CARBON NANOTUBE – BASED COMPOSITES FOR DAMAGE DETECTION AND HEALTH MONITORING

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1 Introduction

Progressively more material systems are being tailored for multifunctionality where sensory and adaptive capabilities may be incorporated. Carbon nanotubes, with their well-known unique mechanical, electrical and thermal properties, are inherently multifunctional. Considerable interest has focused on utilizing nanotubes as reinforcement in composites to tailor mechanical, electrical and thermal properties [1, 2]. Because of the inherent multifunctionality of carbon nanotubes the possibility exists to tailor the structural and functional properties of existing ceramic and polymer-based composite systems for potential applications in sensing and actuation [3-5].

The durability and performance of advanced composites are often governed by properties of the matrix and fiber/matrix interfaces. Toward development of multifunctional composites we have experimentally and theoretically investigated the use of carbon nanotubes as *in situ* sensors for strain and damage. In this paper we examine experimentally and theoretically the potential use of carbon nanotube networks formed in the polymer matrix phase of an advanced fiber composite for use as sensors to detect global strain as well as the onset, nature and evolution of damage. Using direct-current measurements the internal damage accumulation may be monitored *in situ* and may have applications in health monitoring of structures.

2 *In situ* Sensing of Strain and Damage

As a result of the change in reinforcement scales between conventional micron-sized fiber reinforcement and carbon nanotubes with nanometer diameters, it is possible to have carbon nanotubes in the matrix rich areas between fibers in an individual bundle as well as adjacent plies.

By dispersing the nanotubes in the polymer matrix and subsequently infiltrating the dispersed mixture through layers and bundles of conventional fibers the nanotubes are able to form a conductive percolating network in the matrix. Figure 1 shows the relative scale between carbon nanotubes and carbon fibers and the subsequent formation of an electrically conductive percolating network around a square array of fibers.

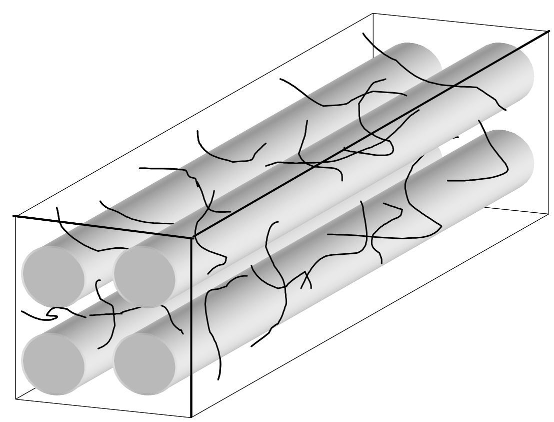

Fig. 1. A 3-D schematic showing carbon nanotubes surrounding an array of conventional micron-sized fibers in an advanced composite for *in situ* sensing.

Electrical percolation with multi-walled carbon nanotubes at extremely low volume fractions enables the creation of *in situ* sensors that are minimally invasive and not likely to substantially alter the in-plane mechanical properties of the fiber composite. To fabricate nanotube/epoxy/fiber composites the carbon nanotubes were first dispersed in the epoxy resin using a calendering approach [6]. The evolution of nanoscale composite structure during the process was evaluated using transmission electron microscopy to ensure a high degree of dispersion. The calendering technique maintains the relatively large aspect ratio of the nanotubes and results in percolation thresholds at or below 0.1 wt% carbon nanotubes. Vacuum-assisted resin transfer molding (VARTM) was then used to

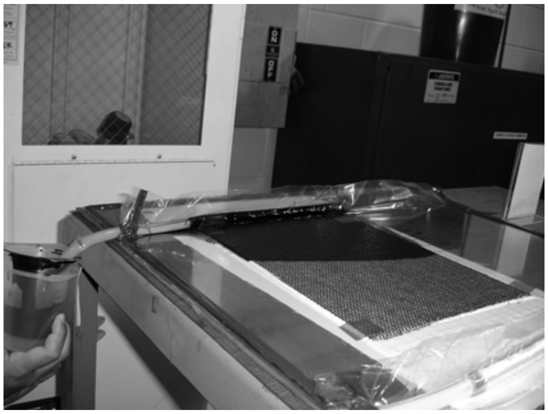

Fig. 2. Infiltration of nanotube/epoxy into a fiber preform using the VARTM process.

manufacture the glass fiber/epoxy composites with embedded carbon nanotubes. Figure 2 shows the infiltration of the nanotube/epoxy suspension into a fiber preform. As-processed nanotube/fiber composites were also electrically conductive indicating that nanotubes are able to penetrate throughout the glass preform and form a conductive percolating network in the polymer matrix [5]. The as-processed composites show linear changes in resistance as a function of applied strain. As cracks form in the composite the conducting paths in the network are subsequently broken (Figure 3). By measuring electrical resistance changes the accumulation of micro-scale damage can be measured. The technique is particularly sensitive to the onset of microcracking and delamination in composites [5].

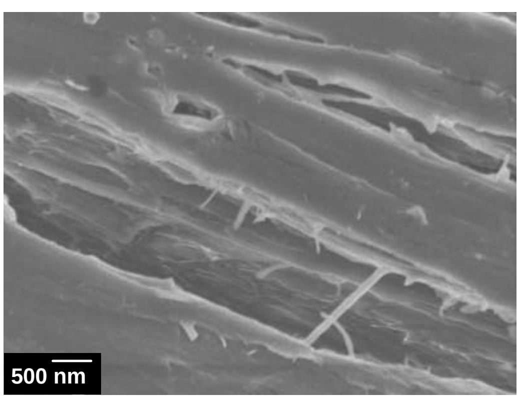

Fig. 3. Breaking of conducting paths in the percolating network by a microcrack.

3 Modeling of Nanotube Composite Sensors

In order to optimize carbon nanotube-based composites for the development of in-situ nanoscale strain and damage sensors it is crucial to develop analytical tools and experimental methodologies to assess their strain / deformation / resistance relations. There is a complete lack of understanding on the physics behind the changes in resistance as influenced by deformation. While some effort has been made in modeling the percolation behavior of nanotube-reinforced composites there is a lack of a unified model that takes into account both the structure of the nanocomposite as well as the structure of the nanotube. Based on creation of the stochastic unit cell we can subsequently examine the influence of applied strain on the electrical resistivity using Monte Carlo simulations and considering the nanotube waviness.

4 Conclusions

In situ monitoring using carbon nanotubes offers potential as both a laboratory tool for evaluating damage progression during testing as well as for in-service health monitoring. We have shown that conductive percolating nanotube networks in traditional fiber composites can accurately detect the onset, nature and progression of damage. The sensitivity of the technique for damage sensing may have broad applications including the assessment of self-healing strategies.

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