Introduction

The sensor/actuator embedded smart materials and systems are essential for structural damage detection and control. There is need for smart structural materials, which can be used to sense strains, and adjust the structural properties so as to achieve desired response. Carbon nanotube composites have the potential to be such a smart structural material. Results (Baughman et al., 1999) have shown that when carbon nanotube films, also called as “buckypapers”, are used as actuators, large actuator strains can be achieved by smaller operating voltages as compared with ferroelectric and electrostrictive materials. Single wall carbon nanotubes (SWCNTs) promise to be such a reinforcement material for nanocomposites because of their superior mechanical properties. Researchers (Hadjiev et al., 2001; Zhao et al., 2001) have studied the Raman band shift in SWCNT's as a function of stress/strain in carbon nanotubes. Raman studies on multi-wall carbon nanotubes have also been carried out (Schadler et al., 1998; Wagner et al., 1998). Though the experiments are carried at nanoscale, the results illustrate the potential of SWCNT as strain/stress sensor. It has also been shown that the electrical band gap changes as a function of axial compression, tension stretch, torsion, and bending strain (Peng and Cho, 2002; Tombler et al., 2000; Yang and Han, 2000). Strong dependence of SWCNT’s band structure on mechanical deformation makes it possible to develop nano-electro-mechanical sensors. Most of the studies to date relate the mechanical deformation with the change in electrical properties at the nanoscale. In this study, change in the electronic property of carbon nanotubes due to strain at macroscale is demonstrated using the experimental results. Such carbon nanotube films have randomly oriented SWCNT's with isotropic strain sensing properties; thus, have multidirectional and multi-location strain sensing capability.

Test set-up

The carbon nanotube films used in this study are produced by mixing SWCNTs with 0.25 mg/ml N,N-Dimethylformamide (DMF) and filtering the mixture through a 0.2 mm teflon membrane. Freestanding carbon nanotube film (Buckypaper) is peeled from the filter after rinsing and drying of the remaining material. The carbon nanotube film is further dried for 24h under vacuum. Figure 1 shows the SEM picture of a carbon nanotube film.
with \( \sim 15 \mu m \) thickness. To explore the strain sensing potential of the carbon nanotube film, it is attached to a 0.25 \( \times \) 2 \( \times \) 24 in. brass specimen and subjected to pure bending moment using two-point loading as shown in Figure 2. For insulation, a PVC film is attached between the brass specimen and carbon nanotube film. High strength epoxy and a vacuum-bonding method is used to attach carbon nanotube film and PVC to the brass specimen in order to ensure the perfect strain transfer – between brass, PVC, and the carbon nanotube film. As shown in Figure 3, a conventional electrical resistance strain gage is attached next to the carbon nanotube film to measure flexural strain for comparison purposes. Load \( P \) is applied in increments using a servo-hydraulic machine. The corresponding change in voltage across the carbon nanotube film is measured using four-point probe measurement (Smits, 1958). Input voltage across two outer probes is kept constant during the measurement and change in voltage across the two inner probes is recorded. Strain measurements are also made using conventional strain gage. The change in voltage is proportional to the change in resistivity of the film (Dharap et al., 2004). The change in voltage due to the change in dimensions of the film is small as compared to the change in voltage due to the change in resistivity of the film (Li et al., 2003).

**Results and discussion**

Figure 4 shows the change in voltage in the carbon nanotube film as a function of measured flexural strain from the conventional strain gage. As the strain measured by the conventional strain gage increases from 0 to \( \sim 600 \mu m/m \) the voltage change measured across the two outer probes increases from 0 to \( \sim 200 \mu V \). A nearly linear trend between the change in voltage and the strain is evident; although, deviation from the linear trend exists. Further study is needed to establish causes for deviation from linear trend such as temperature and gas exposure history (Bezryadin et al., 1998; Collins and Avouris, 2000; Hone et al., 2002). The change in voltage is measured by moving the four-point probe to several parallel locations on a single carbon nanotube film, which also yielded a similar linear trend.

**Conclusion**

It is evident from the experimental study that the carbon nanotube film can be used for measuring flexural strains at the macroscale. Carbon nanotube films are made up of randomly oriented SWCNTs; hence, their electronic properties are independent of direction. Hence taking
measurement along different directions provides corresponding strains. Carbon nanotube films can also be integrated into composites to simultaneously act as strong structural material and sensor. Such composites may find application in smart structures.

References


