Numerical simulation for compression failure of bi-material interface by using cohesive zone model

Li-Ya Liu*, Qing-Sheng Yang†

Department of Engineering Mechanics, Beijing University of Technology

Beijing 100124, PR China

*Presenting author: liuliya@emails.bjut.edu.cn

†Corresponding author: qsyang@bjut.edu.cn

Abstract

The interface plays an important role in the performance of the composite. The cohesive zone model is an effective method to simulate the initiation and propagation of the interfacial crack by properly selecting the parameters. In this paper, a bilinear cohesive zone model is used to simulate the fracture behavior of the interface of bi-material under compression loads. The three-dimensional cohesive element with eight nodes is employed. The load-displacement curves and the interfacial damage modes are obtained for different combinations of materials. The effect of the interfacial parameters on the failure process of the bi-material interface is discussed. The results demonstrate that the compression failure of the bi-material interface severely depends on the properties and geometrics of the two materials. It is also found that the ultimate failure load will increase for the enhanced cohesion strength of the interface.

Keywords: Bi-material interface, Compression failure, Cohesive zone model

Introduction

The metal laminates have broad promising applications in automobile, aerospace, national defense and so on. Their excellent mechanical properties are closely dependent to the interface condition. The basic failure mode of laminates by the low inter-laminar bonding strength is the separation between layers, namely delamination. The failure characteristics is different from those of the general materials [1]. However, the interface of composite material, which is a system formed in the environment of thermology, chemistry and mechanics, has a very complicated structure. The study of bi-material interface plays a vital role in a fundamental understanding of the composite property [2]. In the early 1990s, the corresponding theory and numerical methods for the interfacial performance have been developed. To date, its research is still in the stage of continuous enrichment and improvement.

In the past few years, several cohesive zone models (CZMs) have been proposed to characterize interaction between bi-material components generated by the cohesive forces [3]. Nevertheless, CZM is a phenomenological model rather than an exact physical representation of the failure process in the fracture zone, which belongs to the energy viewpoint [4]. Actually, CZM is an effective method to simulate the failure of bi-material interface by varying the values of cohesive strength and fracture energy of the interface [5]. Atkinson [6] [7] believed that the properties on the both sides of interface of different materials are not abrupt, but gradual, and defined that the interface of different materials is an interface region with a certain thickness, on which cracks are likely to generate and propagate. Chandra et al. [8] used two different forms of CZMs (exponential and bilinear) to evaluate the response of interfaces in titanium matrix composites reinforced by silicon carbide (SCS-6) fibers, and proposed that in addition to the primary parameters, the form of the traction–separation equations for CZMs plays a very critical role in determining the macroscopic mechanical response of the composite system. Hereafter, Kent [9] employed the trapezoidal CZM to analyze mixed mode failure behavior of a thin adhesive layer. Fiedler et al. [10] simulated the failure modes of unidirectional fiber reinforced composites under lateral loading by numerical simulation method. Zhang et al. [11] simulated the progressive debonding between circular inclusion in an infinite plate and matrix interface by using the surface-based cohesive method based on CZM in ABAQUS. However, there are limited studies on the compression failure behavior of bi-material interface now, especially the numerical simulation.

In this paper, the failure behavior of the interface of bi-material under compression was simulated by applying a cohesive finite element method. Then the influence of the interface parameters and geometry on the ultimate failure load of the bi-material laminates was investigated.

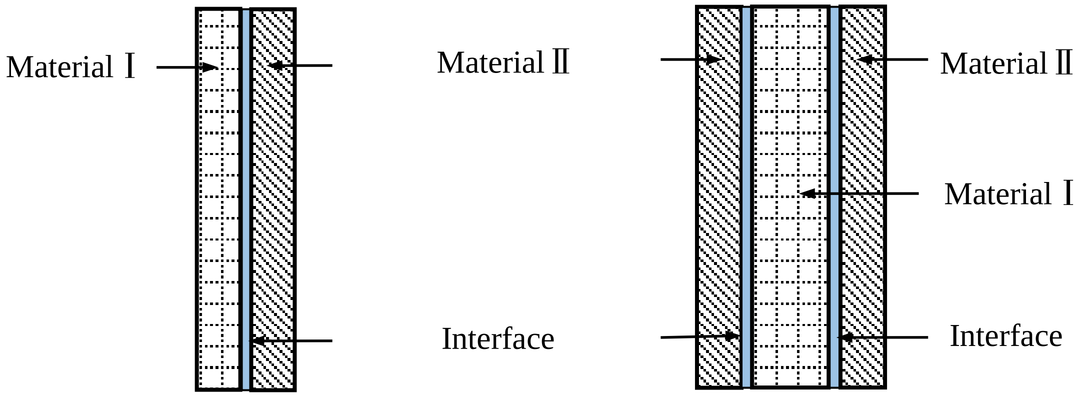
Cohesive finite element model of bi-metal laminates

CZM has been widely used in the simulation of interfacial failure behavior of laminates. In previous research, Hashagen et al. [12] [13] used an interface element based on plasticity theory to simulate delamination failure behavior of the laminates. Paul et al. [14] combined the cohesive interface element based on CZM with the fatigue damage rule to simulate the composite cantilever beam test.

There are different combinations of materials in this work. As shown in Fig. 1a, each of the two plates has a length of 30cm, a width of 10cm, and a thickness of 1cm. Material Ⅰ is hard aluminum alloy and material Ⅱ is rolled aluminum. Young's modulus of the hard aluminum alloy and the rolled aluminum were taken as 70GPa and 68GPa, respectively. The thickness of the hard aluminum alloy plate was gradually increased, and three models were established. The thickness ratios of the hard aluminum alloy plate and the rolled aluminum plate are 1:1, 1.1:1 and 1.2:1.

In another case, as illustrated in Fig.1b. The thickness of both sides of the laminate is 1cm respectively, and the thickness in the center is 2cm. The material of both sides of the laminate is material Ⅰ, the other is material Ⅱ. Other parameters are the same as those described in the previous paragraph. Similarly, the thickness of the hard aluminum alloy plate was gradually increased, and three models were established. The thickness ratios of the hard aluminum alloy plate and the rolled aluminum plate are 1:2, 1.1:1 and 1.3:1.

The static analysis of the interface of the metal laminates was carried out. In order to study the mechanical properties of bi-material interface in compression, the bottom of the plate was fixed, a normal strain was exerted on the top of the model, while the part of left and right sides were clamped along the thickness directions. In those cases, a three-dimensional cohesive element with eight nodes was employed for the interface and the details of the CZM will be given in Section 3.



(a) double-ply laminate **(b) three-ply laminate**

Figure 1. Model of the bi-metal laminates

CZM of bi-material laminates interface

The fracture behavior of bi-material laminates was characterized by using a bilinear cohesive law, in which the fracture energy G_c and the cohesive strength T_c are two pivotal parameters [15]. As shown in Fig.2, the cohesive constitutive model of ABAQUS is the bilinear model, where δ_0 denotes the interface damage and the maximum displacement δ_f denotes the interface failure. In order to observe the influence of geometry on the interfacial failure load of bi-material interface, we selected the proper parameters of CZM. In detail, the cohesive strength T_c = 45Pa, the fracture energy of the double-ply laminate G_c =1.5 J/m^2 and the fracture energy of the three-ply laminate G_c =1 J/m^2.

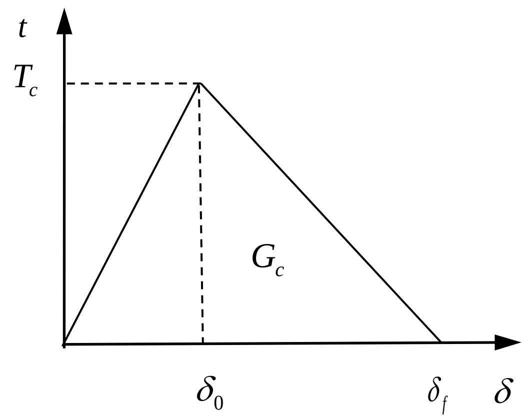


Figure 2. Constitutive relations of bilinear cohesive zone model

Results and discussion

The load-displacement curve of the bi-material interface can be divided into three stages according to the slope value, as shown in Fig.3. Obviously, the three stages of the curve correlating to the three deformation processes of the bi-metal laminates. The first stage is the linear compression stage, that is, the elastic deformation stage, which indicates that the interface has no damage. Afterward, the second stage is the nonlinear loading stage, which indicates the initiation and cumulation of the interface damage. Thereafter, there is a drop of the load-displacement curve in the third stage, which indicates the complete failure of the cohesive interface and the delamination of the laminates.

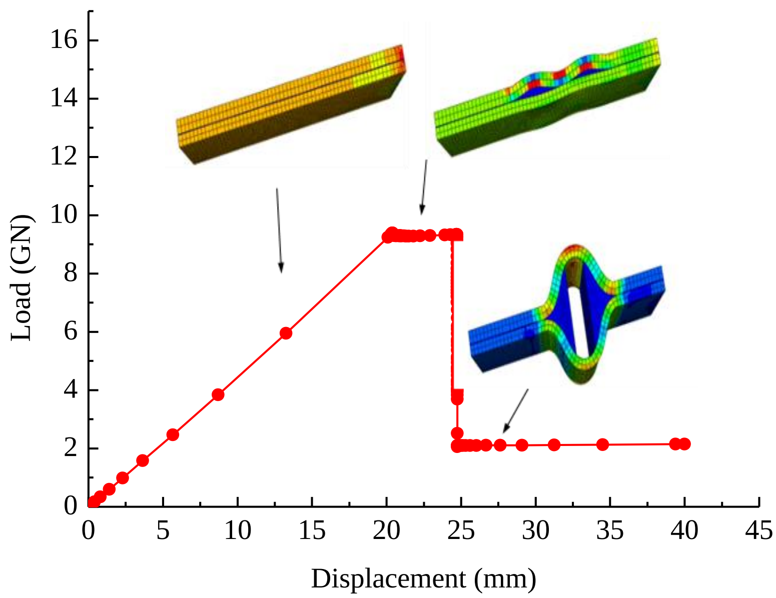


Figure 3. Interfacial debonding process of double-ply laminate

4.1 Effect of the thickness ratio

The prediction of the relationship between the interface bonding strength and the thickness of laminates has theoretical and practical significance for the effective utilization of composite laminates. As discussed in Section 2, the thickness of the aluminum alloy laminate was changed and the load-displacement curves at different thickness ratios were obtained, as shown in Fig.4and Fig.5.

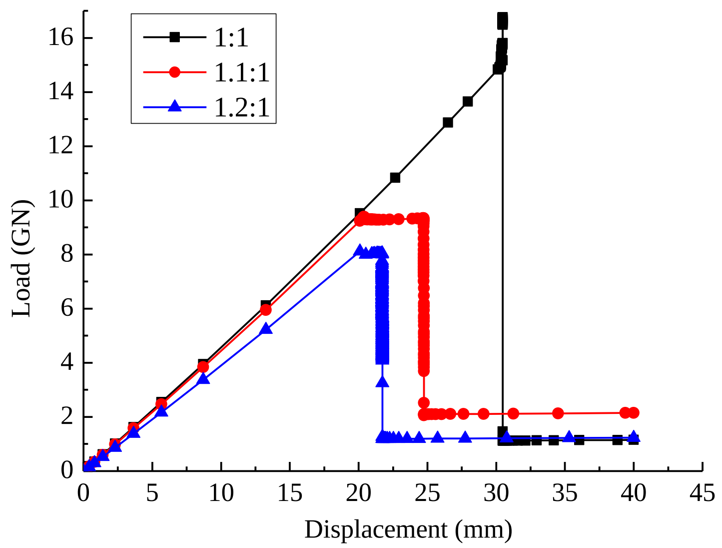


Figure 4. The load-displacement curves for various thickness ratio of double-ply laminate

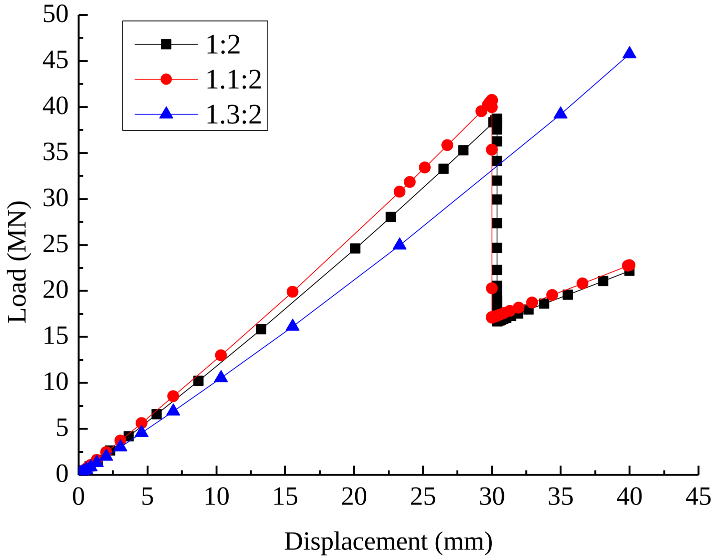


Figure 5. The load-displacement curves for various thickness ratio of three-ply laminate

The results (Fig.4) demonstrate that the ultimate load of the bi-material interface element of the double-ply laminate at critical failure decreases with the increase of thickness ratio. The bearing capacity of the bi-metal laminates is the strongest, when the thickness ratio is 1:1. By observing the linear stage of the curve, it is found that the bi-metal laminate at the thickness ratio of 1:1 is most difficult to bend.

On the contrary, as illustrated in Fig.5, the failure load of the bi-material interface element of the three-ply laminate increases by increasing the thickness ratio. Moreover, the laminate still has the bearing capacity after the failure of the interface. Besides, when the compression displacement is constant and the thickness ratio increases to a certain value, the bi-metal laminates is always in the linear compression stage. As shown in the blue line of Fig.5, the bi-material interface with a thickness ratio of 1.3:1 has no failure when the compression displacement is 4cm.

4.2 Effect of the interfacial parameters

In the practical engineering, the properties of the bi-material interface are closely related to the bonding of the laminates. Practically, the properties of the bi-material cohesive interface are controlled by two key parameters: the cohesive strength T_c and the fracture energy G_c.

In the above section, the typical load-displacement relation was obtained with the initial the double-ply laminate, whose thickness ratio is1:1. In order to study the influence of the two interface parameters on mechanical properties of the bi-material, the fracture energy stayed constant, and the cohesive strength is 55Pa, 45Pa, 35Pa respectively. By observing the load-displacement curves (Fig.6), it is noticed that the ultimate failure load increases with enhancing cohesion strength of the interface. Therefore, the mechanical properties of bi-material interface could be designed by properly increasing the cohesive strength.

In another case, keeping the cohesion strength of the interface unchanged, the value of fracture energy is 2 J/m^2, 1.5 J/m^2 and 1 J/m^2 respectively, and the corresponding load-displacement curves are obtained, as shown in Fig.7. It is found that the fracture energy has little influence on the ultimate failure load, but it also increases with the increase of the fracture energy.

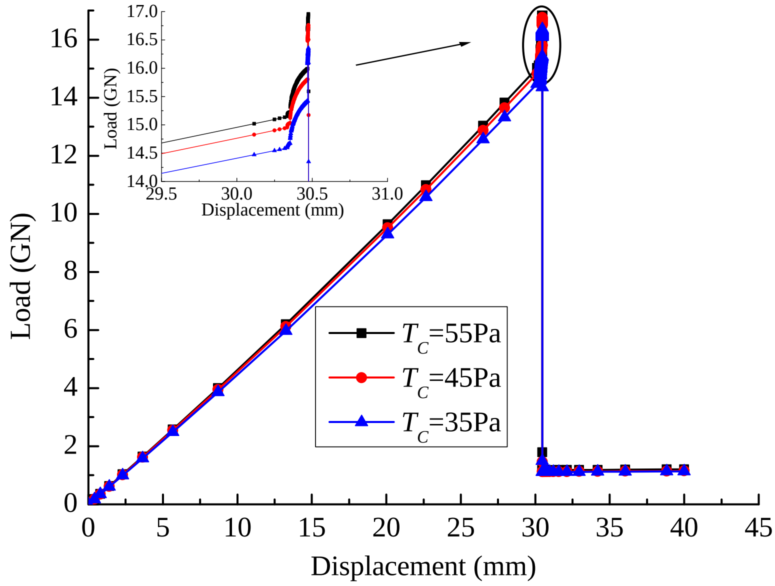


Figure 6. The load-displacement curves for various cohesive strengths

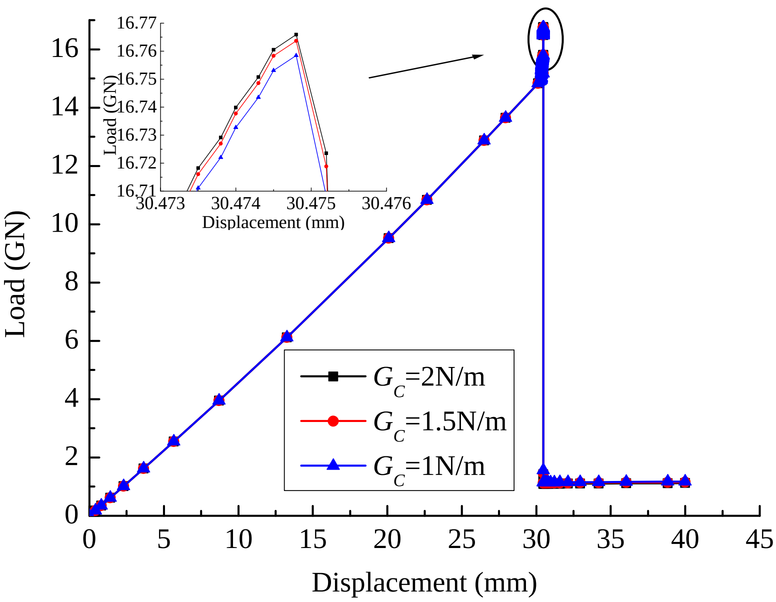


Figure 7. The load-displacement curves for various fracture energies

Conclusions

In this paper, a bilinear cohesive law was applied in cohesive finite element model to characterize the bi-material interface under compression loads. The load-displacement curves and the interfacial damage modes are obtained for different combinations of materials. The conclusions can be summarized as follows:

1. The ultimate load of the bi-material interface element of the double-ply laminate at critical failure decreases with the increase of thickness ratio. Moreover, it is found that the bi-metal laminate at the thickness ratio of 1:1 is most difficult to bend.
2. The failure load of the bi-material interface element of the three-ply laminate increases by increasing the thickness ratio. Besides, when the compression displacement is constant and the thickness ratio increases to a certain value, the bi-metal laminate is always in the linear compression stage.
3. The ultimate failure load increases with enhancing cohesion strength of the interface. Meanwhile, the fracture energy has little influence on the ultimate failure load.

Acknowledgments

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