DAMAGE DETECTION OF EPOXY POLYMER VIA CARBON NANOTUBE FILLERS AND EXTERNAL CIRCUITRY

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Introduction

In recent years, highly conductive carbon nanotubes (CNTs) have been used as additives in the matrix of fiber composites with hopes of enhancing not only the fracture toughness of the composite, but also the ability to detect strain and damage by monitoring electrical resistance [1-3]. Being of small size and high aspect ratio (e.g., 1-30 nm diameter, 0.5-1 μm long), CNTs are promising candidates as multi-functional fillers for structural FRP composites. Studies have shown a large increase of electrical resistance in the CNT composite under loading [4]. However, the sensing of small resistance change associated with small cracks is less investigated. In this present study, external circuitries are introduced to the composite structure to enhance the sensitivity of the resistance change due to small cracks.

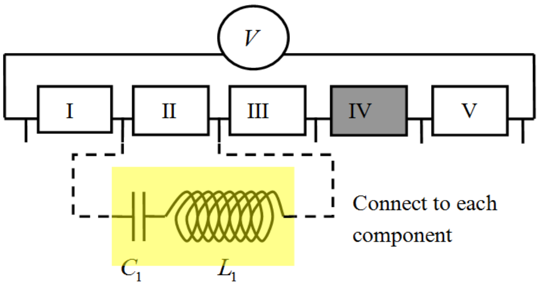

Fig. 1. Illustration of resistor chain with five components. Section IV is damaged.

Circuitry setup

Consider a simple multilayer composite beam with in-plane randomly distributed CNTs in a polymer matrix. For simplicity in the circuitry discussion, the beam is treated as a 1-dimensional resistor chain with five components, as shown in Figure 1. Each component has a lumped resistance of *R*. A voltage is applied to the entire structure and a circuit element is connected to each component in parallel to detect the damage location. A mathematical analysis of this model reveals a 2nd-order system with a resonance. The basis for the resistance-based sensory system is that structural damage causes changes in the resistance and admittance, and such changes are most significant around the resonant peaks.

Finite Element (FE) model

In the present analysis, the lumped resistance for each component in the model is calculated with a finite element approach. Because of the uniform nanostructure in the thickness direction, it is reasonable to consider only one representative layer. The CNTs are considered as 'soft-core' cylinders of length *l* and diameter *d*, and are allowed to penetrate each other [5]. With this assumption, the distribution of the randomly oriented CNTs in the polymer matrix can be obtained by Monte Carlo simulation. The composite layer is thus simulated as a 2-D finite element model in which the CNTs of diameter *d* extend through the entire thickness of the thin film.

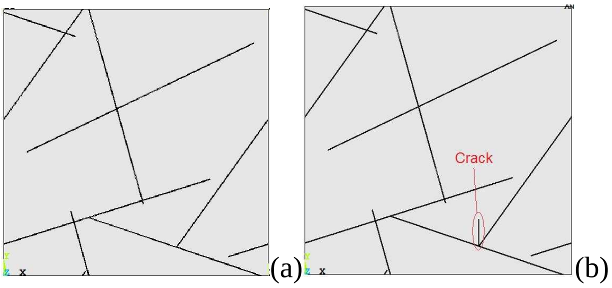

Fig. 2. 2D FE model of composite layer: (a) healthy structure, (b) damaged with a crack

The CNT aspect ratio is taken to be 1000 (diameter of 2 nm, length of 2 μm). The size of the representative composite layer is 2 μm X 2 μm, as shown in Figure 2(a). The conductivity of the polymer matrix and CNT are 10^{-12} S/m and 10^{6} S/m, respectively. If the closest distance between adjacent CNTs is less than 1.8 nm [6], the tunneling effect among CNTs needs to be considered. The tunneling conductivity value is chosen as 10^{-2} S/m based on previous studies [6-7]. With all this information, the conductivity of the composite unit cell is calculated to be $5.2 \text{X} 10^{-3}$ S/m, which compares well (the same order of magnitude) with Chou's result [6]. With one small crack shown in Figure 2(b), the conductivity decreases to 4.92X10^{-3} S/m, 5.5% decrease compared to the healthy structure, indicating the early stage of damage.

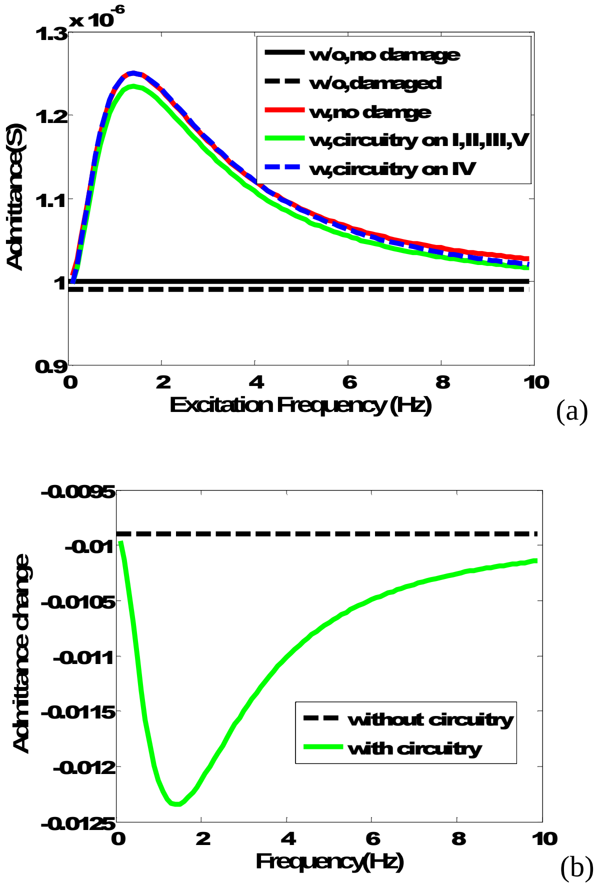

Fig. 3. Electric admittance (a) and admittance change (b) for 1D resistor chain model. Here 'w/o' represents without circuitry and 'w' means with circuitry. L_1=50 kH, C_1=0.01 mF.

Results

The calculated resistance value is applied to the 1D resistor chain model. For each component with length of 10 cm and cross section of 1 cm^2, the lumped resistance is 200 kΩ. The damaged component, IV in Figure 1, has a 5% increased resistance value of 210 kΩ. As shown in Figure 3, the circuitry resonance effect amplifies both magnitudes of the admittance (Y) and the admittance change ($\Delta Y / Y_0$) by 25% at the resonance frequency. With a slightly damaged component IV in the chain, the admittance changes when the external circuitry is in series with the damaged component, but does not have any effect when the admittance is measured at the damage element – this observation shows that such an approach could have potential in identifying the location of the damage as well.

Conclusion

Using a simple five-component beam model, we show that the sensitivity of electrical resistance change in a CNT-polymer composite can be enhanced by adding external circuitry. This method provides an effective way to detect the small damage in CNT composite at early stage. It also has the potential to identify the damage location.

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