A novel cohesive zone model to simulate ductile adhesives in automotive structure metallic joints

Hamed Saeidi Googarchin¹ and Mohammad Hassan Shojaeefard¹ and Mohammad Reza Gheibi¹ and Zohreh Sarvi²

¹Iran University of Science and Technology, Iran
²University of Tehran, Iran

Email: hsaeidi@iust.ac.ir

Abstract: In recent years, increasing utilize of the adhesively bonded joints due to its prominent features in distribution of the stress in bonded area and bonding dissimilar material has led to developing its computational aspects to provide more reliable response. In this regard, cohesive zone model (CZM) as an effective method to simulate bondline is introduced. The crucial aspect of this method is the determination of the relation between traction and separation in fracture process zone (FPZ). In fact, the traction-separation law (TSL) is a material model which must be properly obtained and applied to the adhesive bondline. According to the literature, mechanical response of the adhesive joints in most cases (especially in ductile and semi-brittle adhesives) is depended on the TSL curve shape. In this study, a novel CZM is developed to simulate double cantilever beam (DCB) adhesive joint. The main advantageous this new model is considering non-linear behavior of ductile adhesives in elastic region. DCB coupons fabricated by means of Al 6061 adherends and Araldite 2015 adhesive. After direct extraction of the TSL and obtaining cohesive parameters of the new model, numerical simulation of the DCB is conducted. Finally, sensitivity analysis of cohesive parameters and effect of initial crack length on the DCB response is investigated.

Keywords: adhesively bonded joint, cohesive zone model, traction-separation law, double cantilever beam, initial crack length.

1 Introduction

Applications of adhesively bonded joints in transportation industry have gained widespread acceptance in the manufacturing of lightweight structures. This is due to the distinct features of the adhesive joints such as their capability to join dissimilar materials, much more uniform stress distribution and efficient load tolerating over a larger area of bonding in comparison with the conventional mechanical fastening, e.g. spot welding, piercing, riveting, etc. Meanwhile a higher strength-weight ratio, having the sealing ability, excellent resistance to fatigue loads, better damping characteristics and low cost are the other advantages of bonded joints. For these reasons, not only using adhesive joints can improve the structure efficiency, but also they can improve the joint strength and stiffness. Despite having many advantages, adhesive joints have mostly been used in secondary non-critical elements, such as rear rails, T-tops and side frames in automotive structures, as shown in figure 1. This is due to the mechanical behaviour of these joints which has not yet well understood. In order to generalize the use of adhesive bonding in high-responsibility structures, it is required to accurately predict the fracture behavior of bonded structures.

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In recent years, cohesive zone model (CZM) as a promising theory to design the bonded joints has been implemented because of considering non-self-similar crack growth and the presence of a non-negligible fracture process zone (FPZ). FPZ is a region in the vicinity of the crack tip where plasticity, micro-cracking and several other inelastic processes may take place [1]. One of the crucial aspects of CZM is determining the relation between traction and separation in FPZ, the so-called traction-separation law (TSL). It is worth noting that the shape of TSL for modelling an adhesive plays a critical role in the prediction of a macroscopic mechanical response of the adhesively joined structures [2-7]. Implementing a CZM law, that is not particularly tailored for a given adhesive, may still give a rough prediction of the bonded structures’ behavior [8]. According to the literature, few works focus on the optimal TSL shape to model ductile adhesive layers. A great majority of researchers used the trapezoidal TSL shape to predict the behavior of ductile adhesives, since they found that this cohesive law is an effective TSL which can model the coupling between the behavior of the ductile adhesive/adherend interface (adhesive failure) and the behavior of the adhesive itself (plasticity), cf. [3, 9-11]. However, due to the presence of two singular points in the trapezoidal TSL shape, their derivative is an uncertain value and would cause difficulty in convergence.

The objective of this study is proposing a novel CZM that considers the elastic, plastic and fracture behavior of ductile adhesive materials in mode I loading condition. The model has been validated by comparisons between numerical and experimental load-displacement ($P - \delta$) responses from DCB specimens.

2 Theoretical background

2.1 Extraction of TSL

In order to simulate adhesive joints using CZM, determining the joint TSL as an adhesive bond line material model is required. There are two main methods to obtain a TSL: calibration (inverse) method and direct extraction method. The calibration method considers a pre-defined TSL shape and corresponding parameters are identified through tuning the numerical and experimental $P - \delta$ responses utilizing a manual iterative procedure [8, 12-15] or an automatic optimization strategy [16, 17]. The main drawback of this method is the need to choose a pre-
defined TSL, since it requires some previous knowledge of the joint’s behavior which is not available in many cases. Alternatively, TSL shape can be determined according to direct extracted TSL procedure (direct method) during a fracture characterization test. In fact, in this method, exact TSL is first extracted and then a proper TSL shape is selected and its corresponding cohesive parameters are identified by adjusting the selected TSL shape on the exact one.

According to the direct method, a relation between strain energy release rate (SERR) in mode I and normal crack tip opening displacement (CTOD), $G_I - u$, should be initially extracted. Following by mathematical curve fitting, $G_I = f(u)$ relation is obtained. Finally, direct TSL of the adhesive in mode I can be derived from differentiation of this relation with respect to $u$ [18].

SERR magnitude is also the key parameter for this methodology. In order to determine it in mode I, Compliance Based Beam Method (CBBM) would be utilized [15]. For DCB specimen, equation 1 is developed as follows [15]:

$$G_I = \frac{6P_T^2}{b^2h} \left( \frac{2a_{eq}^2}{h^2E_{eq}} + \frac{1}{5G} \right)$$

(1)

where $P_T$ is the tensile load, $a_{eq}$ is the equivalent crack length, $E_{eq}$ is the equivalent flexural modulus, $b$ is the adherend width, $h$ is the adherend thickness and $G$ is the shear modulus of the adherends, respectively. The equivalent crack length concept can be obtained as [15]:

$$\alpha a_{eq}^3 + \beta a_{eq} + \gamma = 0$$

(2)

where $\alpha$, $E_{eq}$ and $\gamma$ coefficients are

$$\alpha = \frac{8}{b h^3 E_{eq}}; \beta = \frac{12}{5bhG}; \gamma = -C_0$$

(3)

In equation 3, $C_0$ denotes the compliance of the joint, $C = \delta_T/P_T$, at the crack initiation. $\delta_T$ represents the opening displacement at the loading point. Moreover, $E_{eq}$ can be obtained as [15]:

$$E_{eq} = \left( C_0 - \frac{12(a_0 + |\Delta|)}{5b h G} \right)^{-1} \frac{8(a_0 + |\Delta|)^3}{bh^3}$$

(4)

where $a_0$ is the initial crack length and $\Delta$ is a crack length correction coefficient for crack tip rotation and deflection. $\Delta$ is calculated by a linear regression analysis of $C^{1/3}$ versus $a$ data [15].

### 2.2 Proposed CZM description

The following proposed description of CZM accounts for the modelling of adhesive joints which are under mode I loading and would fracture in a 2-dimensional space. In the proposed CZM, TSL shape results from combining exponential hardening and polynomial softening curves as illustrated in figure 2. In this figure, $u_c$ and $u_f$ are the critical and final CTOD, $K_I$ is the initial stiffness considered for the cohesive element, $G_{IC}$ is the adhesive fracture energy (critical SERR), and $\sigma_c$ denotes the critical strength.
In this CZM, when the normal separation is negative, the contact conditions between crack surfaces take place. In order to prevent the material self-penetration, the normal cohesive interaction can be calibrated using the penalty stiffness, $K_p \approx 10^5$-10$^6$ MPa/mm [19]. It is worth noting that the selection of the proposed shape of TSL has been made according to the fact that the proposed particular shape has a very good fitting with the direct TSL extracted for metal-to-metal adhesive joints, as presented in the literature for Mode I [20-22].

The hardening part of TSL is considered by an exponential function [19] to describe the plastic behavior of a ductile adhesive. When joints are bonded by ductile adhesives, the size of FPZ is non-negligible and considering it in the predictive method is fundamental to provide a reliable design [19, 23, 24]. The polynomial softening part of the proposed CZM are derived through simplifying PPR potential [25]. Therefore, Constitutive equation of the proposed TSL is

$$\sigma = \begin{cases} A \left[ m \left( 1 - \frac{u}{u_f} \right)^\alpha \left( \frac{m}{\alpha} + \frac{u}{u_f} \right)^{m-1} - \alpha \left( 1 - \frac{u}{u_f} \right)^{\alpha-1} \left( \frac{m}{\alpha} + \frac{u}{u_f} \right)^m \right] & u_c \leq u \leq u_f \\ 0 & u \geq u_f \end{cases}$$

(5)

where

$$A = \frac{\sigma_c}{B}$$

$$B = m(1 - \lambda_n)^\alpha \frac{m}{\alpha + \lambda_n}^{m-1} - \alpha (1 - \lambda_n)^{\alpha-1} \left( \frac{m}{\alpha} + \lambda_n \right)^m$$

(6)

where $\alpha$ and $m$ represent shape parameter and non-dimensional exponent respectively. Meanwhile $\lambda_n$ is initial slope indicator defined as the ratio of the critical to the final CTOD. It is worth noting that $\alpha$ controls the non-linearity in the overall $P_T - \delta_n$ response (e.g. brittle, plateau and quasi-brittle) [26]. Meanwhile, in this study, a penalty contact algorithm is given by

$$\sigma(u) = K_p u \text{ for } u < 0$$

(7)

Moreover, it is assumed that negative normal tractions obtained from equation 7 would behave in a manner just like contact stresses and would not promote damage.
3 Experimental work

In order to fabricate DCB specimens, Al alloy 6061 T6 substrates are bonded by Araldite 2015, which is a ductile two-component epoxy adhesive. The geometry and dimensions of DCB adhesive joints are depicted in figure 3. The material properties are listed in table 1.

![Geometry and dimensions of the DCB specimens](image)

**Figure 3.** Geometry and dimensions of the DCB specimens

\[(L = 250, l_h=20, a_0 = 30, h = 15, b = 15 \text{ and } t_a = 0.2; \text{ all dimensions in mm}).\]

| Material          | Young’s modulus (GPa) | Poisson’s ratio | Shear modulus (GPa) |
|-------------------|-----------------------|----------------|---------------------|
| Araldite® 2015 [11]| 1.85±0.21             | 0.33           | 0.56±0.21           |
| AA6061 T6 [27]    | 70                    | 0.3            | 26                  |

As shown in figure 4, the joints are loaded under displacement control condition with the rate of 0.5 mm/min. \(P_T - \delta_n\) responses of DCB tests are shown in figure 5. During the test, applied load, length of the propagated crack, \(a\), and normal CTOD were recorded and based on these data, \(G_I\) magnitudes for every \(a\) were calculated. Afterwards, these magnitudes were plotted with respect to respective \(u\) and finally sixth-degree polynomial is fitted on them. Both of these results are illustrated in figure 6. By differentiation of the fitted polynomials with respect to \(u\), direct TSL for each test are obtained, as represented in figure 7.

![DCB test setup](image)

**Figure 4.** DCB test setup

![\(P_T - \delta_n\) responses of DCB specimens](image)

**Figure 5.** \(P_T - \delta_n\) responses of DCB specimens
According to $\sigma - u$ responses, the cohesive parameters of the proposed CZM are identified by the form of data presented in table 2. By applying the average values to the proposed UMAT subroutine programmed in the framework of FE ABAQUS software, the adhesive bond line is simulated. Figure 8 shows the details of the numerical simulation of DCB specimen. Comparison between numerical and experimental $P_T - \delta_n$ elucidated in figure 9, is revealing a good agreement.

Table 2. Cohesive parameters of the proposed CZM

| Specimen No. | $G_{lc}$ (N/mm) | $\sigma_c$ (MPa) | $u_c$ (mm) | $u_f$ (mm) | $K_I$ (N/mm$^3$) | $\alpha$ | $m$ | $\lambda_n$ |
|--------------|-----------------|-----------------|-----------|-----------|-----------------|--------|-----|-------------|
| 1            | 0.4024          | 21.35           | 0.007     | 0.0353    | 9991.1          | 2.5    | 0.1635 | 0.1983     |
| 2            | 0.3895          | 18.43           | 0.010     | 0.0368    | 7367.7          | 2.5    | 0.3396 | 0.2717     |
| 3            | 0.4025          | 21.87           | 0.007     | 0.0337    | 9770.5          | 2.5    | 0.2460 | 0.2374     |
| Average      | 0.3981          | 20.53           | 0.0083    | 0.0352    | 9043.1          | 2.5    | 0.2497 | 0.2358     |

Figure 6. the $G_1 - u$ responses  
Figure 7. $\sigma - u$ curves of DCB specimens  
Figure 8. Numerical simulation and boundary condition of DCB specimen
Fig. 9. Comparison between numerical and experimental $P_T - \delta_n$

4 Conclusion

This paper focuses on proposing a novel cohesive zone model to simulate ductile adhesives due to their plastic behaviour in mode I loading condition. Therefore, TSL is identified by an exponential hardening and a polynomial softening part. In order to validate the model, $P_T - \delta_n$ responses of DCB specimens are experimentally tested and numerically evaluated. In this regard, TSL of the joints is directly extracted and applied to the developed UMAT subroutine. Consequently, it is shown that there is a good agreement between the results.

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