied load do not seem to directly correlate with the observed tensile failure strength of the DLJ. The loads where these bursts of AE energy are observed, quite likely indicate considerable damage accumulation. It would be interesting to investigate whether this results in noticeable changes in mechanical properties (e.g., tensile modulus).

Linear AE source location clearly shows a continuous evolution of increasingly intense AE signals forming a cluster near the end of the adhesive-overlap region (Fig. 3) close to the top sensor in this case. Analogous patterns have been observed for the DLJ monitored up to the proof load level (140 kN) and this is discussed in more detail in [6]. This provides a strong indication that the delamination leading to final failure (Fig. 1, right) originates quite early inside the centre profile near the top of the adhesive overlap.

Taking the distance ratio calculated by the signal-classification routine as a measure of the “similarity” of the AU signals within each “class”, i.e., for each emitter-sensor pair, it is clear that the AU signals are changed by the application of the proof load (Fig. 4). The correct class allocation yields distance ratios not higher than about 100. The signals with distance ratios around 1000 in the graph on the left are assigned to a “wrong” class with respect to the known emitter-sensor pair. The distance-ratio values in the graph on the right (Fig. 4) of about 150 or more hence indicate that changes have occurred in the signal-propagation path between emitter and sensor. A different set of classifying attributes or of prototype signals may change the distance ratio for each signal and/or its class allocation. However, even for other “classifiers” (e.g., attributes) there is still an increase in distance ratio for signals recorded after applying the proof load. A more detailed analysis of the AU signals is currently under way.

There are models, which predict a dependence of the failure load on bond-line thickness (see, e.g., [2, 3]). Essentially, the models predict an increasing failure load with increasing bond-line thickness for the range of thicknesses tested in the experiments. It can be noted that the experimental data do not quite fit this theoretical trend. Within one standard deviation, the experimental failure loads are comparable. Whether this reflects limited statistical significance (three specimens tested per type of DLJ), manufacturing variability (e.g., achieving uniform bond-line thickness sufficiently close to the nominal value), differences in damage accumulation behaviour (e.g., due to variability in lay-up or concentration and distribution of initial defects in the GFRP profiles) or a combination of these factors, is not clear at present.

However, as noted in the introduction, the main purpose of the investigation was to look for experimental evidence that could explain the difference between theoretical (based on Weibull or Generalized Lambda models) and experimental failure loads. The hypothesis was that microscopic damage during loading could result in localized softening and stress reduction and redistribution, i.e., effectively in a non-linear material behaviour. The observed AE activity and intensity, as well as the AU results, can be interpreted as evidence for microscopic damage accumulation starting at relatively low loads, definitely below 50% of the observed failure loads. Considering the AE signal source location, it can be hypothesized that this damage is essentially concentrated in a relatively small part of the centre GFRP profile, i.e. near the end of the adhesive-overlap region. This may effectively yield a mesoscopic or even macroscopic damage area, which renders local stress reduction or redistribution plausible.

Conclusions

Acoustic emission (AE) and acousto-ultrasonic (AU) measurements during tensile tests on adhesively bonded double-lap joints made from pultruded GFRP profiles have shown indications
of microscopic damage accumulation starting at relatively low loads (as low as 50% of the proof loads). AE activity starting at relatively low loads is increasing continuously up to the proof load level (or failure). More intense AE recorded appears to be stochastically distributed and probably relates to coalescence of microscopic defects into mesoscopic or even macroscopic damage areas. AE activity and linear AE signal source location indicate the failure location that is visually observed after failure already at relatively low loads. Microscopic damage accumulation is hence a plausible cause of the discrepancy between experiments and model based strength predictions, as evoked in a recent analysis. However, this will have to be substantiated in further experiments.

Acknowledgment

The technical support of Mr. D. Völki for performing the tensile load test at Empa and discussion of the AE analysis with Dr. J. Bohse (BAM, Berlin) are gratefully acknowledged.

References