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Investigation of strain hardening effects under in-plane shear of unidirectional composite materials

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A micromechanical model of a composite material is subjected to in-plane shear, in order to quantify the shear hardening effect reported in the literature for this deformation state. Solutions for elastic and elastic–plastic models under the same shear loading are presented, using large and small deformation kinematics. The fibres are modelled as transversely isotropic linear elastic and the matrix is assumed to behave according to the Mohr–Coulomb yield criterion. The stress generated in the fibres during loading is investigated for each of the different models. Elastic–plastic matrix material behaviour permitted additional rotation of the fibres in comparison to the elastic model. This rotation was seen to produce the observed strain hardening under in-plane shear.

1. Introduction

The complex failure behaviour caused by the interaction of the different constituent phases make accurate failure prediction for composite materials difficult. Continuum damage models are currently the most popular method for composite material failure prediction. However, these models are based on mesoscale averages of damage processes. An emerging alternative is microscale modelling, where the physical damage mechanisms are modelled explicitly. This approach allows for a better understanding of the failure behaviour, and such models provide good agreement to experimental data. The elastic moduli of different composites have been accurately reproduced using the Representative Volume Element (RVE) approach [1–3], where a small volume of the composite is modelled, containing individual fibres in a region of matrix, and stress and strain fields are homogenised to produce mesoscale values for a lamina. Initial RVEs used square or hexagonal regular arrays of fibres [4]. However, the distribution of the fibres within the matrix was subsequently identified as a major factor in damage initiation and progression [5]. In [2], RVEs were developed which reproduced, statistically, the fibre arrangement found in the composite. This work allowed damage models to be developed [6–9], which were capable of providing good correlation to experimental data, in terms of stress–strain results and damage patterns.

Among the published experimental data was an effect, highlighted in [10], where the composite appeared to strain harden at high in-plane shear strains. Fibre rotation was given as the reason for the observed strain hardening, and this effect is investigated further here.

2. Modelling approach

2.1. Models

Four conditions have been examined in this work:

- *Elastic Small Deformation Theory (SDT) model:* Elastic material properties used, linear geometry.
- *Elastic Large Deformation Theory (LDT) model:* Elastic properties used, non-linear geometry.
- *Plastic SDT model: Elastic–plastic* matrix properties, elastic fibre properties, linear geometry.
- *Plastic LDT model: Elastic–plastic* matrix properties, elastic fibre properties, non-linear geometry.

The SDT analysis did not take the rotations of the fibres into account, but the LDT analysis allows the effects of fibre rotation to be calculated. The four different models, described above, allowed individual stress contributions to the strain hardening effect to be analysed separately.

2.2. Material properties

Although fibre–matrix debonding has been shown to be a critical factor in the damage process at the microscale [11], the results in [10] under in-plane shear indicate that interfacial debonding

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does not occur under in-plane shear until a high global shear strain was reached. The range of shear strains examined in this paper has therefore been kept below the reported final, catastrophic failure strains, which allowed fibre debonding to be omitted. The material investigated here is the high strength, high volume fraction composite HTA/6376, manufactured by Hexcel composites.

2.2.1. HTA fibres

The material properties of the fibres are assumed to be linear elastic and transversely isotropic. No damage has been modelled in the fibres; the elastic moduli from [11] are used and are presented in Table 1.

2.2.2. 6376 Matrix

The matrix material has been modelled using the Mohr–Coulomb yield criterion, using the initial stiffness in Table 1. The Mohr–Coulomb criterion is represented by the following equation

$$\tau + \sigma_n \tan\phi = \tau_c \quad (1)$$

The criterion assumes a shear failure once the shear stress at a point, τ, reaches a value, equal to the yield stress of the material under pure shear, τ_c, with the influence of normal stress taken into account through the second term in Eq. (1), where σ_n is the normal stress; ϕ (known as the friction angle) quantifies the effect of the normal stress on the yield point.

The failure surface in terms of principal stresses (σ_1, σ_3) is:

$$f(\sigma_1, \sigma_3) = (\sigma_1 - \sigma_3) + (\sigma_1 + \sigma_3)\sin\phi - 2\tau_c\cos\phi = 0 \quad (2)$$

Experimental data in [12] provided strength values in tension and compression, which allowed c and ϕ to be calculated as 82.5 MPa and 26°, respectively. No additional damage processes have been modelled in the matrix, as the shear strains were kept small, relative to the strain required to cause damage, as reported in [10]. The matrix was assumed to be a perfectly plastic material.

2.3. Model details

An RVE was created, of size 35 × 35 × 0.4 μm and volume fraction 0.6046, using the Nearest Neighbour Algorithm (NNA), to reproduce the fibre distribution in HTA/6376 [2]. The RVE was meshed using approximately 115,000 elements, predominantly type C3D8, with some C3D6 elements. The surface nodes of the RVE were assigned to groups, based on whether the nodes belonged to a face, edge or corner of the RVE. The corner nodes were used as control nodes, to where displacements were applied. Three dimensional periodic boundary conditions were enforced through constraint equations, which controlled the displacement of the faces and edges relative to the control nodes. The commercial Finite Element package ABAQUS was used to solve the boundary value problem [13].

Table 1
Elastic properties of constituent phases.

	HTA fibre [11]	6376 Matrix
E_{11} (GPa)	238	
E_{22} (GPa)	28	3.64
E_{33} (GPa)	28	
ν_{12}	0.23	
ν_{23}	0.33	0.34
ν_{31}	0.03	
G_{12} (GPa)	24	
G_{23} (GPa)	7.2	1.35
G_{31} (GPa)	24	

3. Results

Previous experimental and modelling studies of composite materials under in-plane shear [10], have indicated a strain hardening effect occurring as the in-plane shear strain on the composite was increased. This has been attributed to fibre rotation, where the stiffer longitudinal axis of the fibre became progressively more aligned with the loading axis. Fig. 1 illustrates the rotation of the fibres in pure shear. Initially, the fibres are aligned with the 1-axis, and lie at an angle of α = 45° to the resultant of the combined shear load, F_{12}, as shown by the dashed lines in Fig. 1. This orientation is altered through the application of the shear strain, so that the angle between the fibre's longitudinal axis and F_{12} is reduced to α'. Therefore the fibre's stiffer longitudinal direction is more closely aligned with the applied load.

To investigate the issue of fibre rotation, the four models, as described in Section 2.1, were used. The homogenised elastic shear modulus was the same for all four models, calculated as 5.09 GPa, which is in close agreement to the published value of 5.2 GPa for HTA/6376 [14]. The elastic model produced almost identical, stress results from both the SDT and LDT analyses. Stress–strain results from the elastic–plastic model are shown in Fig. 2. It can be seen that a strain hardening effect is obtained at higher strain levels from the LDT analysis, which is not obtained in the SDT results.

An investigation into the stress state in the fibres was undertaken, to isolate individual contributions to the hardening effect. An element was chosen from the centre of one of the fibres, where the edge effects, produced through interaction with the surrounding matrix, were negligible. The stress in the longitudinal direction of the fibre was non-existent, and showed no increase in the SDT analysis, however, from the LDT analysis the longitudinal stress in the fibre was seen to increase significantly as shown in Fig. 3, as the fibre aligned itself with the loading axis. The rate of increase of longitudinal stress within the element was greater in the elastic–plastic matrix case.

The shear stress in the same element was similarly investigated. The results from the elastic–plastic model are presented in Fig. 4. The shear stress in the plastic model reflects the yielding behaviour of the surrounding matrix, however, a hardening effect is found here at high strains.

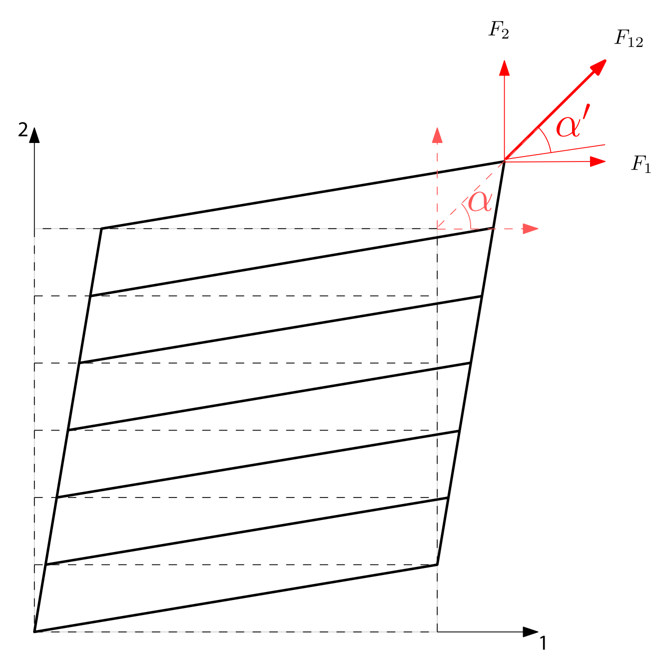

Fig. 1. Pure shear state with relation to the fibre direction.