A NUMERICAL AND EXPERIMENTAL INVESTIGATION ON DELAMINATION BUCKLING BEHAVIOR IN LAMINATED COMPOSITES UNDER COMPRESSIVE LOAD

R. G. Wang[1]*, L. Zhang[1], W. B. Liu[2], F. Yang[1], C. Q. Dai[3], X. D. He[1]
[1] Center for Composite Materials and Structures, Harbin Institute of Technology, Harbin, China,
[2] School of Materials Science and Engineering, Harbin Institute of Technology, Harbin, China,
[3] Network & Information Center, Harbin Institute of Technology, Harbin, China
* Corresponding author (wrg@hit.edu.cn)

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1 Introduction

Delamination in laminated composites is one type of failure that has long been the centre of materials research. The failure is known due to separation at an interphase region, caused by manufacturing defects, object impacts, or high stress concentrations from geometrical discontinuity. Its occurrence can result in significant loss in the structural stiffness, especially under compressive load, and is dangerous because it often occurs inside the components, thus difficult to detect from the surface until catastrophic failure is imminent [1]. Along with the increasing use of advanced composites in structural applications, delamination problems have been of considerable interest and concerns recently.

Finite element analysis (FEA) is often employed for predicting failure in laminated composites. In recent years, cohesive element method has been widely used because it combines both of the stress-based methods [2] and fracture mechanics methods [3] and overcomes their deficiencies. Both delamination initiation and delamination growth can be predicted by zero-thickness volumetric interface elements. Although the delaminations have been investigated both numerically and experimentally and possible analytical models have been developed [4, 5], the systematical analysis based on the cohesive element method is seldom investigated in delaminated composite laminates.

The objective of this paper is to systematically investigate the factors of delamination behavior with both experimental method and cohesive element method which is based on a mixed-mode failure criterion and adopts softening relationships between tractions and separations. The numerical results are obtained by standard ABAQUS procedures.

2 Experimental Work

2.1 Specimen Preparation and Manufacturing

The unidirectional laminated composite panels with embedded through-the-width delamination were manufactured from T700 carbon fiber and epoxy resin containing 20 plies with 0.12 mm thickness of single ply. Teflon films of 0.001 mm thickness were introduced between the 2nd and the 3rd plies in order to form a macro defect.

The ratio of the slender panel dimension is W/L=0.25 (which is recommended [5]), where W and L respectively present the width and the length of the slender panel. A schematic representation of the slender panel geometry is given in Fig. 1, in which point U and L represent the center points of top and bottom surface respectively. Only one quarter of the structure (depicted in Fig. 1 A, B, C, D) has been considered because geometry, boundary condition and applied loads are all symmetric with respect to the x and y axes.

The mechanical properties of the composite material were obtained from standard tests, which are listed in Table 1. The ply material properties and the interlaminar properties are shown in Table 1.

2.2 Specimen Preparation and Manufacturing

Delamination buckling tests are done in compression mode on the Instron 5569 Testing Machine of 50 kN load capacity at a ratio of 0.1 mm/min. For axial loading, the test specimens are placed between the two extremely stiff machine heads, of xhich the lower one is fixed druting the test, whereas the upper

head is moved downwards. Fig. 2 shows the experimental set up for the buckling tests for the plates with two opposite sides clamped and the other two free. The buckling tests are carried out under displacement control and the out plane displacement are obtained by dial indicator placed right on the U and L Point. Seven identical specimens under the same design are tested to get an average buckling load. During the tests, all specimens are loaded uniaxially until the local buckling mode and global buckling mode is reached.

3 Finite Element Method

The zero thickness cohesive elements have their own constitutive equation which is used to relate the stress τ to the relative displacement λ at the interface which can be demonstrated by strain softening models as shown in Fig. 3 for pure mode I loading [4]. After the interfacial normal stress attains its interlaminar tensile strength τ^0 (Point 2 in Fig. 3), the stiffness is gradually reduced to zero (Point 4 in Fig. 3). The constitutive response can be implemented by Eq.1., Where D represents the damage accumulated at the interface, which is zero initially, and gradually reaches 1 when the material is fully damaged.

$$\tau = (1 - D)K\lambda \qquad (1)$$

Under mixed-mode loading, delamination initiation and propagation are predicted using quadratic failure criterions [6] and quadratic interaction between energy release rates [7] separately.

The slender panel has been modeled using 8-nodes 3D layered solid elements. Simultaneously, the interface between two sub-laminates has been modeled by 8-nodes 3D cohesive elements. Surface-to-surface contact element has been placed in the delamination zone to avoid overlaps between elements. The nonlinear solution of the problems presented here is performed using standard ABAQUS procedures**.**

4 Results and Discussion

4.1 Model Validation

Numerical analyses have been performed in order to validate the cohesive element model. Fig. 4 shows the Load-Displacement curve both from FEM and experiment results. The specimen experiences maily two buckling stages: local buckling and global buckling. Although the result from cohesive element method is 316 N lower for local buckling load, and 609 N higher than the experimental result for global buckling load respectively, the numerical result is very similar to the experimental result for both two buckling states, which proves the validation of the cohesive element model.

4.2 Effect of delamination size

In order to expatiate on the delamination size factor, we investigate composite laminates with different delamination sizes 10mm, 15mm, 20mm and 25 mm, respectively under the condition of 1/10 delamination depth position. The stacking sequence of the laminate is $[45º/0º/-45º/0º/45º/0º/-45º/0º/45º/0º]_{2S}$. The whole geometrical model is chosen because the stacking sequence is not symmetric with either x or y axes, as shown in Fig. 1.(a). When the embedded delamination size is not more than 10 mm, the delamination doesn't propagate after local buckling occurs. Except for the composite with 10 mm delamination for which only local buckling occurs, the critical loads of local buckling and delamination growth are all decreased as the delamination size increases from 15 to 25 mm as shown in Fig. 5. It is easy to understand that the extremely large delamination size results in a decrease in the plate resistance against the buckling behavior.

4.3 Effect of delamination depth position

As shown in Fig.6., laminated composites with different delamination depth positions are investigated under the condition of different delamination sizes ranged from 10 mm to 25 mm. The stacking sequence of the laminate is $[45º/0º/-45º/0º/45º/0º/-45º/0º/45º/0º]_{2S}$. It is easy to notice that the buckling mode is influenced by the depth positions of delaminations remarkably. As for 10 mm delamination, no delamination growth occurs no matter what delamination depth position is. When delamination size reaches 15 mm, the delamination propagates only when the delamination is placed at 1/10 depth position. As for 20 mm and 25 mm delaminations, the delaminations placed at 1/10 to 3/10 depth positions propagate. At the same time, the critical load of delamination growth increases with the depth position. Further more, when the delaminations are placed at 0.4 depth position, only global buckling occurs. On all accounts, the delamination depth position plays a predominant

role in determining the delamination buckling behavior, and the composite plate with shallow delamination has extremely low structure stabilization.

5 Conclusions

The cohesive element method has been proved to investigate delamination buckling behavior successfully by the validation of experimental results. The laminated composite panel with embedded delamination experiences two main buckling mode: local buckling and global buckling. The key factors of delamination buckling behavior are investigated numerically concluding delamination size and delamination depth position. As delamination size increases, the buckling mode changes from directly global buckling to local buckling. The laminated plate has high stability when the delamination size is smaller than 10 mm. Otherwise, as the delamination depth position increases, the buckling mode becomes to directly global buckling. The laminated plate with shallow delamination has extremely low structure stabilization.

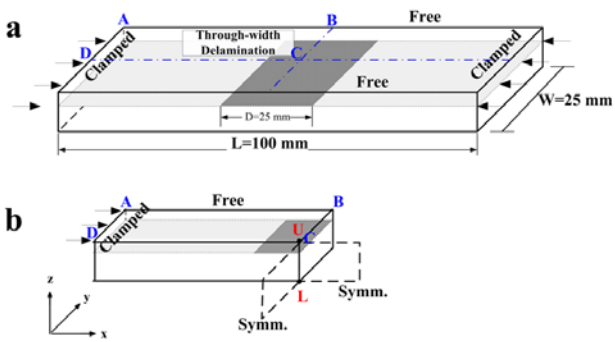

Fig.1. Slender panel geometry, boundary condition and applied load.
(a) For the whole structure. (b) For one quarter structure.

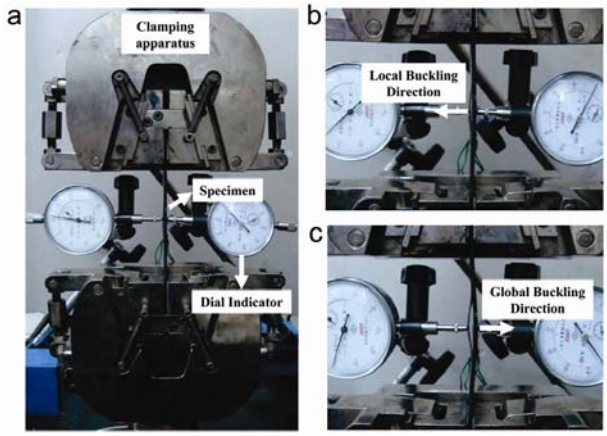

Fig.2. (a) Mechanical test equipment. (b) Local buckling mode. (c) Global buckling mode.

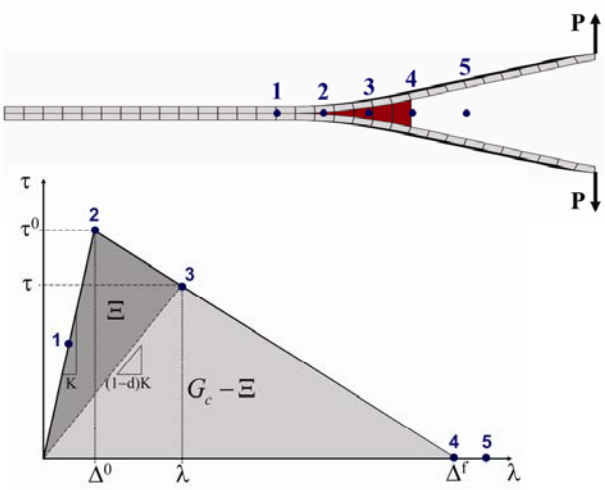

Fig.3. Cohesive law for single mode loading with bilinear constitutive model [5]

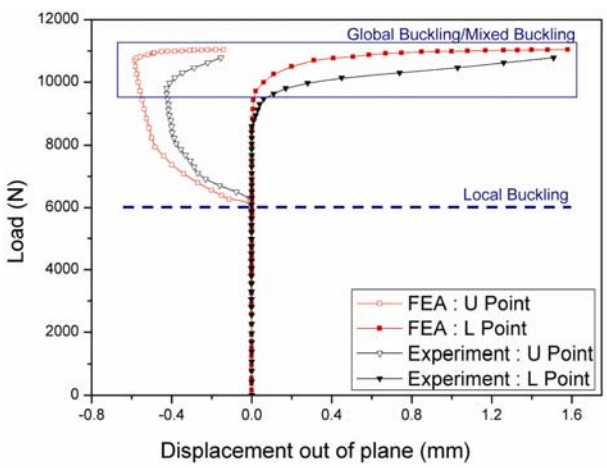

Fig.4. Comparison between numerical and experimental load-displacement curves.

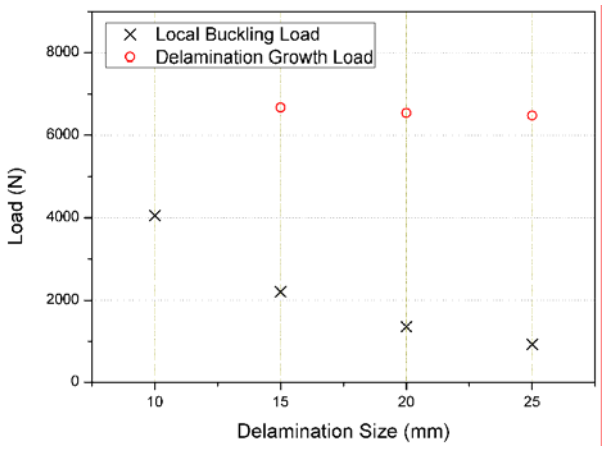

Fig.5. Variation of the critical loads of local buckling and delamination growth as function of delamination size for 1/10 delamination depth position

Table 1
Material properties

Mechanical magnitudes		Properties
Longitudinal Young's modulus	E_{11}	138 (Gpa)
Transverse Young's modulus	$E_{22}=E_{33}$	10.16 (Gpa)
Shear modulus	$G_{12}=G_{13}$	5.86 (Gpa)
	G_{23}	4.79 (Gpa)
Poisson's ratio	$\nu_{12}=\nu_{13}$	0.28
	ν_{23}	0.3
Penalty stiffness	K_P	3 (Gpa)
Interlaminar tensile strength	T	5.71 (Mpa)
Interlaminar shear strength	S	39.91 (Mpa)
Fracture toughness	G_{IC}	0.092 (N/mm)
	$G_{IIC}=G_{IIIC}$	0.269 (N/mm)

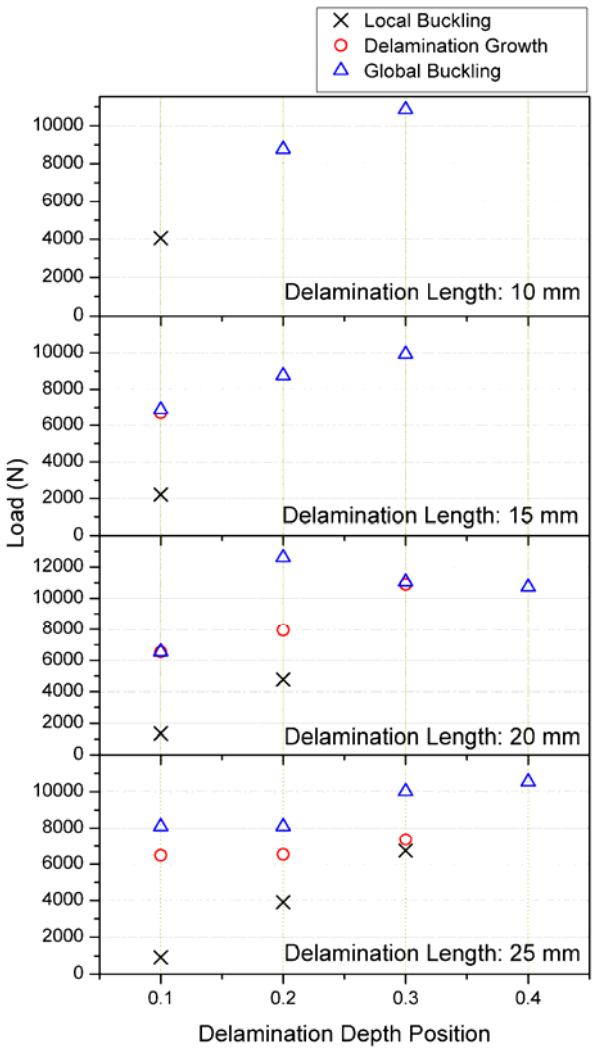

Fig.6. Variation of the critical loads of local buckling, delamination growth and global buckling as function of delamination depth position for different delamination sizes.

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