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A unit circle failure criterion for carbon fiber reinforced polymer composites

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ABSTRACT

A novel invariant-based approach to describe elastic properties and failure of composite plies and laminates has been recently proposed in the literature. An omni strain failure envelope has been defined as the minimum inner failure envelope in strain space, which describes the failure of a given composite material for all ply orientations. In this work, a unit circle is proposed as a strain normalized failure envelope for any carbon fiber reinforced polymer laminate. Based on this unit circle, a failure envelope can be generated from the longitudinal tensile and compressive strains-to-failure of a unidirectional ply. The calculated failure envelope was found in good agreement with experimental data published in the well-known World Wide Failure Exercise.

1. Introduction

Composite materials can offer a unique combination of properties that makes them very attractive to many applications. While in some applications they are a replacement for metallic materials, in others they can be the solution for delivering the required properties. The inherent anisotropy and complex failure mechanisms of these materials are fundamental to their superior properties and design flexibility, but make mechanical characterization rather complex, costly and time consuming. For unidirectional plies, there are four independent stiffness parameters to be measured; *i.e.*, longitudinal, transverse and shear moduli and Poisson's ratio; and five strengths; *i.e.*, longitudinal and transverse tensile and compressive, and shear. Thousands of coupons have been required to generate design allowable for aeronautic structures. Therefore, approaches leading to the characterization of composite materials a reduced number of tests are of significant practical interest, not only for the aeronautic industry, but also for the introduction of these materials in new applications.

Collaborative efforts such as the World Wide Failure Exercise [1] have demonstrated that failure criteria capable of predicting ultimate strength of composite laminates under biaxial loading remain a challenge. Typical failure criteria currently used for fiber-reinforced composites include Tsai-Wu [2], Hashin [3], Puck [4], Christensen [5,6], among others considered [7].

There are many physically based, multi-scale and fracture mechanics-based failure theories with claimed improvements in accuracy as compared to other traditional failure theories. Micromechanics relationships have been considered to predict lamina properties [8] with multi-scale approaches [9–11]. Physically based failure criteria consider specific equations to describe each failure mode: fiber failure and matrix failure [4]. Other criteria based on damage mechanics describe the initiation and evolution of damage leading up to failure [12,13] in some cases with remarkable agreement with experimental data [14]. However, while improvements in accuracy are possible with increasing complexity, these approaches can be complex to be implemented in design.

In a recent work published in the literature, an invariant-based approach to describe elastic properties and failure of composite plies and laminates was proposed [15]. Carbon fiber reinforced plastics were shown to share common stiffness properties if they are normalized by their respective trace of the plane stress stiffness matrix, Tr [Q]. Thus, a "master ply" was defined using universal trace-normalized stiffness components and the trace of the plane stress stiffness matrix becomes the only material property needed for the elastic characterization. In addition, an invariant "omni strain" failure envelope was proposed as the minimum inner

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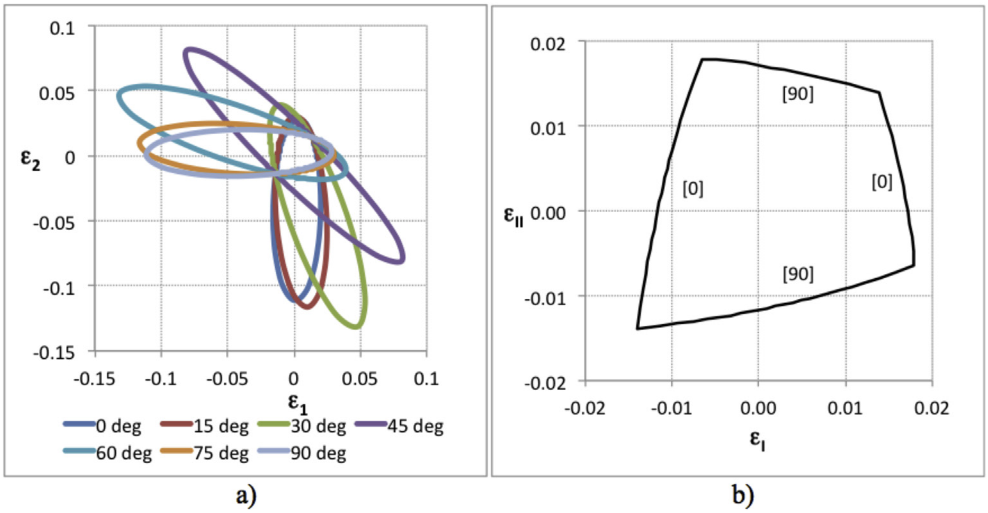

Fig. 1. a) Superposition of LPF envelopes for T700/2510 using Tsai-Wu with Fxy* = −1/2 and E_m* = 0.15. b) Omni strain LPF envelope for T700/2510.

Table 1
Intact and degraded properties of CFRPs (E_m* = 0.15) [17].

Material	E_x	E_y	ν_x	E_s	X	X′	Y	Y′	S
		Intact (Degraded)							
IM7/977-3	191	9.94 (2.09)	0.35 (0.053)	7.79 (1.23)	3250	1600	62	98	75
T300/5208	181	10.30 (2.51)	0.28 (0.042)	7.17 (1.48)	1500	1500	40	246	68
IM7/MTM45	175	8.20 (1.77)	0.33 (0.050)	5.50 (1.00)	2500	1700	69	169	43
IM7/8552	159	8.96 (1.72)	0.32 (0.048)	5.50 (0.95)	2501	1700	64	286	120
T300/F934	148	9.65 (1.89)	0.30 (0.045)	4.55 (1.00)	1314	1220	43	168	48
AS4/PEEK	134	8.90 (2.16)	0.28 (0.042)	5.10 (1.21)	2130	1100	80	200	160
T700/2510	126	8.40 (1.79)	0.31 (0.046)	4.23 (0.96)	2172	1450	49	199	155

Note: E_x, E_y, E_s, and ν_x are the longitudinal, transverse and shear moduli and major Poisson's ratio, respectively; X, X′, Y, Y′ and S are the longitudinal and transverse tensile and compressive and shear strengths, respectively. Elastic moduli in (GPa) and strengths in (MPa). F_{xy}* = −0.5 for intact plies and F_{xy}* = −0.075 for degraded plies. E_m = 3.40 GPa for all materials. Degraded moduli are calculated using micromechanics relations.

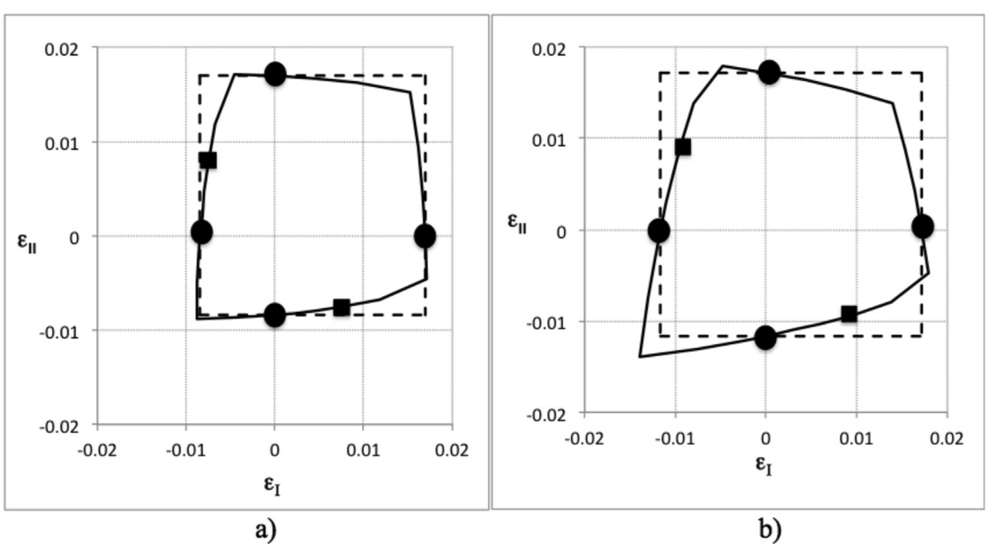

Fig. 2. Omni strain LPF envelopes for two CFRPs based on Tsai-Wu (solid line) and maximum strain (dashed line). a) IM7/977-3; b) T700/2510.

envelope in strain space, which defines the first-ply-failure (FPF) of a given composite material for all ply orientations [15].

The first-ply-failure (FPF) “omni strain” represents the most conservative design where all plies are intact, without any micro cracks. However, laminates can continue to carry load beyond FPF. In fact, first-ply-failure is difficult to be clearly defined in coupon tests. For CFRP hard laminates under uniaxial tension, the stress-strain curve is linear up to failure with no easily observable kink or deviation from linearity to indicate FPF. It is therefore important to define and predict the continued load-carrying capability of