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# Influence of randomly distributed adhesive properties on the overall mechanical response of metallic adhesively bonded joints

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ABSTRACT

The overall strength of adhesively bonded joints is much dependent on the adhesive properties. In contrast to the ideal situation, real adhesive layers always have non-uniform adhesive properties, which result in inaccurate prediction of the overall mechanical behavior. This paper studies the overall strength of metallic adhesively bonded joints depending on their randomly distributed adhesive properties. A developed numerical method using the cohesive zone model modified by a user-defined subroutine is proposed to realize the randomly distributed adhesive properties. A larger number of computational cases have been carried out for the purpose of obtaining satisfactory statistical results. Finally, stress analysis along the adhesive layer with randomly distributed properties is exhibited. The results show that the overall strength of the joints is sensitive to the randomly distributed adhesive properties. The non-uniformity of the overall strength of the joints obeys the Gaussian distribution, with the statistical parameters close to mean values for the random separation strength. Moreover, the overall strength of the joints has a close relationship with the average stress level of the adhesive layers. The randomly distributed adhesive properties and the corresponding standard deviation should be considered for the reliability and safety of adhesively bonded joints.

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## 1. Introduction

Adhesively bonded joints are economical, practical and easy to make [1], thus they have been widely used in a variety of industries for connecting dissimilar materials, such as civil engineering [2–4], automotive [5–7] and aircraft industries [8]. The overall strength prediction of adhesively bonded joints is a meaningful concern for the engineering applications. It is expected that the overall strength of the joints can be predicted when the adhesive properties are determined. Consequently, considerable efforts have been made in developing efficient modeling approaches for assessing the load-bearing capacity of the joints. Especially, the numerical models using the finite element method (FEM) are regarded as effective and useful approaches to study the adhesive bonding issues [9]. Recently, in order to fully study the damage evolution and failure process of the adhesive layer, cohesive zone models (CZMs) introduced into FEM models have been widely employed as a powerful approach [10–13]. With the models, the adhesive layer is modeled as a cohesive surface with the properties given by a traction–separation (*T*–*S*) law that could be regarded as a representation of the constitutive properties of the adhesive layer [10,11].

The previous models have gained a certain success. Most published literatures on this topic have claimed that the proposed modeling predictions agreed with the corresponding experimental results. However, more or less deviations between modeling predictions and experimental results cannot be avoided, which results from two factors: on one hand, the simplifications and uncertainty of material parameters employed in computational models are always inevitable, which would induce the deviations. On the other hand, the main discrepancy between the real and ideal adhesive layers is the non-uniformity of the adhesive properties. The previous model studies usually treated the adhesive properties, such as elastic modulus, strength and toughness, to be uniform along the adhesive layers [14]. The prediction based on this approach is a deterministic approach by using the average properties with an empirical safety factor, which is an appropriate way for many metals, however, not satisfactory for polymeric adhesives and some composite materials since they are more sensitive to micro-defects and microstructures [15–17]. Furthermore, it is really tough to make the adhesive thickness uniform along the adhesive layer in practice. Generally, the local adhesive properties, namely, strength and toughness, vary evidently with the varying thickness along the adhesive layer. Thus the randomly distributed adhesive properties resulted from the non-uniform

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adhesive thickness cannot be neglected. Besides, the standard deviation caused by the non-uniformity of the adhesive properties significantly influences the reliability of the bonding structure. Thus the non-uniformity of the adhesive layer should be taken into account in order to accurately assess the overall mechanical behavior of adhesively bonded joints.

Based on the consideration for addressing the deficiencies of the existing studies, the spatial non-uniformity of adhesive properties is investigated in this paper. A FEM model for metallic single lap joint is established to study the influence from randomly distributed properties of adhesive layers, focusing on the overall strength of the joints affected by the randomness. A developed numerical method using the cohesive zone model modified by a user-defined subroutine is proposed to realize the randomly distributed adhesive properties. And a larger number of computational cases have been carried out for the purpose of obtaining satisfactory statistical results. Moreover, necessary stress analysis and comparison of uniform and random adhesive layers are exhibited as well. Finally, some influence of the randomness and the corresponding standard deviation on the reliability and safety of bonding structures is further discussed. The obtained results provide fundamental principles for the overall strength assessment of adhesively bonded joints with random properties of their adhesive layers.

## 2. Simulation approach

### 2.1. Computational model

In this section, a numerical model of a typical single lap joint (SLJ) is built with the commercially available FEM code ABAQUS. In practice, the width of the metallic adherend sheets used for the joints is far larger than their thickness thus the model can be simplified as a plane strain model with the consideration of saving computational resources without losing accuracy.

Fig. 1a depicts the computational model of the single lap joint, which consists of two same metallic sheets with the thickness of $h$ and the length of $a$ ($=40h$). The sheets are connected by an adhesive layer with the length of $l$ ($=a/3$), which can be also called overlap length. The sheets are meshed using four-node quadrilateral plane strain elements, of which the total number is set to be 1920 upon checking the convergence of the numerical results. Under uniaxial stretching, the joint is taken to deform under plane strain condition. Along the left side of the joint, the horizontal displacement is set to be zero, whereas a uniform displacement of $u$ is applied to the right side of the joint.

The metallic sheets are modeled as classic elastic–plastic solids, with their true stress $\sigma$ versus strain curves $\varepsilon$ fitted using power-law hardening laws [18]:

$$\sigma = \begin{cases} E\varepsilon, & \varepsilon \le \sigma^Y/E \\ \sigma^Y\left(\dfrac{\varepsilon}{\sigma^Y/E}\right)^N, & \varepsilon > \sigma^Y/E \end{cases} \tag{1}$$

where $E$ is Young's modulus, $N$ is the strain hardening exponent, and $\sigma^Y$ is the yield strength. For the present model, the values of the three material properties, namely, $E$, $N$ and $\sigma^Y$, are 70 GPa, 0.02 and 275 MPa, respectively, taken from Ref. [19].

The cohesive zone model modified by a user-defined subroutine is implemented to simulate the adhesive layer with random properties. For the purpose of obtaining better computational accuracy, the overlap region is meshed densely while sparse mesh is adopted in other regions as shown in Fig. 1b.

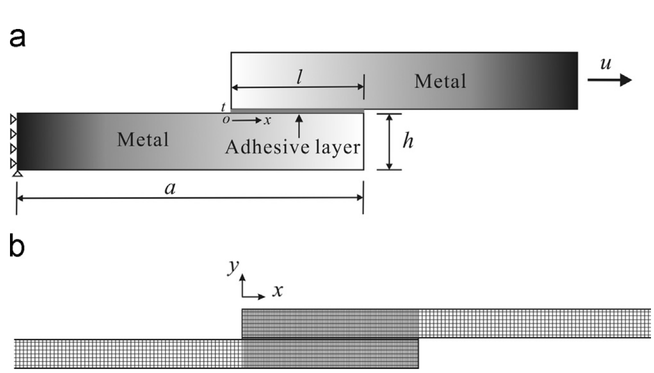


**Fig. 1.** (a) Numerical model of the single lap joint (SLJ) and (b) its finite element mesh.

### 2.2. Cohesive zone model

Cohesive zone models (CZMs) based on traction laws are well suitable to describe the decohesion and damage evolution in multilayer materials and structures. The CZMs require traction–separation ($T$–$S$) relations for characterizing these constitutive laws . So far, considerable research works have focused on the constitutive laws of CZMs and their applications [20]. It has been established that whilst the peak value and area of the $T$–$S$ curve are vital for capturing the interface separation behavior, in contrast, its precise shape is of much lesser significance than the two key parameters [20]. Consequently, for simplicity, the bilinear $T$–$S$ law [20–22] shown in Fig. 2 is selected for the present study. Built upon the bilinear cohesive zone model (CZM), the adhesive, also treated as interface between the two metallic sheets, is modeled with the cohesive zone elements.

Fig. 2 presents the traction–separation ($T$–$S$) relation of the bilinear CZM, with Fig. 2a and b representing the relations in normal and shear directions respectively. To distinguish the normal $T$–$S$ law from the shear one, let the superscript "$n$" denote the normal direction and "$s$" denote the shear direction. In Fig. 2, $u_{\rm m}$ and $u_{\rm c}$ are the maximum and critical separation, respectively, and $T$ is the traction stress.

Since the maximum value of $T^{\rm n}$ is $\sigma_{\rm m}$ while that of $|T^{\rm s}|$ is $\tau_{\rm m}$, the fracture energies in the two directions can be expressed as follows:

$$\Gamma^{\rm n} = \int_0^{u_{\rm m}^{\rm n}} T^{\rm n} {\rm d}u^{\rm n} = \frac{1}{2}\sigma_{\rm m} u_{\rm m}^{\rm n}$$
$$\Gamma^{\rm s} = \int_0^{u_{\rm m}^{\rm s}} T^{\rm s} {\rm d}u^{\rm s} = \frac{1}{2}\tau_{\rm m} u_{\rm m}^{\rm s} \tag{2}$$

As the loading is increased beyond a critical value, the adhesive layer begins to soften and degrade, namely, the adhesive 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 shown in Fig. 2, the quadratic nominal stress criterion is adopted to characterize the damage, described as follows:

$$\left(\frac{\langle T^{\rm n}\rangle}{\sigma_{\rm m}}\right)^2 + \left(\frac{T^{\rm s}}{\tau_{\rm m}}\right)^2 = 1 \tag{3}$$

where $\langle\ \rangle$ represent the Macaulay brackets defined by $\langle x\rangle = (1/2)(x+|x|)$, with the usual interpretation that a pure compressive deformation or stress state does not initiate damage [20–22].

It is assumed that damage occurs when Eq. (3) is satisfied and a single damage variable $D$ based on the total displacement jump

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