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A criterion for failure mode prediction of angle-ply composite laminates under in-plane tension

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ABSTRACT

As the failure of fibre-reinforced angle-ply composite laminates involves basic features of failure of general laminates, its understanding and prediction are of fundamental importance. In this paper, a criterion for predicting the failure mode of angle-ply laminates under in-plane tension is presented. The criterion is able to predict the two different modes of the final failure of angle-ply laminates found in previous experiments: the pull-out of the internal layer due to transverse cracks and delaminations with no fibre breakage, and a single crack across the width of the laminate. The theoretical results demonstrate that the final failure mode of an angle-ply laminate is determined by the value of a failure factor which is related to the thickness and strength of the lamina, the width and ply angle of the laminate, and the interface strength. The pull-out failure occurs when the failure factor is greater than one, and the single cracking occurs when it is less than one. The criterion also shows that the final failure of angle-ply laminates exhibits size effects both in the thickness direction and the width direction. Moreover, the criterion is extended and applied to general angle-ply laminates. The theoretical predictions agree with experimental results.

1. Introduction

Angle-ply laminates are the basic configuration of general multi-directional fibre-reinforced composite laminates. The failure of angle-ply laminates involves transverse cracking, delamination, and fibre breakage, which constitute the basic features of failure of general laminates. Thus, the understanding and prediction of the failure of angle-ply laminates are of fundamental importance for analyses of failure of composite laminates. The failure of angle-ply laminates has been widely studied in the literature. Lauraitis [1] investigated the strength of angle-ply laminates and recognized that the failure of small fiber angle laminates is initiated by interlaminar shear stresses. Pipes et al. [2] studied the failure of $(\pm 30^\circ)_s$ and $(\pm 45^\circ)_s$ laminates, and they found that the initial failure of $(\pm 30^\circ)_s$ laminate is related to the high interlaminar shear stress at the free edge whereas the failure of $(\pm 45^\circ)_s$ laminate is not sensitive to the edge effect. Similar results were obtained by Rotem and Hashin [3]. Their experimental failure study revealed that there are three distinct initial failure modes for E-glass/epoxy angle-ply laminates depending on the reinforcement angle. The onset of failure for reinforcement angles less than 45° is delamination due to the interlaminar shear stress at the edges of the specimen; the onset of failure for a reinforcement angle of 45° is lamina cracking with the stress–strain curve exhibiting predominant ductile behavior; and the onset of failure for reinforcement angles greater than 45° is lamina cracking with stress–strain curve exhibiting brittle behavior. Other work on the failure of angle-ply laminates can be found in [4–20].

The influence of stacking sequence on the failure of angle-ply laminates can be found in [21–23]. In particular, for the case of in-plane tensile loading, Herakovich [23] studied the failure of graphite-epoxy angle-ply laminates with fiber orientations of $\{10^\circ, 30^\circ, 45^\circ\}$ and two different stacking sequences of $[(\pm\theta)_2]_s$ and $[(+\theta)_2/(-\theta)_2]_s$, referred to as clustered and alternating laminates, respectively. Herakovich's experimental results [23] show that there are two different final failure modes for angle-ply laminates, which are the pull-out of the inner layer from the outer layers due to transverse cracks and delaminations without fibre breakage, and failure of a single crack across the width of the laminate parallel to fiber direction of the outer layers. Therefore, Herakovich's observations contain three basic failure modes and

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the related mechanisms of general composite laminates, i.e. transverse cracking, delamination, and fibre breakage. The theoretical analyses of Herakovich [23] show that the increasing thickness of individual layers can increase the interlaminar shear stress, which will lead to easier occurrence of pull-out failure. Otherwise, no detailed quantification of the two different failure modes has been found in the literature. Moreover, the final failure of a general laminate under in-plane tension generally involves delamination and the subsequent pull-out of laminae, but this joint mechanism has not been included in the current failure criteria for laminates [24].

In this paper, a criterion for predicting the failure mode of angle-ply laminates under in-plane tension is presented. The criterion is developed based upon the competition of the in-plane strength of the lamina and the shear strength of the interface between the laminae. It is able to predict the two different modes of the final failure mentioned above. Moreover, the criterion is also extended and applied to general angle-ply laminates, of which the absolute values of the ply angles of the inner layer and the outer layer are different.

2. The criterion for failure mode prediction of classical angle-ply laminates

Classical angle-ply laminates are defined as those made from an equal number of layers oriented at $+\theta$ and $-\theta$ to the loading direction (Fig. 1). We first consider the $[(+\theta)_n/(-\theta)_n]_s$ laminates, which are called clustered laminates in [23] where $n = 2$, and in [21] where $n = 4$. For angle-ply laminates loaded in the direction of the bisector of the fiber angle (Fig. 1), transverse inter-fiber cracking and through thickness cracks parallel to the fiber direction in each lamina are assumed to form with increasing load. The transverse cracks in the laminae are schematically shown in Fig. 2(a). When through thickness cracks form, the angle-ply laminate is assumed to become two parts, which are connected by the interfaces between the internal layer and the outer layers. If we consider the two parts separately, the forces applying on each part consist of the external load F_x and the shear force resulting from the interface shear stress τ (Fig. 2(b)). For a qualitative analysis, strong interfaces will lead to fiber fracture of the laminate, whereas strong fibers will result in delamination between the internal and outer layers, which will result in the failure of the pull-out of the internal layers from the outer layers. In this paper, the two final failure modes will be referred as fiber-fracture failure and pull-out failure, respectively.

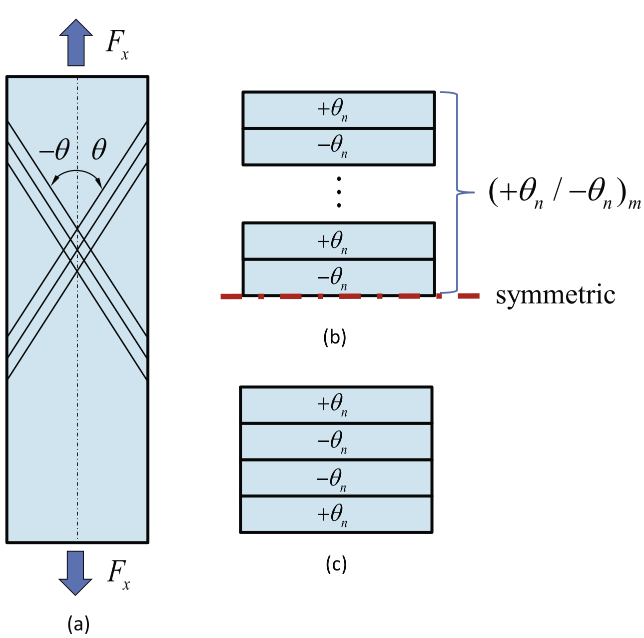

Fig. 1. (a) Classical angle-ply laminate; (b) the general stacking sequence $\{[(+\theta)_n/(-\theta)_n]_m\}_s$; (c) a specific stacking sequence of $m = 1 : [(+\theta)_n/(-\theta)_n]_s$.

In order to obtain a quantitative criterion to determine which failure mode will occur, a separated part is taken from the internal layer (Fig. 2(c)). The plane B on this part is the potential fracture plane when the laminate undergoes fiber-fracture failure. From the equilibrium of this part one can get

$$\tau \cdot 2A = F_1, \tag{1}$$

where τ is the shear stress between the internal layer and the outer layers. The maximum value of τ is the shear strength, which is denoted by τ_0, of the interface between the two layers. The parameter A denotes the area of the longitudinal section of the part, and F_1 denotes the force applied on plane B from the other part of the internal layer. They are given by

$$A = \frac{d^2}{4\tan\theta}, \quad F_1 = \frac{F_{1t}}{\cos\theta}, \tag{2}$$

where d denotes the width of the angle-ply laminate (Fig. 2(b)), and F_{1t} denotes the fiber direction component of F_1. The maximum value of F_{1t} is given by

$$F_{1t}^{\max} = X_t \cdot A_B \sin 2\theta, \tag{3}$$

where X_t is the longitudinal strength of a single lamina, and A_B is the area of the potential fracture plane B, which is given by

$$A_B = (N \cdot t_0) \cdot \frac{d/2}{\sin\theta}, \tag{4}$$

where N is the number of laminae in the internal layer, and t_0 is the thickness of a single lamina. For the laminate in Figs. 1(c) and 2, N equals $2n$.

Substituting Eqs. (2)–(4) into Eq. (1) we can get the critical condition

$$\frac{2Nt_0X_t\tan\theta}{\tau_0 d} = 1. \tag{5}$$

Denoting the left hand term of Eq. (5) as ψ, i.e.

$$\psi = \frac{2Nt_0X_t\tan\theta}{\tau_0 d}, \tag{6}$$

we can get the failure criterion of the clustered classical angle-ply laminate:

$$\begin{aligned} &\psi > 1 \ \Rightarrow\ \text{Pull-out failure;} \\ &\psi < 1 \ \Rightarrow\ \text{Fiber fracture failure.} \end{aligned} \tag{7}$$

Eqs. (5)–(7) reveal that the final failure mode of a clustered classical angle-ply laminate is related to the lamina number N, the geometry parameters of lamina thickness t_0, laminate width d, and reinforcement angle θ, and the mechanical parameters of the shear strength of the interface τ_0 and the longitudinal strength of a single lamina X_t. Moreover, for given $\{\tau_0, X_t\}$, the larger the value of $\{N, t_0\}$ and the smaller the value of d, the easier for the pull-out failure to occur, which shows that the final failure of angle-ply laminates exhibits a size effect both in the thickness direction and the width direction. For wound composite tubes, of which the laminate width can be recognized as $d = \infty$, the value of ψ equals 0, leading to the impossibility of pull-out failure. In terms of θ, the pull-out failure occurs more easily with increasing value of θ. Moreover, for the limit value of $\{\theta = 0^\circ, \theta = 90^\circ\}$, the value of ψ equals infinity and zero, respectively, which indicates that the pull-out failure becomes impossible for $\theta \to 0^\circ$ and the fiber-fracture failure becomes impossible for $\theta \to 90^\circ$.