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Spatial damage detection in electrically anisotropic fiber-reinforced composites using carbon nanotube networks

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ABSTRACT

Due to their small size, carbon nanotubes are able to create electrically conductive networks surrounding structural fiber reinforcements in composites. As damage accumulates in the polymer matrix, cracks break the nerve-like conducting pathways resulting in bulk changes in electrical resistance. To utilize carbon nanotube networks as a potential structural health monitoring (SHM) approach it is necessary to develop techniques capable of detecting localized and site-specific damage. Electrically anisotropic composites were manufactured from unidirectional glass fibers treated with a sizing containing carbon nanotubes. Local damage was introduced to the composite laminates and was assessed by taking electrical measurements from an array of surface mounted electrodes. Conductivity maps generated using electrical impedance tomography (EIT) were compared to the normalized resistance change approach. A center of mass approach was utilized to define the damage location. Both techniques are capable of localizing damage in the composite but EIT has much higher overall spatial sensitivity. The normalized resistance change approach, however, requires significantly fewer measurements and can be utilized for real-time detection of damage.

1. Introduction

Advanced polymer composites are increasingly being used in structural applications because of their desirable properties, such as improved corrosion resistance [1], high strength-to-weight ratios [2] and increased fatigue performance [3] as compared to traditional materials. However, structural failure in composites can be difficult to predict, and subsurface micro-scale cracks initiate in the polymer matrix. Structural health monitoring (SHM) is increasingly necessary to maintain structural integrity, improve safety and reliability, and to reduce maintenance costs. SHM provides diagnostic information on the magnitude and location of damage. A variety of SHM systems have been developed utilizing strain gages [4], fiber optics [5,6], and acoustic sensors [7]. There is increasing interest in developing advanced SHM techniques that can sense large areas, are minimally invasive, and capable of real-time sensing.

It is well established that the electrical properties of carbon fiber composites can be utilized to detect damage. Schulte et al. [8] first demonstrated this approach by attaching electrodes to ends of a carbon fiber/epoxy laminate and monitoring the resistance changes under tensile loading. Fiber fracture resulted in permanent changes in electrical conductivity. Thostenson and Chou [9,10] extended electrical damage sensing to glass fiber composites by utilizing carbon nanotubes dispersed in the polymer matrix as the electrical network. They showed nanotube networks were particularly sensitive to detecting the onset and accumulation of matrix cracking.

Several researchers have worked to advance the electrical resistance approach for damage sensing into an SHM technique capable of locating damage in large-scale structures. Todoroki et al. [11,12] applied the response surface methodology to approximate the location of delamination in carbon fiber composites. Using this statistical technique, they performed one and two-dimensional spatial analysis. However, accurate predications required electrodes to be placed over the entire surface. Angelidis and co-workers [13] proposed a less invasive procedure, referred to as the potential method, where electrodes are placed only at the boundary. As current is sourced between electrode pairs the potential is measured at each electrode and damaged areas approximated by analyzing changes in the potential distribution.

Electrical impedance tomography (EIT) is an imaging technique that reconstructs spatial conductivity from a set of boundary measurements. Similar to the potential method, current injection and voltage measurements are acquired from electrodes around the

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boundary. Schueler and co-workers [14] first suggested the application of EIT in fiber composites for damage mapping. However, at the time of the work reconstruction algorithms had not been developed to account for electrical anisotropy. Hou and Loh [15,16] applied the technique to composite structures by generating conductivity reconstructions of electrically isotropic carbon nanotube sheets. Through their work, they demonstrated the ability to locate inhomogeneous regions, map strain fields, and distinguish between multiple regions of damage. Baltopoulous and et al. [17] applied the EIT technique to carbon fiber composites. The high electrical anisotropy was mitigated by using a woven layup and assuming the laminate to be electrically quasi-isotropic. However, the quality of the generated conductivity images was poor, and additional post-processing was required to accurately approximate the damage location. Improvements in reconstruction algorithms allowed Loyola et al. [18] to extend EIT to electrically orthotropic composites. Measurements were obtained from a thin multi-walled carbon nanotube film on the surface of a unidirectional glass fiber composite (planar conductivity ratio of 1:2). The study served as an introduction of EIT in orthotropic composites and examined the accuracy of the method in terms of detecting and locating various forms of surface damage. One disadvantage of EIT is the time associated with the construction of the electrical conductivity map, making real-time monitoring difficult.

In this paper, we assess localized damage in electrically anisotropic composites using normalized resistance measurements and conductivity maps generated using EIT. The two techniques are compared in terms of real-time application and accurate characterization of the damage site. Glass fibers treated with a sizing containing dispersed carbon nanotubes are used to produce composites with a planar conductivity ratio of 1:5. Holes are drilled into the laminates to represent local matrix and fiber damage, and delamination and matrix cracking is created from drop-weight impact. Three different current injection patterns are introduced for acquiring measurements. Electrical resistance measurements are obtained from a network of electrodes before and after damage. Differential voltage measurements are also collected from the electrode network in order to generate conductivity reconstructions using EIT. Center of mass equations are modified in order to approximate the damage location from the normalized resistance measurements and conductivity reconstructions, and the accuracy of each technique is compared in light of the number of measurements required.

2. Experimental methods and data analysis

2.1. Materials and composites manufacturing

All laminates used in this study were manufactured using the same technique for conductively modifying the fibers with nanotubes and consolidation of the final composite. Unidirectional E-glass nonwoven fabric (Jamestown Distributers) was treated with a fiber sizing containing dispersed multi-walled carbon nanotubes (SIZICYL XC R2G, solid content of 6.2%). The glass fabric also has an epoxy compatible sizing.

The sizing was applied using modified vacuum bag infusion. Illustrated in Fig. 1, the sized fibers were placed on top of a high permeability layer with peel-ply on either side and then sealed with an injection line by a semi-permeable membrane (Dalhtex SP-2, Airtech). The membrane traps the solid content while allowing liquid to evaporate. The assembly was sealed in a vacuum bag and placed under vacuum. The sizing was then drawn into the fibers under vacuum. To assure that the sizing is homogeneous prior to infusion it was first mixed in a centrifugal mixer (ARE-310, THINKY) at 2000 RPM for 30 s and then placed in an ultrasonic bath (Branson 1510) for 15 min. Once the fibers were fully infused they were dried under vacuum at 150 °C for 4 h [19]. The deposition of nanotubes and other solids from the sizing results in a mass increase of approximately 1% [20].

Composites were manufactured using vacuum assisted resin transfer molding (VARTM). Before infusion, the two-part epoxy resin (EPON 862, 862/Epi-Kure W, 100:26.4, Momentive Specialty Chemicals, Inc.) was de-gassed in a vacuum oven for 30 min at 60 °C. Once infused, the composites were cured at 130 °C for 6 h. Square, single-ply laminae measuring 10.2 × 10.2 cm were manufactured for the site-specific damage study. Cross-ply $[0/90]_s$ laminates measuring 8.9 × 17.8 cm were manufactured for impact testing. Unidirectional $[0]_5$ laminates measuring 20.3 × 5.1 cm were manufactured to examine delamination under tensile loading. To promote delamination, the center ply in the laminate was cut in half, transverse to the fiber direction to create a ply discontinuity where delamination would initiate under tensile loading due to shear stresses at the ply ends.

2.2. Electrode placement

Prior to infusion of the epoxy, high temperature masking tape (3 M) was placed at specific locations on the top layer to impede resin flow in the regions where electrodes would be placed and make it easier to expose the conductive network after infusion. The electrode placement geometry is shown in Fig. 2. For each specimen 32 electrodes were attached equidistantly around the boundary. The tape was then removed after the curing. The electrode regions were polished using 320 and 400 grit sandpaper. Silver paint (04999-AB, SPI Supplies) was applied to the surface to ensure a uniform current density at the electrode. Copper wires were then bonded to the electrodes using a silver epoxy (40–3900, Epoxies, etc.).

2.3. Electrical and mechanical measurements

A constant source current of 10 mA was applied between electrode pairs using a Keithley 6430 meter and the voltage was measured using a Keithley 2182A Nanovoltmeter. For switching the current source and voltage measurements between electrodes a Keithley 3706A switch meter was used. The measurements were synchronized using a customized LabVIEW program.

The in-plane conductivity was determined from a separate study [21]. Table 1 shows the longitudinal (σ_0) and transverse (σ_{90}) conductivity for each composite. The ratio between longitudi-

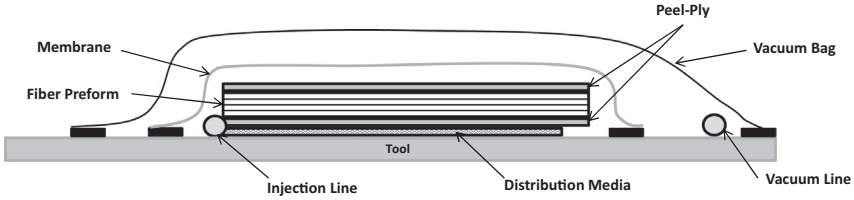

Fig. 1. Illustration of the modified vacuum bag setup used for sizing fibers with nanotubes.