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A unified cohesive zone model for simulating adhesive failure of composite structures and its parameter identification

Yangjian Xu, Yuanqi Guo, Lihua Liang, Yong Liu, Xiaogui Wang*

College of Mechanical Engineering, Zhejiang University of Technology, Hangzhou 310014, China

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ABSTRACT

It has been proven that the shape effect of different cohesive laws can not be ignored in many cases. Such an effect is further investigated and clarified in the present paper. In order to more accurately simulate the adhesive failures of composite structures, it is necessary to develop a unified cohesive zone model (CZM) capable of approaching an arbitrary existing cohesive law. Toward this end, an improved interpolation-based CZM (ICZM) has been developed. The parameters of such a model were generally obtained by inverse analysis. However, success of the inverse analysis greatly depends on the initial guess of model parameters and its analysis technique. Therefore, a two-step inverse analysis method, perfectly matching the present ICZM, has been further developed in our work. The verifications based on both pseudo-experimental and real experimental data have shown that the present developed model and method are robust and can uniformly describe various adhesive failures without need to consider selection of appropriate CZM for different types of fracture problems. Finally, a novel inverse analysis method in combination with two types of experimental information, has been developed to improve the solution reliability and relieve the ill-posed extent of inverse problems.

1. Introduction

Adhesive bonding is currently an important joining method in many composite structures [1–5], and therefore the reliability assessment of the adhesive joint is crucial. So far a number of methods [1,6–11] have been developed to account for this issue, among which linear elastic fracture mechanics methods are dominant. However, their applications are limited in many cases [7,12] since the fracture process zone in the adhesive joint is generally large. The cohesive zone model is an alternative method that is especially suitable for characterizing delamination and debonding of adhesive interfaces, as well as simulating crack initiation and propagation. It has received lots of attentions in the past decades [13–16].

Nevertheless, CZM is a type of phenomenal model. Many different types of traction-separation laws have been developed in the literature. Here several typical and popular cohesive laws are listed, e.g., the bilinear [17], exponential [18], and trapezoidal laws [19]. All of them assume a nonlinear relationship between separation and traction at adhesive interfaces. By integrating the traction curve in terms of its separation, the acquired value represents the fracture energy G_c. Many investigations [20,21] show that G_c is a dominant parameter to affect the interface failure. However, some recent work [22–25] have also indicated that the effect of cohesive law shape cannot be ignored for many adhesive composite structures with metal adherends. It has shown that such an effect is profound, especially for high stiffness ratio between the adherends and the adhesive interface or under mode II loading conditions. Different cohesive zone models usually have their own applicabilities. For instance, the bilinear law is often used to describe brittle fracture while the exponential and the trapezoidal laws are preferred in the characterization of ductile fracture. Therefore, the choice of an appropriate cohesive law is not trivial, especially for high accurate simulation. Besides that, even for the same adhesive material, the thickness variation of adhesive will bring a huge impact on the failure of composite structure [1,23,26–28]. A thinner adhesive layer may cause a brittle fracture of interface while a thicker one can give rise to serious ductile fracture. As a result, the use of a single cohesive law mentioned above will yield an erroneous simulation result. In light of these considerations, a unified cohesive zone model, which can eliminate the shape effect of cohesive law, is desired in the failure evaluation of adhesive joints.

Aiming at the above issue, some researchers, e.g., Shen et al. [29] attempted to develop a uniform cohesive zone model suitable for describing all the different situations. They used the interpolation method to generate several splines to construct their cohesive law. Theoretically, all different types of existing cohesive zone laws can be approached by such a curve-fitting fashion if enough interpolation points

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* Corresponding author.
E-mail address: hpcwxg@zjut.edu.cn (X. Wang).

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are provided. Although this type of model can circumvent the issue of choice of cohesive zone models and have other promising advantages [29], there are still some shortcomings, e.g., low computational efficiency, dependence on initial estimation and limitation for wide applicability etc. Therefore, a further development of this type of model is essential. Toward this end, an improved interpolation-based cohesive zone model is therefore proposed in the present paper.

The inverse analysis is a popular means to identify cohesive zone model parameters, since the CZM is a type of phenomenal model. Strictly speaking, some of its parameters are lack of physical meaning. Aiming at the inverse analysis of the CZM parameters, many investigations have been carried out by using different types of optimization algorithms [14,29–32]. However, for most of the previous work, the inverse analyses are relatively easier to carry out, since only a few parameters need to be identified. The model developed in Shen‘s work [29] can consider the effect of the cohesive law shape but contain more unknowns. With an increase in the number of optimized parameters, the inverse analysis is getting more complicated and less efficient. Moreover, the results from optimization analysis greatly depend on the initial estimation, and the solution will fall into local optimal values more easily with more parameters. In order to overcome these issues, the compromise choice of parameter numbers, which can give consideration to high efficiency and accuracy as well as wide applicability, was discussed in our work. At the same time, an elegant inverse analysis scheme was further developed to ensure the robustness of the interpolation-based CZM.

A good inverse analysis requires providing suitable and comprehensive experimental measured information. In the past, parameter identification of phenomenal models mainly depended on the global response information which was easily obtained from material test, such as loading-displacement response curve [33–35]. Recently, the occurrence of new optical measure tool or method such as DIC greatly promotes the development of experimental mechanics. Local displacement or strain information are used to improve the accuracy of inverse identification of model parameters [29,31,36–39]. However, a better inverse analysis scheme can be constructed with combination of different types of experimental information to relieve the ill-posed property of inverse problems and enable the iteration to converge to a more accurate solution [38,40]. Therefore, a novel inverse analysis scheme based on both local displacement distribution and global load-displacement response curve was developed in our work.

This paper is organized as follows: Section 2 further investigates the shape effect of cohesive law by using two numerical examples. Section 3 introduces the improved interpolation-based cohesive zone model. Subsequently, Section 4 exhibits the inverse analysis scheme and the procedure which is customized for the ICZM mentioned above. Section 5 reports the verification of the improved ICZM and its inverse analysis method. And Section 6 further uses real experimental information to test the present developed method and model, especially the inverse analysis based on two types of experimental information. Final conclusions are presented in Section 7.

2. Effect from cohesive zone model shape

As for the effect of cohesive zone model shape on fracture failure, recently several investigations [22–24] have been carried out. They pointed out that although the cohesive energy in the CZM is considered as a parameter to dominate the interfacial failure, the shape of cohesive zone model will also bring a substantial influence in some specific cases. Here, for further understanding such an effect, three popular interfacial laws: the bilinear, the exponential and the trapezoidal, together with two fracture specimens, were investigated under both mode I and mode II loading conditions, respectively. For the fracture under pure mode I and mode II loading conditions, only one type of fracture mechanism is dominant in both cases and the other one is usually so weak that it can be ignored. For instance, when the mode I fracture was simulated the shear effect on the interface could be ignored. In order to make the simulations based on different interface laws comparable, the same initial stiffness ($k_0 = 8.163$ MPa), peak value of traction ($\sigma_0 = 1.2$ MPa) and fracture energy dissipated ($G_c = 1.30$ N/mm) were considered in the above three interfacial laws, as illustrated in Fig. 1. The above model parameters were assumed according to the material properties of one typical UV curable adhesive. In addition, although the forms of the interfacial laws for describing mode I and mode II fractures are generally different, they were assumed to take the same form in the present study for convenience, which will not bring any influence on the discussion in terms of shape effect of CZM.

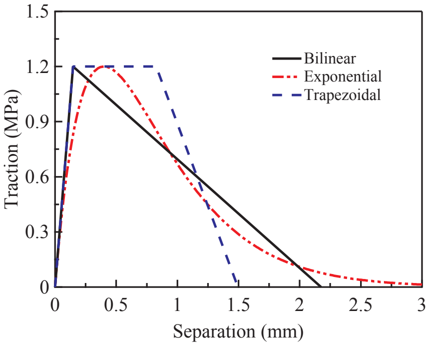

Fig. 1. Three popular cohesive zone models.

Here the analytical expressions of these interfacial laws are simply summarized as follows.

(i) The bilinear law can be written as

$$\boldsymbol{T}(\delta) = \begin{cases} k_0\delta & \text{if } 0 \leqslant \delta \leqslant a_1, \\ \frac{a_2-\delta}{a_2-a_1}\sigma_0 & \text{if } a_1 \leqslant \delta \leqslant a_2, \\ 0 & \text{if } a_2 \leqslant \delta. \end{cases} \tag{1}$$

where a_1 and a_2 are given by $a_1 = \frac{\sigma_0}{k_0}$ and $a_2 = \frac{2G_c}{\sigma_0}$.

(ii) The analytical expression of the exponential law is written as:

$$\boldsymbol{T}(\delta) = \frac{G_c}{b_1}\frac{\delta}{b_1}\exp\left(-\frac{\delta}{b_1}\right) \tag{2}$$

where $G_c = \sigma_0 b_1 e$ and e is the natural constant.

(iii) The analytical expression of the trapezoidal law is written as:

$$\boldsymbol{T}(\delta) = \begin{cases} K_0\delta & \text{if } 0 \leqslant \delta \leqslant c_1, \\ \sigma_0 & \text{if } c_1 \leqslant \delta \leqslant c_2, \\ \frac{\sigma_0}{c_3-c_2}(c_3-\delta) & \text{if } c_2 \leqslant \delta \leqslant c_3, \\ 0 & \text{if } c_3 \leqslant \delta. \end{cases} \tag{3}$$

where $c_1 = \frac{\sigma_0}{k_0}$ and $c_3 = \frac{2G_c}{\sigma_0}-(c_2-c_1)$.

In the present work, mode I and mode II interfacial fractures were investigated by using the double cantilever beam (DCB) and the single lap joint (SLJ) specimens, as shown in Fig. 2, respectively. The materials of two adherends were considered as steel and the adhesive layer was the Kafuter RTV silicon rubber paste. The Young's module of steel used in the simulation is 2e5 MPa and its poisson ratio is 0.3. The adhesive layer was modeled by using cohesive zone models. One key feature of such specimens is that the stiffness of adhesive layer is little compared with that of adherend.

Fig. 3 shows us the simulated load-displacement response curves for both mode I and mode II fractures which correspond to the simulations on DCB and SLJ specimens, respectively. From Fig. 3(a) one can see that all the curves from the three types of interfacial laws are rather close to each other except for their peaks. Therefore, for mode I fracture the effect from the CZM shape is limited in the present example. Giulio et al. [22] has proven that such a shape effect mainly depends on the