Composite Structures 176 (2017) 729–735

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Failure modes and strength prediction of thin ply CFRP angle-ply laminates

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ARTICLE INFO

Article history:
Received 13 April 2017
Revised 10 May 2017
Accepted 6 June 2017
Available online 9 June 2017

Keywords:
Thin ply CFRP angle-ply laminates
Delamination
Laminate theory
Strength
Failure criterion

ABSTRACT

In this paper, the tensile strength and failure modes of thin ply carbon fiber-reinforced polymer (CFRP) angle-ply laminates are investigated by experiments and predicted by Finite element method (FEM) and theoretical model. First, experiments are performed to evaluate the tensile behavior of thin ply CFRP angle-ply laminates fabricated with different fiber areal weights of prepreg (20,60,120 g/m^2) and ply angle (15°, 30°). Experimental results show that thin ply angle-ply laminates present different failure modes, and also the tensile strengths do not increase monotonically with the decrease in fiber areal weight. Second, both theoretical and FEM models are established to predict the strength and failure modes of thin ply CFRP angle-ply laminates with different ply thickness and fiber volume fraction, also two competing mechanisms finally cause the non-monotonic change of strengths of thin-ply laminates which has good agreement with experimental results. Finally, a failure diagram of thin ply angle-ply laminates under tensile load is given, which shows different failure modes (fiber breakage, delamination and transverse matrix failure) for fiber areal weight (0–240 g/m^2) and ply angle (0–90°). Also the delamination is suppressed and the fiber breakage is extended with the decrease of fiber areal weight in the ply angle range of 10°–25°.

1. Introduction

The rapid development of composite laminate with ultra-thin prepregs [1] has attracted more attention in designing advanced composites due to its unique advantages such as higher in situ transverse strength [2]; lower failure sensitivity [3] and matrix cracking resistance [4], which attributes to a systematic delay or near suppression of transverse cracking and delamination growth in thin-ply composites. At present, the thickness of the prepreg material is becoming thinner and thinner [5], which has the fiber areal weight 20 g/m^2 instead of the traditional prepreg with about 135 g/m^2.

The early studies of composite laminates with ultra-thin prepreg focus on the strength characterizations. Sihn et al. [6] studied the tensile mechanical behaviors of the thin-ply quasi-isotropic laminates with the prepreg thickness of 0.04 mm, which exhibited a significantly higher ultimate strength than the traditional ply. Amacher et al. [7]carried out a large number of uniaxial tensile and open-hole compression experiments of the laminates with the thinner prepreg (30–300 g/m^2), which indicated that the initial failure strength and ultimate strength of laminates were greatly improved with the decrease of the fiber areal weight. Arteiro et al. [8,9] predicted the open-hole tensile and compressive response of thin-ply non-crimp fabric laminates using the point and average-stress models. Flaggs and Kural [10] mainly investigated the influences of ply thickness on the laminate strength, which indicated that the thinner plies have higher situ transverse strength. On the other hand, the influences of variable fiber areal weights on the failure modes of transverse crack propagation and delamination for the laminates are also an important research topic. Gergely et al. [11] investigated the failure modes and stress–strain response of thin-ply unidirectional (UD) hybrid composites under tensile loading. Saito et al. [12] examined the restricted effect of ply thickness on the crack initiation and propagation of the 90° layer in [0°/90°$_n$/0°] laminates using two-dimensional (2D) mecroscopic numerical models. Jalalvand et al. [13] predicted all the possible failure modes in glass/carbon UD hybrid laminates using the periodical carbon layer model. Olsson et al. [14] and Kilic et al. [15] investigated the criteria for initiation and growth of bending induced compressive fiber failure in thin ply laminates.

In addition, the interlaminar stress components directly determine the onset and propagation of free-edge debonding. Pipes

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http://dx.doi.org/10.1016/j.compstruct.2017.06.005
0263-8223/

et al. [16] theoretically studied the effect of ply thickness on the interlaminar stress distribution of the composite laminates under uniaxial tension. Wang et al. [17] indicated that the fracture events with debonding and ply delamination were mainly influenced by the interlaminar stress and the layer thickness. Sihn et al. [6] and Amacher et al. [7] also stated that the decreasing of the areal weight of prepregs could effectively weaken the free edge effect, delay and reduce the free edge debonding failure.

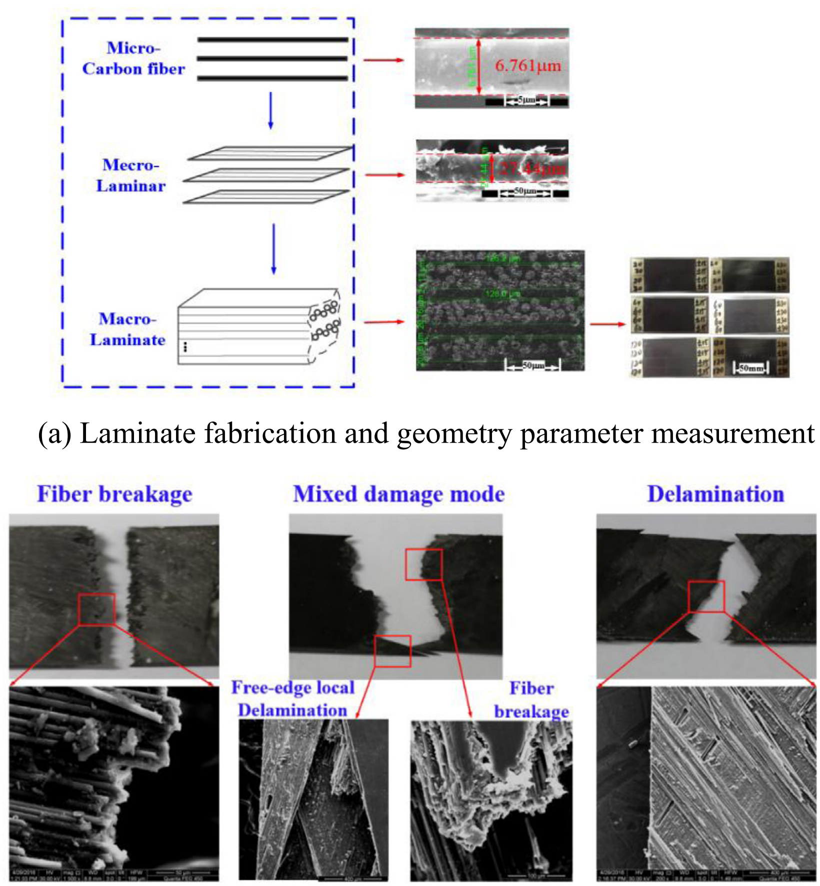
In this paper, both failure modes and strength prediction of thin ply CFRP angle-ply laminates are investigated for three fiber areal weights of prepreg (20, 60 and 120 g/m^2) and two ply angles (15°, 30°). The tensile strength prediction model is established to study the influences of the fiber areal weight on the mechanical behavior of the composite laminates. Also, a failure diagram of angle-ply laminates with ply angle (0°–90°) and fiber areal weight (0–240 g/m^2) is given.

2. Thin ply CFRP angle-ply laminates

2.1. Material and preparation

Composite laminate consists of different ply prepreg layers, which is molded by means of hot pressing technology. Carbon fibers are aligned and spliced by epoxy together to form the laminar. And then many laminas are stacked in some stacking sequence to form a laminate as shown in Fig. 1 (a). Here, the fiber areal weight of the prepreg is controlled before preparation, and the fiber volume fraction and ply thickness of laminates could be calculated for the shaped laminates after preparation. In this study, three variable fiber areal weights (20, 60 and 120 g/m^2) of unidirectional prepreg are considered, where the taps with 60 and 120 g/m^2 are formed through stacking three and six 20 g/m^2 taps together. Here, ultra-thin taps (20 g/m^2) with T-300 carbon fiber and HRC$_1$ epoxy resin are provided by Jangsu Hengshen Co., Ltd in China, which has the fiber volume fraction with 40.27%. According to the Scanning electron microscopy (SEM)photos (Fig. 1 (a)) of ultra-thin taps with 20 g/m^2, the thickness of the single carbon prepreg and the diameter for the single carbon fiber are 27.44 ± 0.5 μm and 6.761 ± 0.3 μm, respectively.

The stacking sequences of the laminates are designed as $[(+\alpha^\circ/-\alpha^\circ)]_{12s}$, $[(+\alpha^\circ{}_3/-\alpha^\circ{}_3)]_{4s}$, and $[(+\alpha^\circ{}_6/-\alpha^\circ{}_6)]_{2s}$, which is corresponding to fiber areal weights 20, 60 and 120 g/m^2,respectively, Also the ply angle α is set as 15° and 30°. Thin ply CFRP angle-ply laminates are manufactured using hot-press technology with the recommended curing cycle (120 °C, 2 h, 0.5 MPa pressure). After demoulding, six composites plates (three kinds of fiber areal weights and two ply angles) with 130 mm * 100 mm in length * width are prepared. Finally, each of the prepared specimen is cut into four tensile samples with the same size (100 mm * 10 mm). Based on the Vernier caliper measurement, both the ply thickness t_L and the interface thickness t_I are listed in Table 1.The average ply thicknesses of specimens (20, 60 and 120 g/m^2 fiber areal weight) are 20.94, 71.06, and 142.25 μm, respectively.Throughout the experimental measurements, the fiber volume fractions V_f of all specimens are calculated as $V_f = (n \cdot \rho_S/\rho_f)/T$, where ρ_S, ρ_f, n and T denote the fiber areal



(a) Laminate fabrication and geometry parameter measurement

(b) Three typical failure modes

Fig. 1. The Laminate fabrication and failure modes: (a) Laminate fabrication and physical parameter measurement. (b) Three typical failure modes.