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Damage and stress evolution in the bondlines of metallic adhesively bonded joints accompanied by bondline thickness effect

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ABSTRACT

Metallic adhesively bonded joints have a wide range of applications in engineering fields. The damage and the stress evolution in the bondlines of the joints would occur simultaneously when the joints are subjected to external loads. In the present research, the influence of the bondline thickness on the damage and stress evolution of metallic adhesive bonding structures are investigated, with the cohesive interface model employed to equivalently simulate the bondline with various thicknesses. A prediction approach is employed to determine the cohesive parameters for the bondline with the thickness varied. Then a numerical example is presented to explore the bondline thickness-dependence strength and stress distribution in the bondline, followed by the validation with the existing experimental and theoretical results. Furthermore, as the main part of this paper, the influences of the bondline thickness on the damage and stress evolution in the bondline are investigated, involving the situations of the extremities and the whole bondline. The results show that, no matter in the extremities or in the whole bondline, the damage and stress evolutions are mutually influential processes, both of which are affected by the bondline thickness significantly.

1. Introduction

Modern engineering structures have an increasing demand for the higher strength/weight ratio, especially in the fields of automobile, aeronautics and astronautic industries. Thus it is significant to use the novel lightweight materials with high strength and new joining techniques. Adhesive bonding is such an advanced joining technique with great potential for lightweight constructions. Compared with traditional mechanical assembly technologies (e.g., bolted, pinned, or riveted methods), it has a lot of advantages, such as reducing the stress concentration, wide applicability and lightweight. Thus adhesively bonded joints have been increasingly used in many engineering fields.

The ultimate failure strength prediction of adhesively bonded joints is one of the most important issues in this field, since the failure strength is a key parameter for design and health evaluation of adhesively bonded structures. Thus some methods are hence developed in order to predict the failure strength when the material parameters of adhesives are predefined. The overall failure strength prediction usually involves two main approaches: the one method to predict the overall strength is to assess the stress distribution in the bondline, either by numerical models or by analytical methods [1–4]. Most of the adhesively bonded joints would lose their load bearing capacity due to the failure of the bondlines, thus the accurate determination of the stress fields in the bondline is the first step to the precise prediction of the failure load of an adhesive joint. The stress corresponding to the critical load when the bondline stress reaches its admissible value is defined as the overall strength. Some failure or strength criteria are usually employed in this approach [5,6], such as the von Mises stress criterion and the principal stress criterion. Other researchers [7] adopted a twofold criterion involving stress and energy conditions simultaneously to predict the failure loads of adhesive joints subjected to diverse loadings. By contrast, the other method to predict the overall strength is a direct one, which is to obtain the load–displacement curves by simulating the loading process of adhesively bonded joints. Then the overall strength or the failure load can be obtained directly.

The first prediction method needs to assess the local stresses in some significant positions such as the extremities of the bondline, instead of the whole bondline, since the stress concentration of the extremities is much noticeable. On the contrary, the latter method for the overall mechanical behaviors is a global method [8], which neglects the stress singularity in the bondline, and it merely concerns the overall mechanical response of the structures subjected to external loads. The peak load could not be always treated as the admissible load because the irreversible damage has occurred in the bondline before the peak load is reached. Thus the

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overall mechanical behaviors should be obtained considering the local damage and stress distribution meanwhile.

Among all factors, the bondline thickness is one of most significant geometrical parameters affecting the overall strength of bonding structure. Thus the investigations on the influence of bondline thickness have been carried out by so many researchers, including the experimental studies [9,10] and the modeling studies [11–13]. Most of the experimental results have indicated that the overall strength of the bonding structures definitely depends on the bondline thickness. Recently, some modeling prediction methods have been established to obtain the computational results compared with the experiments. Moradi et al. [14] presented the influence of the bondline thickness on the failure load of joints by employing the stress and energy-based criteria together with a matched asymptotic procedure. Also the couple stress and energy criterion was employed by other researchers [5,15] to consider the influence of bondline thickness. Some failure load models were usually employed in their investigations. For example, the maximum principal stress criterion was used in Ref. [5] to determine the failure load of joints. Compared with the aforementioned researches, cohesive zone model (CZM) can be regarded as a direct approach, which has been proved to be successful in this topic. The significant advantage of employing cohesive zone model is that the overall mechanical behaviors (i.e., load–displacement curves) of joints can be directly obtained. And the effect of bondline thickness on the overall mechanical behaviors can be clearly presented. Thus the strength (or failure load) of the joints can be determined directly and easily just as the same way as the experimental approaches. The other advantage of CZM is that damage evolution of the interface or bondline could be captured as well. However, the tough challenge of employing CZM in this topic is how to assign the values of the cohesive parameters for various bondline thicknesses. Some good jobs have been done for predicting the overall mechanical strength of bonding structures with various bondline thicknesses. However, the understanding to the mechanisms of thickness-dependence cohesive properties has been still local. Besides, the local and overall stress analysis and damage evolution in the bondline with various thicknesses are lacking as well.

In the present research, a numerical model utilizing finite elements method (FEM) is established to describe the mechanical behavior of the metallic single lap joint subjected to a tensile load. A cohesive interface model considering the damage evolution is employed to simulate the bondline, with the cohesive parameters obtained via the previously proposed thickness-dependence prediction method. The present paper focuses on the mutual influences between the damage evolution and stress distribution in the bondline with various thicknesses. Finally, the effect of the bondline thickness on the accuracy of the ultimate failure strength assessment would be discussed based on the cohesive length scale.

2. Cohesive interface model

2.1. Bilinear cohesive zone model

Cohesive zone models (CZMs) based on traction–separation (i.e., T–S for short) laws are well suitable to describe the de-cohesion behavior in composite structures. The CZMs require T–S relations for characterizing their constitutive laws. So far, considerable researches have focused on the constitutive laws of CZMs and their applications [16,17]. It has been established that whilst the peak value and area of the T–S curve are vital for capturing the interface separation behavior, its precise shape is of less significance [18]. Consequently, for simplicity, the bilinear T–S law shown in Fig. 1 is selected for the present study. To distinguish the normal T–S law from the shear one, the superscript "n" represents the normal direction and "s" denotes the shear direction, which are omitted in Fig. 1 for simplicity, δ_c and δ_f are the critical and failure separation displacement, respectively, and T is the traction stress.

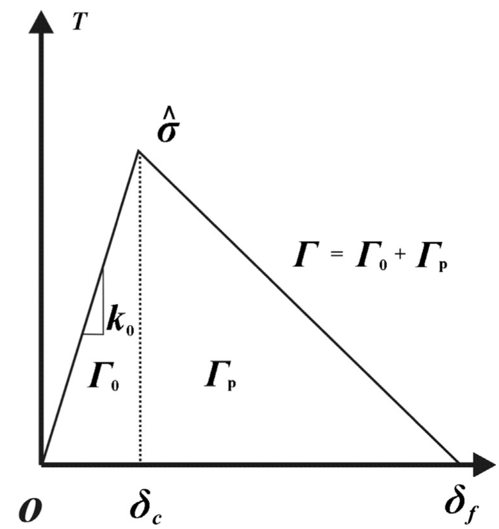

Fig. 1. Typical bilinear traction–separation law of cohesive zone model (the superscripts n and s denoting the normal and shear directions respectively, are omitted).

Since the maximum value of T^n is $\hat{\sigma}^n$ while that of $|T^s|$ is $\hat{\sigma}^s$, the fracture energy in the two directions can be expressed as

$$\Gamma^n = \int_0^{\delta_f^n} T^n d\delta^n = \frac{1}{2}\hat{\sigma}^n \delta_f^n$$
$$\Gamma^s = \int_0^{\delta_f^s} T^s d\delta^s = \frac{1}{2}\hat{\sigma}^s \delta_f^s \quad (1)$$

As the loading is increased beyond a critical value, the cohesive layer begins to soften, and degrade, namely, the cohesive layer is now in the damaged (or softening) state. Typically, damage is initiated when a certain criterion is satisfied. In the present study, inspired by the bilinear law of Fig. 1, the quadratic nominal stress criterion is adopted to characterize interfacial damage, described as

$$\left(\frac{< T^n >}{\hat{\sigma}^n}\right)^2 + \left(\frac{T^s}{\hat{\sigma}^s}\right)^2 = 1 \quad (2)$$

where $< \; >$ represents the Macaulay bracket defined by $<x> = (x+|x|)/2$, with the usual interpretation that a pure compressive deformation or stress state does not initiate damage. The peak traction stress components $\hat{\sigma}^n$ and $\hat{\sigma}^s$ are termed the normal and shear separation strengths, respectively.

2.2. Description of damage evolution

Damage variables describing the extent of damage in cohesive layer have a meaning physically equivalent to that introduced in the continuum damage mechanics (CDM) for engineering materials. In CDM, D is linearly proportional to the ratio of current Young's stiffness E of the material to its initial value E_0, i.e., $D = 1 - E/E_0$, if the damage is isotropic; for anisotropic damage, a tensor **D** is typically used [19].

For the two-dimensional problem employing the cohesive zone model, if the external loading process is mode-independent, or the deformation of cohesive layer is pure normal or shear mode, the damage of cohesive layer would occurs when the traction stress declines after its peak value is reached, and the damage variable