Research article

Flexural strain sensing using carbon nanotube film

Prasad Dharap
Zhiling Li
Satish Nagarajaiah and
Enrique V. Barrera

The authors

Prasad Dharap, Zhiling Li, Satish Nagarajaiah and **Enrique V. Barrera** are all based at the Rice University, Houston, Texas, USA.

Keywords

Sensors, Carbon, Strain measurement

Abstract

Strain sensing characteristic of carbon nanotubes has been established in the past at nanoscale. In this study, it is shown that the carbon nanotube film sensors, made up of randomly oriented carbon nanotubes, can be used as strain sensors at macro level. A nearly linear trend between the change in voltage, measured using a movable four point probe, and strains, measured using conventional electrical strain gage, indicates the potential of such carbon nanotube films for measuring flexural strains at macro level. Isotropic strain sensing capability of the carbon nanotube film sensors, due to randomly oriented carbon nanotubes, allows multidirectional and multi-location measurements.

Electronic access

The Emerald Research Register for this journal is available at
www.emeraldinsight.com/researchregister

The current issue and full text archive of this journal is available at
www.emeraldinsight.com/0260-2288.htm

Sensor Review
Volume 24 · Number 3 · 2004 · pp. 271–273
© Emerald Group Publishing Limited · ISSN 0260-2288
DOI 10.1108/02602280410545399

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 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 SWCNTs with isotropic strain sensing properties; thus, have multidirectional and multi-location strain sensing capability.

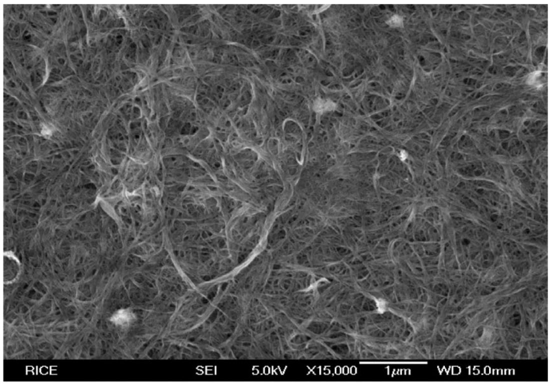
Test set-up

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 24 h under vacuum. Figure 1 shows the SEM picture of a carbon nanotube film

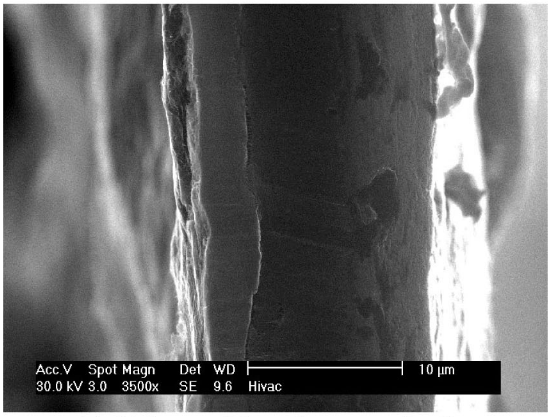
---

The authors wish to acknowledge the support of the Texas Institute for the Intelligent Bio-Nano materials and Structure for Aerospace Vehicles, funded by NASA Cooperative Agreement no. NCC-1-02038.

Figure 1 SEM image of the carbon nanotube film



(a) carbon nanotube film made up of entangled bundles of SWCNT's



(b) thickness of the carbon nanotube film

with ~15 μm thickness. To explore the strain sensing potential of the carbon nanotube film, it is attached to a 0.25 × 2 × 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 ~600 μm/m the voltage change measured across the two outer probes increases from 0 to ~200 μV. 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

Figure 2 Schematic diagram of the bending test set-up

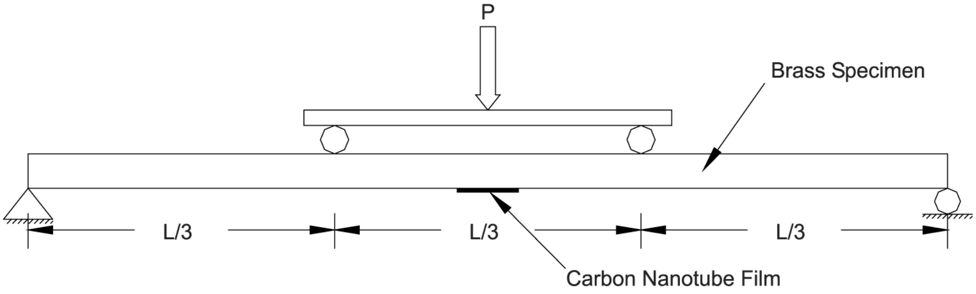


Figure 3 Carbon nanotube film with insulating PVC attached to the brass specimen, and a conventional metal strain gage attached next to the film

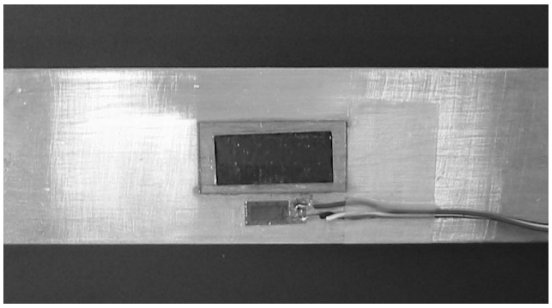
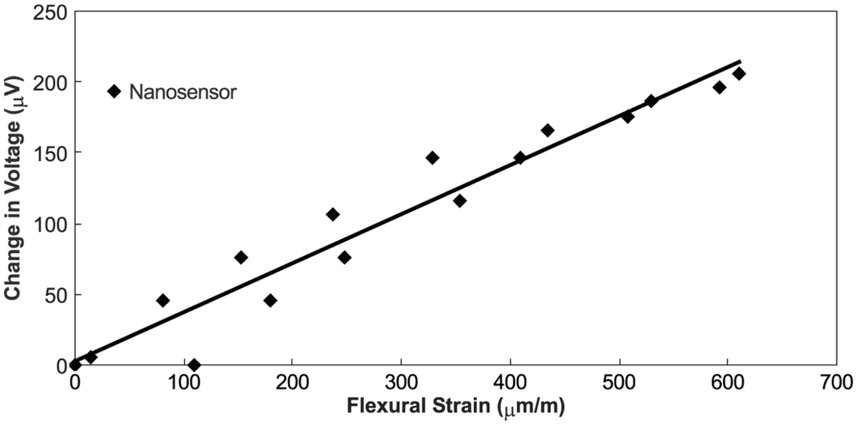


Figure 4 Change in voltage as a function of flexural strain in carbon nanotube film



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

Baughman, R.H., Cui, C., Zakhidov, A.A., Iqbal, Z., Barisci, J.N., Spinks, G.M., Wallace, G.G., Mazzoldi, A., De Rossi, D., Rinzler, A.G., Jaschinski, O., Roth, S. and Kertesz, M. (1999), "Carbon nanotube actuators", *Science*, Vol. 284, pp. 1340-4.

Bezryadin, A., Vershaueren, A.R.M., Tans, S.J. and Dekker, C. (1998), "Multiprobe transport experiments on individual single-wall carbon nanotubes", *Physical Review Letters*, Vol. 80 No. 18, pp. 4036-9.

Collins, P.G. and Avouris, P. (2000), "Nanotubes for electronics", *Scientific American*, pp. 62-9.

Dharap, P., Li, Z., Nagarajaiah, S. and Barerra, E.V. (2004), "Nanotube film based on single-wall carbon nanotubes for strain sensing", *Nanotechnology*, Vol. 15 No. 3, pp. 379-82.

Hadjiev, V.G., Lliev, M.N., Arepalli, S., Nikolaev, P. and Files, B.S. (2001), "Raman scattering test of single-wall carbon nanotube composites", *Applied. Physics Letter*, Vol. 78 No. 21, pp. 3193-5.

Hone, J., Llaguno, M.C., Nemes, N.M., Johnson, A.T., Fischer, J.E., Walters, D.A., Casavant, M.J., Schmidt, J. and Smalley, R.E. (2002), "Electrical and thermal transport properties of magnetically aligned single wall carbon nanotube films", *Applied. Physics Letters*, Vol. 77 No. 5, pp. 666-8.

Li, Z., Dharap, P., Nagarajaiah, S., Barrera, E.V. and Kim, J.D. (2003), "Carbon nanotube film sensor", *Advanced Materials*, Vol. 16 No. 7.

Peng, S. and Cho, L. (2002), "Nano electro mechanics of semiconducting carbon nanotubes", *Journal of Applied Mechanics*, Vol. 69 No. 4, pp. 451-4.

Schadler, L.S., Giannaris, S.C. and Ajayan, P.M. (1998), "Load transfer in carbon nanotube epoxy composites", *Applied Physics Letters*, Vol. 73 No. 26, pp. 3842-4.

Smits, F.M. (1958), "Measurement of sheet resistivities with the four-point probe", *The Bell System Technical Journal*, pp. 711-8.

Tombler, T.W., Zhou, C., Alexseyev, L., Kong, J., Dai, H., Liu, L., Jayanthi, C.S., Tang, M. and Wu, S. (2000), "Reversible electromechanical characteristics of carbon nanotubes under local-probe manipulation", *Nature*, Vol. 405, pp. 769-72.

Wagner, H.D., Lourie, Q., Feldman, Y. and Tenne, R. (1998), "Stress-induced fragmentation of multiwall carbon nanotubes in a plymer matrix", *Applied Physics Letters*, Vol. 72 No. 2, pp. 188-90.

Yang, L. and Han, J. (2000), "Electronic structure of deformed carbon nanotubes", *Physical Review Letters*, Vol. 85 No. 1, pp. 154-7.

Zhao, Q., Wood, J.R. and Wagner, H.D. (2001), "Stress fields around defects and fibers in a polymer using carbon nanotubes as sensors", *Applied Physics Letters*, Vol. 78 No. 12, pp. 1748-50.