Experimental characterization of the tensile behaviour of Nicalon fibre-reinforced calcium aluminosilicate composites

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Mechanical behaviour studies were conducted on Nicalon SiC/calcium aluminosilicate (CAS) composites. Tensile tests were carried out to study the stress-strain behaviour, as well as to identify the failure mechanisms, of unidirectional and cross-ply SiC/CAS composites. The evolution of the various damage modes and the synergistic effects among them were investigated. The effect of the 90° ply thickness on the damage modes was also determined. The composite stiffness reduction during damage evolution was evaluated. A tensile test specimen was designed for glass and glass-ceramic composites to avoid end-tab shear failure and expensive machining as well as to reduce the effect of bending due to misalignment. The results of this work provide insight into the stress-strain behaviour and damage mechanisms of continuous fibre-reinforced ceramic composites which can be very valuable in design with these materials.

1. Introduction
Ceramic matrix composites have received increasing attention during the last decade. Their low density, improved toughness compared to the monolithic ceramics, and high-temperature capability have made them promising candidates for high-temperature structural application [1, 2]. However, the mechanical behaviour of these composites, in which the fibre has a larger strain to failure than the matrix, usually involves extensive damage prior to the ultimate failure. Damage in the well-studied unidirectional fibre-reinforced composites is in the form of regularly spaced cracks in the matrix. This multiple matrix microcracking has been observed in many materials systems [3-5] and was first treated by Aveston et al. [6, 7].

Multi-directional composite laminates exhibit a more complex damage behaviour. Failure mechanisms in cross-ply and angle-ply laminates have been studied for fibre-reinforced polymer matrix composites. Transverse cracking and free-edge delamination are the two major types of damages in these composites.

Transverse cracks form in laminates where a sufficiently large tensile stress exists normal to the fibres as illustrated in Fig. 1 for a (0/90), cross-ply laminate. Garrett and Bailey [8] applied the multiple cracking theory of Aveston and Kelly [7] to the problem of transverse cracking in 0,90,0 cross-ply glass fibre-reinforced plastics. They found that, similar to the matrix cracks in unidirectional composites, transverse cracks in the 90° ply showed a remarkably even spacing which depended on both the ply thickness and the applied stress; the higher the applied stress and the smaller the 90° ply thickness, the smaller the average crack spacing. Parvizi and co-workers [9, 10] extended the studies of transverse cracking to glass/epoxy and graphite/epoxy cross-ply laminates and noted the effect of the transverse ply thickness on the strain for the onset of cracking. They demonstrated both experimentally and from an energy approach that transverse cracking initiates at an increasingly larger strain with decreasing 90° ply thickness and it could be even completely suppressed at sufficiently small ply thicknesses. They also treated the effects of the Poisson's contraction and residual thermal stresses and investigated longitudinal cracking of the 0° plies due to those effects.

Free-edge delamination is generally associated with the out-of-plane normal or shearing stresses (Fig. 2). Elastic analyses have shown that stresses of high gradient can be induced near the free edges of laminates by mechanical, thermal or hygroscopic loadings [11-13]. The magnitude and nature of these stresses depend greatly on the specimen geometry, ply stacking sequence and ply properties besides the applied load. In many cases, the location of the observed

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delamination can be predicted from the calculated free-edge stresses [14]. However, in other cases, delamination does not occur even when the calculated edge stresses are several times larger than the expected material strength. A theoretical approach which unifies the basic concept of fracture mechanics with that of statistical material effective flaws has been developed by Wang and Crossman [15] to solve the problem. The introduction of material effective flaws is an attempt to account for the sources of material weakness and the random nature of their existence while the use of fracture mechanics provides the necessary criterion for the propagation behaviour of the flaws. By calculating the strain energy release rate of a crack at each possible location and comparing it to the property of the laminate, predictions can be made concerning the likelihood of crack propagation at a given location and its onset strain. Successful correlations of this analytical solution with the experimental results have been demonstrated [16, 17].

In fibre-reinforced ceramic matrix composites, in addition to the transverse cracking and delamination modes of failure, matrix microcracking in the 0° plies is expected to occur because of the brittle nature of the ceramic matrix. All these damage modes which occur before the ultimate failure are of prime concern from a design standpoint because they signify the onset of permanent damage and the loss of integrity. In this study, tensile behaviour of unidirectional and 0,90,0 cross-ply laminates of Nicalon fibre-reinforced calcium aluminosilicate (CAS) were investigated. The objective was to provide a systematic characterization of (i) the evolution and mechanisms of damage, (ii) the possible synergisms amongst the various damage modes, and (iii) the effect of damage on composite properties such as stiffness.

A special technique for preparing tensile test coupons is presented here. This technique which involves casting integrated epoxy end tabs was developed especially for fibre-reinforced glass and glass-ceramic matrix composites in order to reduce bending and to facilitate the in situ observation of the microstructural changes during testing.

2. Experimental procedure

2.1. Materials

The composite laminates of Nicalon fibre-reinforced calcium aluminosilicate were produced by a slurry infiltration/hot pressing process followed by a ceraming heat treatment. The unidirectional composite was made of eight plies. The 0,90,0 cross-ply laminates were made with three outer 0° plies on each side and varying number of inner 90° plies (from one to three layers). Fibre volume fraction was 0.36 ± 0.02 in all composites. Properties of the CAS matrix and the Nicalon fibres are listed in Table I.

2.2. Tensile tests

Tensile tests were conducted at room temperature on both unidirectional and cross-ply SiC/CAS laminates.