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Compressive failure analysis for low length-width ratio composite laminates with embedded delamination

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ABSTRACT

For low length-width ratio composite laminates with embedded delamination under compressive loading, different failure modes occur and interact tightly, which catastrophically decrease the load carrying capacity of the laminates. In order to systematically investigate the compressive behaviour of these laminates, a thorough progressive failure model taking into account the interaction among intralaminar failure, interlaminar failure and buckling failure was established. In this model, the intralaminar failure was evaluated with the progressive damage method (PDM), and the interlaminar delamination growth was simulated with the virtual crack closure technique (VCCT). Compression tests of low length-width ratio composite laminates with different embedded circular delaminations were conducted. Good agreements between numerical predictions and experimental results, including failure loads, load-central deflection curves and shapes of delamination growth, were obtained. It follows that under compressive loading, low length-width ratio laminates with small embedded delamination fail due to the buckling and intralaminar failure, while more severe laminate failure is induced by the buckling, intralaminar failure and additional delamination growth for low length-width ratio laminates with large embedded delamination.

1. Introduction

Delamination has become one of the most serious failure modes in laminated composites. Especially for composite laminates under compressive loading, the delamination grows coupling with intralaminar failure and buckling of sub-laminates, which dramatically decreases the load carrying capacity of the laminates. Due to the weakness of interlaminar performance, initial delamination easily occurs during the manufacturing and practical service of composite laminates. To deeply explore the mechanical potential of composite laminates, investigation on compressive behaviour of composite laminates with initial delamination is necessary.

Up to now, most researches have concentrated on the compressive behavior of slender rectangular composite laminates with initial delaminations [1–11]. Mohammadi and Shahabi [1] investigated the post-buckling behaviour of slender composite laminates with through-width delaminations. They showed that delamination growth can easily occur in slender composite laminates even for the laminates with small delaminations. Liu et al. [2,3] studied delamination growth of slender composite laminates with through-width delaminations, and concluded that delamination growth largely decreases the global buckling load of composite laminate. However, only a few researches have concentrated on low length-width ratio composite laminates with initial delaminations [12–14]. Fu and Zhang [12] employed a finite element model taking into account delamination growth and the buckling to explore the compressive behaviour of low length-width ratio composite laminates with embedded delamination. They showed that compressive strength of the laminate is highly influenced by the initial delamination size. Tay [15] indicated that the occurrence of delamination growth in low length-width ratio laminates depends on the material fracture toughness and the initial delamination size. In addition, failure analysis of low length-width ratio laminates with through-width delaminations is essentially one-dimensional in behaviour because delamination can only extend in the length direction [16]. In contrast, failure analysis of low length-width ratio laminates with embedded delamination is a complex three-dimensional problem, in which different three-dimensional failure modes closely interact and lead to destructive damage. Therefore, more attention should be focused on the compressive failure of low length-width ratio composite laminates with embedded delamination.

Nowadays, advanced numerical methods are adopted to predict delamination growth in composite laminates. Liu et al. [2,3] used the

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virtual crack closure technique (VCCT) and cohesive zone modeling (CZM) respectively to examine delamination growth of slender composite laminates with through-width delaminations. Both methods were validated to be effective to describe the delamination growth in the composite laminates. Nikrad et al. [4] utilized the CZM to predict delamination propagation in slender composite laminates with off-center delaminations under compression. With CZM, Xiao et al. [17] simulated the delamination progressive propagation process in slender laminated composite with open hole under tensile loading. Generally, the VCCT is not sensitive to mesh sizes and thus requires less computational cost. It requires to pre-set an initial defect or crack in composite laminates. In contrast, the CZM doesn't demand any initial defect or crack, but it is strict with the mesh size and requires more computational cost [18].

To explore the compressive behaviour of low length-width ratio composite laminates with embedded delamination, compressive tests of the laminates with different embedded circular delaminations were carried out, which also provided the data for validating the numerical model. A thorough progressive failure model taking into account the interaction of different failure mechanisms was established and validated. According to the compressive failure characteristics of the laminates with embedded delamination, the intralaminar failure in the laminates was evaluated by the progressive damage method (PDM) and the interlaminar delamination growth was revealed with the VCCT. Based on the experimental outcomes and the numerical results, the significant effects of delamination diameter on the compressive behavior, especially on the compressive failure mechanisms of low length-width ratio composite laminates with embedded delamination, were disclosed.

2. Compressive tests for composite laminates

The compressive tests were carried out according to ASTM D7137/D7137M-07. Three types of composite laminates with different embedded delaminations were designed. For each type of the laminate, three specimens were tested. All specimens were made of T300/QY8911 carbon-fiber bismaleimide prepreg with a lay-up of $[(45/0/\text{-}45/90)_3/45/0//\text{-}45/90/(90/\text{-}45/0/45)_4]$, where the symbol '//' denotes the position of artificially induced circular delamination. And a PTFE film was laid between plies to form the delamination [19]. Table 1 lists the mechanical properties of composite materials obtained from the manufacturer. Geometry dimensions of specimens are illustrated in Fig. 1, in which the length l = 150 mm, width b = 100 mm and thickness h = 4 mm. The embedded delamination diameters are $\Phi_1 = 20$ mm, $\Phi_2 = 30$ mm and $\Phi_3 = 50$ mm respectively.

The compression tests were conducted in a compression testing machine, INSTRON 8803, equipped with a 250 kN load cell. They were carried out in a displacement control mode, at a crosshead speed of 1.25 mm/min. Specimens were supported by a fixture manufactured according to ASTM 7137/D 7137M-07. Four strain gauges were stuck to specimens to ensure the application of pure compressive loading, and their positions are shown in Fig. 1, in which c = 25 mm. Out-of-plane

Table 1
Material properties of T300/QY8911 composite.

Mechanical magnitudes	Properties	Mechanical magnitudes	Properties
E_{11} (GPa)	131	X_T (MPa)	1239
E_{22} (GPa)	9.64	X_C (MPa)	1081
E_{33} (GPa)	9.64	Y_T (MPa)	39
ν_{12}	0.3	Y_C (MPa)	189
ν_{13}	0.3	Z_T (MPa)	39
ν_{23}	0.3	Z_C (MPa)	189
G_{12} (GPa)	4.84	S_{12} (MPa)	81
G_{13} (GPa)	4.84	S_{13} (MPa)	81
G_{23} (GPa)	3.2	S_{23} (MPa)	81
G_{IC} (J/m^2)	252	G_{IIC} (J/m^2)	665
G_{IIIC} (J/m^2)	665		

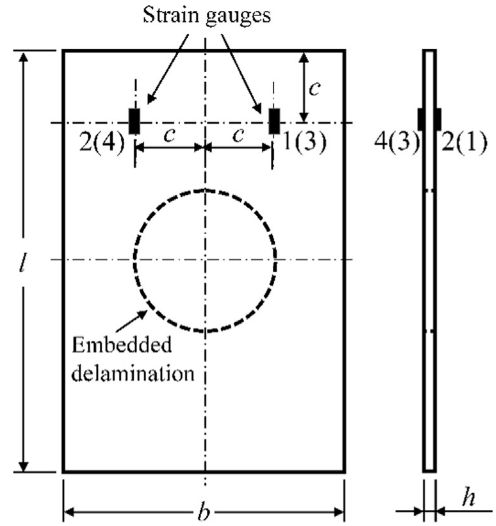

Fig. 1. Geometry of a specimen with circular delamination.


Fig. 2. Experimental devices.

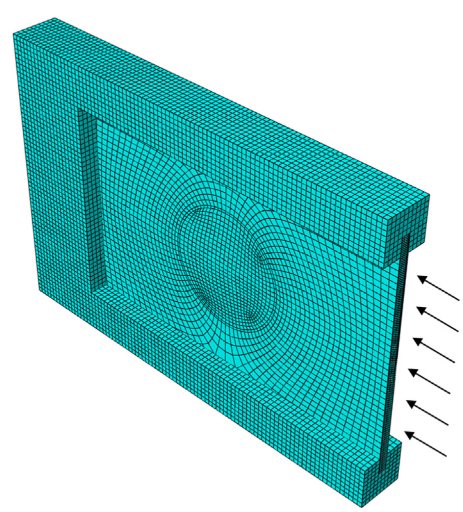
Fig. 3. Finite element model.