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Piezoresistive effect of the carbon nanotube yarn embedded axially into the 3D braided composite

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ABSTRACT

A new method for monitoring 3D braided composite structure health in real time by embedding the carbon nanotube yarn, based on its piezoresistivity, in the composite axially has been designed. The experimental system for piezoresistive effect detection of the carbon nanotube yarn in the 3D braided composite was built, and the sensing characteristics has been analyzed for further research. Compared with other structural health monitoring methods, the monitoring technique with carbon nanotubes yarns is more suitable for internal damage detection immediately, in addition the strength of the composite can be increased by embedding carbon nanotubes yarns. This method can also be used for strain sensing, the development of intelligent materials and structure systems.

Introduction

Carbon nanotube yarn

Carbon nanotubes have a unique nanostructure and can be considered as one-dimensional quantum wires. After Iijima [1] discovered the carbon nanotube in 1991, it has attracted vast research interest owing to its excellent electrical, thermal, and mechanical properties [2–4]. Carbon nanotubes can be destroyed only with a very high strain of 15%–20% [5], and the original cross section of the carbon nanotube can be recovered after unloading. This unique feature makes it possible to braid with carbon fiber and strengthen substrates without affecting the mechanical properties of the composite.

Carbon nanotube materials can be used to design micro sensors because they can detect physical parameters including stress, sound waves, and acceleration [4]. Carbon nanotube yarns are characterized by good electrical conductivity [6,7], high hardness, and piezoresistive property, and it can be used in structural health monitoring system for composites without changing the existing strain distribution or the integrity of the material. Piezoresistive effect is that the resistance of one kind of material changes under external forces.

The resistance of piezoresistive materials changes when they are deformed by external force. Carbon nanotube yarn can be used as a sensor based on its piezoresistive property to monitor the structural health of composite materials in real time by embedding the yarn in the axial direction. Tomber et al. [8] found that carbon nanotubes have a high sensitivity to resistance changes induced by deformation. Their experimental results show that the conductivity of carbon nanotubes decreased from $10^{-5}\,\Omega^{-1}.cm^{-1}$ to $10^{-7}\,\Omega^{-1}.cm^{-1}$ when the deformation ratio is increased from 0% to 3.2%. Further, the whole process of resistivity change with external force is reversible. Therefore, the carbon nanotube yarn sensor can be used as a highly sensitive pressure-sensing element.

Three-dimensional braided composite

3D braided composites, as a type of advanced composite material, have some excellent properties, such as high strength, high modular ratio, and high damage tolerance [9], and they have become an important structural material in various fields, such as aviation and space. Further, they have been widely used in the automotive, medical, and sports industries, among many others. However, three-dimensional braided composites are subjected to various types of stress and strain during usage, which causes structural damage and may lead to serious accidents and huge losses.

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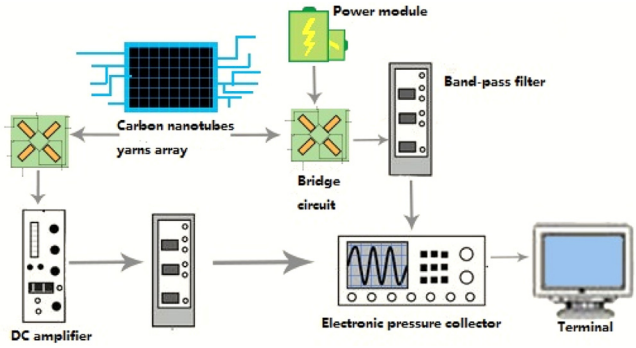

Fig. 1. Experimental system based on carbon nanotube yarns.

Fig. 2. Rectangular 3D braided platform.

Therefore, it is vital to perform real-time monitoring for 3D braided composite structural health [10].

In this paper, a carbon nanotube yarn sensor based on piezoresistivity has been developed. It can be embedded vertically in 3D braided composites in the axial direction to achieve the real-time monitoring of parts during operation and solve key technical problems [11,12].

Experiment

A new method for monitoring 3D braided composites structure health using axially embedded carbon nanotube yarn has been designed according to the theory of carbon nanotube yarn sensors.

Experimental system for piezoresistive effect detection

The design of the experimental system for piezoresistive effect detection of carbon nanotube yarns in composite includes a signal data acquisition module, which is based on the carbon nanotube yarn sensing technology, and signal processing and storage modules. The background server should have a set of software for data analysis and diagnosis including system identification, model updating, condition assessment, and the prediction of service life.

Carbon nanotube yarn is a long line formed by billions of carbon nanotubes, which are connected by Vander Waals force. The resistance of the line changes when it is subjected to deformation, and the initial resistance value can be recovered when the stress is unloaded [13]. The yarn is insulated and processed into a sensing electronic component. It can monitor damage to composites by calculating the electrochemical impedance change of the carbon nanotube yarn.

The experimental system is constructed based on the piezoresistive property of carbon nanotube yarn, and it can monitor damage to a composite preform by detecting the location of damage, temperature, and so on. Furthermore, the system has the ability to process real-time data to obtain real-time damage state information on composite materials [14–16]. The system is made up of power module, carbon nanotubes yarns array, DC amplifier, Wheatstone bridge, and so on. The components of the system based on carbon nanotube yarn sensing technology are shown in Fig. 1.

In the system, the output value of the Wheatstone bridge reflects the strain of the carbon nanotube yarn array.

Embedding carbon nanotube yarn into 3D braided composites

In 3D braiding technology, the four-step braiding method with the 1×1 style [17] can be divided into some different styles

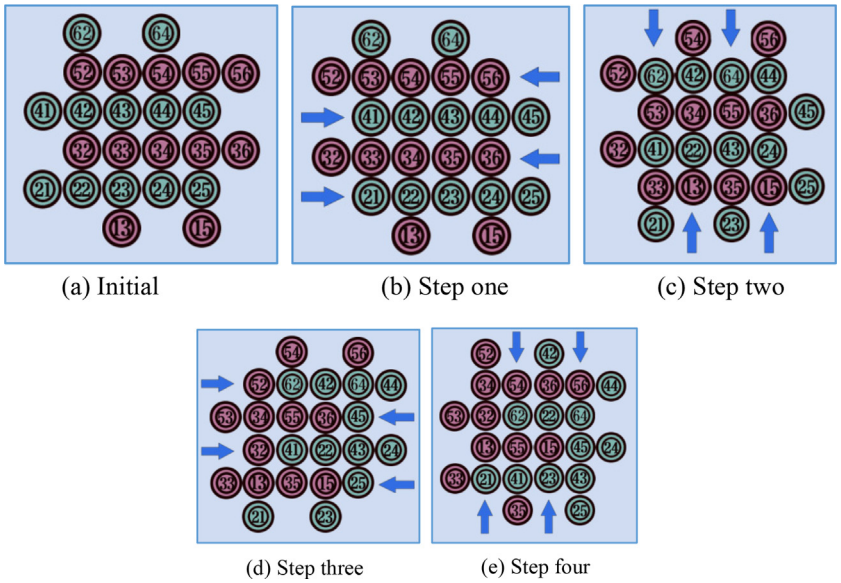

Fig. 3. Four-step braiding process.