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Delamination prediction in composite laminates under low-velocity impact

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ABSTRACT

This paper presents a damage analysis process of composite laminates subjected to low-velocity impact. Drop weight tests were carried out on specimens with two kinds of stacking sequence. Ultrasonic C-Scan was used to investigate the delamination area of each interface. Numerical models were built based on a damage model where cohesive contact method was involved. The efficiency of delamination modeling was discussed and the damage model was validated. The results of the FEM were found to agree well with experimental observation. According to the results, a prediction process of delamination shape was made for composite laminates under low-velocity impact. The delamination area was found to distribute symmetrically around the impact point while the shape is related to the ply angles of the layers close to the interface. The prediction was proved to have good accuracy and efficiency.

1. Introduction

Delamination is one of the common failure modes in composite laminates. It appears in the interface of two adjacent layers and can significantly reduce the compression strength of laminated structures. One of the main elements that lead to delamination is low-velocity impact. Impact with low velocity will cause excessive stress cross the interface of layers with different ply angles and delamination appeared after the failure of interface material.

Since delamination always takes place inside composite layers, it is difficult to characterize it without breaking the laminated structure. Therefore, the prediction of delamination in composite laminates became necessary during the service period of composite structures.

Studies have been done throughout the world to reveal the delamination damage behavior in composite laminates. Generally, they can be divided into two categories: experimental analysis, and numerical analysis.

A large amount of experiments were carried out on the damage behavior of composite laminates. Tita [1] tested three kinds of composite plates with typical stacking sequences under different impact energies. The mechanical behavior of the specimens was classified by the ratio of absorbed energy versus impact energy. Matrix crack and delamination were found when the fraction of absorbed energy was above 35%, while fiber rupture appeared as the fraction increased to 75%. Schoeppner [2] investigated the delamination threshold load of composite laminate under low velocity impact. The threshold load level was obtained from the load–time history or load–displacement plot, at which a sudden load drop occurs due to specimen stiffness loss as a result of laminate level damage. Sebaey [3] and Lopes [4,5] studied the effect of mismatch angle between plies on the delamination areas of composite laminates. Specimens with different stacking sequences were subjected to drop weight impact, and damages under different load levels were gained through C-Scan. The results indicated that by reducing the mismatch angle between the adjacent layers, the response of CFRP composites to low velocity impact could be improved. The experiments made by these researchers were mostly based on drop weight impact machines. Hou [6] and Joshi [7] carried out impact tests using a gas gun. This kind of loading method can avoid repeated loading appeared in drop weight tests, and impact energy can be easily controlled in the experiment procedure.

Many researchers also focused on the damage detection in composite materials. There are mainly two kinds of nondestructive inspection (NDI) method that are used in delamination analysis. Ultrasonic C-Scan is the most common technique to obtain damage caused by impact loads. Since the wave impedance of damaged material is different from the original material, the damage area can be drawn clearly by ultrasonic microscope. The other method that is widely used is lamb wave detection. In the research of Kessler [8], Bruno [9], Guo [10] and Su [11], lamb wave is used

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for damage inspection in composite materials. The method is effective for the determination of the presence and severity of damage, but difficult to investigate the damage shape and position directly.

There are also many other techniques for damage detection. Zhu [12] and Zou [13] proposed a vibration-based evaluation method to determine the location and size of debonding in composite structures. Lahuerta [14] describe a technique for measuring the delamination length in mode I tests based on video image processing. In the studies of Jody [15] and Zabala [16], damage visual enhancement technique was used to highlight the damage scope in composite laminates.

In these experimental studies, delamination scopes obtained were superimposed together. Although the damage is characterized by the total area, it is difficult to distinguish a delamination area of an interface from another. In order to study the relationship of stacking sequence and delamination area, it is necessary to investigate the damage behavior between each pair of adjacent layers.

Due to the big cost of experiments, researchers have paid more attention to numerical approach. The basis of numerical analysis is the damage theory models for composite materials. Hinton [17] concluded 12 leading theories for predicting failure in composite laminates. The predictions were compared with experimental evidence and the effectiveness of each theory was discussed. Several theories were found to be accurate for intra-laminar damage prediction but few considered the delamination behavior. Eijo [18] presented a numerical method based on the refined zigzag theory to model delamination in composite laminated plates. The quadrilateral QLRZ finite element was used for predicting the laminate kinematics. Results show that both the onset and the evolution of delamination were accurately predicted by the QLRZ element. Moura [19] proposed a new double failure criterion based on the combination of failure theories presented by Tsai-Wu, Hashin, Choi and Becker. The criterion identified the matrix rupture and delamination separately. Liu [20] performed a nonlinear progressive damage model to predict the ultimate strength and the failure processed of composite laminates. A three-dimensional strength criterion in terms of strains, which concluded fiber damage, matrix damage and delamination, was developed in the analysis model. Martinez [21,22] developed a matrix-reinforced mixing theory to predict delamination in composite laminates in ply drop-off test and drop-weight impact test. The method was proved to be less time consuming and applicable in structures with multi-plies. Zubillaga [23] considered that delamination was caused by matrix cracks, and developed a failure criterion based on the energy release rate and fracture toughness of the interface.

Among the numerical studies, cohesive elements were widely used to simulate the delamination behavior of composite laminates. These elements were used to connect two surfaces of an interface whose thickness is taken as zero before the deformation of the body occurs [24]. Delamination was simulated by controlling the constitutive model of cohesive elements. Recently, many studies have been done to improve the application of cohesive elements. Camanho [25] proposed a mixed-mode criterion for the delamination model based on cohesive elements. In the criterion, both tensile stress and shear stress are considered to account for the delamination. In the study of Jalalvand [26], cohesive elements with a random distribution of strength were embedded between the layers for modeling of delamination. Numerical results were found to agree well with the experimental observations. Xin [27] and Turon [28] studied how the mesh density of cohesive elements affects the delamination area. It was found that more elements will lead to more accurate result.

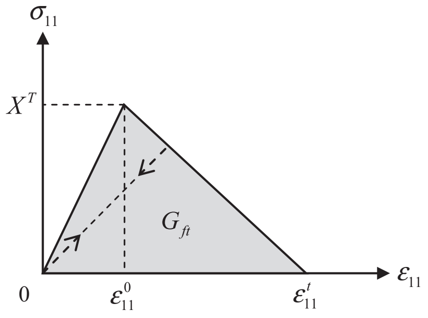

Fig. 1. Stress–strain relationship for fiber tensile damage.

It can be seen that many methods have been proposed to predict the delamination behavior in composite laminates. However, few of the researchers focused on the shape of delamination area in each interlayer of a laminate, since the delamination scopes obtained from the tests were always superimposed together.

This paper presented a damage analysis process for composite laminates under low-velocity impact. First, a damage model for composite materials is proposed which has considered intra-laminar and inter-laminar damage. Then, drop weight tests were carried out on laminated composite specimens. Ultrasonic C-Scan was used to investigate the delamination area in each interface and image processing method was applied to characterize the damage scopes. Based on the damage model, numerical simulations were made to study the efficiency of delamination modeling. Validation was also made for the damage model, and numerical result was found to agree well with experimental observation. Furthermore, the relationship of stacking sequence and delamination shape was summarized. Several conclusions were made and some future work was listed.

2. Damage criteria and evolution

The damage behavior of composite laminates can be divided into two types: intra-laminar damage and inter-laminar damage. The intra-laminar damage consists of fiber damage and matrix damage, while the inter-laminar damage is mainly contributed by delamination.

2.1. Intra-laminar damage

2.1.1. Damage criteria

Hashin damage criteria were used to model the damage appeared within layers. The criteria were formulated below.

Fiber damage:

$$F_f^t = \left(\frac{\sigma_{11}}{X^T}\right)^2 \geqslant 1 \quad (\sigma_{11} \geqslant 0) \tag{1}$$

$$F_f^c = \left(\frac{\sigma_{11}}{X^C}\right)^2 \geqslant 1 \quad (\sigma_{11} \leqslant 0) \tag{2}$$

Matrix damage:

$$F_m^t = \left(\frac{\sigma_{22}}{Y^T}\right)^2 + \left(\frac{\tau_{12}}{S^L}\right)^2 \geqslant 1 \quad (\sigma_{22} \geqslant 0) \tag{3}$$

$$F_m^c = \left(\frac{\sigma_{22}}{Y^C}\right)^2 + \left(\frac{\tau_{12}}{S^L}\right)^2 \geqslant 1 \quad (\sigma_{22} \leqslant 0) \tag{4}$$

σ_{11}-normal stress in the fiber direction;
σ_{22}-normal stress in the transverse direction;