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Numerical analysis on load-bearing capacity and damage of double scarf adhesive joints subjected to combined loadings of tension and bending

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ABSTRACT

The load-bearing capacity and the damage level of the double scarf joint (DSJ) under combined loadings of tension and bending were investigated numerically, which takes into account the effects of scarf angle and adhesive type. A finite element method (FEM), which includes a mixed-mode cohesive zone model (CZM) with a bilinear shape, was employed to govern the interface separation behaviors. At the point corresponding to the ultimate loading, it was observed that the interface damage level of DSJ with the ductile adhesive is higher and more uniform than that of the joint with the brittle one. More than that, the numerical results illustrated that the failure of DSJ is controlled not only by the ultimate loading, but also by the applied displacement until complete failure. Therefore, the failure energy, which is defined as the integral of the loading with respect to the displacement, was adopted to estimate the joint performance. Subsequently, the numerical results showed that the failure energy of the joint with the ductile adhesive is higher than that of the joint with the brittle one. Furthermore, all the discussed characteristic parameters of a DSJ with a given adhesive, including ultimate loading, the von-Mises equivalent stress and interface damage level corresponding to the ultimate loading, and the failure energy, were inversely proportional to the scarf angle. Finally, through comparing with the existing experimental measurements, the adoptive method was validated.

1. Introduction

Adhesive joints, with many advantages over conventional mechanical fastening techniques, are an ideal joining method of lightweight and high strength. Strength estimation and failure mechanism examination are crucial to widen the technological applications of adhesive joints subjected to external applied loadings, especially in aerospace and automotive industries. Among all types of adhesive joints, the scarf adhesive joint is commonly adopted to join fiber reinforced laminate composite elements and components for more uniform stress distributions [1–3]. The examinations concerning the effects of the scarf angle on the joint performance under uniaxial tensile loading have been carried out in many studies [2,4–6], which show that the failure loads increase as the characteristic angle decreases. Furthermore, the double scarf adhesive joint (DSJ), with the similar advantages as the single scarf adhesive joint (SSJ), is also used widely in mechanical industries. The obvious characteristic of the DSJ is the geometric configuration, which has acute and obtuse angles at the ends of the substrates and the top of the double scarf, respectively [3]. In addition, comparing with the single lap adhesive joint (SLJ), adopting the SSJ and DSJ avoids bending when subjected to uniaxial tensile loading. However, a pure tensile loading is rare in actual applications. Commonly, the external loading is a combined loading with tension and bending together. Thus, the failure mechanism (including joint load-bearing capacity and damage level) of the joint under combined loadings should be examined deeply to promote practical applications.

Failure of adhesive joints is dictated by the mechanical properties of the adhesive [7–11] and the stress states of the adhesive layer controlled by the geometrical configurations and constraint effects [4,12]. In addition, failure was demonstrated to take place progressively as energy dissipates gradually at the crack tip [4,7–11,13]. Furthermore, failure generally occurs in the adhesive layer with a lower stiffness than that of the adherends, which has been proved by previous investigations [4,8–11,14–15]. The onset of damage can be predicted without requiring any initial crack using the existing stress- or strain-based criteria [13]. However, the obvious disadvantage of these methods is the mesh dependence

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caused by the singularities at the edge of the adhesive. Fracture mechanics approach is mesh independent but an initial crack is indispensable [16,17]. Owing to the complex failure behavior of the adhesive joint, it is difficult to obtain a universal failure criterion to various situations. Alternatively, cohesive zone models (CZM) can simulate the damage onset and growth with mesh independence and dispensable initial crack, maintaining the possibility to characterize the behavior of the structure up to failure [7–15]. Especially, an efficient finite element computational method with the core of CZM was certified by Castagnetti et al. [18], which showed that the so-called Tied Mesh method has the advantage of numerical precision and computational speed. Moreover, the evaluation of the cohesive parameters influence was carried out by Campilho et al. [19], which allowed a critical perception of the effect of these parameters on numerical predictions.

For the mixed-mode strength, Spaggiari et al. [20] discussed various criteria aimed to thin adhesive films. In their study, they mentioned that the responses in Mode I (normal stresses) and Mode II (shear stresses) of the adhesive are significantly different. In addition, they concluded that it is difficult to find a limit stress using the traditional criteria for ductile and brittle materials. Furthermore, they also pointed out that the Stassi D′Alia criterion can find an equivalent stress value, which is valid irrespective of the loading conditions.

In the present study, the load-bearing capacity and damage level of a DSJ with various scarf angles and adhesives subjected to the combination of tension and bending are examined using a mixed-mode CZM with a bilinear shape coupled with a finite element subroutine (performed in ABAQUS® [21]), which takes into account the normal-shear mixed stress state at the scarf interface. The numerical analysis is validated with existing experimental results. The effects of scarf angle (30°, 45°, 60°) and adhesive properties (three types) on the load-bearing capacity, the von-Mises equivalent stress distributions at the interface and damage level corresponding to the ultimate loading of DSJs are evaluated. Finally, the energy required for the joint failure, which is described as the stretch energy of the resultant loading that is equal to the area under the load–displacement curve of the DSJ, is also estimated.

2. Numerical analysis

2.1. DSJ model

A finite element model of a DSJ subjected to a combined loading of tension and bending is introduced for analysis, as shown in Fig. 1. Two adherends [I] with the same materials are bonded with the adhesive layer at the scarf interface. Young′s modulus and Poisson′s ratio of the adherends [I] are denoted as E_1 and ν_1, those of the adhesive layer [II] are E_2 and ν_2, respectively. The length and the width of the adherends are $2l_1$ and $2w$. The thickness of the adhesive layer [II] is denoted as t_2. The material and geometric parameters are listed in Table 1.

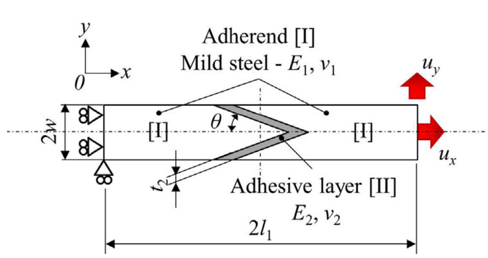

Fig. 1. A model of DSJ with boundary conditions.

Table 1
Material and geometric parameters of the DSJ.

E_1 (GPa) [5,6]	ν_1 [5,6]	$2l_1$ (mm)	$2w$ (mm)	t_2 (mm)
209	0.29	100	20	0.1

Supposing that the width of the adherends of the joint selected in the present study is far larger than the thickness (thin plate specimen), the DSJ can be simplified as a 2D plane-strain problem. Correspondingly, Cartesian coordinates (x, y) are adopted in modeling. As for the boundary conditions, they are defined as: (1) the free end of the left adherend [I] is constrained both in the x- and y-direction; (2) the tension and bending loading, which is simulated by controlling the displacement increment method along the x- (u_x) and y-direction (u_y) ($u_x=2u_y$), is applied to the free end of the right adherend [I], respectively.

The progressive nonlinear failure occurs at the adhesive interface, which results from the extremely great difference in stiffness between the adherend and the adhesive [3]. Subsequently, a geometrical and material nonlinear numerical analysis is performed in ABAQUS® to simulate the mechanical behavior of the DSJ by adopting a CZM to simulate damage initiation and growth, which is discussed in details in Section 2.2. The parameters of the cohesive elements are set as described in Section 2.3 according to the chosen adhesive.

The FEM model with mesh details is shown in Fig. 2, where the geometrical thickness of the adhesive layer (for easier visual effect) is different from the real thickness t_2. Accordingly, the adhesive layer [II] is built as a single layer using four-node cohesive elements, which share nodes with the neighboring elements in the adherends (as shown in Fig. 2 with a magnified view of the CZM elements at the interface and the connection details). The adherends [I], which are high-strength steel [5,6], are defined as isotropic elastic for simplicity. In addition, they are meshed using four-node quadrilateral plane-strain elements. The adhesive region is densely meshed using biasing effects while sparse meshes are used in other regions for higher computational accuracy. In addition, optional viscous damping is implemented between node pairs to improve convergence [15].

In order to examine the effects of the scarf angle θ on the performance of the joint, it is chosen as 30°, 45° and 60°, respectively. In addition, the effects of the properties of adhesives on the performances of the joint are also analyzed, in which three adhesives [8] are selected: a brittle adhesive (AV138/HV998) [22], an intermediate adhesive (Hysol EA 9321) [23] and a ductile adhesive (Hysol EA 9361) [24], respectively. The tensile stress–strain curves of the bulk adhesives are shown in Fig. 3 [8].

2.2. CZM

Based on the Traction–Separation (T–S) law, CZM is widely used to analyze the de-cohesion in composite structures [8–11,13–15]. It must be pointed out that the adhesive layer using CZM is a generalized interface phase rather than a material. T–S curve can be considered as a representation of the constitutive relation of the equivalent interface [9]. A bilinear assumption model [25–27], in which a critical energy release rate G_c and a cohesive strength σ_u are vital to capture the interface separation behavior [9–11,15,28], is employed in this study. Owing to the combined loadings, a complex stress state of the joint is present with mixed-mode (Mode I and II) damage propagation, as shown in Fig. 4 [8–11,13,19].

According to the existing research findings [8–11,13], it can be noticed that the constitutive relationship before damage onset is calculated using:

$$\boldsymbol{\sigma} = D\boldsymbol{\delta} \tag{1}$$

where $\boldsymbol{\sigma}$, $\boldsymbol{\delta}$ and $\mathbf{D}$ are the vector of interface finite element stresses, the vector of relative displacements and a diagonal matrix