RECENT PROGRESS IN RESISTANCE-BASED DAMAGE SENSING OF CARBON NANOTUBE-FIBER COMPOSITES

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1 Introduction

Sensing the onset of local damage, such as matrix cracking, delamination, fiber pull-out and breakage in composite materials is challenging. The initiation of small-scale damage which leads to ultimate failure of a structure is particularly difficult to detect, since the mechanical behavior of a composite part is not noticeably affected by this. In recent years, several different approaches towards non-invasive damage detection, including ultrasonic C-scanning, X-ray imaging and acoustic emission measurement, have been utilized. The current work focuses on resistance-based damage sensing in electrically conductive composites using carbon nanotubes. In these materials, damage initiation and propagation will sever the conductive network, resulting in increases in electrical resistance which can be measured *in situ*.

2 Electrical Percolation for *in situ* Sensing

Over the past 25 years, the modification of composites using conductive fibers to achieve electrical percolation has been extensively studied [1-2]. In order to sense the onset of local damage, the scientific base has progressed from micron-sized conductive fibers to carbon nanotubes. Due to the high aspect ratios of the nanotubes, electrical percolation can occur in polymer resins at concentrations below 0.1 wt.% [3].

2.1. Tension Loading

We have demonstrated that resistance-based sensing is highly sensitive to tension-induced damage [3]. In Fig. 1, significant increases in resistance are observed across the composite at strains above 0.25% after which microcracks form. Upon failure, the conductive network is severed, resulting in a drastic increase in resistance.

2.2 Compression Loading

While it is intuitive that damage accrued during tensile loading will result in an increase in resistance across a composite, it is interesting and relevant to examine the electrical behavior of composite materials under compression and shear loadings as well. The response of an axially loaded disc-shaped specimen (20 ply, 45º off-axis E-glass/epoxy) with embedded carbon nanotubes to quasi-static compressive loading is plotted in Fig. 2 [4]. Resistance is measured across the specimen diameter and is observed to decrease during linear elastic loading. During damage accumulation, applied load pins cracks closed, causing resistance to increase disproportionally. Only after unloading does resistance increase substantially, accurately reflecting the amount of damage accumulated.

2.3 Impact Loading

The effect of impact damage on the electrical response of a composite panel with an electrically-percolating carbon nanotube network is evaluated using a drop-weight tower [5]. Electrical resistance measured across the composite panel increases after each successive impact, indicating the formation of damage within the composite.

3 Processing of Carbon Nanotube Composites

A major challenge associated with the processing of carbon nanotube-based composites is achieving a high degree of dispersion without sacrificing aspect ratio. Toward this end, Thostenson and Chou [6]

adopted a calendering method in which a three-roll mill is used for nanotube dispersion.

Recently, an alternative method of processing carbon nanotube composites using a nanotube-based sizing agent has been developed [7]. This method results in composites with localized concentrations of carbon nanotubes at the fiber surface and is effective in sensing matrix cracking. Furthermore, this method has proven to be highly adaptable for processing thick-section composites [7].

4 New Research Area - Dynamic Behavior

Due to their complex, rate-dependent mechanical behavior, research into damage sensing in composites under dynamic loadings is of great interest. Recent efforts at studying the dynamic compressive behavior of these materials (identical in morphology to those evaluated under quasi-static compression) using the split Hopkinson pressure bar apparatus have been undertaken.

4.1 Split Hopkinson Pressure Bar Experiment

In the split Hopkinson pressure bar experiment, a specimen is sandwiched between two rigid, cylindrical, long (length >> diameter) bars, referred to as the incident and transmission bars, typically assumed to behave in a linear elastic manner [8]. A striker bar (less than one-fourth of the incident bar length) is propelled using a gas gun toward the incident bar free end [9]. The resulting impact causes a compression wave to travel to the bar-specimen interface. Depending on experimental and material factors (specimen thickness, bar/specimen acoustic impedance ratio), a fraction of the compression wave is reflected through the incident bar as a tensile wave while the remainder passes through the specimen to the transmission bar [10]. The incident (σ_I), reflected (σ_R) and transmitted (σ_T) pulses (measured via strain gages mounted far from the bar-specimen interface) are plotted in Fig. 3. Time-shifting these pulses to the bar-specimen interface and applying classic Kolsky data reduction [11] (which assumes linear elastic behavior of the bars and stress equilibrium of the specimen) enables the determination of specimen stress and deformation rate during the experiment, based on the incident, reflected and transmitted pulses.

Efforts including matching specimen and bar cross-sectional area, as well as selecting an appropriate specimen thickness and appropriate bar material were made in order to ensure that specimens achieved stress equilibrium during Hopkinson bar testing (Fig. 4) [4].

4.2 Dynamic Behavior of Carbon Nanotube-Based Composites

Fig. 5. depicts the progression of electrical resistance over time, measured across the diameter of a specimen impacted multiple times via Hopkinson bar loading. Permanent increases in resistance occur after impact loadings #5-7 in Fig. 5; this behavior corresponds to a loss of specimen stiffness which is observed in the stress-strain behavior during these impact cycles [4]. As the striker bar velocity (and thus the impact energy) is increased, the specimen resistance also increases accordingly (Fig. 6) [4]. Upon failure due to delamination (Fig. 7), resistance increases drastically. The sensitivity of resistance-based damage sensing is demonstrated through this study and efforts into measuring the high-rate resistance changes occurring during impact are underway.

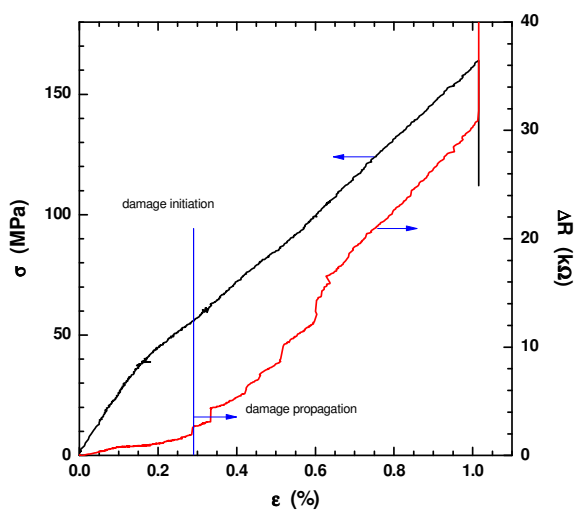

Fig.1. Mechanical and electrical response of a $[0/90]_s$ carbon nanotube/E-glass/vinyl ester composite under quasi-static tensile loading [3]

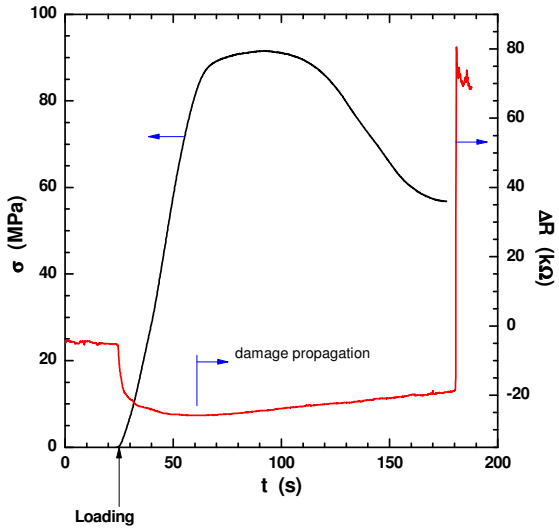

Fig.2. Mechanical and electrical response of a carbon nanotube/E-glass/SC-15 composite specimen under quasi-static compression loading [4]

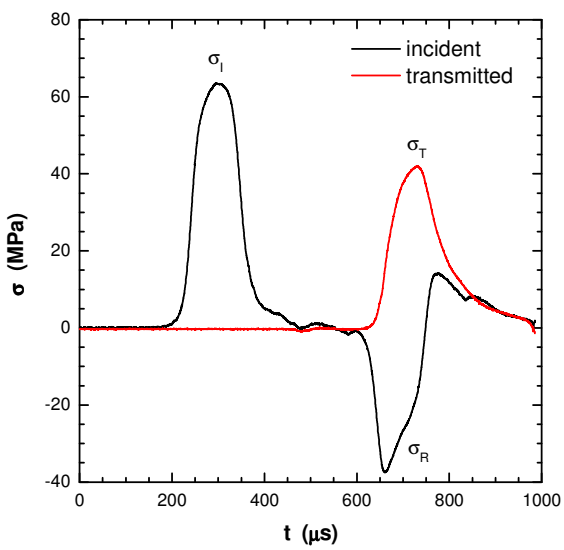

Fig. 3. Bar stress calculated using strain gage measurements in real time. Incident, reflected and transmitted pulses (here, compressive stress is positive) are denoted on the graph.

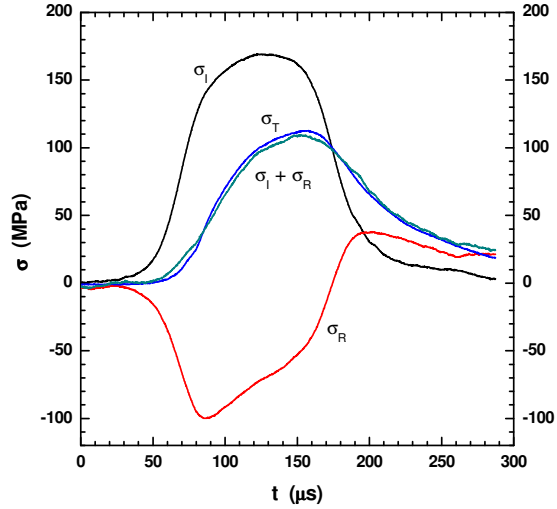

Fig. 4. Demonstration of equilibrium development time [4]. The sum of the time-shifted incident σ_I and reflected σ_R pulses is equal to the time-shifted transmitted σ_T pulse for a carbon nanotube-based composite specimen.

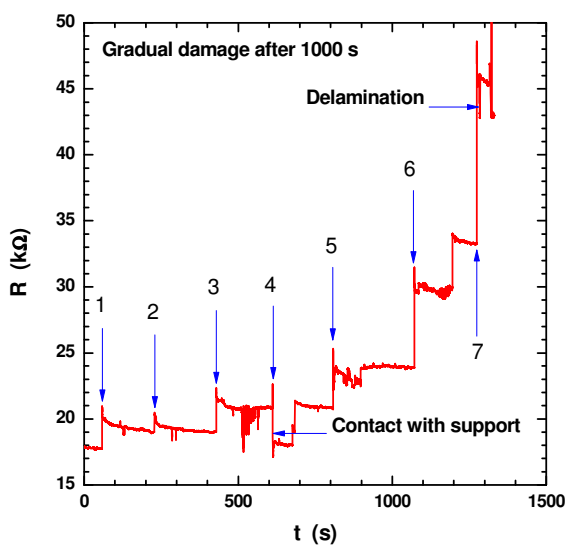

Fig. 5. Resistance increase after multiple impacts for a carbon nanotube/E-glass/SC-15 composite [4]

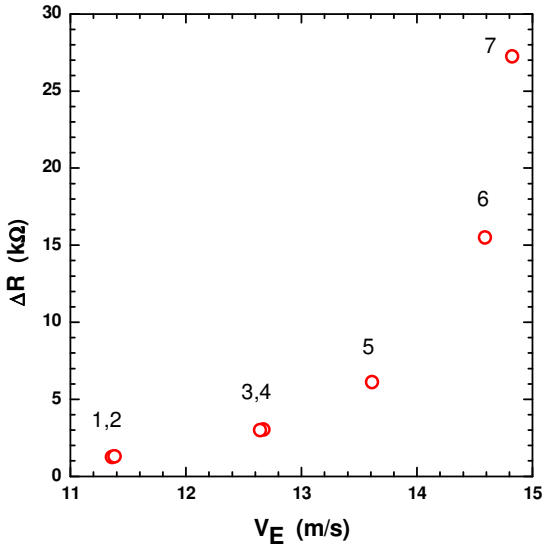

Fig. 6. Resistance baseline increases after each impact (numbers indicate impact sequence) plotted vs. striker bar velocity [4]

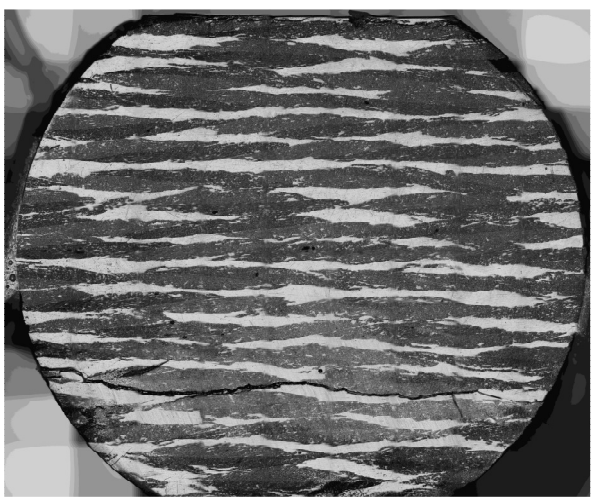

Fig. 7. Quasi-cylindrical specimen exhibits failure due to delamination after successive Hopkinson bar impacts [4].

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References

[1] D.M. Bigg "Mechanical, thermal and electrical properties of metal fiber-filled polymer composites". *Polym Eng Sci* Vol. 19, No. 16, pp 1188-1192, 1979.

[2] X.J. Wang, S.K. Wang, D.D.L. Chung "Sensing damage in carbon fiber and its polymer-matrix and carbon-matrix composites by electrical resistance measurement". *J Mater Sci* Vol. 34, No. 11, pp 2703-2713, 1999.

[3] E.T. Thostenson, T-W. Chou "Carbon nanotube networks: Sensing of distributed strain and damage for life prediction and self healing". *Adv Mater* Vol. 18, No. 21, pp 2837-2841, 2006.

[4] A.S. Lim, Q. An, T-W. Chou, E.T. Thostenson "Mechanical and electrical response of carbon nanotube-based fabric composites to Hopkinson bar loading". *Compos Sci Technol* Vol. 71,No. 5, pp 616-621, 2010.

[5] L.M. Gao, T-W. Chou, E.T. Thostenson, Z.G. Zhang, M. Coulaud "*In situ* sensing of impact damage in epoxy/glass fiber composites using percolating carbon nanotube networks". *Carbon* in press, 2011.

[6] E.T. Thostenson, T-W. Chou "Processing-structure-multi-functional property relationship in carbon nanotube/epoxy composites". *Carbon* Vol. 44, No. 14, pp 3022-3029, 2006.

[7] L.M. Gao, T-W. Chou, E.T. Thostenson, Z.G. Zhang "A comparative study of damage sensing in fiber composites using uniformly and non-uniformly dispersed carbon nanotubes". *Carbon* Vol. 48, No. 13, pp 3788-3794, 2010.

[8] R.M. Davies "A critical study of the Hopkinson pressure bar". *Philos. Trans. R. Soc. London, Ser. A* Vol. 240, No. 821, pp 375–457, 1948.

[9] B.A. Gama, S.L. Lopatnikov, J.W. Gillespie Jr. "Hopkinson bar experimental technique: A critical review". *Appl. Mech. Rev.* Vol. 57, No. 4, pp 223-250, 2004.

[10] A.S. Lim, S.L. Lopatnikov, J.W. Gillespie Jr. "Development of the split-Hopkinson pressure bar technique for viscous fluid characterization". *Polymer Testing* Vol. 28, pp. 891-900.

[11] H. Kolsky "An investigation of the mechanical properties of materials at very high rates of loading". *Proc. Phys. Soc. London, Sect. B* Vol. 62, No. II-B, pp 676–700, 1949.