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Effect of damage on failure mode of multi-bolt composite joints using failure envelope method

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ABSTRACT

Failure envelope method is comprehensively used in failure mode prediction of multi-bolt composite joints. The method is based on the assumption that bolt load distribution proportion is constant till failure. However, bearing damage and net-section damage must have some influence on the load distribution and then change structure failure mode. In this paper, tensile experiments of two-bolt and three-bolt joints were conducted to obtain the failure modes and other properties. Three dimensional (3D) finite element models involving damage were constructed, and the results were consistent with experimental data. Then, the models were used to study the effect of damage on failure mode of multi-bolt composite joints. The results show that failure mode prediction with failure envelope method should involve the effect of composite damage. Compared with net-section damage, bearing damage has greater influence on failure mode. Based on conventional failure envelope method, a new evaluation procedure involving damage was proposed.

1. Introduction

Composite materials have been extensively used in aerospace and many other industries. Due to limitations of manufacture and maintenance, bolted joints are quite commonly used in composite structures [1]. However, the drilling of holes cuts the fiber and causes local stress concentration, resulting in reduction of load carrying capacity. To ensure safety and increase weight saving efficiency, the joint structures must be designed seriously, and their mechanical behavior should be studied carefully [2–5]. The failure mode and strength are important properties for composite bolted joints.

The main failure modes of multi-bolt joints include net-section failure, bearing failure and shear out failure as shown in Fig. 1. The bearing failure is a progressive process, while net-section failure and shear out failure occur immediately and catastrophically. The latter two failure modes may reduce the load carrying capacity or cause instant failure of the whole structure. That is the reason why bearing failure mode is preferred in joint structural design and the other two modes should be avoided. By adjusting ±45° layer ratio and the end distance of connected objects, shear out failure can be suppressed and the main failure modes are the other two failure modes. The control of failure modes is very important for bolted joint structure design, thus failure mode prediction methods of multi-bolt composite joints are needed to be investigated.

Many researchers have investigated mechanical properties of single-bolt composite joints [6–8]. Compared with single-bolt joints, there are various load transferring paths in multi-bolt structures, causing more complicated structural characters. Current mechanical investigations on multi-bolt joints mainly focus on bolt load distribution [9–14] and predictions of failure modes and strength. The failure envelope method is a common accepted engineering method for failure mode and failure load prediction.

The failure envelope method is originally proposed by Hart-Smith [15] to predict tensile and bearing failure of double-lap multi-bolt joints with quasi-isotropic or near-quasi isotropic lay-ups. He found that a linear interaction exists between the bearing stress along the bolt hole and the remaining tension stress running by that hole to be reacted elsewhere (bypass stress). Based on the experimental results, he proposed the bearing-bypass failure envelope. Then, Crews and Naik [16], Rao et al. [17], Camanho et al. [18,19], Bois et al. [20] applied and developed the method. In the failure envelope, the line corresponding to bearing failure is a contour line determined by single-bolt bearing strength. But Liu et al.

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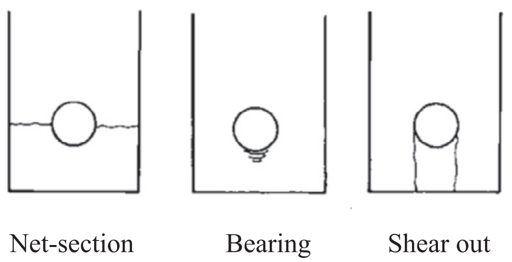

Fig. 1. Failure modes of multi-bolt composite joints.

[10,21] indicated that bypass load influences bearing failure strength, and corrected the failure envelope.

But all these researchers assumed that bearing stress and bypass stress has a constant ratio throughout the failure process. As a matter of fact, load distribution between bolts would change once composite damage occurs, and the bearing and bypass stress ratios can also be affected. Therefore, the effect of damage on failure mode of multi-bolt composite joints using the failure envelope method deserves to be further explored.

In the present paper, theory of failure envelope method was briefly introduced. Tensile experiments of two-bolt and three-bolt composite joints were conducted, and 3D finite element models considering damage were constructed. Based on the numerical model, bolt load distribution was investigated, and the effect of composite damage on failure mode was analyzed.

2. Theory of failure envelope method

Principle of the failure envelope method is shown in Fig. 2. Line ACE is the failure envelope of multi-bolt composite joints, and it can be obtained by single-bolt joint bearing experiment and open-hole laminate tensile experiment.

Line AC represents the cut-off line of ultimate bearing failure and line CE represents that of ultimate net-section failure. The failure envelope is related with joint geometry and laminate stacking sequence, et al.

Bearing stress at point A corresponds to the ultimate bearing failure strength of single-bolt laminates σ_{bru}, Bypass stress at point E is related to ultimate net-section tensile failure strength of open-hole laminates σ_{netu}.

The strength equations are shown as following:

$$\sigma_{bru} = F_{bru}/Dt \tag{1}$$

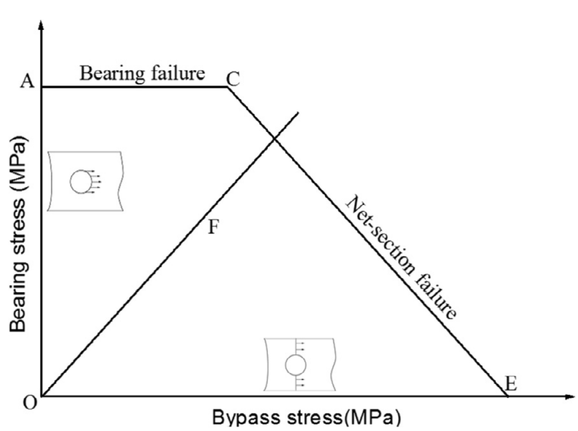

Fig. 2. Sketch map of failure envelope method.

$$\sigma_{netu} = F_{netu}/(W - D)t \tag{2}$$

where F_{bru} and F_{netu} denote bearing and net-section tensile failure loads respectively. D denotes hole diameter, t denote laminate thickness, and W denotes laminate width. Equation of line CE is

$$K_{brc}\sigma_{br} + K_{tc}\sigma_{by} = \sigma_t \tag{3}$$

where K_{brc} denotes the stress concentration factor caused by loaded-hole tensile stress, while K_{tc} denotes the stress concentration factor caused by open-hole tensile stress. σ_{br} and σ_{by} denotes bearing and bypass stresses respectively. σ_t denotes the laminate tensile strength.

The two factors could be calculated by the composite stress concentration relief factor C_{re} from elastic isotropic stress concentration factors K_{te} (net-section tension) and K_{bre} (bearing stress), respectively.

$$K_{brc} = 1 + C_{re}(K_{bre} - 1) \tag{4}$$

$$K_{tc} = 1 + C_{re}(K_{te} - 1) \tag{5}$$

Bearing and bypass stresses show linear relationship under applied load and that is described by line OF. The slope of line OF is shown as following:

$$K = \sigma_{br}/\sigma_{by} \tag{6}$$

in which,

$$\sigma_{by} = F_{by}/(W - D)t \tag{7}$$

$$\sigma_{br} = F_{br}/Dt \tag{8}$$

where F_{by} and F_{br} are the bypass and bearing loads, respectively. Bypass stress σ_{by} and bearing stress σ_{br} increase with the applied load, resulting in growth of line OF. When line OF intersects with failure envelope, the joint gets ultimate failure. Bearing failure occurs with the intersection at line AC, while net-section failure occurs with the intersection at line CE.

As mentioned before, the method is based on the hypothesis that joint failure is a linear process with constant load distribution. This simplifies the analysis but loses important information such as damage. In application of composite joints, the damage is likely to occur before their ultimate failure. When damage occurs in multi-bolt joint, the load distribution will change with the variation of K, and this may vary the failure mode.

3. Methodology

3.1. Specimen and experimental procedures

The experiment included two specimen groups: two-bolt joint (J2) and three-bolt joint (J3). There were three specimens in J2 group and two specimens in J3 group. The two groups had the same material and joint parameters except bolt number. Geometry of J3 is shown schematically in Fig. 3. For convenience of reference, bolts and holes are numbered 1# to 3# from left to right.

The fixture and specimens were made from carbon/epoxy composite materials T300/5228A. Laminates had a quasi-isotropic stacking sequence of $[0/45/90/-45]_{3S}$. The mechanical properties of the composite material are listed in Table 1[22]. The bolts with diameter of 6 mm were made from aerospace grade Titanium alloy, whose modulus and Poisson's ratio are 110 GPa and 0.3, respectively. Washers were placed on both sides of the laminate.

Specimens were assembled with bolt torque of 0.5Nm. The torque could represent the worst assembly condition of joint. On the other hand, it could reduce friction between specimen and fixtures to make the load transferring through bolts.