Composite Structures 108 (2014) 129–136

Contents lists available at ScienceDirect

Composite Structures

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

A novel characteristic curve for failure prediction of multi-bolt composite joints

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ARTICLE INFO

Article history:
Available online 19 September 2013

Keywords:
Bolted joints
Mechanical behavior
Finite element analysis (FEA)

ABSTRACT

A novel characteristic curve determined by tensile, compressive and shear-out characteristic length is presented to predict failure load and failure mode of mechanically fastened composite joints. In contrast to the existing curves, the novel one introduces a shear-out characteristic length and provides capability to predict shear-out failure. A mathematics formulation of the novel curve is proposed based on the expression of Chang's characteristic curve and shear-out characteristic length. A series of tests were carried out and nonlinear finite element analyses were conducted to obtain the tensile, compressive and shear-out characteristic lengths for the novel curve. Following tensile tests of two-bolt and three-bolt joints were performed, and the failure loads and modes were numerically predicted by the characteristic curve method with the novel curve and Chang's. The numerical results obtained from the curve presented show good agreements with the experimental outcomes and better accuracy on both failure load and failure mode.

1. Introduction

Advanced carbon fiber reinforced composite material, which has gradually replaced metal materials and become primary components of structures, has been widely used in the aerospace field owing to the advantages of high strength-to-weight ratio and high stiffness-to-weight ratio etc. However, more difficulties have been introduced to designers on structure failure analysis since composites has different mechanical properties from metal, such as anisotropic, brittle and poor interlaminar strength. Especially for the mechanical joints, which are the weakness of composite structures [1,2], the failure is arduous to be understood on account of complicated stress concentration along the fastener hole and intricate contact load distribution. Moreover, various failure modes emerged in practice [3,4] involve disparate failure mechanism, which compounds the troubles of accurate failure predictions.

It has been found that the ratio of width-to-hole-diameter, the ratio of edge-distance-to-hole-diameter and ply orientation play important roles in tensile, shear-out, bearing, cleavage and pull-through failure modes, among which there is a little research on cleavage and pull-through failure modes [5–8] since the two failure modes only happen in special cases. Tensile failure is a primary failure mode of multi-bolt joints [9–11] but a dangerous one since the final failure occurs suddenly, which may cause catastrophic disasters. Shear-out failure is another suddenly-occurred failure mode [12,13]. In contrast to the tensile and shear-out failure modes, bearing failure propagates slowly [14–16], which provides an alert of failure and thus is recommended by the designers. It is worth noting that both the shear-out failure and bearing failure significantly depend on the edge-distance of bolt joints with given ply orientation, width and hole-diameter. To utilize the full potential of composite materials as structural elements, accurate failure mode forecast, especially for clearly distinguishing sudden failure mode and slow failure mode, is significant for multi-bolt joints.

To predict failure mode and ultimate strength, Chang presented the characteristic curve method [17], which adopts the concept of tensile and compressive characteristic length proposed by Whitney and Nuismer [18,19] and evaluates the failure of joints based upon the stress state on an artificial curve instead of the boundary of the fastener hole. A cosine form of the curve was determined by Chang among the researches of elliptical, straight line and cosine forms [17], since it could yield accurate failure modes and strength results. Now the characteristic curve method with the cosine form curve is widely used in failure analysis of composite mechanical joints [20–22]. However, in Kweon's work [20], a bearing failure mode predicted by Chang's characteristic curve is not consistent with the shear-out failure mode resulted from tests. That gives a motive to modify Chang's characteristic curve in current work.

Moreover, some other curve forms are also used in practice. Xiong [23] adopted a characteristic curve of polyline form to predict tensile failure of composite multi-bolt joints and obtained a

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http://dx.doi.org/10.1016/j.compstruct.2013.09.019

good correlation with test data. Zhang [24] defined another characteristic curve with absolute value function of cosine and sine to predict the failure location and failure mode, from which a tensile failure was effectively predicted compared with the experimental results.

It is noteworthy that all of the aforementioned characteristic curves, which were used to predict tensile, bearing and shear-out failure modes, only pass through the tensile and compressive characteristic points. Indeed, there are countless curves pass through the two points, from which good failure predictions with tensile or bearing failure mode could be obtained. However, an arbitrary form of characteristic curve ignoring shear-out mechanics behaviors is hard to predict shear-out failure reliably.

To overcome such drawbacks, a novel characteristic curve passes through tensile, compressive and shear-out characteristic points by introducing a shear-out characteristic length defined by Agarwal [25], is proposed to evaluate the failure of multi-bolt composite joints. A series of specimens were designed and tested to obtain tensile, bearing and shear-out failure modes and failure loads. Based on ABAQUS® [26], nonlinear finite element analyses for these specimens were conducted to calculate tensile, compressive and shear-out characteristic lengths taking use of Yamada–Sun failure criterion [27]. Two-bolt and three-bolt carbon-to-carbon double-lap joints were also tested to verify the predicted failure loads and failure modes. Experimental outcomes and predicted results by characteristic curve method with the curve presented and Chang's are compared and discussed.

2. A novel characteristic curve

Chang's characteristic curve, which is proved to be one of the most widely applicable to failure prediction of composite mechanical joints, has the following mathematic expression [17]:

$$r = R + R_t + (R_c - R_t)\cos\theta \qquad -90^\circ \leqslant \theta \leqslant 90^\circ \tag{1}$$

where r is the distance between the center of hole and the characteristic curve. R denotes the hole-diameter, and R_t and R_c are the tensile and compressive characteristic length respectively. The angle θ, anticlockwise measured from the symmetry axis, ranges from $-90°$ to $90°$ as shown in the upper half of Fig. 1a.

With Chang's characteristic curve method, final failure of joints is detected when the modified Yamada–Sun failure index [27] in any ply of the laminates equals to unit at any point of the characteristic curve [17]. The location (angle θ) at which failure index first reaches the value of unit on the characteristic curve provides an estimate of the failure mode, as shown in the lower half of Fig. 1a. The tensile failure mode corresponds with the failure location $75° \leqslant |\theta| \leqslant 90°$ and the bearing failure mode is relative to the failure location of $0° \leqslant |\theta| \leqslant 15°$. Moreover, shear-out failure mode is in accord with the failure location of $30° \leqslant |\theta| \leqslant 60°$.

To predict the ultimate failure of composite joints including shear-out failure accurately, Agarwal [25] extended characteristic length concept and firstly defined tensile, bearing and shear-out plane on failure location respectively. The tensile plane is on the cross section of the joint, and the bearing plane is on the symmetry plane of the joint, and the shear-out planes are along the hole edge, as shown in Fig. 1b. Meanwhile, a concept of shear-out characteristic length, which is used to predict shear-out failure, was proposed based on the shear-out plane. In the subsequent research, Ramkumar [28] defined the shear-out characteristic length is the distance from point E to point S clearly, as shown in Fig. 1b. Similar to the definition of tensile characteristic point T and the compressive characteristic point B, the shear-out characteristic point S is determined by shear failure load and unnotched shear strength of the laminates. With point stress failure criterion and average stress failure criterion, Ramkumar [29] calculated shear-out characteristic length and further predicted shear strength of multi-bolt joints. Eriksson et al. [30] also calculated shear-out characteristic length with point stress failure criterion.

Fig. 1b also depicts the intersection points of the aforementioned characteristic curves and Agarwal's shear-out plane [25], from which irreconcilable conflicts that different curves intersect shear-out plane at different points (F, Z and X) and all of the intersection points are disaccording with point S could be observed. The reason is that all the characteristic curves ignore the shear-out characteristic length. Unfortunately, the intersection points show different shear-out strength predictions resulted from different characteristic curves.

To obtain an accurate prediction of shear strength, a novel characteristic curve which passes through the tensile, compressive and shear-out characteristic points (denotes by point T, B and S respectively) is proposed, as shown in Fig. 1c. The tensile characteristic length R_t, compressive characteristic length R_c and shear-out characteristic length R_s are also illustrated in Fig. 1c. To provide a comparison, the Chang's characteristic curve is also plotted in dotted line.

Based upon the mathematic expression of Chang's characteristic curve, an additional term which equals to zero on compressive and tensile characteristic points, is presented to make the novel characteristic curve pass through shear-out characteristic point. Thus, the equation for the novel characteristic curve could be written as:

$$r = R + R_t + (R_c - R_t)\cos\theta + 2\alpha|\sin\theta|\cos\theta \qquad -90^\circ \leqslant \theta \leqslant 90^\circ \tag{2}$$

The additional term is located on the most right of Eq. (2). The angle θ is measured in a counter-clockwise direction from the symmetry axis, which is consistent with the definition of Chang's characteristic curve. When θ equals to 0° or ±90°, which denotes the compressive or tensile characteristic point, the additional term equals to zero. But when θ equals to ±45°, the additional term equals to α, which is defined as a distance between the novel characteristic curve and Chang's characteristic curve, as show in Fig. 1c.Thus, r_s, which is relative to the distance $\overline{OS}$, can be calculated according to Eq. (2) or by R and R_s in the light of the triangle formulation:

$$r_s = (R + R_t + (R_c - R_t)\cos\theta_s + 2a|\sin\theta_s|\cos\theta_s) = \sqrt{R_s^2 + R^2} \tag{3}$$

where the angle θ_s has the sine function expression as follows

$$\sin\theta_s = \frac{R}{\sqrt{R_s^2 + R^2}} \tag{4}$$

By substituting formula (4) into Eq. (3), the explicit representation of α is obtained:

$$\alpha = \frac{\sqrt{R_s^2 + R^2}\left[R_s^2 + R^2 - (R + R_t)\sqrt{R_s^2 + R^2} - R_sR_c + R_sR_t\right]}{2RR_s} \tag{5}$$

From Eqs. (2) and (5), the expression of the novel characteristic curve could be obtained. The evaluation method of failure modes for the novel curve is similar as that of Chang's, as shown in the lower half of Fig. 1c. In case of ignoring the impact of shear-out characteristic length, $\alpha = 0$, thus the novel curve could degenerate to the Chang's characteristic curve [17].

3. Validation

A series of tests including open hole tensile strength (OHT) of laminates, fastener hole bearing strength of laminates (or composite laminates bearing (CLB) strength) and fastener hole shear-out