IN-PLANE MECHANICAL BEHAVIOUR OF A GLASS/EPOXY COMPOSITE


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RESUMO

Foi identificado experimentalmente o comportamento mecânico bidimensional dum compósito quasi-unidirecional de vidro/epóxido. Uma atenção especial foi dada ao comportamento ao corte, tendo sido analisados os seguintes ensaios: o ensaio de tracção de laminado simétrico a ±45° e o ensaio de tracção fora dos eixos de ortotropia. O ensaio de laminado simétrico a ±45° serve apenas para identificar o comportamento linear inicial. O ensaio de tracção fora dos eixos de ortotropia fornece a resposta completa ao corte, mediante a apropriada interpretação dos resultados experimentais. Mostrou-se, através duma análise por elementos finitos, que o método de Chamis e Sinclair é adequado ao compósito estudado e aos provetes ensaiados.

ABSTRACT

The in-plane mechanical behaviour of a quasi-unidirectional glass/epoxy composite was identified experimentally. A special attention was given to the in-plane shear behaviour. Two test methods were examined: the ±45° tensile test and the off-axis tensile test. The ±45° tensile test is only suitable to determine the initial linear shear response. The off-axis tensile test gives the complete shear stress-strain response if an appropriate data reduction is performed. It was shown by a finite element analysis that the simple data reduction method of Chamis and Sinclair is adequate to the composite material and the specimens tested.

KEYWORDS: Composites, mechanical behaviour, shear.

1. INTRODUCTION

The polymer matrix composites reinforced with continuous fibres are an important class of structural materials, commonly used in thin laminates made up from individual plies (or laminae) stacked and consolidated in a proper way. The mechanical response of such structures can be accurately modelled by the Classical Lamination Theory (CLT), if the mechanical properties of individual plies are known [1]. Once a single ply in a thin laminae is assumed to be a state of plane stress, only its in-plane mechanical behaviour is needed. The experimental identification of in-plane mechanical behaviour of continuous fibres composite materials must employ loading devices that guarantee the creation of a uniform and
pure stress state in the gauge section of the specimens. Due to its orthotropic nature, this ideal goal is difficult to achieve, even for the simple uniaxial loading in the directions of material symmetry [2,3]. The difficulties are very pronounced when one attempts to obtain a uniform pure shear stress field, as required by the measurement of in-plane shear properties [3,4,5].

A number of experimental methods have been purposed to determine the in-plane shear response of composite materials. The torsion test of thin-walled tubes is considered to be the most accurate test method for identification of both in-plane shear modulus and shear strength, but is very expensive to perform [6]. Among the other proposed shear test methods, the following have been generally accepted as well suited to determine the shear characteristics of continuous fibres reinforced composites: the Iosipescu test [5,6,7], the ± 45° tension test [4,8,9,10] and the off-axis tension test [3,4,9,10].

The objective of this work is to evaluate the complete in-plane stress-strain response of a glass/epoxy composite. A special emphasis will be put on the in-plane shear response identification, using the ± 45° tension test and the off-axis tension test.

2. ORTHOTROPIC MECHANICAL PROPERTIES

The Hooke’s law for an orthotropic lamina in a state of plane stress and referred to the material principal coordinate system (figure 1), can be written as [8]:

\[
\begin{bmatrix}
\varepsilon_1 \\
\varepsilon_2 \\
\varepsilon_6
\end{bmatrix} = \begin{bmatrix}
1/E_1 & -v_{21}/E_1 & 0 \\
-v_{12}/E_1 & 1/E_2 & 0 \\
0 & 0 & 1/G_{12}
\end{bmatrix} \begin{bmatrix}
\sigma_1 \\
\sigma_2 \\
\sigma_6
\end{bmatrix},
\]

(1)

where \(E_1\) is the longitudinal Young modulus, \(E_2\) is the transversal Young modulus, \(G_{12}\) is the in-plane shear modulus, \(v_{12}\) and \(v_{21}\) are the in-plane Poisson’s ratios.

![Figure 1 – In-plane material principal coordinate system.](image-url)

The engineering constants (\(E_1\), \(E_2\), \(G_{12}\), \(v_{12}\) and \(v_{21}\)) only describe the initial linear elastic behaviour. However, fibre composites exhibit a physically non-linear response, and as such
the following complete stress-strain curves are needed to fully characterise the orthotropic mechanical behaviour:

\[ \varepsilon_i = f(\sigma_i), \quad i = 1,2,6 \quad \text{and} \quad \varepsilon_j = g(\sigma_j), \quad i, j = 1,2. \tag{2} \]

Associated with the first stress-strain relations there are three important properties: the longitudinal strength \(X_1\), the transverse strength \(X_2\) and the in-plane shear strength \(X_6\).

3. EXPERIMENTAL WORK

The composite material used in this work was a quasi-unidirectional glass/epoxy composite, with 7% of the fibres in the transverse direction, supplied by PPG in a prepreg form, under the trade name PV245\textsuperscript{®}. Laminate plates were fabricated in hot press accordingly to the manufacturer’s cure schedule, with the following layups: \([11]_{8t}\) and \([\pm 45^\circ]_{2t}\). Tensile coupons were cut from the plates, with the shape and dimensions shown in figure 2. Aluminium alloy end-tabs were bonded on both ends of some specimens using epoxy adhesive (Araldite Standard\textsuperscript{®}).

![Figure 2 – Tensile specimens (a) longitudinal, (b) transversal, (c) \([11]_{8t}\) and (d) \([\pm 45^\circ]_{2t}\).](image-url)
The quasi-static tensile tests were conducted in a Instron Model 4208 universal testing machine, at a crosshead displacement rate of 0.25 mm/min. The strains were measured using an Instron clip-on type extensometer, with a 50 mm gauge length, and also with CEA-13-250UW-350 strain gages and EA-06-125RD-350 rosette strain gages. The loads were applied to the specimens through rigid clamps and were measured using an Instron 100 KN load cell. The tabless specimens were loaded according to the procedure suggested by Hojo et al. [11], with abrasive paper inserts between the specimens and the grips. Figure 3 shows the general appearance of failed specimens, from which it is clear that the ultimate failure are free from any stress concentration effects due to rigid clamping of the specimen’s ends.

4. IN-PLANE TENSILE BEHAVIOUR

The stress-strain curves in the longitudinal and transverse directions are shown in figure 4. The moduli $E_1$ and $E_2$, and the principal Poisson’s ratio $\nu_{12}$, were determined from the experimental data by linear regression analysis. The mean experimental values of the engineering elastic constants along with the longitudinal and transverse strength ($X_1$ and $X_2$) are presented in table 1.
Figure 4 – Stress-strain diagrams (a) in the longitudinal and (b) in the transverse directions.

Table 1 – In-plane tensile properties.

<table>
<thead>
<tr>
<th>$E_1$ (GPa)</th>
<th>$E_2$ (GPa)</th>
<th>$\nu_{12}$</th>
<th>$X_1$ (MPa)</th>
<th>$X_2$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40.83</td>
<td>19.52</td>
<td>0.24</td>
<td>1063.2</td>
<td>103.0</td>
</tr>
</tbody>
</table>

5. IN-PLANE SHEAR BEHAVIOUR: ±45° TENSILE TEST

The ±45° tension test was introduced by Petit [8]. This test method involves the measure of the axial load $P$ applied to a ±45° symmetric laminate, and the measure of the laminate axial strain $\varepsilon^0_1$ (in the direction of $P$) and the laminate transverse strain $\varepsilon^0_2$ (in the orthogonal direction of $P$). From these experimental data the shear stress $\sigma_6$ and the shear strain $\varepsilon_6$. 
referred to the material principal coordinate system, can be obtained as proposed by Rosen [12]:

\[ \varepsilon_6 = \varepsilon_1^0 - \varepsilon_2^0 \quad \text{and} \quad \sigma_6 = \frac{P}{2A}, \]

where A is the cross sectional area of the specimen.

The experimental shear stress-strain diagrams are shown in figure 5. The shear modulus \( G_{12} \) was obtained from these diagrams by linear regression analysis. The mean value of \( G_{12} \) is presented in table 2.

Figure 5 – Shear stress-strain relationships obtained using the ± 45° and the off-axis tensile tests.

Besides the initial shear modulus, it is very unlikely that the ± 45° tensile test gives the true in-plane shear response of orthotropic composite materials. In fact, several concerns have been raised about the test, including the influence of free edge stresses, stacking sequence, the validity of equations 3, fibre rotation, residual thermal stresses and transverse matrix cracking [4,8,13,14].
6. IN-PLANE SHEAR BEHAVIOUR: OFF-AXIS TENSILE TEST

The off-axis tensile test was employed for the first time by Chamis and Sinclair [9]. In this technique a uniaxial load \( P \) is applied to the specimen at an angle of 11° to fibre direction (figure 6), and it is assumed that in the gauge section there is a pure tensile stress state, referred to the laminated axis:

\[
\overline{\sigma_1} = \frac{P}{A}.
\]  

(4)

The stresses in the material principal coordinate system are assumed to be related to the load \( P \) by the transformation equations:

\[
\begin{align*}
\sigma_1 &= \frac{P}{A} \cos^2 \theta \\
\sigma_2 &= \frac{P}{A} \sin^2 \theta. \\
\sigma_6 &= \frac{P}{2A} \sin 2\theta
\end{align*}
\]  

(5)

On the other hand, the shear strain \( \varepsilon_6 \) in the material principal directions can be determined using a three gauge strain rosette, allowing the identification of shear-strain relationship.

![Figure 6 – Off-axis tensile test.](image)

The above procedure was used to obtain the shear stress-strain response of the composite material under study (figure 5). The mean value of initial shear modulus \( G_{12} \) is given in table 2 and was determined using the same procedure employed for the \( \pm 45^\circ \) tension test. This value agrees very well with the value calculated from the following orthotropic transformation equation [1]:

\[
\frac{1}{G_{12}} = \frac{1}{\sin^2 \theta \cos^2 \theta} \left( \frac{1}{E_1} \left( \frac{\cos^4 \theta}{E_1} - \frac{\sin^4 \theta}{E_2} \right) + \frac{2v_{12}}{E_1} \sin^2 \theta \cos^2 \theta \right). 
\]  

(6)
in which \( E_1 \) is the laminate modulus in the load direction (table 2).

### Table 2 – In-plane shear modulus.

<table>
<thead>
<tr>
<th>( \theta^\circ )</th>
<th>( E_1 ) (GPa)</th>
<th>( G_{12} ) (GPa)(1)</th>
<th>( G_{12} ) (GPa)(2)</th>
<th>( G_{12} ) (GPa)(3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11,3</td>
<td>36,5</td>
<td>6,87</td>
<td>7,24</td>
<td>7,14</td>
</tr>
</tbody>
</table>

(1) The \( \pm 45^\circ \) tension test.
(2) Values based on the initial modulus \( E_1 \).
(3) Values obtained from the linear portion of the \( \sigma_6 \) \( (\epsilon_6) \) curves.

It is claimed the off-axis tension test is suitable not only to identify the initial in-plane shear modulus, but also the total shear stress-strain curve, including the ultimate shear stress. However, a state of pure shear does not exist in the gauge section of specimen, and so a failure criterion is needed to determine the shear strength from the ultimate tensile stress of the specimen, \( \sigma_{ir}^f \). The mean experimental value of \( \sigma_{ir}^f \) can be found in table 3, along with the associated magnitudes of the stresses, \( \sigma_i^f (i = 1,2,6) \), in the material principal coordinate system, calculated using equations (5). The shear strength \( X_6 \) can thus be estimated by the Tsai-Hill strength criterion [1]:

\[
\left( \frac{\sigma_1^f}{X_1} \right)^2 - \frac{\sigma_1^f \cdot \sigma_2^f}{X_1 \cdot X_2} + \left( \frac{\sigma_2^f}{X_2} \right)^2 + \left( \frac{\sigma_6^f}{X_6} \right)^2 = 1. \tag{7}
\]

The magnitude of \( X_6 \) calculated from the above procedure (table 3) is practically equal to the shear stress \( \sigma_6^f \), so this is the stress component that controls the ultimate failure.

### Table 3 – In-plane shear strength.

<table>
<thead>
<tr>
<th>( \theta^\circ )</th>
<th>( \sigma_1^f ) (MPa)</th>
<th>( \sigma_2^f ) (MPa)</th>
<th>( \sigma_6^f ) (MPa)</th>
<th>( X_6 ) (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11,32</td>
<td>304,46</td>
<td>292,75</td>
<td>11,75</td>
<td>59,54</td>
</tr>
</tbody>
</table>

The shear response identified using the method of Chamis and Sinclair presented above is the true shear response of the composite material if in the gauge section of the specimen the stress state is characterized by equation (4) or by equations (5). However, it is well known [3] that the end constraints arising from rigid clamping of specimen’s ends may lead to a more
complex strain field in the gauge section. The finite element code ABAQUS 5.5 was used to evaluate the strain and stress fields in the specimen’s section between loading fixture, simulating a tensile test in the linear elastic domain. The results obtained (figure 7) reveal an extensive gauge section where the laminate tensile stress $\sigma_1$ varies less than 4.5%. Therefore, the hypothesis of a homogeneous state defined by equations (5), on which the method of Chamis and Sinclair rely, is admissible.

Figure 7 – Stress field in off-axis tensile specimen.

7. CONCLUSIONS

The principal conclusions of this paper are as following:

- the loading arrangement promotes the right failure mode of the specimens tested;
- the $\pm 45^\circ$ tensile test and the data reduction method of Petit are suitable to identify the initial linear shear response;
- the off-axis tensile test and the data reduction method proposed by Chamis and Sinclair are appropriate to identify the in-plane shear response of the composite studied.
8. REFERENCES