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Composites Science and Technology 66 (2006) 1455–1464
COMPOSITES SCIENCE AND TECHNOLOGY
www.elsevier.com/locate/compscitech

Modelling the nonlinear shear stress–strain response of glass fibre-reinforced composites. Part I: Experimental results

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Received 9 September 2004
Available online 4 June 2005

Abstract

The ASTM D3518/D3518M-94(2001) Standard Test Method for "In-plane shear response of polymer matrix composite materials by tensile test of a ±45° laminate" is based on the uni-axial tensile stress–strain response of a ±45° composite laminate which is symmetrically laminated about the midplane. For long glass fibre-reinforced epoxy composites, the test shows a highly nonlinear shear stress–strain curve. This work is concerned with the development of a material model to predict this mechanical behaviour. Part I discusses the experimental program with tensile tests on $[+45°/-45°]_{2s}$ laminates and off-axis $[10°]_8$ composites. Cyclic tensile tests have been performed to assess the amount of permanent shear strain and the residual shear modulus.

Part II focuses on the development of the material model and the finite element implementation. Two state variables have been introduced to represent the shear modulus degradation and the accumulation of permanent shear strain. The model has also been applied to the simulation of a three-point bending test on a $[+45°/-45°]_{2s}$ laminate.

Keywords: A: Polymer-matrix composites (PMCs); B: Mechanical properties; C: Damage mechanics; D: Mechanical testing

1. Introduction

Several test methods have been proposed to determine the inplane shear stress–strain response of a fibre-reinforced composite [2]. The ASTM D4255/D4255M-01 Standard Test Method for "In-plane shear properties of polymer matrix composite materials by the Rail Shear Method" uses the three- or two-rail shear test. The ASTM D5379/D5379M-98 Standard Test Method for "Shear properties of composite materials by the V-Notched Beam Method" is another example.

As these standards require specialized fixtures, the inplane shear stress–strain response is often determined by using the ASTM D3518/D3518M-94(2001) Standard Test Method for "In-plane shear response of polymer matrix composite materials by tensile test of a ±45° laminate" (or the equivalent ISO 14129:1997 Standard "Fibre-reinforced plastic composites – Determination of the in-plane shear stress/shear strain response, including the in-plane shear modulus and strength, by the plus or minus 45 degree tension test method"). This standard is based on the uni-axial stress–strain response of a ±45° laminate which is symmetrically laminated about the midplane.

In this work, the latter standard is used to study the nonlinear shear stress–strain response of a long glass fibre-reinforced epoxy composite. Also, a comparison is made with the 10° off-axis tensile test, which has received much attention during the last decade [3–8].

Part I discusses the experimental results for the static tensile tests on $[+45°/-45°]_{2s}$ laminates and off-axis $[10°]_8$ composites. Also, cyclic tensile tests on $[+45°/-45°]_{2s}$ laminates have been performed.

In Part II [1], the development of the material model is treated. Two state variables are introduced to describe

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0266-3538/$ - see front matter
doi:10.1016/j.compscitech.2005.04.014

the nonlinear shear stress–strain response of the long glass fibre-reinforced epoxy composite. All results are validated with finite elements.

2. Material and experimental set-up

2.1. Material

The material under study was a glass/epoxy composite. The glass reinforcement was a unidirectional E-glass fabric (Roviglas R17/475). In the fibre direction $\vec{e}_{11}$, the reinforcement was 475 g/m^2, while in the direction $\vec{e}_{22}$, the reinforcement was 17 g/m^2. The epoxy matrix was Araldite LY 556.

Four stacking sequences were manufactured: $[0°]_8$, $[90°]_8$, $[+45°/-45°]_{2s}$ and $[10°]_8$, with the angle referred to the direction $\vec{e}_{11}$. The layups $[0°]_8$ and $[90°]_8$ were used for characterization in the orthotropic material directions, while $[+45°/-45°]_{2s}$ and $[10°]_8$ were used for shear tests.

All specimens were manufactured by vacuum assisted resin transfer moulding with a closed steel mould. The thickness of all specimens was 3.0 mm and the fibre volume fraction was about 50%. The samples were cut to dimensions on a water-cooled diamond saw.

The inplane elastic properties of the individual glass/epoxy lamina were determined by the dynamic modulus identification method described by Sol et al. [9,10] and are listed in Table 1.

Apart from the dynamic modulus identification method, static tensile tests on the $[0°]_8$ and $[90°]_8$ layups have been performed to check the values of the elastic properties and to determine the static strengths. It is important to mention that the mechanical behaviour in the $\vec{e}_{11}$ and $\vec{e}_{22}$ direction is linear up till failure. This is demonstrated for the $\vec{e}_{22}$ direction in Fig. 1.

The elastic properties, calculated from the mechanical tests, are listed in Table 2. If compared to the values in Table 1, the agreement is satisfactory.

The tensile strength properties were determined from the $[0°]_8$ and $[90°]_8$ stacking sequence and are listed in Table 3.

2.2. Experimental set-up

For characterization of the shear behaviour of the glass/epoxy composite, tensile tests were performed on the $[+45°/-45°]_{2s}$ and $[10°]_8$ stacking sequence.

Table 1
Inplane elastic properties of the individual glass/epoxy lamina (dynamic modulus identification method)

E_{11} [GPa]	38.9
E_{22} [GPa]	13.3
ν_{12} [−]	0.258
G_{12} [GPa]	5.13

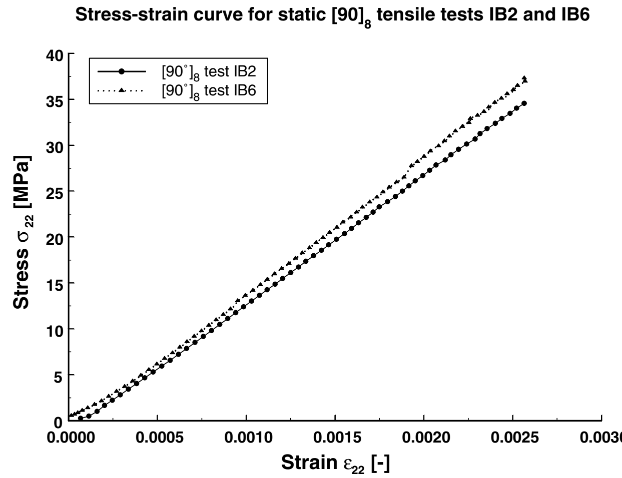

Fig. 1. Stress–strain curve for static $[90°]_8$ tensile tests IB2 and IB6.

Table 2
Inplane elastic properties of the individual glass/epoxy lamina (mechanical testing)

E_{11} [GPa]	42.4
E_{22} [GPa]	14.2
ν_{12} [−]	0.245

Table 3
Tensile strength properties of the individual glass/epoxy lamina

X_T [MPa]	901.0 ± 38.0
ε_{11}^{ult} [−]	0.025
Y_T [MPa]	36.5 ± 1.1
ε_{22}^{ult} [−]	0.0025

All tensile tests were performed on an electromechanical Instron testing machine with a loadcell of ±100 kN. The tests were displacement-controlled with a speed of 2 mm/min and both load and displacement were recorded.

The layout of the specimens is illustrated in Fig. 2.

All specimens were instrumented with three separate strain gauges, in the 0°, 45° and 90° direction, respectively. A strain gauge rosette was not suitable, because

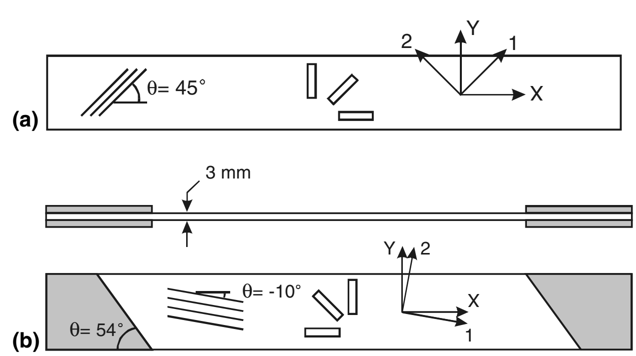

Fig. 2. Layout of the (a) $[+45°/-45°]_{2s}$ specimens and (b) $[10°]_8$ specimens.