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Effect of transverse cracking on stiffness reduction of hygrothermal aged cross-ply laminates

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Abstract

An analytical model based on the notion of the stress perturbation function is developed and applied to study the effect of multiple cracks in aged cross-ply laminates on the stiffness of a laminated composite. 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. This hygrothermal effect is taken into account to assess the changes in the longitudinal modulus due to transverse cracking. The obtained results represent well the dependence of the degradation of elastic properties on the cracks density and hygrothermal conditions. Through this theoretical study, we hope to contribute to the understanding of damage of aged composite materials.

Keywords: Hygrothermal effect; Transverse cracking; Cross-ply laminates; Stress perturbation function; Stiffness reduction

1. Introduction

In most continuous fiber cross-ply composite laminates, transverse matrix cracking or microcracking takes place in the 90° plies at strain levels which are very small compared to the ultimate failure strain of the laminate. In general, these transverse matrix cracks are equally spaced in the longitudinal direction. This phenomenon has been observed in polymer matrix composites by Garrett and Bailey [1], Parvizi et al. [2], Highsmith and Reifsnider [3], Wang [4], Ogin et al. [5], Smith and Wood [6], and Liu and Nairn [7]. They have found that transverse matrix cracking typically starts at low strain levels in the weakest 90° plies and manifest in continual drop in the laminate stiffness with either increased or repeated loading. Although the formation of transverse cracks does not precipitate into catastrophic failure, their presence can be very undesirable, such as a loss of stiffness. This effect is important in applications relying on dimensional stability.

It is clear, therefore, that the capability to predict the occurrence of transverse cracking and its effect on residual stiffness is necessary in the design and utilization of cross-ply laminates. Many analyses have been developed which attempt to evaluate the stiffness loss in the cracked laminate. The shear-lag method [3,8–15] and variational methods [16–18] are among the most commonly used procedures. Stiffness reduction due to the transverse matrix cracks in various composite laminates has been studied by Highsmith and Reifsnider [3] using shear-lag method. They assumed a thin boundary layer, referred to as a shear layer, in the vicinity of the layer interface. Tensile stresses in the uncracked layers are transferred to the cracked layers via the shear layer. They also assumed that shear stresses are not dominant within the boundary layer. The procedure for finding the stiffness reduction is simple. However, it is not easy to determine the thickness of the boundary layer.

Flaggs [8] studied tensile matrix failure in composites laminates. The analysis was based on the two-dimensional

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shear-lag theory with the use of mixed-mode strain energy release rate. Even though good agreement was observed with experimental data for thinner 90° layers, this analysis is not applicable for thicker 90° layers.

Laws and Dvorak [9] practised the shear-lag concept to deduce the degraded stiffnesses of a cracked cross-ply laminate taking the effects of residual stresses into consideration. It was pointed out that residual stresses give rise to permanent strains when the applied load is large enough to cause transverse cracking, and further that these strains actually are negligible.

Lim and Hong [10,11] applied the shear-lag model to a cross-ply laminate and also included the effects of thermal residual stresses. It was established that the thermal residual stresses significantly influence the transverse cracking in graphite/epoxy laminates, more so than in glass/epoxy composite systems. This is discernible since the graphite/epoxy systems have a higher degree of orthotropy in elastic constants as well as in thermal expansion coefficients.

Lee and Daniel [12] proposed a simplified shear-lag analysis that used a progressive damage scheme. It was assumed that the next set of cracks was developed when the maximum axial stress in the plies reached the strength of the layer. They assumed linear shear stress distributions in each layer throughout the thickness. In their formulation, a shear-stress-free condition on the crack surface is not satisfied. Berthelot [13] employed a shear-lag concept to obtain the general form of the stress distributions in 0° and 90° layers. They proposed a particular form of the variation of the longitudinal displacement across the thickness of 0° plies which yields a good agreement of the stress distributions with finite element analysis. Tounsi et al. [14,15] have studied the stiffness reduction in aged cross-ply laminates using a modified shear-lag models by introducing the stress perturbation function. Stiffness reduction in a transversely cracked cross-ply fibre composite laminate was studied by Hashin [16] using variational method. The normal ply stress in the load direction was assumed to be constant over the ply thickness. The stiffness reduction due to transverse cracking is in good agreement with the experimental results. However, damage progression and accumulation cannot be determined by using this analysis. The principle of minimum complementary energy was also used by Varna and Berglund [17] to predict the stress fields in a cracked cross-ply laminate. The strain-energy release rate has also been calculated by Nairn [18] using a variational analysis. It is a two-dimensional thermo-elastic analysis assuming that normal ply stress in the load direction to be constant over the ply thickness.

In this paper, a complete parabolic shear-lag analysis [13] is used with some modifications to predict the effect of transverse cracks on the stiffness degradation of hygrothermal aged composite laminates. 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 [19–25]. The hygrothermal stresses [26–31] and the water-induced microcracks [32] are not taken into consideration in the present study. 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 analysis

It is well known in many studies [19–25] 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 [33]:

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

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

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

$$v_{\mathrm{LT}} = V_{\mathrm{f}} v_{\mathrm{f}} + V_{\mathrm{m}} v_{\mathrm{m}}. \tag{4}$$

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

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

E_{f}, G_{f} and v_{f} are the Young's modulus, shear modulus and Poisson's ratio, respectively, on the fibre, and E_{m}, G_{m} and v_{m} are corresponding properties for the matrix.

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

2.1. Stiffness reduction model in the cross-ply laminates

Transverse matrix cracking is a common damage mode in cross-ply laminates under uniaxial tension. The matrix cracks develop in the fiber direction and extend across the 90°-ply width from the free edges.

For ideally equidistanced crack spacing in 90° layers for symmetric and balanced laminates, Joffe et al. [35] showed using the stiffness reduction model that the crack spacing $2l_0$ (Fig. 1) reduces the extensional stiffness of the specific composite laminates according to

$$\frac{E_x}{E_{x0}} = \frac{1}{1 + a\bar{\rho}R(\bar{l}_0)}, \tag{6}$$

where $\bar{\rho} = \frac{1}{2\bar{l}_0}\left(\bar{l}_0 = \frac{l_0}{t_{90}}\right)$ is normalised crack density and a is a known function, dependent on elastic properties and geometry of 0° and 90° layer:

$$a = \frac{E_{90} t_{90}}{E_0 t_0} \left(\frac{1 - v_{xy} v_{xy}^0}{1 - v_{xy} v_{yx}}\right) \left(1 + \frac{v_{xy} S_{xy} (t_0 + t_{90})}{S_{xx} t_0 + S_{yy} t_{90}}\right). \tag{7}$$