Flexural Failure of Unidirectional Carbon /Epoxy Composites: Effects of Interleaving and Flexural Rate

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Abstract: The effects of a low-modulus high-strain interleaf layer, introduced at the midplane, on unidirectional carbon/epoxy laminates under flexural loading were investigated. The apparent energy-to-fail of the laminates increased significantly whereas the maximum load decreased slightly upon interleaving. Real-time microscopic observations during static flexure tests at the lowest deflection rate indicated a dramatic change of failure mode from the dominantly compressive fracture of the baseline laminate to the dominantly tensile fracture process upon interleaving. Failure modes of interleaved and baseline laminates showed no significant changes with test rate in the deflection rate range of 10⁻⁴ to 10⁰ m/sec.

Keywords: Continuous-fiber composites, Three-point flexure, Interleaving, Rate effect, Failure mode.

Introduction

As compared to aluminum or steel, continuous carbon/epoxy composites are known to be highly advantageous in terms of their higher specific strength and specific modulus. One of the known disadvantages of carbon/epoxy composites is their lower impact energy absorption capability [1,2]. The appearance of delaminations upon impact loading significantly weaken the structure, resulting in lower stiffness and residual compressive strength after impact [3-6].

Liu [7] reported that delamination was induced by bending stiffness mismatch between plies. In the cross-ply laminate construction, the transverse shear crack and bending crack in the 90° laminate may create delamination cracks along 0°/90° interfaces [8]. Improvement in the interlaminar fracture toughness (IFT) appeared to be a way to enhance the impact resistance of laminates [9-13]. Sela et al. [14] observed large increases in IFT using a tough layer in the middle plane of the laminate. Gandhe and Griffin [15] found that the impact penetration energy of interleaved specimens compared to that of non-interleaved laminates was almost twice as strong.

It is of interest to compare the increment of IFT with that of the impact penetration energy. The energy consumption of the laminate under loading can be divided into five major parts: delamination, fiber pullout, fiber fracture, debonding and splitting [16]. Fiber pullout and fiber fracture dissipate more energy than the others. Adding a highly shear strain layer within the laminate increases not only the IFT, but the failure mode may also change.

In our previous report [17], two series of unidirectional specimens in which the fiber orientation was parallel to the length of specimen (0° laminate) were prepared for a drop-weight impact test at the reflection rate of 1.1 m/s (meter/second) and for a static flexure (1.7×10⁻⁴ m/s) test. For the impact specimens, the baseline laminates were composed of 30 plies of T300 carbon/epoxy prepreg and the interleaved laminates included an additional layer of 3 sheets of poly(ethylene-co-acrylic acid) (PEAA) film introduced at the midplane of the baseline laminate. The span-to-thickness (S/t) ratio of the impact plate was approximately 16. In fabricating flexural specimens, both the baseline and interleaved laminate were made of 24 prepreg tapes but the interleaved laminate had 2 plies of PEAA film inserted into the midplane. The S/t ratios of the baseline and interleaved laminates were ca. (=circa) 14 and ca. 13, respectively.

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The energy-to-fail of specimens increased significantly and the initial compressive crack under the loading nose apparently delayed to a higher deflection upon interleaving for both the impact and static tests. From the view of the failure sequence in the static test, the introduction of a soft layer into the laminates not only postpones the compressive crack initiation but also suppresses the crack propagation. As a result, the failure process in the baseline laminates is dominated by the compressive crack propagation while the failure in the interleaved laminates is dominated by tensile fracture. The dramatic change of failure mode upon interleaving indicates that the normal compressive stress concentration is reduced and stress is redistributed under flexural loading.

In order to ensure that the influence of the small differences in the samples geometry (such as S/t ratio) and test conditions (such as bending fixture) between the static flexure and the drop-weight impact tests were insignificant to our conclusions [17], a series of experiments were designed to confirm the previous results. In this study, 2 plies of PEAA were inserted in the middle plane of the 0° unidirectional laminates. More detailed observations regarding the role of interleavies in composites are presented in this paper. Static flexure tests and low velocity impact tests were performed. The entire failure process and load-deflection relations were recorded under the static flexure test. The influence of the rate effect on the failure process and mechanical properties was also discussed.

### Experimental

1. **Materials**

   Carbon/epoxy prepreg tapes were supplied from Toray Industry Co. The fiber type of prepreg was T300 and the matrix was a mixture of bisphenol-A and novolac epoxies with dicydiadime as the hardener. Fabrication of baseline laminates required 24 layers of prepreg tape stacked unidirectionally while the interleaved laminates were composed of 2 layers of poly(ethylene-co-acrylic acid) (PEAA) film which is Primacor 3440 manufactured by the Dow Chemical Co., inserted in the midplane of 24-ply unidirectional specimens. A single layer of prepreg tape and PEAA film are approximately 0.13 and 0.1 mm in thickness, respectively. The elastic modulus of PEAA (ca. 0.1 GPa) [18] is much lower than the prepreg tape.

   Both the baseline and interleaved laminates were cured at 130 °C under a pressure of 0.5 MPa for 2 hr. All laminates were cut into 70 mm in length and 12.7 mm in width. The baseline laminates were ca. 2.77±0.05 mm in thickness and the interleaved laminates were ca. 2.92±0.11 mm in thickness.

2. **Static flexure**

   A universal test machine (Instron 1125) equipped with a three-point bending fixture was used. The diameters of the loading nose and the support dowels were 5.0 mm. The span between the supports was 40 mm. The span-to-thickness (S/t) ratio of the baseline and interleaved laminates were ca. 14 and ca. 13, respectively. Flexure tests at deflection rates of 1.7×10⁻⁶ m/s (the low deflection-rate) and 8.3×10⁻⁶ m/s (the intermediate deflection-rate) were performed at room temperature. A stereomicroscope equipped with a camera was used to record the entire failure process during the low deflection-rate tests.

3. **High-rate flexure**

   A servohydraulic dynamic high rate test system (MTS 819) equipped with a bending fixture, which was a duplicate of that used in the static flexure testing, was used for the high deflection-rate (1.2 m/s) tests at room temperature.

4. **Scanning electron microscopy**

   Fractographic features of specimens after flexural testing were examined by scanning electron microscopy. Secondary electron images of the fracture surface were taken by using of a JEOL JSM 6400 scanning electron microscope operated under an acceleration voltage of 25 kV.

### Results

1. **Static flexure**

   In order to understand the entire sequence and the effect of interleaving, we took pictures at the low deflection rate for both the baseline and interleaved laminates. These pictures correspond to the load drop on the load-deflection curve.

   The load-deflection curve and optical micrographs of the baseline laminates are shown in Figures 1 and 2, respectively. The loading nose comes in contact with the upper surface of the specimen (Figure 2(a)), and the curve rises linearly. The first load dent which appears as the first compressive crack is initiated and the kinkband is formed under the loading nose (Figure 2(b)). This amount of deflection is defined as the deformation of the initial generation of the compressive crack (A₀). Before reaching the maximum load (P_max), the compressive crack grows slowly and the load drop falls slightly again (Figure 2(c)). After the peak load, the com-