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Test method

Compression testing of continuous fiber reinforced polymer composites with out-of-plane fiber waviness and circular notches

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ABSTRACT

We investigated the face-stabilized Open-Hole Compression (OHC) test method for evaluating the effects of fiber waviness on the compression strength of continuous carbon fiber reinforced polymer composites. Temporal evaluations of the load-deformation response, acoustic emissions and optical microscopy are used to understand the failure modes and damage progression in the OHC specimen. The failure modes observed are structurally correlated to matrix failure and kink zone formation leading to fiber fracture. The results show how the resin pocket plays a more critical role than the layup in influencing the initiation of damage in the composite specimens.

1. Introduction

Compression testing is not a trivial task in continuous high strength and high modulus fiber reinforced polymer composites. The compression test of a composite specimen can be considered a structural test having complex interactions between local failures and structural instabilities [1]. In the compression test, several failure mechanisms can occur independently or interact with each other, e.g. fiber crushing, matrix failure, delamination, longitudinal splitting and fiber kinking. The failure mechanism interactions make the compression tests very sensitive to geometry perturbations or defects such as out of plane fiber waviness or porosity. However, in composite structures, these defects can occur anywhere including near holes, cut-outs or other geometrical discontinuities. For example, in a composite fuselage, holes are used in bolted joints between structures such as frames or shear ties, and often designers cannot preclude with certainty the presence of waviness defects in those locations. Further, the stress concentration associated with these holes is usually the driving factor in design. For this reason, the Open-Hole Compression (OHC) test method is typically used for determining the compression properties (such as compression strength) of continuous high modulus symmetric and balanced composites [2].

In the OHC test, a notched specimen is face supported using a multi-piece bolted support fixture. This test method has proven its ability to capture the effects of notches under compression loads. Despite the success of using the OHC specimen in capturing the effects of notches, the specimens for the OHC are usually manufactured in environments that are not typical of the actual manufacturing conditions of the composite structure. Thus, it may be advantageous to incorporate defects directly into the OHC specimen to produce modified strength. Fiber waviness (or sometimes called wrinkles, tiger or zebra stripes according to industrial vernacular) is one type of the common manufacturing defect encountered during the manufacture of composite structures (Fig. 1).

Fiber waviness may be caused by non-uniform consolidation pressure, interactions with other layers or

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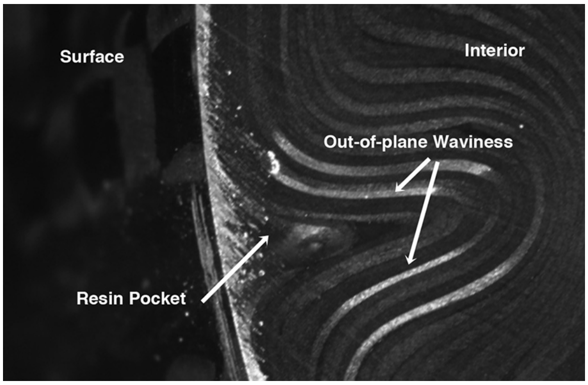

Fig. 1. Example of a severe fiber waviness profile in a composite structure.

ply drop-offs. The waviness can typically affect all or some of the plies in a laminate stack. A survey of the literature reveals significant interest in this topic, yet a large volume of work on compression properties in fiber reinforced composites does not consider the interactions between notches and fiber waviness. The studies have conclusively shown that fiber waviness can significantly affect the un-notched tension and compression stiffness and strength properties [3–6]. There are limited references in the literature on the common amount/magnitude of waviness to be expected in industrial practice. It is likely that many industries may consider this to be a proprietary feature of their design. One study investigating the fatigue failures in carbon-fiber based bicycle forks showed significant amounts of waviness in the cross-sectioned specimens [7]. Potter et al. [8] showed that the influence of defects such as waviness must be explicitly included in determining allowable properties of composites. Bradley et al. [9] investigated methods to directly correlate experimentally determined strain fields and compressive strengths with analytical predictions. Their results showed that, under compression loading, large interlaminar shear and normal strains occurred as a result of layer waviness. Elhajjar et al. [10] previously presented an investigation of the behavior of notched carbon/epoxy laminates containing out of plane fiber waviness defects using the average stress fracture criterion to predict the failure of notched composites containing localized waviness loaded in tension.

In this study, we investigate the feasibility of using the Open Hole Compression (OHC) test for evaluating the effects of out-of-plane fiber waviness in continuous fiber reinforced composites. The OHC specimens are fabricated containing intentional waviness in unidirectional and multidirectional continuous carbon fiber/epoxy laminates. The proposed specimen design incorporates the OHC specimen with controlled levels of fiber waviness created using steel rods to initiate the perturbations in the plies. In addition, the effects of the waviness-associated resin pockets on the mechanical response have been experimentally evaluated. Temporal evaluations of the load response, acoustic emissions and optical microscopy are used to understand the failure modes and their relationship to the load drops observed during the test.

2. Experimental approach

The OHC specimens in this study were fabricated using carbon-fiber epoxy in prepreg form and the specimen geometry in ASTM D6484 [2]. The prepreg (resin pre impregnated fibers) was used for the specimens to reduce the variability in the processing since they produce more controlled fiber volume fractions and ply thicknesses. The fiber and epoxy used were a Toray prepreg T700GC-12K-31E fiber with the #2510 epoxy system [11] (Table 1). For each specimen fabricated, sixteen prepreg plies were tailored and stacked in unidirectional and multidirectional sequences. The multidirectional plies had the stacking sequence of $[0/45/90/-45/0/45/-45/0]_S$. The laminates were cured using a ‘press-claving’ approach where uniform heat and pressure are applied per the recommended 121 °C cure cycle. Several methods have been reported in the literature for creating fiber waviness profiles. Some of these profiles have been successfully replicated in a study on fabrication methods by using ply drop offs or transverse strips of composite material to trigger the waviness profile [12]. The use of metallic rods to initiate the out of plane waviness has been previously proposed [10]. One study has shown how waviness can be made with oversized plies made to conform to a given geometry [13]. Wisnom and Atkinson [14] artificially induced waviness in composite rings and were able to measure the post-cure waviness using a displacement-based technique applied during the manufacturing stage. Potentially, any method can be used to induce the waviness to more closely resemble the as built composite structure. In this study, we use the method of the metallic rods with a post-cure step of adding an additional epoxy resin (Table 2) pocket in the cavity left by the waviness profile. The waviness in the specimens was introduced in the composite by displacing the plies with a close-tolerance steel rod separated from the composite using a Teflon sheet. The diameters for the rods used correspond to the waviness desired (from 0.48 to 0.81 mm). The bar was then easily removed from the composite specimen after the curing process was completed. The specimen is further processed with epoxy filling of the cavities since, in manufacturing environments, the resin

Table 1
Mechanical properties of the carbon/epoxy T700GC-12K-31E/#2510 Prepreg [11].

E_1 GPa (Msi)	E_2 GPa (Msi)	ν_{12}	G_{12} GPa (Msi)	F_1^{tu} GPa (ksi)	F_2^{tu} GPa (ksi)	F_1^{cu} GPa (ksi)	F_2^{cu} GPa (ksi)	F_{13}^{Su} GPa (ksi)	F_{13}^{Su} GPa (ksi)
125 (18.1)	8.4 (1.23)	0.309	4.22 (0.613)	2.16 (314.4)	0.049 (7.09)	1.45 (209.1)	0.20 (28.8)	0.15 (22.4)	0.085 (12.4)