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Transverse cracking and elastic properties reduction in hygrothermal aged cross-ply laminates

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Abstract

The changes in the mechanical properties as a result of multiple transverse cracking in the hygrothermal aged cross-ply laminates are examined theoretically. Most authors have studied transverse matrix cracking in cross-ply lay-ups and used the longitudinal Young's modulus as an indicator of the extent of damage development. Reductions of typically only a few percent have been found at saturation crack spacing. Some authors have studied the effect of matrix cracking on Poisson's ratio. The results show large reductions at saturation transverse cracking. In this work the degradation of the longitudinal and the transverse properties of the hygrothermal aged cross-ply laminates due to transverse matrix cracking under longitudinal tension was studied. First, the material properties of the composite are affected by the variation of temperature and moisture, and are based on a micro-mechanical model of laminates. Consequently, the hygrothermal conditions degrade the stiffness of the laminate. This degradation is taken into account to assess the changes in Poisson's ratio and longitudinal modulus due to transverse cracking.

Keywords: Transverse cracking; Hygrothermal aged cross-ply laminates; Stress perturbation function; Poisson's ratio; Longitudinal Young's modulus

1. Introduction

Laminated fibre re-inforced polymers have been under study for many years due to their high strength and stiffness over weight ratio and the fact that the directionality of their mechanical properties can be tailored to meet the requirements of any given application. One of the key features of this material class is their damage initiation and propagation behaviour which, in contrast to monolithic materials, is spatially distributed in nature and comprises a variety of mutually interacting damage modes. The most common damage modes are matrix cracking, delamination growth and fibre fracture.

In particular, matrix transverse cracks appear at a much lower stress than those predicted by classical lamination theory and first ply failure criterion. A review of the available literature results shows that the damage parameter under investigation has always been the longitudinal Young's modulus [1–7]. However, transverse ply cracks may lead to only a few percent reduction in the longitudinal stiffness of cross-ply laminates. The change in Poisson's ratio is of considerable interest since this transverse property appeared to exhibit large reductions and is very sensitive to the phenomenon of matrix cracking. Most authors have, however only reported degradations at saturation crack spacing or have only considered one type of lay-up. A number of models are available in the literature which attempt to theoretically predict the evolution of Poisson's ratio as a function of matrix crack density. Shear lag theory [8,9], elasticity analysis [2] and continuum damage mechanics [10] have all been used as modelling approaches.

In this work a systematic study will be made of the influence of transverse matrix cracking on the evolution of both the longitudinal Young's modulus and the Poisson's ratio in the hygrothermal aged cross-ply laminates. Both complete parabolic shear-lag analysis [6,7] and progressive shear model [7] are used with some modifications to predict the

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effect of transverse cracks on the stiffness degradation of composite laminates. First, general expression for longitudinal modulus reduction versus transverse crack density is obtained by introducing the stress perturbation function. Good agreement is obtained comparing prediction with experimental results. This latter is also modified by introducing the stress perturbation function [11]. In addition, we have used the two modified models [6,7] to predict the Poisson's ratio degradation. In the second part of this investigation, the hygrothermal effect on the material properties of the laminate is taken into account to evaluate the stiffness loss in cross-ply laminates containing transverse cracks. It is well known that during the operational life, the variation of temperature and moisture reduces the elastic moduli and degrades the strength of the laminated material [12–16]. In this study, the hygrothermal stresses [17–22] and the water-induced microcracks [23] are not taken into consideration. But the material properties are assumed to be functions of temperature and moisture. Both ambient temperature and moisture are assumed to have a uniform distribution. The plate is fully saturated such that the variation of temperature and moisture are independent of time and position. The obtained results illustrate well the dependence of the degradation of elastic properties on the cracks density and hygrothermal conditions.

2. Theoretical modelling

It is well known in many studies [12–16] that the material properties are function of temperature and moisture. In terms of a micro-mechanical model of laminate, the material properties may be written as [24]

$$E_{\rm L} = V_{\rm f}E_{\rm f} + V_{\rm m}E_{\rm m} \tag{1}$$

$$\frac{1}{E_{\rm T}} = \frac{V_{\rm f}}{E_{\rm f}} + \frac{V_{\rm m}}{E_{\rm m}} - V_{\rm f}V_{\rm m}\frac{\nu_{\rm f}^2\left(\frac{E_{\rm m}}{E_{\rm f}}\right) + \nu_{\rm m}^2\left(\frac{E_{\rm f}}{E_{\rm m}}\right) - 2\nu_{\rm f}\nu_{\rm m}}{V_{\rm f}E_{\rm f} + V_{\rm m}E_{\rm m}} \tag{2}$$

$$\frac{1}{G_{\rm LT}} = \frac{V_{\rm f}}{G_{\rm f}} + \frac{V_{\rm m}}{G_{\rm m}} \tag{3}$$

$$\nu_{\rm LT} = V_{\rm f}\nu_{\rm f} + V_{\rm m}\nu_{\rm m} \tag{4}$$

In the above equations, $V_{\rm f}$ and $V_{\rm m}$ are the fibre and matrix volume fractions and are related by:

$$V_{\rm f} + V_{\rm m} = 1 \tag{5}$$

$E_{\rm f}$, $G_{\rm f}$ and $\nu_{\rm f}$ are the Young's modulus, shear modulus and Poisson's ratio, respectively, of the fibre, and $E_{\rm m}$, $G_{\rm m}$ and $\nu_{\rm m}$ are corresponding properties for the matrix.

It is assumed that $E_{\rm m}$ is a function of temperature and moisture, as is shown in Section 3.2, then $E_{\rm L}$, $E_{\rm T}$ and $G_{\rm LT}$ are also functions of temperature and moisture.

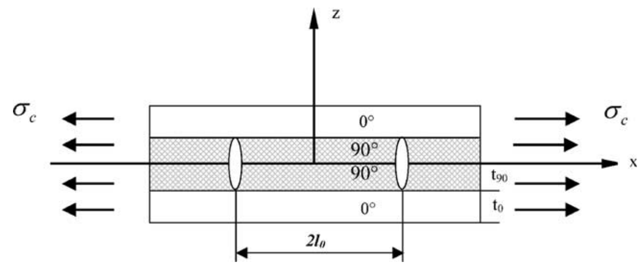

Fig. 1. Transverse cracked cross-ply laminate and geometric model.

2.1. Model formulation

In the present analysis, we have modified the two models [6,7] (Complete parabolic shear-lag model and progressive shear-lag model) using the same methodology developed by Joffe and Varna [11].

Consider the idealised cross-ply laminates shown in Fig. 1. When such laminate is loaded in uniaxial tension the first damage which occurs is transverse cracking in the middle layer. The spacing between cracks is assumed to be equidistant, which means that laminate contains a periodical array of cracks in 90° layer. The geometry of the repeatable unit used for modelling is shown in Fig. 1. Dimensionless coordinates can be introduced:

$$\bar{z} = \frac{z}{t_{90}};\quad \bar{l}_0 = \frac{l_0}{t_{90}};\quad \alpha = \frac{t_0}{t_{90}};\quad \bar{x} = \frac{x}{t_{90}};\quad h = t_0 + t_{90} \tag{6}$$

Loading is applied only in x-direction and the far field applied stress is defined by $\sigma_c = \frac{1}{2h}N_x$, where N_x is applied load.The following analysis will be performed assuming generalized plane strain condition:

$$\varepsilon_y^0 = \varepsilon_y^{90} = \varepsilon_y = \text{const} \tag{7}$$

The symbol (−) over stress and strain components denotes volume average. They are calculated using the following expressions:

a. In the 0° layer:

$$\bar{f}^0 = \frac{1}{2l_0}\frac{1}{t_0}\int_{-l_0}^{+l_0}\int_{t_{90}}^{h} f^0\,\mathrm{d}x\,\mathrm{d}z = \frac{1}{2\bar{l}_0}\frac{1}{\alpha}\int_{-\bar{l}_0}^{+\bar{l}_0}\int_{1}^{\bar{h}} f^0(\bar{x},\bar{z})\,\mathrm{d}\bar{x}\,\mathrm{d}\bar{z} \tag{8}$$

b. In 90° layer:

$$\bar{f}^{90} = \frac{1}{2l_0}\frac{1}{t_{90}}\int_{-l_0}^{+l_0}\int_{0}^{t_{90}} f^{90}\,\mathrm{d}x\,\mathrm{d}z = \frac{1}{2\bar{l}_0}\int_{-\bar{l}_0}^{+\bar{l}_0}\int_{0}^{1} f^{90}(\bar{x},\bar{z})\,\mathrm{d}\bar{x}\,\mathrm{d}\bar{z} \tag{9}$$

By using the strains in the 0° layer (which is not damaged and, hence, strains are equal to laminate strains, $\varepsilon_x = \bar{\varepsilon}_x^0$), etc. and assuming that the residual stresses are zero, the