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A hybrid numerical and imaging approach for characterizing defects in composite structures

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ABSTRACT

In this study, a hybrid approach coupling hyperspectral near infrared imaging with a progressive finite element method is proposed for characterization of the elastic and failure response of composites with non-uniform variations of the wrinkles profile through the thickness and across the structure dimensions. In this approach, hyperspectral near infrared spectroscopy is used to create a 3D profile of the surface resin pockets with the capability of measuring resin thickness from approximately 125 to 2500 μm. These resin pockets are directly correlated to underlying ply level wrinkling as confirmed by optical microscopy. The 3D mapped resin plane obtained from the hyperspectral imaging is used to morph a ply-by-ply finite element model of a carbon-fiber/epoxy resin laminated plate using a progressive damage failure methodology. The results show the capability of the hybrid method to predict the structural response in laminated composites containing spatially distributed and non-uniform ply-level wrinkling.

1. Introduction

Composite structures in practice can be subject to various types of defects during manufacturing. Such defects can serve as initiation sites for matrix cracking, fiber kinking, fiber/matrix debonding and delamination. Of the possible defects, ply-level out-of-plane waviness or wrinkling can lead to the highest degradation of mechanical properties [1–4] and is the most challenging of defects to detect using conventional approaches. Ply waviness can be caused by wrinkles in bagging or non-uniform consolidation pressure, interactions with other layers or ply drop-offs. Processing parameters including length of cure, cooling rate, and tool plate material can also influence the development of wrinkles in the laminates [5].

Current analysis methods for composites with defects are limited by the ability of nondestructive methods to adequately and economically characterize the defect levels in the structure. Sutcliffe et al. [6] used an X-ray image analysis technique to determine the fiber waviness. This technique provided good agreement with results from the polished prepreg (preimpregnated fibers) samples. Similarly, Nikishkov et al. [7] proposed a method for automated generation of finite element meshes for unidirectional composites with waviness defects using X-ray computed tomography. Pain and Drinkwater [8] used an ultrasonic array to extract the scattering of the interior of the composite structure. Pulsed terahertz response of the composite is shown to provide clear indications of the fiber waviness [9] but characterization of wrinkle levels continues to be an area of concern and is likely to be limited by a variety of factors such as the stacking sequence and the thickness of the structure in question. Ultrasonic characterization methods are difficult to interpret because elastic wave propagation is highly dependent on stacking sequence effects and interactions with other defects, such as porosity, which can occur at the same time as wrinkle defects. The computed tomography methods previously discussed are limited to testing specimens of small sizes and are currently not practical for many types of composite structures.

In the absence of reliable stochastic or multi-physics models that account for manufacturing, it is not possible at this point to accurately predict the locations where defects occur before manufacturing. Even if the wrinkle defect is visible, it is not currently possible to reliably determine its depth non-destructively using methods that are commonly used, such as ultrasonic inspection. In other cases, excess resin on the composite surface might result from a wrinkle in the bagging material, so there is no underlying composite feature. NDI methods based on ultrasound can detect resin pockets in excess of 1000 μm but cannot typically measure pockets that are less than 1000 μm deep. Thermoelastic stress analysis methods have also been proposed to identify resin pockets and wrinkles, but these require a cyclic application of load [10].

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Thus there exists the need for robust, portable and accurate methods for providing identification and depth measurement of wrinkles in composite structures.

Chemometric data processing methods can be used to characterize the relationship between the spectra and the resin thickness and provide the correlation to predict a point-by-point local resin thickness and thus produce thickness maps of the scanned resin surface. Recent advances in hyperspectral near infrared (NIR) sensing and data processing technologies have made real-time infrared methodologies a viable solution for accurate analysis of composite structures. NIR imaging can accurately measure surface resin on composite materials from 125 to 2500 μm thick, detecting virtually all resin pockets, resin-filled surface wrinkles and other surface resin features [11]. The resin-rich areas on the surface are usually an indicator that wrinkles are affecting some or all of the plies in a laminate stack.

In this study, we propose using NIR hyperspectral imaging and progressive damage finite element analysis for advanced distributed damage characterization in composite structures. Our approach overcomes the obstacles facing accurate mechanical analysis of the structure as it is built without simplifying assumptions of defect levels. The progressive modeling approach is based on the Hashin–Puck's continuum damage criteria and cohesive layers. A finite element mesh generation technique with the capability of meshing layers separately has been developed to transform the resin thickness maps to a finite element mesh with a ply-by-ply representation including cohesive layer failure interfaces in between the plies. The proposed method is demonstrated on a continuous plain weave fabric carbon fiber/epoxy laminate.

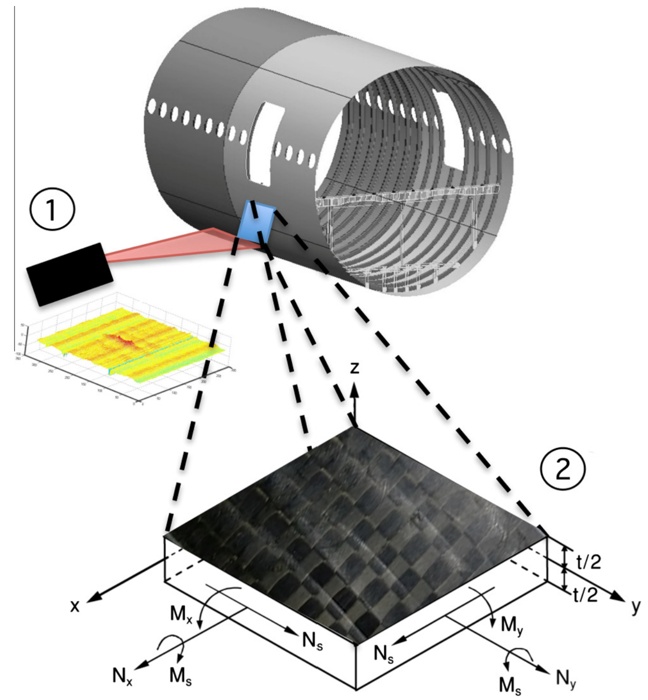

Fig. 1. Schematic of analysis framework. (1) Composite part is scanned with hyperspectral NIR imaging for surface resin pockets and wrinkles. (2) Progressive damage analysis is performed on sub-zone or entire structure if needed. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2. Method

In our proposed method, a push-broom near infrared (NIR) hyperspectral imaging approach is used to scan the composite structure and produce a map of the resin depth on the surface. This map is subsequently used to generate a morphed finite element model corresponding to the non-uniform wrinkling in the structure. A progressive damage-based finite element method is used to predict the elastic and failure response at any desired location. The result is not only a defect map, but also a detailed structural health assessment of the distributed damage due to the non-uniform ply waviness in the structure. The steps involved in this method are comprised of the following:

(1) In the push-broom NIR hyperspectral imaging approach, a line of pixels is measured and the sample is moved along a path that is perpendicular to the imaging line. The push-broom approach to imaging is capable of high spatial resolution to completely define the resin features by generating a 3D profile of the resin features on the surface of the composite structure (Fig. 1).
(2) The 3D profile of the resin is subsequently used to modify the finite element mesh of the structure in question. Information from the resin profile is used to introduce wrinkles from the 3D surface resin map. The mesh-morphing program is capable of adjusting the thickness of the plies to the newly imposed constraints. Optical microscopy confirms the link between wrinkle depth and the resin thickness on the surface.
(3) A progressive finite element method comprising continuum damage zone theory and cohesive layers is used to compute the structural stiffness and strength for the structure or sub-zone of the structure under the given loading combination.

3. Experiments and numerical simulations

3.1. Experimental method

The specimens in this study were fabricated from aerospace grade plain weave carbon-fiber epoxy fabric in prepreg (resin pre-impregnated fibers) preform. The prepreg is 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 T700SC-12K-50C/#2510 plain weave fabric prepreg system [12]. The basic mechanical properties of the unidirectional tape prepreg system are tabulated in Table 1. The base procedure for fabrication of the test panel was modified to account for the wrinkling.

Several methods have been reported in the literature for creating the ply wrinkling profiles. Some of these profiles have been successfully replicated in a study on fabrication methods by using ply drop offs and transverse strips of composite material to trigger the waviness profile [13]. These methods have the drawback of inclusion of foreign material into the laminate. The use of metallic rods to initiate the out-of-plane waviness has been previously proposed [14,15]. In this procedure, the wrinkling is limited to the number of rods used and cannot usually generate large areas of waviness with random and non-uniform features. One study has shown how waviness can be created with oversized plies that conform to a given geometry [16]. In this study, the oversized ply method is used to create the random wrinkle distribution in the specimen. The oversized composite prepreg layers were packed into an aluminum mold. A silicon sheet of 5 mm thickness is applied over the composite to assist with consolidation. The laminates were cured using a 'hot-press' approach where uniform heat and pressure are applied per the recommended 121 °C (250 °F) cure cycle. The NIR data was collected using a hyperspectral imaging system (Via-Spec Stage (MRC-920-044) with a SWIR hyper-