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Finite element analysis of the influence of cohesive law parameters on the multiple delamination behaviors of composites under compression

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ABSTRACT

Interaction between the delamination and postbuckling of composite laminates under compressive load is an important issue. The evolving profile of nonlinear fracture process zone due to delamination crack propagation is largely affected by the geometrically nonlinear behavior of composites. Until now there is no unified cohesive zone model (CZM, or called cohesive law) that can represent all true fracture process zones during the delamination of composites under various loads and environments. The purpose of this paper is to study the influence of cohesive law parameters on the postbuckling and delamination behaviors of composites under compression by 3D finite element analysis (FEA). An improved Xu and Needleman's CZM and a bilinear CZM are used to study multiple delamination growth comparatively. Taking the composite flat laminates with initial through-the-width multiple delaminations as example, the effects of cohesive shape, cohesive strength and cohesive element thickness on the delamination behavior are studied. The proposed model is validated by using experimental data and its robustness and computational efficiency are highlighted by comparing with different CZMs. It is found that the fracture process zone is largely affected by the geometrically nonlinear deformation at the unstable delamination stage between the initial buckling and global buckling.

1. Introduction

Carbon fiber reinforced composites have been increasingly used in the fields of aerospace and aircraft due to high strength/stiffness-to-weight ratios. Yet, complicated failure mechanisms of laminated composites pose a large challenge to the design and application of composites [1,2]. In particular, delamination is commonly considered as an important failure mode affecting the stiffness and strength of composite structures largely. Furthermore, when composites are applied to stiffen panels of airplane structures, they often meet compressive loads [3], under which complicated interactions between buckling, postbuckling and delamination growth occur. It is important to propose robust numerical methods to predict the buckling and postbuckling behaviors as well as the delamination mechanisms of composites.

In recent decades, a lot of research has been devoted to the delamination and postbuckling behaviors of composite laminates. Chai et al. [4,5] established 1D and 2D delamination buckling models to evaluate the energy release rate for delamination crack growth. Kardomateas and Schmueser [6], Kutlu and Chang [7] and Whitcomb [8] studied the effect of delamination growth on the stability of composite laminates by proposing 2D and 3D analytical models. Suemasu [9] studied the effects of through-width equal size, equally-spaced multiple delaminations on the compressive behaviors of composite panels. Bolotin [10] explored the delamination buckling mechanism by considering the interactions between local buckling, damage accumulation, delamination crack growth and global buckling. For the through-the-width multiple delaminations, Hu [11], Hwang and Liu [12], Cappello and Tumino [13], Karihaloo and Stang [14], Suemasu et al. [15] and Guo et al. [16] studied the effect of nonlinear deformation on the buckling and postbuckling behaviors. Furthermore, Han et al. [17] studied the postbuckling behavior of composite laminates by considering the combination of different load types. Kim and Kedward [18] derived analytical solutions for the buckling initiation and delamination of composite plate and divided the

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unstability modes into two categories: local buckling for sub-laminates and global buckling for the whole structure. Local buckling appears for some sub-laminate which imposes additional bending stresses on neighboring sub-laminates, followed by the irreversible unstable delamination and the final global buckling of structures.

Buckling and postbuckling behaviors of composites are accompanied by the degradation of stiffness and strength due to delamination [19]. Accurate prediction of the delamination initiation and growth gains insight into the understanding of the interaction between buckling and delamination. Currently, finite element analysis (FEA) has become a powerful tool to study the stability and delamination problems of composite laminates including different delamination shapes, sizes and load types. Combined with FEA, some advanced numerical techniques including the cohesive theory and virtual crack closure technique (VCCT) are developed rapidly for the prediction of delamination [20]. The VCCT was first proposed by Rybicki and Kanninen [21] based on Irwin's crack-tip energy analysis [22] and its maximum advantage is to calculate the energy release rate (ERR) for crack propagation. The basic thought of VCCT is that the energy required for the crack propagation length Δa is equal to that for closing two separated crack surfaces with crack length Δa, without the need to consider the crack-tip singularity. Krueger [23] made a comprehensive review on the VCCT focusing on the finite element implementation and numerical robustness. Later, Xie and Biggers [24], Leski [25], Orifici et al. [26], Pietropaoli and Riccio [27] and Liu et al. [28–30] used the VCCT to study the delamination or interface crack propagation. Unfortunately, the VCCT cannot predict crack initiation although it can be competent for crack propagation because it was developed within the framework of linear elastic fracture mechanics (LEFM). Cox and Yang [20] pointed out that the critical conceptual limitation of LEFM is representing all the material nonlinearity during crack propagation as a point process, which is not consistent with true finite-size nonlinear process zone where the crack-tip nonlinear phenomena are active.

For ductile delamination failure of composite laminates, the plastic deformation zone is generally not neglectable compared with the sizes of structure. The cohesive theory in the framework of the elastoplastic fracture mechanics was first introduced by Dugdale [31] and Barenblatt [32] to describe discrete fracture as the material separation across the interface, where the progressive degradation of strength and the irreversible energy dissipation occur within the fracture process zone, as shown in Fig. 1. As a projection of the continuous model on the discontinuous interface, the CZM assumes that the failure of the interface is governed by the relationship between the traction and displacement jump (or called separation). Compared with VCCT, the cohesive theory can predict crack initiation and propagation efficiently.

Currently, there are already a lot of CZMs in terms of the shape of traction–displacement jump curves. Unfortunately, there is still no conclusion on what kind of CZM the true interface is subjected to, although various CZMs are increasingly used to model the interface separation. Thus, an important issue emerges on how the shape and strength of CZM govern the progressive failure of the interface. Rots [33] showed that the shape of the strain-softening branch of the constitutive model is an important input parameter which has significant influence. Volokh [34] compared the bilinear, parabolic, sinusoidal and exponential CZMs in simulating a rigid block-peel test and showed the shape of CZMs has significant influence on the numerical results. Chandra et al. [35] made a comprehensive review on a series of issues on the CZMs and pointed out the shape of interface models has big influence on the load responses of composites. Alfano [36] compared the effects of the bilinear, linear-parabolic, exponential and trapezoidal cohesive law shapes on the load-responses of mode-I double cantilever beam. His conclusion was that whether or not the shape of the softening curve is an important parameter may depend on the boundary value problem, in particular on the ratio between the interface toughness and the stiffness of the bulk material. Song et al. [37] showed the influence of cohesive softening shape becomes significant as the relative size of fracture process zone compared to the structure size increases for quasi-brittle materials, while the cohesive parameters including material strength and cohesive fracture energy are considered more important than the cohesive softening shape. Turon et al. [38] and Harper et al. [39] used the bilinear CZM, Goyal et al. [40] and Liu et al. [41] used the exponential CZM to study the effect of cohesive strength on the mixed-mode delamination of composite laminates in terms of the double cantilever beam (DCB), the end-notched flexure (ENF) test and mixed-mode bending (MMB) specimens. Freed and Banks-Sills [42] studied the effect of cohesive strength on the load responses of composites by using the polynomial CZM proposed by Needleman [43]. The general conclusion is that the cohesive strength affects the softening part of the load–displacement curve represented by the unstable delamination behavior to a large extent. Campilho et al. [44] also showed that the composite joint with ductile adhesive is highly affected by different cohesive shapes including the triangular, exponential and trapezoidal shapes.

As a particular delamination case of composite laminates under compression, complicated interactions between the postbuckling and delamination affect the stiffness, stability and strength largely. For the stability and delamination problems, the evolving profile of true ductile/brittle fracture process zone is interrupted by the geometrically nonlinear deformation of structures. From the mathematical point of view, some cohesive laws in front of the crack tip governing the interface failure were measured well by experiments [45–47] provided that these CZMs with different shapes were superimposed representing the profile of the true physical process zone. However, it may be a more challenging task for measuring mixed-mode CZMs for the delamination growth under compression. Thus, a favorable and important work is to model the delamination growth under the interruption of stability factors by evaluating the effects of different CZMs including the cohesive shape and strength on the load responses of composites. Recently, Alfano et al. [48,49] demonstrated by global sensitivity analysis that few cohesive law parameters including the cohesive shape, fracture energy and cohesive strength are important under beam loading. However, it is not clear about the effects of cohesive law parameters for the compressive case because the delamination problems for composites under compression using 3D CZMs are almost not studied.

In this paper, we use an improved Xu and Needleman's exponential CZM [50] proposed by van den Bosch et al. [51] and McGarry et al. [52] and the bilinear CZMs proposed by Camanho et al. [53] and Turon et al. [54] to predict the delamination behavior of composites. The novelty of this paper is to study the effects of

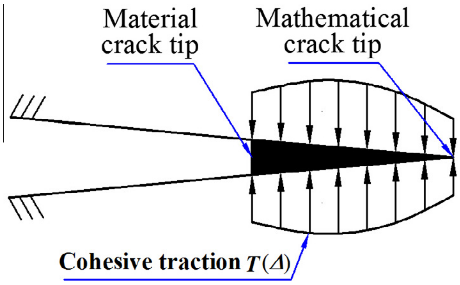

Fig. 1. Fracture process zone in the framework of elastoplastic fracture mechanics.