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Delamination detection with carbon nanotube thread in self-sensing composite materials

Jandro L. Abot [a,*], Yi Song [a], Maruthi Sri Vatsavaya [a], Sandeep Medikonda [a], Zachary Kier [a], Chaminda Jayasinghe [b], Nathan Rooy [a], Vesselin N. Shanov [b], Mark J. Schulz [c]

[a] *Department of Aerospace Engineering and Engineering Mechanics, University of Cincinnati, Cincinnati, OH 45221-0070, USA*
[b] *Nanoworld Laboratory, Department of Chemical and Materials Engineering, University of Cincinnati, Cincinnati, OH 45221-0012, USA*
[c] *Nanoworld Laboratory, Department of Mechanical Engineering, University of Cincinnati, Cincinnati, OH 45221-0072, USA*

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ABSTRACT

Laminated composite materials can reach high mechanical properties at low weight. Composite materials, however, are susceptible to damage due to their low interlaminar mechanical properties and poor heat and charge transport in the transverse direction to the laminate. Moreover, methods to inspect and ensure the reliability of composites are expensive and labor intensive. Recently carbon nanotube forests were spun into thread that is tough and electrically conductive. The thread was integrated into composite materials and used for the first time as a sensor to monitor strains and detect damage including delamination in the material. These self-sensing composites were found to be very sensitive to damage and will help to revolutionize the maintenance of composite structures, which will now be based on their condition and not their amount of use.

1. Introduction

Monitoring the integrity of composite materials is a broadly important practical problem and this paper shows that it is an area where nanotechnology can help. Composites are the material of choice to improve structural performance and efficiency in an increasing number of advanced applications including aircraft, spacecraft, automobiles, ships, and civil infrastructure. Damage in composites is difficult to detect because delamination and fiber breakage occur inside the material and the damage is often not obvious at the surface. Usually some method of internal inspection is needed to identify small damage in composites. This is in contrast to metals that usually experience cracks starting from their surfaces. The surface cracks propagate transversely through the thickness of the metal and can be visually detected. Another limitation of composite structures is that they may fail catastrophically which can have unfortunate consequences from a safety and economic standpoint.

To ensure the integrity of composites, non-destructive evaluation (NDE) methods have been under development for more than 20 years. The methods include ultrasound, laser vibrometry, acoustic emission, X-ray, eddy current, or thermal wave imaging, which produce an image that allows the detection of hidden damage like matrix cracking, fiber breakage, delamination, and fatigue fracture. Overall, NDE methods constitute the most accurate approach to inspect composites. They are however expensive, time consuming, and require that the component or vehicle be taken out of operation for inspection.

More recently, approaches for in situ inspection which is called structural health monitoring (SHM) have been proposed in the literature to provide frequent or continuous monitoring for damage in composite materials [1–28]. SHM approaches include vibration analysis, strain measurement using piezoresistive metallic foil gages, fiber optical or piezoelectric sensors, stress wave propagation methods, piezoresistive carbon fibers, luminance, and others. These methods have not found widespread application for several reasons. In the case of metallic foil strain gages (only usable on external surfaces) and acoustic emission methods of damage detection, too many sensors are required to detect small cracks over large structures. Fiber optic Bragg gratings can provide a large number of low bandwidth strain measurements along one fiber optic cable, micro-bend type fiber optic sensors can sense both pressure and strain, and interferometric fiber optics can provide very high sensitivity [1,5]. However, limitations of fiber optics include fiber brittleness, difficulty in handling and making connections

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* Corresponding author. Present address: Abot Composites Consulting, 873 Markley Woods Way, Cincinnati, OH 45230, USA. Tel.: +1 (513) 616 3449; fax: +1 (513) 556 5038.

E-mail address: jlabot@gmail.com (J.L. Abot).

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due to the large number of fibers, difficulty in measuring strains in different directions at the same location, the high cost of the optical demodulator, and the large number of fibers needed to monitor damage on large composite structures.

Wave propagation methods were developed to increase the area of coverage of a sensor and to monitor damage over large uniform components. Acousto-ultrasonic wave propagation methods are active methods that use piezoelectric transducers that act as both a sensor and actuator to send and receive waves [1,7]. But limitations of these methods are that wave dispersion occurs in structures that have complex geometry or anisotropic material, and the signal processing and damage detection analyses are complicated. The piezoelectric material is brittle and is best to use on the surface of structures to avoid any chance of compromising the integrity of the material. Also, an amplifier is needed to generate the diagnostic signal, which adds complication to the system.

The carbon microfiber reinforcement in composite materials could also be used to detect damage by monitoring the change in electrical resistance of the fiber [11–24]. Damage including fiber- and matrix-dominated modes would break some of the fibers or modify their cross-sectional area and thus cause their electrical resistance to change [11–20]. Delamination is a critical damage and failure mode in composite materials and has been the focus of studies using this method [12,14,17–19]. Fatigue and other failure modes under dynamic loading conditions can also be captured with this method [21–23]. In addition, the change in electrical resistance can be correlated with the strain by relying on the piezoresistive characteristics of the carbon fiber [24]. The advantage of this method is that the sensor is also an integral part of the structure. But the sensitivity to damage may be low since there are millions of parallel microfibers in a composite and damage to a small number of fibers generates a small effect on the resistance because the fibers are parallel resistors that can also conduct laterally. Also, carbon microfibers do not exhibit a tailorable piezoresistive effect and the method cannot be applied to non-conductive fibers like glass or aramid. The latter can be corrected by introducing carbon fibers into glass yarns to significantly increase their electrical conductivity and then use them for damage detection [25]. Recently, the concept of using carbon nanotubes dispersed in a polymeric matrix as piezoresistive sensors was introduced to monitor strain and failure mechanisms in glass fiber composites [26]. A remarkable sensitivity of this new method was demonstrated when identifying the nature and progression of matrix-dominated damage in glass fiber reinforced nanocomposites [27,28].

In general, SHM techniques have difficulty detecting initiating damage in composite structures with high feature density (at joints, sections with varying thickness or curvature, or complex geometry) and without altering the material's microstructure. SHM techniques may also compromise the integrity or reliability of the structure by requiring many sensors.

2. Concept of self-sensing composite

We propose that a practical way to monitor a composite material for damage down to the microstructure level is to integrate micro- or nano-scale continuous materials with sensing capabilities into the composite. In particular, thread spun from carbon nanotube (CNT) forests can be used as the sensor element, and damage can be monitored through electrochemical impedance spectroscopy (EIS) measurements. Sensor thread can be bonded onto the surface or embedded throughout the composite material. These sensors, used for the first time here, are able to monitor strains and detect damage and failure including delamination without altering the integrity or reliability of the structure, and without adding weight to the structure.

2.1. Carbon nanotube thread

Producing nanotube sensor materials starts with growing a carbon nanotube forest. The forest is drawn (Fig. 1a) and twisted into a fine thread (Fig. 1b) and wound onto a spool. This method of spinning thread was developed a few years ago [29,30]. The CNT thread in this study is spun from a mm-tall CNT forest with a density of more than five billion CNT per square centimeter [31,32]. The carbon nanotubes consist of two or three concentric graphitic layers with an outer diameter of about 9 nm. Each cross-section of thread typically contains more than 1000 carbon nanotubes. Multiple threads can be twisted simultaneously to form yarn. A two-thread yarn is shown in Fig. 1c. Drawing the nanotubes from the forest without twisting produces a ribbon as shown in Fig. 1d. The thread and ribbon material is being integrated into composites in different configurations to sense damage. The CNT threads in this study have a diameter of about 10–30 μm and they are coated with a thin dielectric layer to isolate it from carbon microfibers in laminated composites. Typically, a polyurethane or epoxy-based coating with a thickness of a few microns is applied to the thread and later cured.

The stress–strain behavior of the CNT thread under quasi-static uniaxial loading was found to be highly dependent on the CNT morphology and the thread fabrication process. The elastic modulus, tensile strength, and strain to failure can be tailored based on the twist of the thread. The electrical resistivity of the CNT thread is as low as $10^{-4}\ \Omega$ cm thus allowing the development of a robust and efficient SHM system. This CNT thread should be useful through the temperature range of −200 °C to over +200 °C. CNT thread is smaller in diameter and lighter than metal wire, tougher than carbon fiber, and can be tied in a knot without being weakened. Thus CNT thread is suitable as a distributed sensor material.

2.2. Piezoimpedance property

Carbon nanotube thread and ribbon have a piezoimpedance property that depends on the exact construction of the material

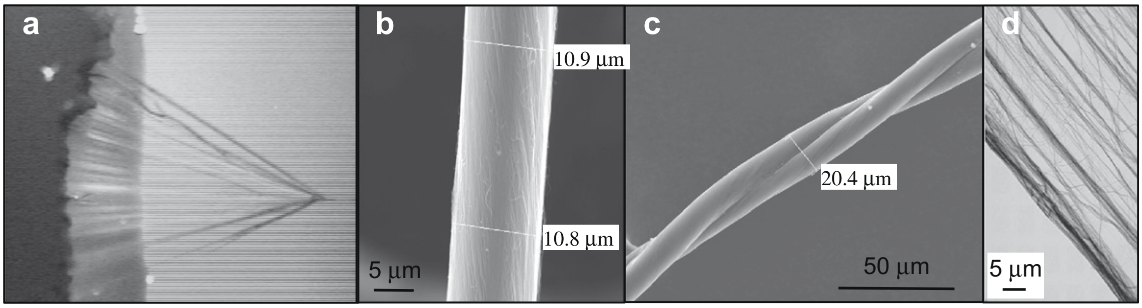

Fig. 1. Carbon nanotube materials that can be used for sensing. (a) CNT being pulled and twisted from a CNT forest. (b) A CNT thread. (c) Two strands twisted simultaneously to form a yarn. (d) A CNT ribbon.