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Numerical analysis of effects of adhesive type and geometry on mixed-mode failure of adhesive joint

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ABSTRACT

In the present study, the effects of the adhesive type and geometry (adhesive thickness and scarf angle) on mixed-mode failure of double scarf adhesive joint (DSJ) under uniaxial tensile loading were numerically examined using the finite element subroutine which coupled with a mixed-mode cohesive zone model (CZM). Especially, the effects of the adhesive type, which actually represent the influences of the cohesive parameters in mode I and mode II, on the mechanical properties of DSJ were discussed systematically. The numerical results reveal that the ultimate tensile loading and the necessary energy for failure of DSJ are controlled by the intrinsic components in mode I and mode II with different rates. Accordingly, the mathematical expressions for the ultimate tensile loading and the failure energy of DSJ with respect to the thickness-dependency cohesive parameters in two modes (I and II) and the scarf angle were deduced to identify each contribution in each mode component for a given type of adhesive. In addition, the numerical results also demonstrate that relationship between the interface damage level (corresponding to the ultimate tensile loading) and the adhesive thickness is not monotonous. However, as an increase of the adhesive thickness, the uniformity of damage level distribution is enhanced. Furthermore, the variation of the interface damage level with respect to the scarf angle is also not monotonous for each adhesive thickness. It can be concluded that the effects of the scarf angle and the adhesive thickness on the mixed-mode failure of DSJ are coupled rather than independently.

1. Introduction

As an ideal alternative joining method compared with the conventional mechanical fastening techniques, adhesive joint, due to its merits such as lightweight and high strength, has been widely used in industries. Consequently, the failure mechanism examination plays a crucial role in the design aiming to improve the safety and economy of adhesive structures. Thus, in order to promote practical applications, it is of great importance to examine the failure mechanism (including joint load-bearing capacity and interface damage level) of the joint under external loading.

Plenty of investigations [1–6] had illustrated that failure takes place progressively as energy dissipates gradually at the crack tip. The progressive failure process is mainly attributed to the mechanical properties of the adhesive and the stress states of the adhesive layer controlled by the geometrical configurations and constraint effects [1–5]. In addition, owing to lower stiffness of the adhesive layer compared with that of the adherend, failure generally occurs in the adhesive layer [7,8].

For the cohesive failure, cohesive zone model (CZM) is widely used to capture 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 [1–8]. In addition, Castagnetti et al. [9] represented the advantages of numerical precision and computational speed by adopting an efficient finite element computational method with the core of CZM. Moreover, Campilho et al. [10] examined the influences of cohesive parameters. As for the mixed-mode strength, Spaggiari et al. [11] stated that the responses in mode I (normal stresses) and mode II (shear stresses) of the adhesive are significantly different. However, the main control parameters that determine the mechanical properties of the adhesive joints have not yet been analyzed systematically. Liao et al. [12] discussed the effects of influential parameters on the load-bearing capacity of single scarf adhesive joint using dimensional analysis preliminarily. Pardoen et al. [13] also investigated the related factors, such as the material properties and the geometry, on the responses during the wedge opening process via dimensional analysis. The previous investigations demonstrated that the influential parameters affect the

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mechanical properties of the adhesive joint collectively rather than individually. However, quantitative analysis with exact expression has not yet been carried out.

In the present study, a double scarf adhesive joint (DSJ) under uniaxial tensile loading was adopted as the research object, in which the interface experiences tensile/shear stresses under external loading. Assuming that the cohesive failure occurs in the adhesive layer, the mechanical performances of DSJ with different adhesive types and various geometries (adhesive thicknesses & scarf angles) under uniaxial tensile loading were examined by using a mixed-mode CZM with a bilinear shape coupled with a finite element subroutine (performed in ABAQUS® [14]). Accordingly, the effects of adhesive type and geometry on the mixed-mode failure of adhesive joint were analyzed numerically. The intrinsic parameters of the adhesive with the label Hysol® EA9361 [15] were chosen as the benchmark values for the cohesive parameters. In the evaluation of the adhesive type, the influences of varied parameters corresponding to the benchmark cohesive values were studied numerically. In addition, the effects of geometry including the adhesive thickness which influences the cohesive parameters [3], and the scarf angle which affects the interface stress state, were also analyzed to identify the failure mechanism of DSJ. Furthermore, mathematical expressions for the ultimate tensile loading and the necessary energy for failure of DSJ with respect to the thickness-dependency cohesive parameters in two modes (I and II) and the scarf angle were examined.

2. Numerical analysis

2.1. DSJ model

In order to examine the effects of control parameters on the failure mechanism of the adhesive joint, the mechanical performances of DSJ subjected to uniaxial tensile loading, which experiences the tensile/shear stresses state at the adhesive interface, was investigated. Fig. 1 shows a DSJ model, in which two adherends with the same material are bonded together by using the adhesive layer with thickness of t_2 and scarf angle of θ. Young's modulus and Poisson's ratio of the adherends are denoted as E_1 (209 GPa) and ν_1 (0.29), and those of the adhesive layer are E_2 and ν_2, respectively. The length and the width of DSJ are $2l_1$ (100 mm) and $2w$ (20 mm), respectively.

As a 2D plane-strain problem (thin plate specimen), Cartesian coordinates (x, y) were adopted in modeling. As shown in Fig. 1, with full constraints at the left end of DSJ, the uniaxial tensile loading was simulated by controlling the displacement increment along the x-direction (u) at the right end of DSJ.

2.2. Finite element method

In the finite element analysis, the geometrical thickness of the adhesive layer (for easier visual effect) is different from the real thickness t_2. Accordingly, the adhesive layer was built as a single layer using four-node cohesive elements, which share nodes with the neighboring elements in the adherends. The adherends, which were defined as isotropic elastic for simplicity, were meshed using four-node quadrilateral plane-strain elements. The adhesive region was meshed densely using the biasing effects while the other regions were meshed sparsely for higher computational accuracy and efficiency. In addition, optional viscous damping was implemented between node pairs to improve convergence.

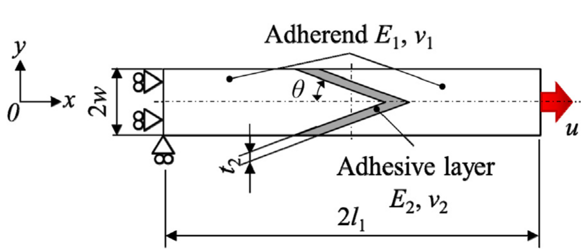

Fig. 1. A DSJ model with boundary conditions.

In order to capture the progressive nonlinear failure occurred at the adhesive interface, a material and geometrical nonlinear numerical analysis was performed in ABAQUS® by adopting a CZM to simulate damage initiation and growth. Bilinear traction–separation (T–S) curve was adopted as the constitute law for the adhesive layer with definite thickness. In the T–S curve, the cohesive strength σ and the critical fracture energy G are the main parameters, which govern the interface separation behavior [8,16]. In addition, since the scarf interface is not perpendicular or parallel to the tensile loading, the mixed-mode (mode I and mode II) failure should be taken into account.

Under the mixed-mode condition, damage initiation is controlled by a quadratic stress criterion through the following relation [2,3,6,10],

$$(\sigma_I/\sigma_{u,\mathrm{I}})^2+(\sigma_{II}/\sigma_{u,\mathrm{II}})^2=1 \tag{1}$$

where σ_{I} and σ_{II} are the stresses at the interface element in mode I and mode II, while $\sigma_{u,\mathrm{I}}$ and $\sigma_{u,\mathrm{II}}$ are the cohesive strengths of the given adhesive in mode I and mode II, respectively. Correspondingly, the damage level D, which can be expressed according to the total displacement jump $\Delta=\sqrt{(\delta_{\mathrm{I}})^2+(\delta_{\mathrm{II}})^2}$ [3–5], is given as

$$D=\frac{\Delta_f(\Delta_{\max}-\Delta_o)}{\Delta_{\max}(\Delta_f-\Delta_o)} \tag{2}$$

where Δ_o and Δ_f are the total displacements for damage onset and complete failure, respectively; Δ_{max} represents the maximum total displacement ever experienced during the loading history; Δ_f is calculated by $\Delta_f=2G/\sqrt{(\delta_{o,\mathrm{I}})^2+(\delta_{o,\mathrm{II}})^2}$, where G is the total energy released during the separation of the adhesive layer.

In addition, a linear fracture criterion is chosen to determine the damage propagation, which is expressed as [2,3,6,10]

$$G_{\mathrm{I}}/G_{\mathrm{Ic}}+G_{\mathrm{II}}/G_{\mathrm{IIc}}=1 \tag{3}$$

3. Results and discussions

The load-bearing capacity of the adhesive joints has been extensively estimated by employing the ultimate loading [17–20], which is denoted as F_u. In addition, the failure energy E_f was also introduced to evaluate the joint performance [12] as

$$E_f=\int_0^{u_u} F\,du \tag{4}$$

where u_u is the ultimate displacement corresponding to the resultant loading F dropping from the ultimate value to zero, which indicates complete failure. The physical significance of the failure energy is to illustrate the energy required for the failure of the joint with a given scarf angle and selected adhesive. In this study, the effects of the adhesive type and the geometry of the adhesive layer were examined, respectively.

3.1. Effect of adhesive type

As for the effect of the adhesive type, the real dominant factor is the cohesive parameters. The benchmark values were chosen as the cohesive parameters of the selected adhesive (a ductile adhesive with the label Hysol® EA9361 [15]). However, Xu and Wei [3] pointed out that the cohesive parameters are adhesive thickness-dependency. To eliminate the influence of the adhesive thickness on