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Study of Impact Damage Behavior in Woven Carbon Fiber Plates

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Abstract

Composites are being used extensively in aerospace structures as their properties offer significant advantages such as better strength to weight capacity. However, failure in composite structures due to low-velocity impact raises a maintenance concern because it can lead to an invisible damage. Hence, the objective of this study is to investigate impact damage behavior in woven composite plates via microscopic examinations. Several specimens were fabricated and were subjected to different levels of impact energy. Scanning Electron Microscopy (SEM) and X-ray imaging were used to examine the impacted area. The results showed that the impact damage is dependent on the plate thickness and also the impact energy. The outcome of this research will help to establish an efficient modelling technique for non-destructive evaluation of composites.

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1. Introduction

Composites are engineered materials that are made by combining two or more constituent materials. They are usually built up of separate thin layers consisting of polymer matrix reinforced with high strength fibers. The primary function of the fibers is to carry load along the direction of the fibers, while the polymer matrix transfers stresses between the fibers and acts as a glue to hold them together [1]. Often composites are in the form of laminates, made of layers of different fiber orientations that are bonded together. The physical properties of composites generally are anisotropic in nature with the stiffness of a composite laminate depending on the orientation of the fibers, relative to the direction of the applied load [1]. Composites are widely used in various applications such as aircraft because of their unique properties that can be tailored to meet specific requirements.

One major concern related to the composite structural integrity is its vulnerability to low-velocity impact. Low-velocity impact is often caused by bird strikes, tool drop during manufacturing and servicing, or runway debris. Such impacts may result in various forms of damage modes that can lead to a severe reduction in strength and integrity of composite structures. The brittleness of the polymer matrix and the interlayer spacing between fibers and matrix could lead to the impact damage spreading to the entire structure [2, 3]. The severity of the different damage modes depends on a variety of parameters such as the velocity and mass of the impactor and the material orientation of the composite structure [4, 5]. Several patterns of impact damages in composite laminates have been reported [4–6]: oval shape for a circular impactor shape or approximately rhombus or triangular shape for a diamond shape impactor. The problem with the low-velocity impact damage is that it is often not visible or barely visible for typical visual inspection [3]. Visible damage can be clearly detected and remedial action could be taken immediately to maintain the structural integrity. But this is often not the case for impact damage in composites. A major concern is the growth of hidden, undetected defects caused by low-velocity impact and fatigue [7]. Failure to detect this internal damage at an early stage may result in a catastrophic failure of the composite structure.

The failure process caused by low-velocity impact in composites is a complex phenomenon. Different failure modes and mixed damage modes may occur. Matrix cracking, delamination, fiber debonding and fiber breakage are examples of various failure modes [3]. There have been several studies on the mechanism of damage initiation and propagation of composite laminates [8, 9]. It has been established that the damage first initiates by the matrix cracks directly under the impacted area due

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to the large stress concentration. After initiation, the cracks usually propagate between fibers, primarily along the fiber–matrix interface [10]. Cracks are generally perpendicular to the direction of load and extend over the entire thickness of a ply. For a cross-ply plate, the cracks propagates through the entire thickness of the ply but are unable to propagate into the adjacent ply that has fibers aligned in a different orientation [1]. Thus, the cracks terminate at the interface of two plies. However, the resulting high interlaminar stresses produce favorable conditions for starting a delamination along the ply interface. Additional delamination starts and propagates as a result of fatigue. At the time when more delaminations appear, another type of damage is also observed [11]. The presence of cracks or delaminations prevents load distribution between plies, and a composite is essentially reduced to individual plies to support the applied load. When the weakest ply fails, it will trigger failure in the fibers; fibers may start debonding and fracturing begins to appear [1], [11].

Different test apparatus is used to simulate various types of impact such as air-gun tester, impact pendulum type, hydraulics impact and drop-weight. Several testing parameters are important to be considered before choosing an appropriate test apparatus [12]. The amount of kinetic energy of the projectile or impactor is one of the essential parameters, which derived from the mass, height and velocity of the impactor [13]. The amount of damage may be different, although the same amount of kinetic energy is used, for instance, using a large mass and low velocity or using a smaller mass with higher velocity. Therefore, the selection of the appropriate test procedure must be carefully chosen in order to ensure highest similar condition to the impact conditions experienced by the actual structure [14]. At the moment, a drop-weight impact tester is used by most researchers to simulate low velocity impacts by a larger impactor. In a drop-weight test, a stationary specimen is impacted by a falling weight where the impactor mass and height are variables that will provide variation in impact energies.

During the impact by a spherical projectile or impactor, this event causes pressure onto the specimen, hence developing a stress distribution and initiates the failure modes. For low-velocity impacts, no significant damage is introduced during the early stage of the impact, which means that the stress level remains low. M.T.H Sultan [15] performed several impacts on 12-ply woven carbon fiber with range of impact energies from 0.4 to 42 J. It was found that matrix cracking started at 21 J and the fiber breakage started at a range of 20 to 31 J. M. A. Perez [16] detected impact damage on unidirectional CFRP by using an ultrasonic method. The B- and C-scans results indicate the impact location and depth can only be viewed after impact energy of 40 J was executed. Impact testing using drop-weight type tester was implemented on a sandwich GFRP plate by Z. Y. Zhang [17]. It was found that the damage presence on the back surface of the plate started at 7 J of impact energy and the damage area increased with the increasing impact energy. D.A. Wyrick [18] investigated on how repeated impact loadings going to induce a damage or delamination on 16-ply quasi CFRP plate. He performed 1, 10 and 100 times repetition of 3, 10 and 30 J energy of the impact testing. It was observed that the 3J impact energy can create a damage on the surface after 10 times repetition, meanwhile a delamination appearance started to show after 4-6 times repetition of 10 J impact. At 30 J of impact energy, the delamination is already started without the need of more impact testing. From these works, it can be seen that the required energy to create the defects is different between different type of laminates. It is important to know the energy that the specimen will take to initiate a failure mode and how much energy it will absorb. Even though the same impact energy may be used for different type of composite specimen, the damage area may not be same. Therefore, a proper study of low velocity impact damage mechanism becomes important in order to analyze the characteristic of the composite laminate after being impacted with different impact energy levels.

The focus of this contribution is the understanding of the behavior of impact damage in composite laminates and its failure mechanism. The low- impact testing was performed on several composite plates, and the impacted surface was further investigated. The further goal of this study is actually to help establish the modeling and simulation of impacted composite laminate for advanced future research [19].

2. Methodology

2.1. Specimen preparation

Fig. 1 shows the flowchart of the experimental methodology. The material used in this experiment is a woven [0/90] prepreg of carbon fiber reinforced epoxy. The nominal thickness of the prepreg is 0.3 mm. The prepreg was then used to prepare composite plates with a dimension of 50 mm x 50 mm. In this work, the fabrication of the composite plates employed a hand lay-up technique. The fabrication began with the arrangement of few pregregs in a mold. A mixture of epoxy were poured into the mold. The mold was tightly closed using upper mold assembly in order to remove any air bubbles in it. A release agent was coated on the upper mold to help preventing specimens from sticking onto the mold after curing process. For curing process, the composite stack was hold at 120°C for 6 hours using a laboratory oven. The specimens were machined cut from the mold plaque using a diamond cutter to the required dimension. The composite plates were fabricated with different number of plies; (i) 8-ply with thickness of 2.4 mm, (ii) 16-ply with thickness of 4.8 mm, and (iii) 24-ply with thickness of 7.2 mm. For each composite plate with different ply number, 5 specimens were prepared making the total of 15 specimens.