An experimental investigation on the three-point bending behavior of composite laminate

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Abstract. The response of composite laminate structure to three-point bending load was investigated by subjecting two types of stacking sequences of composite laminate structure by using electronic universal tester (Type: WDW-20) machine. Optical microscope was selected in order to characterize bending damage, delamination, and damage shapes in composite laminate structures. The results showed that the \([0/90/-45/45]_2s\) exhibits a brittle behavior, while other laminates exhibit a progressive failure mode consisting of fiber failure, debonding (splitting), and delamination. The \([45/45/90/0]_2s\) laminate has a highly nonlinear load–displacement curve due to compressive yielding.

1. Introduction

Composite materials have been competitive alternatives to traditional metallic materials for a while, due to their lower density, higher stiffness, higher strength, and better fatigue resistance when compared to steel or aluminum. Such properties enable composites to be an ultimate candidate for structural applications in aerospace and automotive products [1]. In order to understand more fully the process of damage initiation and propagation in carbon fiber composites, a series of tests have been performed by using a three-point beam test. Beam tests have an advantage over plate tests in that they allow a physical observation of the damage evolution process and information is not restricted to the post test examination of the failed specimens [2]. Quasi-static and dynamic loading of composite laminates result in complex damage mechanisms, among which multiple delamination and interfacial fractures are dominant ones. Damage initiation and growth in composite structures subjected to bending loads have been studied by numerous researchers, using various FE models [3]. The use of a three-point support flexural test to predict the stiffness of anisotropic composite plates in bending was studied by J.P. Nunes et al, and the results show that the flexural behavior of the composites depends on several factors, such as fiber orientation, laminate stacking, surface waviness and molding temperature [4]. Three-point beam impact tests on T300/914 carbon fiber composites have been performed by S.R. Hallett, and the results show that the consistent values are elastic deflection to failure and hence peak impact force. Once the peak force has been reached, failure initiates by fiber fracture at the back face [5]. Several methods have been proposed for determining mechanical properties of laminated composite materials. Those methods consider several specimen configurations with different laminate arrangements subjected to static loading. In the case of unidirectional
laminated composites, the mechanical properties can be divided into two main categories: normal and shear properties. Concerning in-plane or intralaminar shear properties, there exist a variety of different shear test methods depending on the specimen geometry, the type of applied load and the laminate configuration [6]. Many studies have been carried out on bending properties of composite laminate by considering several factors, such as fiber orientation, laminate stacking, and manufacturing conditions [7-13]. In this study, three point bending of the laminates composite structure was investigated. Two types of stacking sequence were chosen for bending test, [0/90/-45/45]_{2S} and [45/45/90/0]_{2S}. To characterize the bending loads in composite laminate structures, optical microscope was used. The load-displacement curves were obtained to characterize the failure mechanisms in the composite laminate by considering the effects of stacking sequences used.

2. Materials and experimental

2.1 Materials

Unidirectional Prepreg carbon fiber/epoxy produced by Toray Company was used to manufacture composite laminates.

2.2 Laminates Fabrication

Laminates fabrication, which consist of two different stacking sequences, was prepared by heat pressure composite process. The pressure was 2 MPa, the cure was at 80°C for 30 min, and the post-cure was at 120°C for 2 h. The dimension of the entire sample was 16 cm x 16 cm (length*width). Table 1 represents the calculated mechanical properties of the produced lamina.

Table 1. Mechanical properties of composite lamina

| Property                      | Value       |
|-------------------------------|-------------|
| Young modulus (longitudinal)  | E_{1} = 135.0 GPa |
| Young modulus (transverse)    | E_{2} = 8.91 GPa |
| Shear modulus                 | G_{12} = 98 GPa  |
| Poisson ratio                 | 0.3         |
| Layer thickness               | t = 2 mm    |

The testing equipment used in the experiments included flat-panel vulcanizer, electronic universal tester (Type: WDW-20) machine (Figure 1), and optical microscope (Nikon eclipses E200), as listed in Table 2.

Table 2. Testing equipment

| Number | Name                   | Model            |
|--------|------------------------|------------------|
| 1      | Vulcanizing machine    | XLB              |
| 2      | electronic universal tester | WDW-20         |
| 3      | Optical microscope     | Nikon eclipses E200 |
Three-point bending test

The three-point bending tests were conducted with an electronic universal tester (Type: WDW-20) machine. The applied velocity of the bending load was 2 mm/min. Figure 2 shows the load configuration for a beam in three-point bending test. Different stacking sequence laminate types were tested, firstly quasi-isotropic and secondly unbalance stacking sequence. Load–displacement plots were obtained for each test specimen, and three specimens of each type of composite laminate were tested. Table 3 shows the lay-up, number of ply and dimensions for each specimen. The dimensions and all the procedures of the three-point bending test were in accordance with standard ASTM D7264/D7264M–07 [14]. The flexural stress $Q_f$ is given by the following equation:

$$Q_f = \frac{3FL}{2bh^2}$$

Table 3. Specimen characteristics and specifications

| Laminate type               | Specimen name | Lay-up    | N of plies | Span L (mm) | Width b (mm) |
|-----------------------------|---------------|-----------|------------|-------------|--------------|
| Quasi-isotropic stacking sequence | Qu1          | [0/90/-45/45]$_{2s}$ | 16         | 40          | 15           |
|                             | Qu2          | Same      | 16         | 40          | 15           |
|                             | Qu3          | Same      | 16         | 40          | 15           |
| Unbalance stacking sequence  | Un1          | [45/45/90/0]$_{2s}$ | 16         | 40          | 15           |
|                             | Un2          | Same      | 16         | 40          | 15           |
|                             | Un3          | Same      | 16         | 40          | 15           |

(Qu means quasi-isotropic, Un means unbalance)

where

$Q_f$ is the flexural stress, in megapascals (MPa);

$F$ is the load in newton’s (N);

$L$ is the span, in millimeters (mm);

$h$ is the thickness of the specimen, in millimeters (mm); and

$b$ is the width of the specimen, in millimeters (mm).
In Figure 2, $F =$ applied force, $R_1 =$ indenter radius, $R_2 =$ fixed support radius, $h =$ specimen thickness, $L =$ support span and $M =$ specimen length.

### 3. Results and discussion

#### 3.1 Three-point bending test

This section describes the experimental results after the various composite samples were broken under three-point bending (initial delamination, matrix crack, fiber crack). All results were plotted in terms of applied load versus center displacement of the sample under the crosshead of the electronic universal tester machine. All the samples for two stacking sequences had the same span length, thus making it possible to superimpose the load/displacement plots for each group of samples. This allowed a more accurate comparison of the resulting curves. The two stacking sequences were considered to evaluate the better stacking sequence and their mechanical properties $[0/90/-45/45]_{2s}$ call quasi-isotropic, $[45/45/90/0]_{2s}$ call unbalance stacking sequence and $s$ means symmetric. In each case, there is reasonably good correlation in the results. For these samples, the failure mechanism observations were reproducible.

**Laminate: $[0/90/-45/45]_{2s}$**

Figure 3 illustrates the load-displacement plots for laminate composite structures of $[0/90/-45/45]_{2s}$ consisting of 16 layers. The observations of the curve was bending stiffness to peak load due to no delamination observed and no oscillations before peak load. The curves can be divided into three regions. The first region, linear in appearance, can explain the elastic deformation of the composite laminate. The deformation represents when the displacement of the indenter was affected in the upper surface, due to the presence of some imperfections on the surface of the laminate. The second region after the load reached a peak value, significant drop of about 30–60 % of the peak load in the load-displacement curve was observed in composite laminate structures, and this sudden drop was due to the fiber cracking (Figure 4). After the crack initiated in tensile side, it propagated to the compressive side within all types of specimens before the final failure occurred. After the load drop, the specimen continued to sustain the load but never exceeded the previous peak load as only the reinforcement
carried the load, which is reflected in the third region. In this region, plateau region was observed until reaching the final failure.

Laminate: $[45/45/90/0]_{2s}$

As seen in Figure 3, the behavior of composite laminate in this situation was bending stiffness, delamination and oscillations during the test until peak load in the laminate. This stacking sequence showed a little oscillations before peak load, which may result from vibrations of the supports, some defects in composite laminates, dents and delamination in the top and bottom faces of laminate composite structures, and initiation of damage in the specimens. The curves were divided into three regions. The first region, linear in appearance, can explain the elastic deformation of the composite laminate. The second region after the load reached a peak value, significant drop of about 20–50% of the peak load in the load-displacement curve was observed in composite laminate structures, and this sudden drop was due to the fiber cracking and delamination. After the load drop, the specimen continued to sustain the load but never exceeded the previous peak load as only the reinforcement carried the load, which is reflected in the third region. In this region, plateau region was observed until reaching the final failure (Figure 5). The maximum fiber stress at failure on the tension side of a flexural specimen is considered the flexural strength of the material. Comparing the two types of stacking sequences used in this test, $[0/90/-45/45]_{2s}$ had superior advantages, such as high peak load, small damage area, and no delamination, to $[45/45/90/0]_{2s}$, due to different lay-ups, fiber orientations, and difference in their respective fiber modulus. The $[0/90/-45/45]_{2s}$ exhibited a brittle behavior, but other laminates exhibit a progressive failure mode consisting of fiber failure, debonding (splitting), and delamination. The $[45/45/90/0]_{2s}$ laminate had a highly nonlinear load–displacement curve due to compressive yielding.

![Figure 3](image_url). Electronic universal tester plot of load vs. displacement of composite laminate
3.2 Optical microscopic images

Optical microscope results show shapes of the failures occurred in the samples, it was observed that the highly delaminated area occurred in $[45/45/90/0]_{2s}$ unbalance stacking sequence due to the orientation of the layer, and fiber orientation, as seen in Figures 6 and 7, which present the photos taken in transverse direction of the composite laminates for two types of the stacking sequences.
As seen in Figure 6, the photos show a small delaminated area, small damage area, which almost has the same damage shape in upper surface of the laminate. However, in Figure 7, bigger delaminated area, big damage indentation, various damaged shapes, fiber failure, and debonding (splitting) are observed. These observations could be attributed to the important role and effects of fiber orientation on composite laminates.

4. Conclusion

Three point-bending test behavior of the composite laminates was investigated. Three point-bending results showed that $[0/90/-45/45]_{2s}$ exhibits a brittle behavior, but other laminates exhibit a progressive failure mode consisting of fiber failure, debonding (splitting), and delamination. The $[45/45/90/0]_{2s}$ laminate has a highly nonlinear load–displacement curve due to compressive yielding. Comparing the two types of stacking sequences used, $[0/90/-45/45]_{2s}$ in upper face has lower fail area, delamination, indentation in damage location, and damage size sensitivity than $[45/45/90/0]_{2s}$. This behavior is attributed to variation on stacking of the layers in composite laminate, fiber orientation, and mechanical property of lamina.
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