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A critical plane-based fracture criterion for mixed-mode delamination in composite materials

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ABSTRACT

A new critical plane-based mixed-mode delamination failure criterion is proposed in this study. First, many existing models are reviewed and their capability to handle the mixed-mode fracture of general anisotropic materials are discussed. Following this, a previously developed critical plane approach is extended to analyze the interfacial fracture of composite materials by considering the anisotropic fracture resistance under mixed-mode loadings. Next, comparison with extensive experimental data available in the literature is performed to demonstrate the validity of the proposed criterion. A general good agreement is observed between the model's predictions and experimental observations. Finally, some conclusions and future work are drawn based on the proposed study.

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1. Introduction

Due to the superior high strength and stiffness properties of composite materials, many aircraft components, from secondary structures (aileron, flaps, elevator, and rudders) to primary structures (tailplane, floor beams, and fleet), are made of composite materials. The failure mechanism of composite materials under multiaxial loadings is not well-understood, especially compared to that of structural metals. Severe interlaminar damage can be caused by impact events within the composite laminate [1]. Some defects introduced during the manufacturing process can affect the overall structural integrity of the components made of composite materials [2]. The difficulty of detecting these interior damages makes the problem more difficult in practical conditions. Thus, delamination is considered as one of the most critical damage for composite materials [1,3–5].

The interlaminar delamination process may result from pure mode I, mode II, or mixed-mode loadings. For single mode delamination, the failure criteria can be easily established by comparing the measured energy release rate (G) to the critical value (G_c). Unlike the pure mode cases, the prediction of mixed-mode delamination is much more complex due to the complicated underlying failure mechanisms. Extensive experiments have been conducted using different type of specimens, such as DCB, ENF, MMB, and ELS specimens [6–9], to investigate the mixed-mode fracture of composite laminates. The experimental results are shown graphically in the form of a failure locus to illustrate the relationship between each G components. Most existing failure criteria are obtained by fitting the experimental data through empirical or semi-empirical functions (e.g., power function or exponential function). A failure criterion may be expressed by one single equation [10,11] or several individual equations [12]. Since the measurement methods of pure mode I and mode II fracture toughness are well-developed, it is preferable to select the pure mode fracture toughness (G_{Ic} and G_{IIc}) as two basic material properties to describe the mixed-mode failure responses. In most existing failure criteria, more calibration parameters are usually introduced in addition to the pure mode fracture toughness (G_{Ic} and G_{IIc}) [7,10,12–14]. Most existing failure criteria require three or more parameters and need data fitting under different mixed-mode ratios.

In view of the above mentioned deficiencies of existing models, this study proposes a novel fracture criterion based on a critical plane approach and the modified Tsai-Wu strength theory [15]. The proposed criterion has two advantages over existing criteria: (1) It is derived based on the local failure mechanism of composite

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materials under mixed-mode loading conditions; (2) For each composite material, only two parameters (fracture toughness under pure mode I and pure mode II) are required to predict the failure under arbitrary mixed-mode conditions. Some representative experimental data of various composite materials are collected to verify the accuracy of the proposed failure criterion.

2. Existing mixed-mode fracture criteria

Extensive studies have been performed to investigate the nixed-mode delamination in different composite materials [7,8,12,16–18]. For most experiments, the mode I and II fracture toughness were obtained and the failure locus can be illustrated by plotting G_I against G_{II} in a (G_{II}, G_I) coordinate system. Alternatively, the total fracture toughness ($G_T = G_I + G_{II}$) can be plotted against the mixed-mode ratio (G_{II}/G_T).

A sound failure criterion should satisfy at least two extreme conditions: pure mode I condition ($G_{II} = 0$, $G_I = G_{Ic}$) and pure mode II condition ($G_{II} = G_{IIc}$, $G_I = 0$). In addition, a good failure criterion should be able to capture the unique “overshoot” phenomena in some experiments for composite laminates [7,12,17]. The “overshoot” is the phenomena that the mode I component will increase with certain amount of G_{II} and then decrease to zero when applied G_{II} equals to G_{IIc}. This creates an “overshoot” region in the *GI* vs. *GII* plot and has not been observed for mixed-mode fracture for isotropic materials. Most existing failure criteria can satisfy the first feature, i.e., in the (G_{II}, G_I) coordinate system, the two reference points (($G_{II} = 0$, $G_I = G_{Ic}$) and ($G_{II} = G_{IIc}$,$G_I = 0$)) can be satisfied. Only a few of them can capture the “overshoot” phenomenon. The existing failure criteria can be classified into two categories: failure criteria with the restriction of $G_I \le G_{Ic}$ and failure criteria without the restriction of $G_I \le G_{Ic}$. In the following section, several selected failure criteria will be reviewed and discussed in detail.

One significant gap among all existing failure criteria is that no mechanism modeling is incorporated to explain the experimental observations, e.g., why the “overshoot” occurs for mixed-mode fracture of composite laminates and what is the relationship of this “overshoot” with basic material properties. One of the objectives of the proposed study is to investigate the mechanism of the mixed-mode interfacial fracture and develop a mechanical model to explain the above questions.

2.1. Failure criteria with the restriction of $G_I \le G_{Ic}$

Although some failure criteria cannot capture the “overshoot” behavior for composite materials as mentioned above, they do work well for some types of composite materials. Among them, the linear criterion and the power law are the most cited failure criteria in the failure analysis of composite materials due to their simplicity and ease of use.

2.1.1. Linear criterion

For most composite materials, the pure mode II fracture toughness (G_{IIc}) is much larger than G_{Ic}. A simple mixed-mode failure criterion was established by normalizing each component with their corresponding pure-mode fracture toughness as [10]

$$\frac{G_I}{G_{Ic}} + \frac{G_{II}}{G_{IIc}} = 1. \quad (1)$$

This failure criterion assumes that the contribution of single mode fracture toughness to the mixed-mode fracture toughness is linear. To establish this simple linear failure criterion, only two parameters are needed. Due to its simplicity, it was employed to study the mixed-mode delamination behavior in different composite materials [13,19,20]. The limitation of this failure criterion is that the only trend it can describe is a linear curve determined by single mode fracture toughnesses (G_{Ic} and G_{IIc}). The failure loci of composite materials vary significantly from linear to convex as recorded in many different fracture toughness experiments [7,12,21]. Thus, the linear criterion may yield non-accurate results for many composite materials.

2.1.2. Power law

As a generalized version of the linear criterion, two more parameters have been adopted in the following form as [22]

$$\left(\frac{G_I}{G_{Ic}}\right)^{\alpha} + \left(\frac{G_{II}}{G_{IIc}}\right)^{\beta} = 1. \quad (2)$$

where α and β are the arbitrary parameters, which can be adjusted to fit for various experimental data [10,23,24]. The linear criterion is a special case of the power law criterion when $\alpha = \beta = 1$. The power law criterion has an inherent constraint which requires $G_I \le G_{Ic}$ and $G_{II} \le G_{IIc}$. Therefore the mode I component cannot exceed the mode I fracture toughness G_{Ic} and this constraint makes it impossible to describe the “overshoot” behavior observed in some composite materials.

2.2. Failure criteria without the restriction $G_I \le G_{Ic}$

The previous two failure criteria cannot capture the phenomenon that G_I can exceed G_{Ic} with the introduction of G_{II}. Many efforts have been made to establish more general mixed-mode failure criteria without the restriction of $G_I \le G_{Ic}$. Some of the existing models are briefly described below.

2.2.1. Exponential hackle criterion

To model the delamination within composite materials, a function $\sqrt{1 + (K_{II}/K_I)^2}$ was proposed as a measurement of fracture surface hackle' angle [25]. A hackle criterion was developed based on pure-mode I fracture toughness, Young's moduli, and an arbitrary constant χ in the following form [25]

$$G_I + G_{II} = (G_{Ic} - \chi) + \chi N. \quad (3)$$

where $N = \sqrt{1 + G_{II}/G_I\sqrt{E_{11}/E_{22}}}$. G_{Ic} is pure mode I fracture toughness. E_{11} and E_{22} are longitude and transverse Young's modulus, respectively.

This early form of hackle criterion can describe the phenomenon that G_I will increase as G_{II} is introduced, but it did not take G_{IIc} into account. Therefore it cannot satisfy the reference point (G_{IIc}, 0) in the (G_{II}, G_I) coordinate system and this criterion is an inappropriate choice as a general mixed-mode criterion. To overcome this drawback, an improved exponential hackle's criterion was developed by introducing pure mode II fracture toughness, G_{IIc} and a new parameter, γ as shown below [13],

$$G_I + G_{II} = (G_{Ic} - G_{IIc})e^{\gamma(1-N)} + G_{IIc}. \quad (4)$$

This general failure criterion can describe different failure criterion curves from concave to convex and satisfy the three basic features discussed above. One possible drawback is that it needs many parameters to determine the failure criterion including: two single mode fracture toughnesses, two modulus values, and an arbitrary fitting parameter.

2.2.2. Linear interaction criterion

Another type of failure criterion was developed by considering the interaction of mode I and mode II components. To describe the

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