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Effects of nonlinear viscoelastic behaviour and loading rate on transverse cracking in CFRP laminates

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Abstract

The progressive multiplication of matrix transverse cracks in cross-ply laminates made of long carbon fibre reinforced polymer (CFRP) is addressed in this study. Monotonic tensile tests performed on $[0_3/90_3]_S$ laminates at 120 °C have shown a marked dependence of cracking development on loading rate. This paper aims to assess the impact of the material nonlinearity on the loading rate sensitivity of the damaging process. A "shear-lag" damage analysis, using the nonlinear correspondence principle and appropriate failure criteria, is carried out to numerically predict the cracking evolution. This work shows that, though important, the material nonlinearity of the undamaged material does not significantly enhance the loading rate sensitivity of the cracking process and it cannot explain alone the phenomenon. On the other hand, taking into account the loading rate dependence of the critical strength, together with the R-curve effect, which gives good predicted cracking curves, suggests that the observed rate effect pertains to the viscoelastic character of the damaged material in the process zone close to crack fronts.

Keywords: A. Polymer–matrix composites; B. Non-linear behaviour; C. Transverse cracking; C. Failure criterion; Loading rate effect

1. Introduction

High-performance CFRP composite laminates are used in several aircraft structural parts due to weight saving and high lifetime demands in aeronautic applications. The next generation of supersonic aircraft, for instance Concorde's successor, will travel at speeds that cause significant heating of the aircraft structure owing to friction in the atmosphere. During a flight at a speed of Mach 2, the maximum surface temperature will range between 100 °C and 130 °C, depending on the considered part of the structure. Under such service conditions involving high temperature and mechanical loads, the candidate composites may display a variety of damage modes, such as matrix cracking, fibre breakage, interfacial debonding between matrix and fibre, or delamination between plies. In cross-ply laminates subjected to tensile thermo-mechanical loadings, transverse matrix cracking is usually the first damage mechanism to be observed and it creates initiation sites for further and potentially more harmful damage events. Therefore, transverse matrix cracking must be assessed and monitored in order to guarantee the structural integrity.

The recent literature contains few experimental and analytical studies of the influence of viscoelastic behaviour and loading rate on matrix cracking. Time dependent matrix cracking in transverse plies of cross-ply carbon/epoxy laminates was experimentally investigated and modelled in [1–5]. Under quasi static loading, it is observed that the matrix cracking growth rate depends upon the loading rate at temperatures of 110 °C [1] and 120 °C [4] or even at room temperature [2,3]. A probabilistic failure model involving loading rate has been proposed by Ogi and Takao [1], giving a good agreement between experimental results and

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numerical simulations under monotonic loading. However, it provides little physical understanding, though the cracking behaviour can be phenomenologically described.

The evolution of transverse matrix cracking in a carbon/epoxy composite laminate of the type $[0_m/90_n]_S$ will be addressed in this research. A significant influence of loading rate on the damaging process at 120 °C has been previously experimentally brought out [4]. Several phenomena might explain this effect, notably the viscoelastic behaviour of the undamaged material in the 90°-plies and that of the damaged material around crack tip vicinities. Some numerical simulations meant to display the effect of possible factors have been proposed in previous papers: a one-dimensional (1D) linear viscoelastic shear-lag approach, which takes into account thermal stresses, has been implemented in [6,7]. Several failure criteria (critical stress, critical strain and Reiner-Weissenberg or critical free energy density), used to describe cracking evolution as a function of load level assuming a constant loading rate, give very close numerical results. The failure criteria can properly display the loading rate effect only if a stress rate dependence is incorporated into the critical values. Then a two-dimensional linear viscoelastic analysis has been developed in [6]. The numerically predicted crack density curves show that, even if the 2D stress state is taken into account, the viscoelastic character of the undamaged material is not marked enough to explain alone the influence of the loading rate on cracking curves. The improvement brought about by the incorporation of thermal stresses is not significant at the considered temperature for the studied material.

However, creep-recovery tests conducted at the studied temperature reveal that the material at hand displays a marked nonlinear viscoelastic behaviour. This raises some further questions, such as: how do transverse cracks grow if the nonlinear viscoelastic character of material is taken into account? And can the material nonlinearity increase the influence of loading rate on cracking?

This paper aims to provide preliminary answers to these questions. First, the experimental results concerning the crack density as a function of applied tensile load, assuming a constant stress rate, are described in Section 2. Then, by using a simplified 1D Schapery model, a material characterization procedure is proposed in Section 3 in order to approximately identify the nonlinear stress–strain relationship of the material in the 90°-plies. A damage growth analysis is carried out in Section 4. Some simplifying assumptions are proposed in order to apply the nonlinear correspondence principle. A numerical program strategy meant to predict the cracking evolution is detailed in Section 4.4. Some discussions and conclusions are contained in the last section.

According to the knowledge of the authors, in the recent literature, very few works present a viscoelastic model involving the nonlinear behaviour of the undamaged material to describe the transverse cracking on the ply scale. Zhang et al. [8] have proposed a micromechanical model involving the nonlinear viscoelastic behaviour of the matrix. The "localized" matrix cracking on the fibre scale is well modelled by a so-called "smeared crack" approach. However, this model using a repeating independent unit cell containing only one "elastic" fibre does not deal with the non-homogeneous damage kinetics induced by the ply-scale transverse cracks.

2. Experimental results [4]

A carbon/epoxy composite laminate made of IM7/977-2 system with $[0_3/90_3]_S$ stacking sequence and a nominal ply thickness of 0.125 mm, has been studied. The coupons, 140 mm long and 20 mm wide, were designed and provided by CCR-EADS (Corporate Research Centre, France, of the European Aeronautic Defence and Space Company). The material is made up of long carbon fibres possessing a high modulus of elasticity and of a two-phase toughened epoxy resin. The thermo-elastic properties of the unidirectional ply experimentally obtained at 120 °C are given in Table 1.

Monotonic uniaxial tensile tests were conducted on the cross-ply laminates at a temperature of 120 °C to measure transverse matrix crack density as a function of applied load. Three different loading rates (1.3216 MPa/min, 132.16 MPa/min and 1321.6 MPa/min), producing cross-head velocities of 0.01 mm/min ($\sim 10^{-7}\ s^{-1}$), 1 mm/min ($\sim 10^{-5}\ s^{-1}$) and 10 mm/min ($\sim 10^{-4}\ s^{-1}$), respectively, were prescribed.

The tests were stopped several times before the failure of specimens to count the number of transverse cracks (N) on the useful length (L_u) of the polished edges by using an optical microscope; the average crack density, defined by $\rho = N/L_u$, can thus be obtained.

Here the useful length is the " gage length", i.e. the length along which transverse cracks are counted under an optical microscope (see Fig. 1 for details). While the total length of the specimen is 140 mm, the 80 mm-value is chosen as the "useful length" in this study. The specimen

Table 1
Elastic properties and coefficients of thermal expansion (CTE) of the unidirectional ply at 120 °C

Property		Value
Longitudinal modulus (GPa)	E_{11}	148
Transverse modulus (GPa)	E_{22}	7.12
In-plane Poisson's ratio	ν_{12}	0.326
In-plane shear modulus (GPa)	G_{12}	3.3
Longitudinal CTE (10^{-6} °C)	α_1	0.23
Transverse CTE (10^{-6} °C)	α_2	30

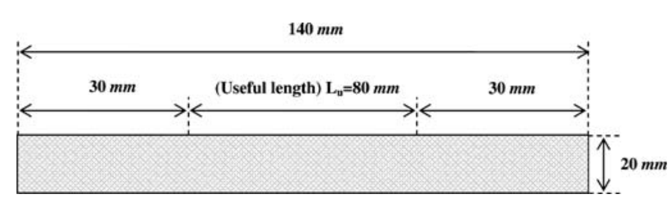

Fig. 1. Specimen geometry.