Carbon 140 (2018) 413–427

Contents lists available at ScienceDirect

Carbon

journal homepage: www.elsevier.com/locate/carbon

First report of capacitance-based self-sensing and in-plane electric permittivity of carbon fiber polymer-matrix composite

Asma A. Eddib, D.D.L. Chung*

Composite Materials Research Laboratory, Department of Mechanical and Aerospace Engineering, University at Buffalo, The State University of New York, Buffalo, NY, 14260-4400, USA

A R T I C L E I N F O

Article history:
Received 5 July 2018
Received in revised form
22 August 2018
Accepted 31 August 2018
Available online 3 September 2018

A B S T R A C T

Capacitance-based damage self-sensing and the in-plane electric permittivity of continuous carbon fiber polymer-matrix composite are unprecedentedly reported. Capacitance-based self-sensing is advantageous over previously reported electrical-resistance-based self-sensing in not needing intimate electrical contacts and that two (rather than four) contacts suffice. Using a 220×220-mm^2 unidirectional one-lamina polyamide-6-matrix composite, the capacitance (2 kHz) is measured in the through-thickness and in-plane directions using 25×25-mm^2 aluminum-foil electrodes that are sandwiching and coplanar, respectively. Due to the composite's conductivity and the LCR meter's limitation, a dielectric film (adhesive tape) is positioned between electrode and specimen. In practice, this film can be the paint on the composite. Judiciously positioned artificial damage (1.1-mm diameter through-holes) causes the through-thickness capacitance to increase monotonically and the in-plane capacitance to decrease monotonically with increasing damage, due to the effect of the damage on the fringing electric field. The relative permittivity is 2160 ± 510 and 1640 ± 330 for the longitudinal and transverse directions, respectively, with anisotropy 1.3. The DC resistivity is 0.0072 ± 0.0004 and $10.9 \pm 0.9\,\Omega$ cm in the longitudinal and transverse directions, respectively, with anisotropy 1500. The conductivity controls the current spreading, while the high permittivity provides the capacitance effect. The resistivity anisotropy causes the dependence of the capacitance-based sensing on the fiber orientation.

1. Introduction

Due to the high strength, high elastic modulus and low density of continuous carbon fibers, carbon fiber polymer-matrix composites are important structural materials for lightweight structures, such as aircraft, satellites and sporting goods. Because of the strategic nature and aging of aircraft and related structures, nondestructive evaluation (NDE) is needed. This relates to structural health monitoring, which allows damage to be detected for timely repair and safety enhancement. For wide applicability, the method of evaluation should be suitable for existing structures, rather than being limited to new structures that involve unconventional composites (such as continuous carbon fiber composites containing carbon nanotubes) or require the embedment of sensors (such as optical fibers) in the composites. In addition, it is preferred that the evaluation method is suitable for real-time monitoring, so that the damage can be detected as it occurs and the evolution of the damage can be monitored.

Self-sensing refers to the ability of a structural material to sense its own condition without the need for embedded or attached sensors. Relevant attributes to be sensed include stress, strain, damage, temperature, etc. Due to the aging of aircraft, structural health monitoring of the airframe is critically needed. Compared to the use of attached or embedded sensors, the advantages of self-sensing include low cost, high durability, large sensing volume and absence of mechanical property loss. Embedded sensors tend to degrade the mechanical properties of the structural material, in addition to being not amenable to repair or maintenance.

Self-sensing involving electrical resistance measurement has been widely reported in continuous carbon fiber polymer-matrix composites [1–10]. This method is based on the effect of defects on the electrical resistivity of the composite. Due to the electrical conductivity of carbon fibers and the nonconductivity of the polymer matrix, defects such as delamination and fiber breakage affect the conductivity of the composite [1].

* Corresponding author.
E-mail address: ddlchung@buffalo.edu (D.D.L. Chung).
URL: http://alum.mit.edu/www/ddlchung

https://doi.org/10.1016/j.carbon.2018.08.070

There are disadvantages to the resistance-based self-sensing. Its implementation involves the application of electrical contacts. The electrical resistance associated with an electrical contact must be small enough, so that it does not overshadow the resistance associated with the volume of the material under evaluation. Thus, the electrical contacts must be high in quality, with the electrically conductive material (typically a metal) that makes up the electrical contact being in intimate contact with the structural composite material. Even if the resistance of the electrical contact is small, it may still vary as the condition (e.g., stress, strain, damage, temperature, etc.) changes. This means that both the resistance of the electrical contact and the resistance within the composite material can change with the condition. The resistance within the composite is the quantity that is indicative of the condition. The variation of the contact resistance with the condition may cause the measured resistance to be not indicative of the condition. To alleviate this problem, four electrical contacts rather than two contacts are used [11], thereby largely eliminating the contact resistance from the measured resistance. In spite of its superior reliability, the four-probe method makes the implementation of the technique more difficult and more expensive.

The alternating current (AC) impedance is a related quantity that can be measured. It differs from the direct current (DC) resistance in that it is a complex quantity that consists of a real part (the resistance) and an imaginary part (the capacitance and inductance, with the capacitance being more relevant than the inductance). An advantage of impedance measurement over resistance measurement relates to the essential absence of the effect of polarization on the measured impedance, in contrast to the gradual increase in the measured DC resistance as the measurement progresses [12,13].

Because the impedance includes the resistance (its real part), the measurement of the impedance involves the same issues as mentioned above in relation to the measurement of the resistance. The real part of the impedance has been used for providing self-sensing [14].

The variation of the impedance with the frequency can be analyzed in terms of equivalent circuit models for describing the electrical behavior. The analysis typically involves the fitting of the curve in the Nyquist plot (plot of the imaginary part of the impedance to the real part of the impedance for various frequencies). However, the equivalent circuit model obtained by the curve fitting is not unique. As a consequence, the values of the circuit parameters (resistances and capacitances) in the circuit model are only meaningful in the context of the particular circuit model and are not generally meaningful.

Capacitance-based self-sensing has been previously reported in steel [15] and cement-based materials (without any conductive admixture) [16–19] by the same research group as this work, using the same method as this work. Capacitance measurement of conductive materials is unconventional. Steel is more conductive electrically than carbon fiber composites. The success of capacitance-based self-sensing in steel suggests that success in carbon fiber composites is likely. This paper provides the first report of capacitance-based self-sensing in carbon fiber composites.

The electrical behavior of a material involves both the electrical conductivity (pertaining to the conduction behavior) and the electric permittivity (pertaining to the dielectric behavior). The permittivity relates to the electric polarization, which involves the interaction of electric dipoles and/or space charges in the material with the applied AC electric field. The frequency of the AC electric field affects the type of interaction. The conductivity relates to the resistance, whereas the permittivity relates to the capacitance.

Carbon materials are well-known for their conductivity, which is utilized for numerous applications, including electrochemical electrodes (for batteries, supercapacitors, etc.), electromagnetic interference (EMI) shielding (as needed to protect electronics and to shield radiation sources), electrical-resistance-based self-sensing (the ability of a structural material to sense its own condition without embedded or attached devices), and resistance heating (e.g, for deicing). An electrochemical electrode is an electronic conductor, the permittivity of which can affect the performance of the electrode. The dielectric behavior is important for EMI shielding and low-observability (Stealth), because its contributes to the ability of the material to absorb electromagnetic radiation. On the other hand, for applications in electrical conduction, the dielectric behavior tends to be disadvantageous, as the capacitance causes signal propagation delay, as commonly described in terms of the RC time constant.

The permittivity is a fundamental material property that is relevant to the capacitance-based sensing mentioned above. In particular, the in-plane permittivity of the continuous carbon fiber composite is relevant. However, the in-plane permittivity has not been previously reported for any continuous carbon fiber composite.

Carbon materials have received much attention in relation to the conductivity and associated applications. Much less attention has been given to the permittivity, partly because of the common assumption that the permittivity is not significant for a material that is highly conductive. This assumption stems from the notion that a highly conductive material would short-circuit the two electrodes of a parallel-plate capacitor used to measure the capacitance of the material sandwiched between the two electrodes. However, this short-circuiting problem can be avoided by positioning a dielectric film at the interface between the specimen and at least one of the two electrodes. The avoiding of the short-circuit situation is also necessitated by the fact that an LCR meter used to measure the capacitance is not designed to measure the capacitance of an electrical conductor.

The objectives of this paper are (i) to show the feasibility of capacitance-based self-sensing in a continuous carbon fiber polymer-matrix composite, (ii) to develop the methodology for the capacitance measurement, (iii) to evaluate the effectiveness of the self-sensing for various electrode configurations and various damage locations relative to the electrode positions, and (iv) to determine for the first time the in-plane electric permittivity of a continuous carbon fiber composite.

2. Methodology of capacitance-based sensing

The parallel-plate capacitor geometry is commonly and classically used for measuring the capacitance of a material that is sandwiched by the two sandwiching plates (i.e., two conductor plates referred to as electrodes). The capacitance is in the direction perpendicular to the plates. However, coplanar electrodes can be used instead to measure the in-plane capacitance.

A pitfall in capacitance measurement pertains to the fact that the LCR meter is not designed for measuring the capacitance of an electrical conductor. When an impedance meter is used for testing a conductive material, such as a carbon, the capacitance value that it outputs can be off from the true value by a large amount (even off by orders of magnitude) [20,21].

A parallel-plate capacitor is associated with a fringing electric field, which spreads to the region surrounding the parallel conductive plates. In case that the sandwiched material is conductive and extends from the sandwiched region to the region away from the electrodes, the fringing field becomes large and the measured capacitance (the apparent capacitance) becomes higher than the value in the absence of the fringing field. The fringing field serves as a probe, as the measured capacitance is sensitive to the