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Exploiting carbon nanotube networks for damage assessment of fiber reinforced composites

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ABSTRACT

An approach for damage inspection of composite structures utilizing carbon nanotubes (CNT) networks is investigated. CNT are dispersed in an epoxy using a processing technique compatible with commonly employed composite manufacturing techniques and subsequently used as matrix for a structural glass fiber reinforced composite. The developed electrical conductivity of the composite system is verified experimentally. The electrically conductive CNT network within the GFRP is exploited through distributed electrical voltage measurements to sense and, ultimately, locate damage in the plane of the composite plate. Damage in the form of cracks or delamination interrupts the continuity of the CNT network separating and isolating regions of the conductive network. Employing electric potential fields these changes can become measurable and can provide information for inversely locating the damage. Electrical Resistance Tomography (ERT) is formulated and experimentally applied to measure changes in the potential fields and deliver electrical conductivity change maps which are used to identify and locate changes in the CNT networks. These changes are correlated to capture the damage in the composite. Different damage modes are studied to assess the capabilities of the technique. The technique shows sensitivity to very small damages; less than 0.1% of the inspected area. The solution of the inverse ERT problem delivers a conductivity change maps which offers an effective localization with nearly 10% error and an inspection area suppression of around 75%. The proposed methodology to create CNT networks enables the application of ERT for Non-Destructive Evaluation of composite materials, previously not possible due to lack of conductivity, thus offering damage sensing and location capabilities even in-situ.

1. Introduction

Damage assessment of composite materials and structures is becoming increasingly important as a consequence of their increased use in a variety of primary importance applications, such as energy and aerospace. Various Non-Destructive Evaluation (NDE) techniques are available to detect damage in composites with the most commonly employed being ultrasonic (e.g. C-scan) and thermography. The latest years Acoustic Emission, Fiber Bragg Gratings and use of vibration-based methods have attracted a great amount of attention. In parallel, the progress in nanotechnology has enabled the development of novel materials routes for developing multi-functional material systems that incorporate approaches for damage detection.

Products of nanotechnology, such as Carbon Nanotubes (CNT), Carbon Black (CB) or other nano-particles, have been proposed as additives for mechanical performance enhancement of composites through their incorporation in the matrix [1]. Promising results have been reported in fatigue, fracture and post impact performance of such systems [2]. In parallel to the mechanical performance, the integrated nano-particle networks within polymer matrices can be employed for damage sensing and monitoring of the composites performance. This added functionality enables a multifunctional performance of composites. Most of the reported works in this direction are based on the Electrical Resistance Change Method (ERCM) where the apparent macroscopic resistance of the conductive network is monitored. Relation has been proven between the recorded electrical resistance change and the loading incidents and/or the mechanical degradation of the

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material. Studies have covered a wide spectrum of materials; nanocomposite polymers [3] and polymer foams [4], Glass Fiber Reinforced Plastics (GFRP) [5–8], Carbon Fiber Reinforced Plastics (CFRP) [9]. Finite Element (FE) models have also been employed to verify the experimental findings [10]. It can be said that electrical-based methods, such as ERCM, offer the potential of a tool for sensing the development and evolution of damage as well as health monitoring of conductive composite structures.

In order, however, for both nano-particle networks and electrical based methods to reach real applications at large scale, further developments are needed; developments to extend the capabilities in the localization of the damage and the estimation of its size based on the needs of practice. A number of studies have worked in extending electrical sensing principles to 2D using electrical conductivity mapping [11], electric potential fields [12] or other approaches [13]. A brief summary of the ideas is presented in Ref. [14].

Some works have been reported in the recent in the direction of exploiting nano-particle networks in structural composites to provide 2D inspection information. Hou et al. [15] employed a tomographic approach to demonstrate multifunctionality of a specially prepared CNT-based film. The system was used as a sensing element on the surface of a structure and was able to detect impact incidents. Ye et al. [16] used dispersed CB and copper chloride nano-particles in Glass/Epoxy composites for enabling electrical damage sensing. They proposed a tomographic approach and used the change of electrical resistance as a damage index. An intuitive probabilistic formulation was employed, where the cumulative contribution of individual sensing paths is considered for delivering damage assessment maps. The technique performed well in assessing and quantifying impact induced damage. Proper et al. [17] developed a Multi Wall CNT (MWCNT) network into a Kevlar composite. Following, an external electrode grid was attached on the surface of the plate to sense the potential distribution. They were able to point to the location of the impact damage by comparing the patterns before and after impact damage and relating the grid potentials to the conductivity distribution within the composite. Loyola et al. [18] demonstrated the performance of Electrical Impedance Tomography (EIT) as an embedded Structural Health Monitoring (SHM) methodology, where following a purpose-specific process a conductive and strain-sensitive film was deposited within the electrically non-conductive GFRP structure. The actively sensing region partly covered the GFRP part, was 80×80 mm in dimensions and employed 32 peripheral electrodes. An intuitive current pattern definition was employed being adjusted for the anisotropic electrical properties of the sensing region. The results indicated that EIT can detect and locate different modes of damage with good sensitivity. Alternative routes based on nanotechnology and multi-physics fields have also been proposed by Guzman de Villoria et al. [19] enabling good spatial resolution for sensing damage in composites. Viets et al. [20] demonstrated damage mapping of carbon nano-particles modified GFRP via electrical resistance measurements. They dispersed MWCNT at 0.3% wt. and 0.7%wt and CB at 12%wt in the matrix of GFRP via three-roll mill mixing. Following, they deployed a series of silver ink strip electrodes over the surface of a composite part; 10 per side with the two sides being perpendicular. They used out-of-plane resistance measurements occurring from pairs of opposite-side electrodes to monitor the damage developed by impact. It was shown that the detection and localization of barely visible impact-related damages via electrical resistance measurements was possible with the developed technique. The significant influence of the different nanoparticles and filler contents on the results of the damage mapping, especially regarding the sensitivity of the resistance to damage, was shown. More recently, Tallman et al. [21] used CB for enabling electrical monitoring of GFRP composites. They established a preferential aligned arrangement of the CB particles and determined the sensitivity of the EIT to through-hole damage as well as the ability of the technique to capture impact and multiple damage sites. They demonstrated the considerable potential of conductivity-based health monitoring for glass fiber reinforced polymer laminates with conductive networks of nanoparticles in the matrix.

In the present work, a methodology is presented to develop a 3D CNT network in the matrix of a fiber reinforced composite, which is subsequently exploited to sense damage and through a proposed tomographic technique to provide information of the location of the damage. For developing the CNT network, a processing technique compatible with conventional composite manufacturing technologies is utilized. The sensing scheme takes a step further from the state-of-the-art in sensing studies utilizing CNT networks by providing a structured methodology to calculate inspection maps for locating damage in composite parts. Electrical Resistance Tomography (ERT) [11,22] protocol is used for collecting and processing the experimental recordings, transferring technology and experience from other scientific fields [23,24]. The outcome of this ERT inverse problem solution is a map of the expected electrical conductivity changes, corresponding to the part under inspection. From this map, one can identify regions of interest (e.g. high change in conductivity) and such a technique can serve as a tool for the NDE of composite parts. It is believed that the proposed approach is scalable and can serve as the basis for further applications of CNT networks in real structures.

This work expands the state-of-the-art by presenting a case study which synergizes nanotechnology for composites and superior NDE techniques. It builds upon existing experience [25,26] and formalizes the NDE methodology, bridging the field between the research by Proper et al. [17], Hou et al. [15], Viets et al. [20] and Tallman et al. [21] in terms of combination of materials (MWCNT) and electrical sensing application (i.e. electrode design and positioning, post-processing framework).

Both the material preparation process and NDE methodologies proposed are extendable to other nano-particle as long as the amount of nano-particles in the matrix is above the percolation threshold to reach a conductive network throughout the composite. In this sense, a critical advantage of the CNT exists as the percolation can be reached much lower in weight percentage and, consequently, the processing of the epoxy is less affected and the mechanical properties of the composites are not sacrificed.

2. Principle idea of the work

The CNT reinforced GFRP essentially represents a three-phase composite system comprising the matrix, the CNT network and the glass fibers. Both the glass fibers and the matrix are insulating phases. The only path for electrical charge transport in the composite is the conductive CNT network. The network extends throughout the matrix of the composite providing an efficient path for electron flow, similar to a distributed network of resistors [27]. The conductivity of the composite system is leveraged for NDE. The principle idea of this work is illustrated in a simplified way in the schematic of Fig. 1. For clarity, glass fibers are excluded from the schematic.

In practice, the tools in hand are a current source and a voltage meter. Injecting a current at different points of the CNT network stimulates different regions of the network and develops a different voltage distribution throughout the material. Thus, as it seems natural, when monitoring the voltage at the same end of the network a different voltage value will be recorded (Fig. 1-a, b). Maximizing the sensitivity of the voltage measurement by adjusting the current injection point seems like a logical approach.