Alternative Methods to Measure the Adhesive Shear Displacement in the Thick Adherend Shear Test

Lucas F. M. da Silva a,∗, R. A. M. da Silva a, J. A. G. Chousal a and A. M. G. Pinto b

a Departamento de Engenharia Mecânica e Gestão Industrial, Faculdade de Engenharia, Universidade do Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal
b Departamento de Engenharia Mecânica, Instituto Superior de Engenharia do Porto, Rua Dr. António Bernardino de Almeida 431, 4200-072 Porto, Portugal

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Abstract
There are standard tests to determine the adhesive properties, one of the most used being the Thick Adherend Shear Test (TAST). This test assumes that the adhesive deforms only in shear. The standard method recommends the use of a special extensometer attached to the specimen. The use of this extensometer needs a very experienced technician, in addition to requiring high costs of production. In this work, the adhesive shear deformation is measured with a conventional clip gauge used for tensile tests. The steel deformation correction is made using a non-contact method (optical) that gives only the adhesive deformation and a numerical analysis. The objective of this study was to evaluate the applicability of a simpler method of measuring the adhesive deformation and to evaluate methods without contact for the measurement of the deformation of thin adhesive layers. The results show that a simple clip gauge can be used to measure the adhesive deformation, provided a correction factor is applied.

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Keywords
Epoxy, acrylic, steel, lap-shear, mechanical properties, adhesives, finite element stress analysis, thick adherend shear test

1. Introduction

The use of structural adhesives is increasing. One of the main advantages of this technique is that it allows to bond different materials and reduces the weight of the structures. However, its use is still limited due to a lack of general design criteria and material models that correctly represent the mechanical behavior of the adhesive. The adhesive yield is dependent on the hydrostatic stress and it is impor-
tant to measure the mechanical properties under different modes of loading. Tensile and shear testing is usually used. There are two possibilities for testing in shear: torsional shear and tensile shear. Torsional shear tests include tests on bulk specimens, butt joints and the napkin ring test (ASTM E 229). In the napkin ring test, the adhesive fillets both inside and outside should be removed because they make the calculation of the shear strength and modulus less exact. The outer fillet is easy to remove. However, the inner fillet is impossible to clean away. The butt joint has advantages when an adhesive of low viscosity is used because it is difficult to fill a napkin ring joint properly. Adams and Coppendale [1] designed a jig to produce fully filled joints with low viscosity adhesives. The torsion test needs a means to cause twisting and measuring the resulting rotational motion. In other words, it requires specialized equipment.

It is possible to generate shear using the linear movement of a standard tensile testing machine. There are two principal tensile shear tests: the Thick Adherend Shear Test (TAST) and the Butterfly Test. The latter includes notched beam (Iosipescu) and notched plate (Arcan) test methods. The TAST is more popular because it is easier to make and test the specimens. This test has been widely used and studied in the literature [2–11]. The conventional single-lap shear joint (ASTM D 1002), which is used for comparison and quality control of adhesives, subjects the adhesive to a complicated state of stress. Therefore, it is not suitable for the determination of the true adhesive properties. Using stiff and thick metallic adherends, the adhesive is in a state of essentially uniform shear over most of the overlap and peel stresses are reduced. Two forms of the TAST are used, as developed by Krieger [2] in the USA and Althof [3] in Europe. The main difference between the two tests is the size of the specimen: the Althof specimen is half the size of Krieger’s. They both developed extensometers for measuring the very small displacements across the bondline. The extensometer measures not only the displacement of the adhesive, but also the displacement of the adherend. Therefore, it is necessary to apply a correction to the measured displacements. According to ISO 11003-2, the correction should be deduced from the measurement of the shear strain on a ‘dummy’ specimen consisting of the adherend material alone. Vaughn [4] suggests that the adherend correction can be derived from simple elasticity assuming that the adherends experience pure shear only. However, finite element analysis (FEA) shows that direct axial stress is also present in the adherend [4–6]. Thus, an accurate correction cannot be properly calculated assuming that the adherends experience only pure shear. To take this into account, it is better to use a FEA correction. Nevertheless, a simple elasticity correction is shown to be acceptable as long as the adhesive layer is not too thin. Chiu and Jones [7] studied the influence of both adhesive and adherend thicknesses. The thicker the adhesive layer or the adherend, the more uniform is the shear stress profile. As regards the specimen fabrication, ISO 11003-2 recommends machining the specimens from two plates bonded together. However, this technique has disadvantages such as the effect of cutting on the highly stressed region at the end of the adhesive layer where initial failure is likely to occur. Vaughn
[4] proposes that a better solution is to machine the adherends to the correct dimensions before bonding.

The extensometer recommended by the TAST standard has the inconvenience of needing a correction, besides being difficult to apply on the specimen. One way to solve the correction problem would be to use another method of measurement that measures only the deformation of the adhesive and that is easy to implement. An optical method is a possible solution. In this work, the adhesive shear displacement was measured using a specially designed non-contact technique developed by Chousal and Gomes [12]. The adhesive displacement was also measured using a conventional clip gauge of 25 mm used for tensile tests. In this case, a correction is necessary but it is extremely easy to use and is available in any material testing laboratory. A FEA was carried out to evaluate the correction to apply in the case of the clip gauge and to evaluate the stress distribution in the adhesive.

2. Experimental

2.1. Materials

Three adhesives were selected: a very flexible acrylic adhesive (DP-8005 from 3M), a very stiff epoxy adhesive (Araldite AV138/HV998 from Huntsman) and an intermediate stiffness epoxy adhesive (Araldite 2015 from Huntsman). Tensile tests (BS 2782) on dogbone specimens were carried out to confirm the stiffness of the adhesives. The tensile mechanical properties of the adhesives used are shown in Table 1.

2.2. Specimen Fabrication

The TAST specimens were fabricated individually according to Vaughn [4, 10]. The mould, for specimens’ alignment, was made of steel to assure a good thermal conductivity (essential not to have adhesive overheating which would modify the properties of the adhesive). The mould can produce six specimens at one time. To control the overlap length and the excess adhesive, steel shims were inserted into the gaps once the adherends were brought together. The geometry is presented in Fig. 1. The substrates were machined from bars of DIN Ck 45 steel. The bonding area was

<table>
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<tr>
<th>Table 1. Tensile properties of adhesives used</th>
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<tr>
<td>Young’s modulus ( E ) (GPa)</td>
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<tr>
<td>Tensile strength ( \sigma_t ) (MPa)</td>
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<tr>
<td>Failure strain ( \varepsilon_f ) (%)</td>
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* Manufacturer’s data.
initially degreased with acetone, shot blasted with corundum and again cleaned with acetone before the application of the adhesive. This is a common approach to prepare the surface of carbon steel [13].

The cure of the adhesives was carried out in a hot press. The temperature was measured by a thermocouple placed next to the adhesive. Adhesive DP-8005 was cured at room temperature and adhesives AV138/HV998 and 2015 were cured at 100°C for 10 min.

2.3. Test Procedure

The specimens were tested on a MTS servo-hydraulic machine 312.31 with a load cell of 250 kN. The specimen was attached to the machine by a specially designed fixture to avoid any bending moment. The test speed was 0.1 mm/min and 10% of the maximum load cell capacity was used for test recording. Three specimens were tested for each adhesive.

The adhesive displacement was measured by two methods: using a MTS clip gauge (initial length of 25 mm and resolution of 0.1 µm) and using a video microscope instrument with a lens of 200 magnification (see Fig. 2).

In the case of the clip gauge, since its length (25 mm) is longer than the overlap length of the TAST specimen (5 mm), the clip gauge measures not only the adhesive displacement but also the steel displacement corresponding to the remaining 20 mm. Therefore, it is necessary to apply a correction in order to obtain only the adhesive displacement. The correction was obtained experimentally using an optical instrument (video microscope) that gives only the adhesive displacement and by a finite element analysis (see Section 4).

In the case of the video microscope, the adhesive displacements were obtained by spatial correlation of image pairs acquired initially (non-deformed) and during loading. The spatial correlation, performed in the spectral domain, is a Fast Fourier
Transform (FFT) of the product of two functions. The spatial correlation for a point within the frame being analyzed is computed by the expression [14]:

\[ r \circ d = \text{FFT}(R(\xi, \eta) \cdot D^*(\xi, \eta)), \]

where \( R \) and \( D \) represent the FFTs of functions \( r \) and \( d \), respectively, and the superscript asterisk (*) is the complex conjugate symbol. Functions \( r \) and \( d \) are, in this case, the non-deformed and deformed areas surrounding the point being analysed, respectively. These areas correspond to the square areas in images R0 and D0, respectively, of Fig. 3. This procedure consists in the transformation of the diffraction halo that is characterized by the local displacement vector \((u, v)\). The spectrum obtained results in a signal with a peak located at the position \((u, v)\) in the second spectral domain (last FFT from Fig. 3). By detecting this peak one can determine the mean displacement suffered by the central point of the area considered [14]. Repeating this process of double FFT and peak detection for the whole image, the field of displacements (in-plane) is obtained.

An in-house developed computer programme uses this Fourier transform procedure to compute the displacement between two points and the whole displacement
field. The texture of the object must be speckle-like, which is the case for the majority of materials. The area recorded by the 200× lens was about 1.1 mm × 0.9 mm (see Fig. 4a). A length of 0.78 mm (adhesive thickness) corresponds to 488 pixels; therefore the raw resolution of the system was 1.6 µm/pixel. The computer

Figure 4. Displacement field obtained with the spatial correlation technique for adhesive 2015: (a) area processed, (b) deformation in the elastic range (schematic representation on the right side), (c) deformation in the plastic range (schematic representation on the right side).
programme is also able to perform a sub-pixel analysis which increases the measurement precision up to 10 times.

3. Experimental Results

The failure, observed with naked eye, was cohesive within the adhesive in all cases. The failure surface in the case of adhesive AV138/HV998 is shown in Fig. 5 for illustration purposes.

Typical stress–strain curves in shear for all the adhesives tested are shown in Figs 6, 7 and 8. Two curves are presented for each case, one with the strain corresponding to the clip gauge that includes the steel deformation (referred as ‘steel + adhesive’ in the graphs) and one obtained by spatial correlation of video data that accounts for the deformation of the adhesive only (referred as ‘adhesive’ in the graphs). The two curves are coincident for adhesive DP-8005, which means the steel deformation is negligible in this case. Note that in Fig. 6 the ‘adhesive’ curve ends at approximately 100% strain because at that moment the reference point used for spatial correlation is out the video frame. In the case of adhesive 2015, the ‘steel + adhesive’ curve is also quite close to the ‘adhesive’ curve. This adhesive is also relatively flexible and the steel deformation can almost be neglected. However, in the case of adhesive AV138/HV998, the ‘steel + adhesive’ and ‘adhesive’ curves are quite different. This is because this adhesive is very stiff and the steel deformation represents now a substantial part of the total deformation recorded by the clip gauge. It is mandatory in this case to apply a correction in order to obtain the right shear modulus of the adhesive. Table 2 shows the shear modulus obtained from the two curves (‘steel + adhesive’ and ‘adhesive’) for comparison purposes and the shear strength (coincident for the two curves). The shear strain to failure presented in Table 2 was obtained from the ‘steel + adhesive’ curve because it is
Figure 6. Shear stress–shear strain curves of adhesive DP-8005.

Figure 7. Shear stress–shear strain curves of adhesive 2015.

not always possible to get the last part of the curve by spatial correlation (case of adhesive DP-8005) due to image focus problems at break point.

The spatial correlation technique enables not only to obtain the displacement between two points but also the whole displacement field. This is illustrated in Fig. 4 for adhesive 2015. Two displacement fields are presented: one in the elastic range, corresponding to a stress of 10 MPa (Fig. 4b), and the other one in the plastic
range, for a stress of 15 MPa (Fig. 4c). The displacement field in the elastic range presents a linear variation along the adhesive thickness. However, in the plastic range, the displacement field is approximately constant at the borders next to the steel suggesting that most of the adhesive deformation is taking place in the middle of the adhesive layer. This effect has been reported before [15] and is attributed to the constraining effect of the steel.
4. Clip Gauge Correction Factor

The results presented in Section 3 show that the spatial correlation technique is a good method for determining the adhesive displacement in the TAST. However, the type of equipment required and the laborious image treatment does not make this equipment suitable for everyday use. On the other hand, the conventional clip gauge, available in any materials testing laboratory, is a very practical method. The problem is that it needs a correction, especially in the case of stiff adhesives. For relatively flexible adhesives, such as polyurethanes, acrylics and soft modified epoxies, the correction may be negligible. The correction can be calculated for each point by subtracting the steel displacement. Another way of obtaining the adhesive displacement is by applying a correction factor (CF) according to equation (2):

$$ CF = \frac{u_{\text{steel+adhesive}}}{u_{\text{adhesive}}}, $$

where $u$ is the displacement. In the elastic range, the correction factor is constant and also equal to the relation $G_{\text{adhesive}} / G_{\text{steel+adhesive}}$, where $G$ is the shear modulus. For the plastic range and assuming a perfectly plastic case, the steel displacement remains approximately constant and the adhesive deformation increases. In the plastic range, CF is not constant and increases as the adhesive deformation increases. For ductile adhesives, CF approaches unity as in the case of adhesives DP-8005 and 2015. The CF in the elastic range given by the three adhesives tested is presented in Fig. 9 (‘CFexp’ curve) as a function of the shear modulus determined by the clip gauge. It covers any case from very flexible adhesives to very stiff adhesives ($E \approx 500–5000$ MPa).

The correction factor was also determined by a finite element analysis. The commercial program ABAQUS (version 6.5-1) was used [16]. The TAST specimen

![Image](image_url)

**Figure 9.** Experimental and theoretical correction factors as a function of the adhesive shear modulus.
was modelled with 2D 8-node continuum isoparametric elements with four Gauss points (reduced integration). A plain strain analysis was done since the width of the specimen is larger than the thickness. An elastic simulation was done with a load of 1000 N. The boundary conditions and the mesh used are presented in Fig. 10. The shear and peel stress distributions obtained are presented in Fig. 11 for adhesive 2015. The shear stress is practically uniform and the peel stress is negligible which reinforces the suitability of the TAST for determining adhesive shear properties [10]. The correction factor was then determined by plotting the longitudinal displacement along path $L$, which corresponds to the clip gauge reading, as shown Fig. 12. The results are presented in Fig. 13. The displacement along path $L$ includes both the steel and adhesive displacements. To obtain only the adhesive
displacement, the longitudinal displacement was plotted along path \( T \) (see Fig. 12) and the results are presented in Fig. 14. The same was done for adhesives AV138 and DP-8005, and the results are summarized in Table 3. The CF compares very well with that obtained experimentally (see curve ‘CFtheor’ in Fig. 9).

In order to validate CF, additional tests were carried out with another adhesive. The epoxy adhesive Araldite AV118 from Huntsman was used. The shear stress–shear strain curves are shown in Fig. 15. The ‘adhesive’ curve is not shown beyond the maximum stress because problems in focusing image were encountered. The shear modulus obtained with the clip gauge (‘steel + adhesive’ curve) and the true shear modulus obtained with the spatial correlation technique (‘adhesive’ curve) are indicated in Table 4 along with the prediction of the shear modulus using the correction factor determined above. The predicted shear modulus (using the clip gauge shear modulus and the correction factor) compares very well with the true shear modulus determined with the correlation technique, which validates the correction factor.
Figure 14. Longitudinal displacement along path $T$ for adhesive 2015.

Table 3.
Steel and adhesive displacements computed from the finite element analysis for the determination of the correction factor

<table>
<thead>
<tr>
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<th>DP-8005</th>
<th>2015</th>
<th>AV138/HV998</th>
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<tbody>
<tr>
<td>Steel + adhesive displac. (path $L$) (mm)</td>
<td>0.0345</td>
<td>0.0128</td>
<td>0.0055</td>
</tr>
<tr>
<td>Adhesive displac. (path $T$) (mm)</td>
<td>0.0327</td>
<td>0.0110</td>
<td>0.0037</td>
</tr>
<tr>
<td>Correction factor (steel + adhesive displac./adhesive displac.)</td>
<td>1.06</td>
<td>1.17</td>
<td>1.50</td>
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</table>

5. Conclusions

The standard TAST was investigated using an innovative non-contact method for measuring displacements, the spatial correlation, and a conventional clip gauge for tensile tests. The following conclusions can be drawn:

1. The spatial correlation method can measure displacements with a resolution of 1.6 $\mu$m/pixel with a 200× lens.

2. The shear stress–strain curves obtained with the spatial correlation are accurate enough for the determination of adhesive shear properties provided the strain does not go beyond 100%.

3. The spatial correlation method can give the displacement field which can be useful for detecting defects or interface effects.
Figure 15. Shear stress–shear strain curves of adhesive AV118.

Table 4.
Predicted shear modulus for adhesive AV118 using the experimental correction factor (see Fig. 9) and $G = 811$ MPa

<table>
<thead>
<tr>
<th>Shear modulus $G$ (MPa) (steel + adhesive curve)</th>
<th>Shear modulus $G$ (MPa) (adhesive curve)</th>
<th>Predicted shear modulus $G$ (MPa) with CF = 1.40</th>
</tr>
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<tr>
<td>811 ± 119</td>
<td>1095 ± 19</td>
<td>1135.4</td>
</tr>
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</table>

4. The deformation measured by the conventional clip gauge needs a correction, especially for stiff adhesives.

5. A calibration factor curve was determined both experimentally and numerically that can correct the clip gauge reading in the elastic range.

References