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Study on the delamination behavior of thick composite laminates under low-energy impact

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ABSTRACT

In order to study the delamination of thick composite laminates under low-energy impact, damage prediction and analysis were presented in this paper. The impact tests were carried out on specimens with three kinds of stacking sequence under three energy levels, and followed by the nondestructive tests to obtain the delamination region. Then numerical models were built to simulate the delamination behavior of composite laminates. The simulation results showed a good correlation to the experimental observations. Furthermore, delamination characteristics in plane and its extension through thickness direction were put forward. The delamination shape was found enclosed by Archimedes spiral and the fiber direction of the layer above and below. The delamination location was limited by the impact zone and the fiber distribution. In the thickness direction, the extension area was found decreased layer by layer. Moreover, the characteristics above were revealed through the analysis of damage mechanism. Finally, the verification of the predicted results was presented based on experiments. The realization of delamination prediction may contribute to evaluating residual strength and optimizing airplane structures.

1. Introduction

Carbon fiber reinforced composite laminate structure has been widely used for its high strength and designability. However, when it is subjected to low-energy impact, delamination appears within the structure mainly [1], and this invisible damage will significantly reduce the residual strength of laminates. Since analysis and optimization of composite laminate structures are important in many industries, it is necessary to find a way to predict delamination within composite structures.

A number of studies were carried out on the delamination behavior of composite laminates. Caprino [2] tested CFRP composite laminates under different impact energy levels. It was found that damage could be ignored when the energy fell to a set value. Similarly, this value was verified as the threshold level by Reed [3], Sjoblom [4] and Olsson [5]. Olsson [6] also made conclusion that the critical load for delamination growth is insensitive to geometry and boundary conditions. Schoeppner [7] investigated the delamination threshold load and found that the damage of laminate level occurs as a sudden load drop due to stiffness loss of the specimen. Hong [8] proposed a linear relationship holds between delamination area and impact energy, and found that the mismatch of bending stiffness between adjacent laminate can be correlated with the delamination area on the interface. Lopes [9,10] considered the dispersed stacking sequence of laminates to study the effect of mismatch angle between plies on delamination. Pavier [11] described a technique for replicating impact damage artificially by including PTFE film delamination. Composite laminates with various in-plane thicknesses [12] and dimensions [12–14] have been examined to study the size effects on delamination, respectively.

The study on delamination caused by impact is established and can be divided into two parts in method: experimental study and numerical study. When it comes to experiment, drop weight tests and non-destructive inspection (NDI) techniques are in common use to implement low-energy impact and damage detection respectively. As the essential part of experimental study, many kinds of NDI methods have been used in delamination analysis, which include ultrasonic wave, radial, acoustic emission, etc. Ultrasonic is easy to penetrate object, and it is also good at positioning. Another widely used method is X-ray. For the CT image can effectively determinate the delamination existing, X-ray Computed Tomography (CT) detecting technique is used in damage inspection. Besides, infrared detecting technology is employed to detect damage in carbon fiber resin matrix composite, and it is found that the detection rate of this method has been improved. In addition, laser is also suitable for the detection of damage within the composite. As a

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typical laser detection, the digital shearography have been widely used in detection on site [15].

Though experimental method is a direct way, there are also many weaknesses. For example, delamination obtained from NDI is affected by shading each other. Therefore, in most cases, delamination is shown in the form of superimposing for it is hard to distinguish the delamination of an interface from another. Besides, experiments consume lots of time, work force, material resources, and it is easy influenced by uncertainty factors. For the reasons, the development and application of numerical method is promoted.

In numerical aspect, damage model is the basis and key for studying impact damage of composite laminates. Collombet [16–18] used maximum threshold stress to judge whether the matrix was damaged. Since the damage caused by impact is resulted from many factors and their interaction, this model was considered too simple. Instead of one-parameter model, more scholars have developed it into a variety of polynomial functions. In the studies of Moura [19], Farooq [20] and Batra [21], Hashin criterion provided was used to predict the impact damage in composite laminates. Meo [22] divided the damage modes into fiber failure, matrix cracking and matrix crushing, so it can be used to predict intra-laminar damage. Hou [23,24] added delamination as another damage mode in order to consider inter-laminar damage. There are also many other failure criteria for delamination prediction. As the similarity of the damage extended process to the fracture process of cracks, these criteria were expressed in an energy way instead of stress or strain. Lammerant [25] proposed a spring-element model in the interface, and delamination was defined as the failure of spring-elements, which is controlled by the strain energy. In the study of Li [26,27], strain-energy-release rate was used in the damage extension criterion. When the rate reached the threshold level, delamination extended along the direction that the rate was in the largest value. In addition, cohesive elements have been widely used in the analysis of damage extension process in the interface. Zou [28] introduced a layer of cohesive elements to connect two adjacent surfaces, so delamination can be simulated by controlling the cohesive elements.

So far, researchers have carried out much work to study the factors that affect the delamination behavior: Clark [29] proposed that the primary factors controlling damage in the model are the orientation and sequence of the two plies making up the interface; second-nearest neighbor effects appear to be minor. Choi [30] investigated the generation and propagation of matrix cracking and delamination, and revealed the relationship of the two kinds of damage. Hitchen [31] presented that the delamination shape was influenced by splitting and fiber fracture in the ply below the delamination. Moura [19] carried out impact tests on carbon/epoxy composite laminates, and made the following conclusions: delamination only happened between the adjacent layers with mismatch angles; the distribution of delamination was along the fiber direction of the layer below with a shape of double leaf. Long [32] tested two kinds of thin laminates under different impact energy. Based on the results, delamination shape was predicted for two adjacent layers with different ply angles.

It can be found that many studies have been carried out on delamination behavior. Most studies have proposed new numerical models based on certain damage models, and then predicted delamination by simulation indirectly. However, few of them have proposed a method to predict delamination, or revealed factors that affect delamination. The prediction of delamination shape proposed by Long [32] was very interesting, it focused on the shape of delamination area in each interlayer of a laminate, but only the relationship of stacking sequence and delamination was summarized. Therefore, this paper will continue to establish prediction method for delamination distribution in each interlayer. When delamination of the interfaces considered can be obtained effectively in prediction, the design of stacking sequence will be promoted.

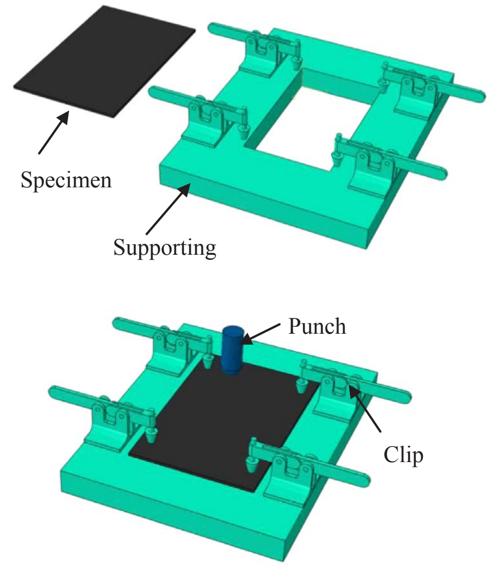

Fig. 1. Specimen and fixture.

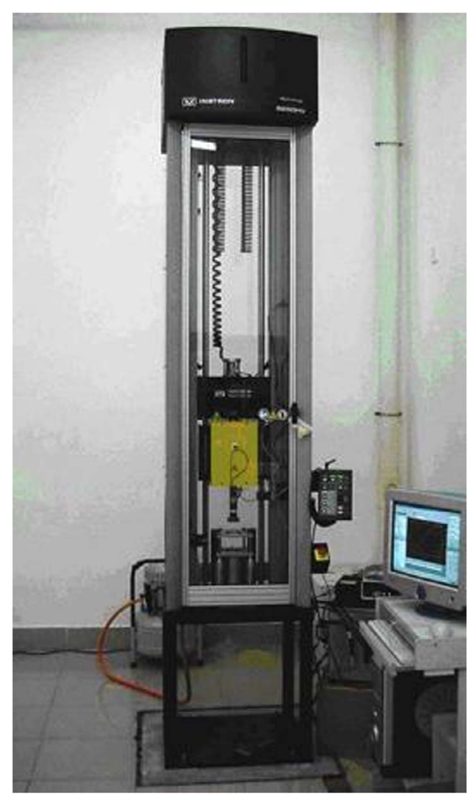

Fig. 2. Drop-weight machine.

In this paper, drop weight tests were carried out to 5 mm thick carbon fiber composite laminates for studying the delamination extension; specimens in three kinds of stacking sequence were tested under three impact energy respectively to involve more combination of ply angles, while ultrasonic C-scan was used to get the delamination of