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Damping and Stiffness Enhancement in Composite Systems with Carbon Nanotubes Films

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ABSTRACT

Structural damping is an essential design parameter for many engineering applications. We demonstrate here the potential for the use of multi-walled carbon nanotube films in structural systems where vibrational energy dissipation is important. These films can provide a light weight, minimally intrusive alternative to conventional damping materials such as visco-elastic polymers. In addition, because of their multifaceted properties, damping materials utilizing carbon nanotubes are expected to be superior to traditional materials and may enhance the performance of the system by increasing structural stiffness and thermal stability.

INTRODUCTION

Carbon nanotubes (CNTs) have been shown to possess an amazing blend of mechanical properties such as high elastic modulus (~1TPa), strength (~50GPa) and low density (1.3g/cm^3) [1-5]. Due to this extraordinary combination, carbon nanotubes are being heavily researched for use as structural components in engineering systems. However the potential of augmenting damping in structural systems by using CNTs has not yet been fully explored in the literature.

Structural damping is an important aspect of many engineering applications. Traditional damping materials, being polymeric materials, perform well in terms of energy dissipation and damping, but only at low temperatures (below 60°C). Another limitation is that when damping films are integrated into composite systems, mechanical properties and structural integrity are often sacrificed [6-9]. This is due to the low modulus and strength of polymeric materials. CNTs, which possess high modulus and strength to weight ratios, along with good thermal stability, and a large surface area to volume ratio, show promise as a damping material. Minimally intrusive CNT films could potentially be seamlessly integrated into composite systems without a decrease in stiffness/strength of the host structure. The mechanical properties of the composite system may even be enhanced rather than diminished by such reinforcement due to the outstanding mechanical properties of CNTs. Also, because CNTs are thermally stable up to temperatures around 800°C, CNT-damping films may far exceed the operating temperatures of traditional polymeric materials.

EXPERIMENTAL DETAILS

Aligned multi-walled carbon nanotube (MWNT) arrays were produced on silica (SiO$_2$) substrates (25.4×25.4mm in size) using catalytic thermal chemical vapor deposition (CVD) of a xylene/ferrocene mixture at 800°C for a time of 15 minutes (detailed in Refs. [10, 11]). This process yielded a film of CNT with a length of ~50μm. Silica was used as a substrate because it can be readily used for the growth of aligned MWNT films as shown in the scanning electron microscopy (SEM) image shown in figure 1.
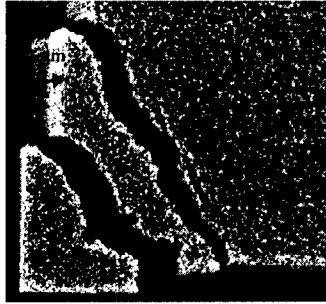
Figure 1. SEM image of aligned CVD grown CNT film.

A piezoelectric sheet was bonded to the CNT film (anchored on SiO_2 substrate) with an acrylic adhesive by the application of uniform pressure of 0.5MPa. The piezoelectric material was used because by applying a sinusoidal voltage, it provided for a convenient method of inducing a dynamic bending in the composite beam. A baseline beam was also created in a similar fashion by sandwiching a silica substrate and piezoelectric sheet together without the CNT film. The dimensions of the beams are shown in figure 2.
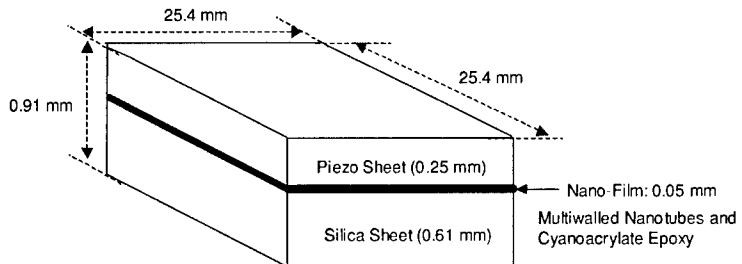

Figure 2. Schematic of sandwich test samples for damping characterization.

Both the beams were tested in the same manner. First, one end was rigidly clamped, creating a cantilever system. The dimensions of the setup were the same for both beams; cross-sectional dimensions of 25.4×0.91mm and cantilever length of 22.9mm. The piezoelectric sheet was excited by applying an alternating voltage and sweeping from low to high frequency, creating a bending moment in the beam. The response to this bending moment was measured with strain gauges mounted at the root of the beam [12]. A finite element model was developed in order to quantify the observed behavior.

RESULTS

Experimental observations and Beam Modeling

The composite beams were tested in a flat-wise bending mode by applying an alternating voltage to the piezoelectric sheet, and sweeping it from low to high frequency. Figure 3 shows the strain response of the baseline and CNT reinforced beams for an input of 50Vrms to the

piezoelectric sheet (along with finite element beam modeling calculations). It can be seen that the magnitude of the beam root strain at resonance is significantly reduced by CNT reinforcement. This qualitatively corresponds to an increase in the damping of the system. In addition, the shift in the bending mode frequency from 700Hz to 840Hz suggests an increase in composite beam stiffness.
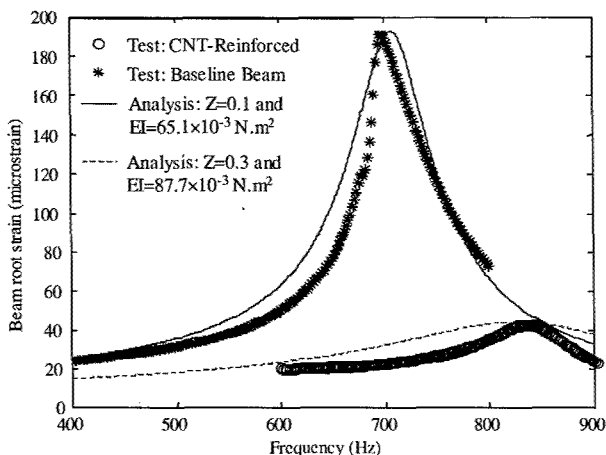

Figure 3. Experimental data of beam response and comparison to modeling results.

In order to quantify the increase in damping and stiffness observed in the experimental results, a finite element beam model was developed. The cross-sectional bending stiffness, EI, and mass per unit length, ρA were calculated from the data in table 1. From this model, the equation of motion for the beam is given as:

$$[M_b]\{\ddot{w}\}+[(1+Z_b.j).K_b]\{w\}=Q_b$$

(1)

where Q_b and Z_b are the piezoelectric force moment and structural damping ratio, respectively. M_b and K_b are the global mass and stiffness matrices as described in Reference 13. The beam bending strain can then be found from the solution for w, the beam response, and is found to be:

$$\varepsilon_{zz}(x) = z\frac{\partial^2 w}{\partial x^2}$$

(2)

where x is the longitudinal axis and z is the thickness direction of the beam. A detailed discussion of the model is developed in reference 13.

Table I. Properties of Composite Beam Materials

Sandwich Beam Components (25.4 mm × 25.4 mm)	Young's Modulus (GPa)	Thickness (μm)	Density g/cm^3
PZT-5H	69	250	7.8
Silica	131	610	2.33
Multiwalled Nanotubes that comprise the Nano-Film	1000 (data for individual tubes)	50	1.1-1.5
Adhesive Layer	3	50	0.8

The analysis of the baseline composite beam resulted in a cross-sectional bending stiffness of 65.1×10^{-3}Nm^2 and a mass per unit length of 0.12g/mm. A good correlation between the beam model and observed data is seen for a damping ratio (Z_b) of 0.1, where both the correct bending mode frequency (700 Hz) and strain were predicted ($\sim40\times10^{-6}$). The CNT reinforced beam analysis also showed a good correlation with the experimental data for a damping ratio of 0.3. The cross-sectional stiffness was found to be 87.7×10^{-3}Nm^2. The results of the model are also shown in figure 3 and compared to the experimental data. From this, it can be concluded that the CNT reinforcement increases the composite damping by 200% and the stiffness by 30% compared to the baseline beam.

Analysis of Film Microstructure

SEM was used to investigate the microstructure of the nanotube layer in the composite structure. Figure 5 reveals that the CNT film contained a network of densely-packed, cross-linked nanotube clusters. This unusual film morphology is not characteristic of CVD grown CNT arrays and is a result of the applied pressure (~0.5 MPa) during the curing of the acrylic adhesive. The connectivity of the CNTs in the film suggests that these strong interactions between the tubes are a primary source of energy dissipation when adjacent clusters are displaced relative to one another. As a consequence, the CNT reinforced film exhibits a significant increase in damping. In addition, the cross-links between tubes offer an effective method of load transfer between tubes resulting in improved beam stiffness
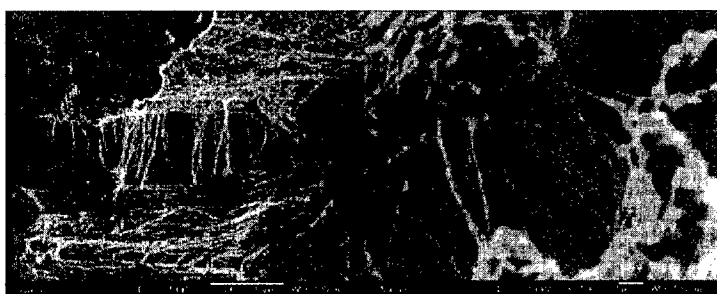

Figure 4. SEM image of cross-linked network morphology of CNT film after application of uniform pressure of 0.5 MPa.

Molecular Dynamics Simulations

Molecular dynamics simulations were conducted in order to better understand the role of inter-tube friction on the damping response. Four aligned single walled nanotubes with an inter-tube separation of 3.35Å were considered. A momentum impulse was applied along the axial direction of one tube. Figure 5 demonstrates the reduction in impulse velocity as a function of time for the system for externally applied pressures of 0GPa, 0.5GPa, and 1.0GPa. This decrease in velocity is due to energy dissipation caused by inter-tube friction. It can be seen from figure 5 that damping of the impulse is greatly enhanced as the external pressure is increased.

Figure 5. MD simulation showing increased damping characteristics of SWNT upon application of external pressure.
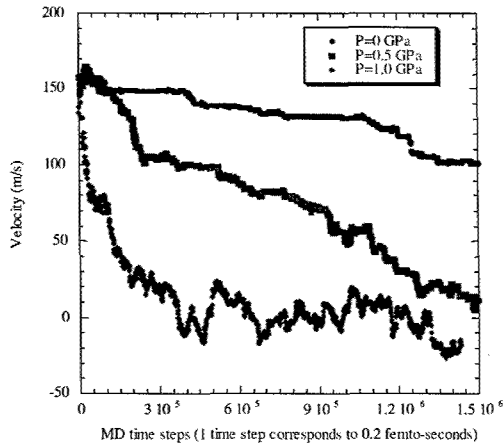
Properties Comparison with Conventional Damping Materials

Table 2 lists the properties of two commercially available damping polymers, 3M 1SD-112 (acrylic) [14] and Soundcoat Dyad-606 (polyurethane) [15], along with the properties that have been determined for the CNT damping film. The density of the damping film is similar to that of the commercial polymers. Conventional polymeric materials also degrade at higher temperatures and can only be used at temperatures below ~100°C. CNTs however, are thermally stable at temperatures as high as 800°C. The modulus of the CNT damping film is 100 times higher than the Soundcoat polymer, adding mechanical integrity to any system where it is utilized. The thickness of the CNT film was also much less that the two commercial materials.

Table II. Property Comparison with Commercial Damping Materials

Property	3M-ISD-112	Soundcoat Dyad-606	Nano-Film
Modulus at 850 Hz and room temperature	400 psi (2.75 MPa)	4.5×10^4 psi (0.3 GPa)	41.2×10^6 psi (284 GPa)
Density	0.9 gm/cm^3	1.2 gm/cm^3	1.1 gm/cm^3
Thickness	127 μm	500 μm	50 μm
Temperature Limit	65° C	70° C	~600° C
Frequency Limit	1 KHz	1 KHz	Tested up to 4 KHz

CONCLUSION

The use of carbon nanotube films in damping applications show potential for several advantages over traditional polymeric materials. The experimental data presented here shows that such a film may provide a 200% increase in damping over a baseline system. SEM analysis of the film microstructure suggests energy dissipation is a result of strong inter-tube connectivity caused by the application of pressure during sample fabrication. Finite element modeling of the composite system showed good correlation with experimental data. Molecular dynamics simulations indicated that inter-tube friction was the dominant mechanism for damping within the nanotube film. In addition to providing this energy dissipation, these films are minimally intrusive, thermally stable, light weight, and may increase the stiffness and strength of the system.

ACKNOWLEDGEMENTS

REFERENCES

1. J.P. Lu, Phys. Rev. Lett. **79**, 1297 (1997).
2. E. Hernandez, C. Goze, P. Bernier, A. Rubio, Phys. Rev. Lett. **80**, 4502 (1998).
3. M. M. J. Treacy, T. W. Ebbesen, J. M. Gibson, Nature **381**, 678 (1996).
4. P. Poncharal, Z.L. Wang, D. Ugarte, W.A. de Heer, Science **283**, 1513 (1999).
5. M. Yu, O. Lourie, M. J. Dyer, K. Moloni, T. F. Kelley, R. S. Ruoff, Science **287**, 637(2000).
6. W. H. Liao, K. W. Wang, Journal of Sound and Vibration **207**, 319 (1997).
7. C. Brackbill, L. E. Ruhl, G. A. Lesieutre, E. C. Smith, Journal of the American Helicopter Society **45**, 34 (2000).
8. A. Baz, S. Poh, Journal of Shock and Vibration **7**, 81 (2000).
9. C. L. Davis, G. A. Lesieutre, Journal of Sound and Vibration **232**, 601 (2000).
10. Z. J. Zhang, B. Q. Wei, G. Ramanath, P. M. Ajayan, Appl. Phys. Lett. **77**, 3764 (2000).
11. B. Q. Wei, Z. J. Zhang, G. Ramanath, P. M. Ajayan, Appl. Phys. Lett. **77**, 2985 (2000).
12. B. Q. Wei, N. Koratkar, P. M. Ajayan, "Non-intrusive damping films featuring carbon nanotubes", Proceedings of the 43rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Denver, Colorado, April 22-25, 2002.
13. N. Koratkar, I. Chopra, AIAA Journal **38**, 1113 (2000).
14. 3M Bonding Systems Division, "Material Data Sheets", 3M Center, Building 220-7E-01, St. Paul, MN, 55144-1000, February 1999.
15. J. M. Biggerstaff, J. B. Kosmatka, J. Comp. Mater. **32**, 21 (1998).