A TECHNIQUE FOR IN-SITU HEALTH MONITORING OF LARGE POLYMER COMPOSITE STRUCTURES MADE OF CARBON FIBERS AND CARBON NANOTUBE NETWORKS

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Abstract

A novel and practical technique is developed to detect, locate and quantify damages in large polymer composite structures (LPCSs) made of carbon fiber and carbon nanotube networks. In this technique, the epoxy resin was modified by adding multiwalled carbon nanotubes to make the resin electrically conductive. This modified epoxy resin was then incorporated with long carbon fibers to make large plates. Two sets of grid points were mounted on the surface of the large plates. The first set was used to apply the electric current and the second set was utilized to measure the electric potential. The electric potentials across the second set of grid points were measured and used as a reference set. The large plates were drilled and impacted to simulate the different damages. It is shown that drilled holes, impact damages are detected, located and quantified in the plates based on the significant changes in electric potential.

1. Introduction

Carbon fiber reinforced polymer composites (CFRPCs) are used in many industrial applications due to their high strength-to-weight and stiffness-to-weight ratios. One of the critical challenges in the practical use of CFRPC is to monitor the health of CFRPC structures in real-time due to their susceptibility to different types of damages [1]. The long term use of the composites depends a lot on the ability to detect and locate the damages in the structures. Various non-destructive evaluation (NDE) techniques such as X-ray tomography [2,3], ultrasonic C-scanning [2,4], liquid penetrant [2,5], acoustic emission [2,4,6], piezoelectric active sensors [2,7], fiber optics [2,4,8]and measuring electrical conductivity along the direction of carbon fibers [2,9] have been used for health monitoring of CFRPC structures. However limited in-situ capabilities and poor spatial resolution put the limitation for the usefulness of NDE techniques. Over the past few years, measuring electrical conductivity of the carbon fibers was used as a technique to indicate the presence of damage by many researchers [9-24]. Since carbon fibers are electrically conductive along the fiber direction, by applying an electric current over two probes at two points along the direction of the fibers, the change in electric potential can be taken as an indication of damage in CFRPC structures. Schulte and Baron [9] first proposed electrical resistance change measurement (ERCM) for structural health monitoring, which can be used to monitor internal damage of CFRPC. The problem with this technique is that since the resin is not conductive, one cannot use the technique to detect resin cracks. The majority of damage at the relatively low loads is due to matrix cracking and delamination, rather than to fiber breakage. As such, the usefulness of this technique is limited. Recent advent of polymer nanocomposites where carbon nanotubes (CNTs) are added in polymers has provided the impetus for scientists and researchers in producing functionally tailored matrix and fibers. This is because of CNTs possess outstanding properties including structural, mechanical, electrical, and thermal properties [25]. The outstanding properties of CNTs combined with their small size offer them not only for the modification of polymers but also for detecting both strain and subsequently failure in polymer matrix composites (PMCs). Adding CNTs at small concentrations in a polymer matrix to form electrically conductive networks distributed around the structural fiber reinforcement displays piezoresistive behavior. The piezoresistive behavior of the CNT networks enables their use as highly responsive sensors to monitor initiation and detection of matrix cracks in the structures [26-28]. Zhang et al. [29] embedded CNTs in graphite fiber/epoxy laminates to improve their electrical conductivity in thickness direction due to continuous electrical conduction pathways made by CNTs in between graphite fibers. This approach was used to detect delamination created by inserting a Teflon film in the laminates. They found that there is a good correspondence between the delamination length and changes in through-thickness electrical resistance. Kostopoulos et al. [30] dispersed CNTs in carbon fibers/epoxy composite not only for improving the electrical conductivity of the composite in transverse direction but also for detecting matrix cracks in the composite. They found that the addition of CNTs in the composites acts as direct sensors with high damage sensitivity to detect matrix damage accumulation during monotonic and cyclic tensile loading. The above works illustrate very interesting and innovative attempts to monitor damage in CFRPC coupons with small size using CNT networks. No technique is found to detect and locate damage in LPCSs made of carbon fibers and CNT networks. Here, we present a technique to detect, locate and quantify damage in large carbon fibers/epoxy/CNTs composite plates.

2. Experimental methods

2.1. Materials

MWCNTs with 95% of purity, diameters of 2-20 nm and lengths of 1 µm to more than 10 µm were purchased from Bayer Material Science. Plain weave woven carbon fibers (5.7 oz/yd2) purchased from US Composites, Inc. with thickness of 0.01 inch, Epon 862 and EPIKURE W purchased from Miller-Stephenson Chemical Company were utilized as reinforcement, epoxy resin and curing agent respectively.

2.2. Methods

2.2.1. Fabrication of composite plates

To manufacture the carbon fibers/epoxy/ MWCNTs composite plates, 0.3 wt% MWCNTs (as the optimal quantity of MWCNTs) [27] were dispersed into epoxy resin mixed with curing agent (26.4 wt %) using three roll milling (EXAKT 80E, EXAKT Technologies Inc). The mixture was heated up to 60^{0}C for 20 min in a vacuum oven to remove air bubbles. The modified epoxy matrix was dispersed in six layers of plain weave carbon fabric by hand lay-up. The composite plates were cured using an autoclave.

2.2.3. Composite plate specification and electrical measurement strategy

The specification of composite plate and a new strategy of electric potential measurement (EPM) for in-situ damage monitoring are schematically illustrated in Figure 1. In this figure, two sets of grid points are mounted on the surface of the plate. Each set consists of 40 electrical contact points. Each contact point is made from electrically conductive silver-epoxy paste. The first set of grid points labeled from1I to 40I spaced at 3 inches apart is used to apply a constant electric current to CFRPC structures. The second set of grid points labeled from1V to 40V spaced at 3 inches apart is diagonally shifted by 0.197 inch with respect to the first set to measure electric potentials. Electrical wires are attached to the two grid points to make electrodes. Then the electrodes are connected to the data acquisition system.

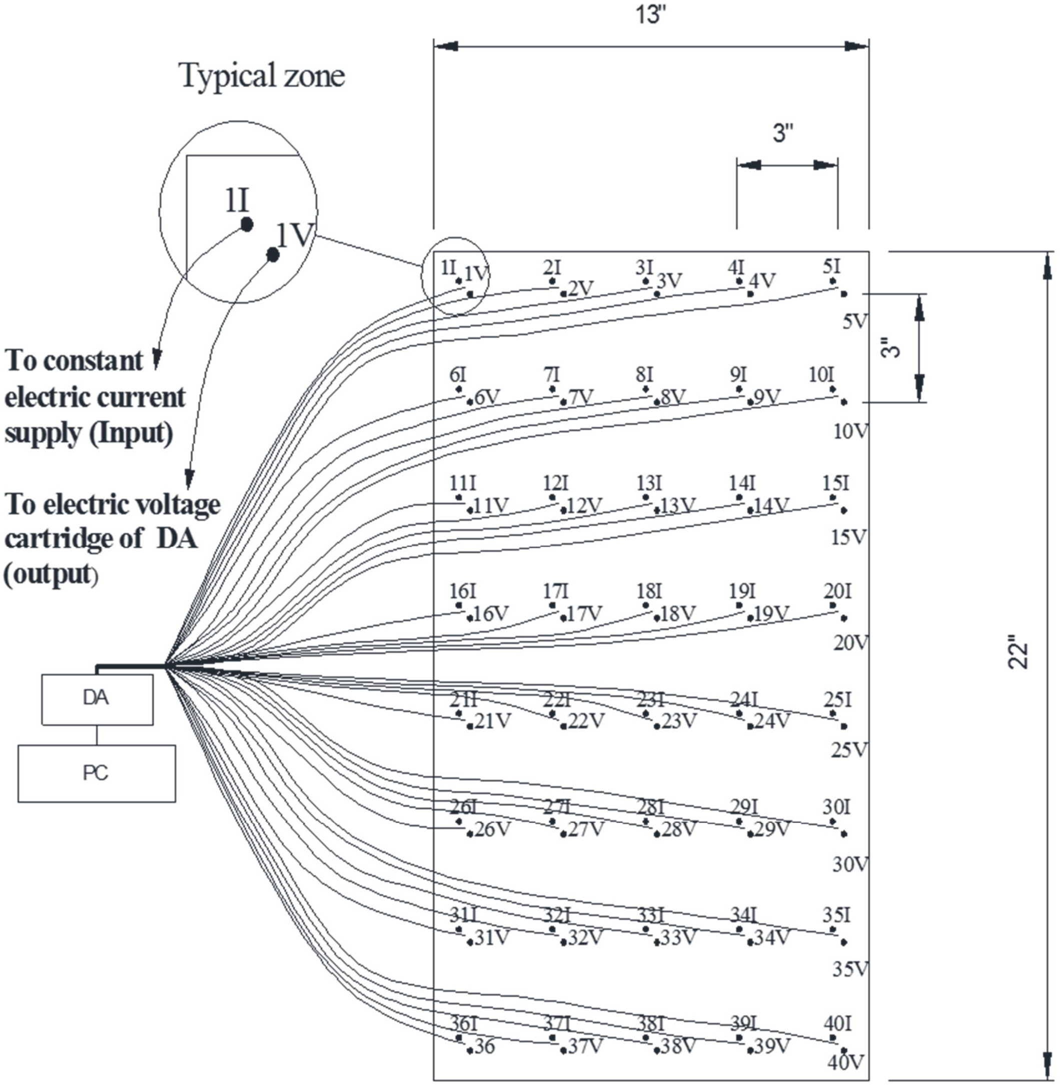

Figure 1. Schematic illustration of composite plate specification and strategy of EPM

2.2.4. Electric potential measurements

The EPM is used to detect damage in carbon fiber/epoxy/ CNTs composite plates. The EPM adopts the electrically conductive carbon fibers and CNTs themselves as self-sensing materials. The EPM was performed by four-probe method using Keithley 6220 DC, Keithley 218A. A constant current (100 mA) was directly applied by the mounted first grid points through the plate using Keithley 6220 DC. Then the electric potential across the second grid points was measured using Keithley 218A. Electric potential change (EPC) is expressed by:

$$\Delta V(\%) = \frac{V_{f,iv,jv} - V_{I,iv,jv}}{V_{I,iv,jv}} \times 100 \tag{1}$$

Where $V_{I,iv,jv}$ and $V_{f,iv,jv}$ represent the initial and final electric potential values between grid points iv and jv respectively.

3. Drilled holes and impact tests

Two damage types were introduced in carbon fibers/epoxy/MWCNTs composite plates. One was drilled holes of different sizes at different locations in the plates. The other was impact loading caused by collision with high velocity projectiles and drop weights in the plates. The plates were subjected to high velocity impacts with energy of 78J produced by 318 mg aluminum particle travelling at 700 m/sec using a gas gun. The drop weights were applied on the clamped plates placed on electrically non-conductive rigid supports to create the low velocity impacts.

4. Result and discussion

The electric potentials between pairs of second set of grid points spaced at 3 inch apart before damage for 22×13 inch carbon fibers/epoxy/0.3wt% MWCNTs composite plate 1 were measured and used as reference values. A hole of size 1/16 inch was drilled in plate 1. The values of electric potentials were measured after the hole was drilled. These values were compared against the reference values. The difference between the values of the electric potentials and the reference values was calculated based on Eq. (1). Hole 1 is detected and located based on the significant local variations in distribution of the electric potential change (EPC) as shown in Figure 2a. Subsequently another hole of size 2/16 inch was drilled. It is observed from Figure 2b that the significant local variations in distribution of the EPC reveal the locations of holes of sizes 1/16 and 2/16 inch drilled in plate 1. Other holes were then introduced. Observing Figure 2c, holes of sizes 1/16, 2/16, 3/16, 4/16, 5/16 and 6/16 inch respectively in plate 1 are detected and located based on the significant local variations in distribution of the EPC. Figure 2d shows the effect of hole size on the change in electric potential. In this figure, the numbers below the curve represent the pairs of electric potential probes. This pair of probes is closest to the hole. The numbers above the curve indicate the EPC in percent. A clear relationship between hole size and change in electric potential is observed in Figure 2d. This reveals the capability of the technique to determine severity of the damages.

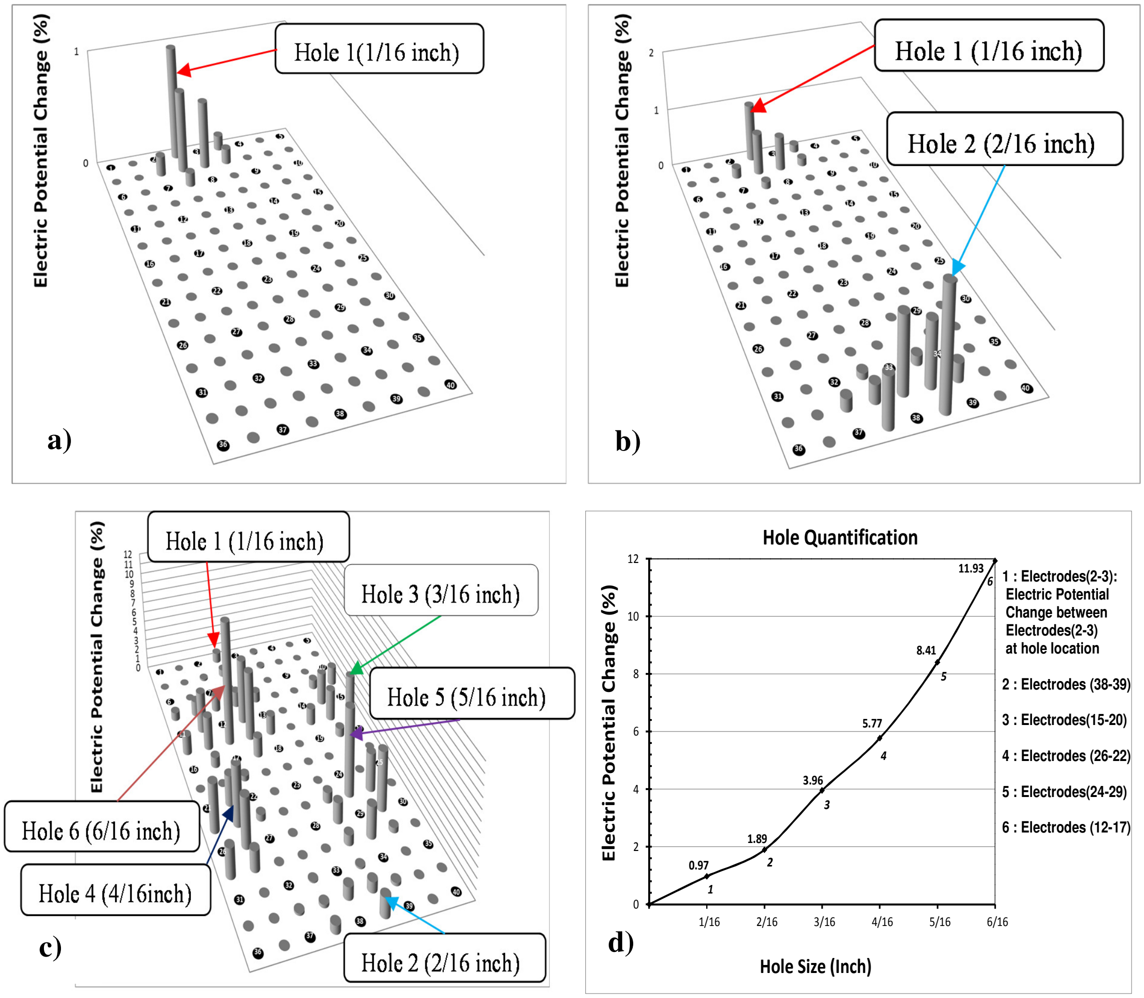

Figure 2. Electric potential change distribution of plate 1 after drilling a) hole 1 (1/16 in), b) holes 1 and 2 (1/16 and 2/16 in), c) holes 1, 2, 3, 4, 5 and 6 (1/16, 2/16, 3/16, 4/16, 5/16 , d) the effect of hole size on the change in potential

High velocity projectiles were impacted using gas gun at two different locations of plate 2. Impact damages 1 and 2 are detected and located distinctly according to the significant local variations in the EPC distribution for plate 2 as shown in Figures 3a and 3b. Plate 3 was tested under low velocity impact created using drop weights with different energy levels ranging from 1J to 3J. These energy levels were applied to create barely visible impact damages (BVIDs) which cannot be detected by visual observations. Figures 3c to 3d show the locations and values of the changes in electric potential for plate 3 due to low velocity impact tests. Observing Figures 3d, it is clear that BVIDs 1, 2 and 3 produced by different energy levels at different locations in plate 3 are detected and located distinctly.

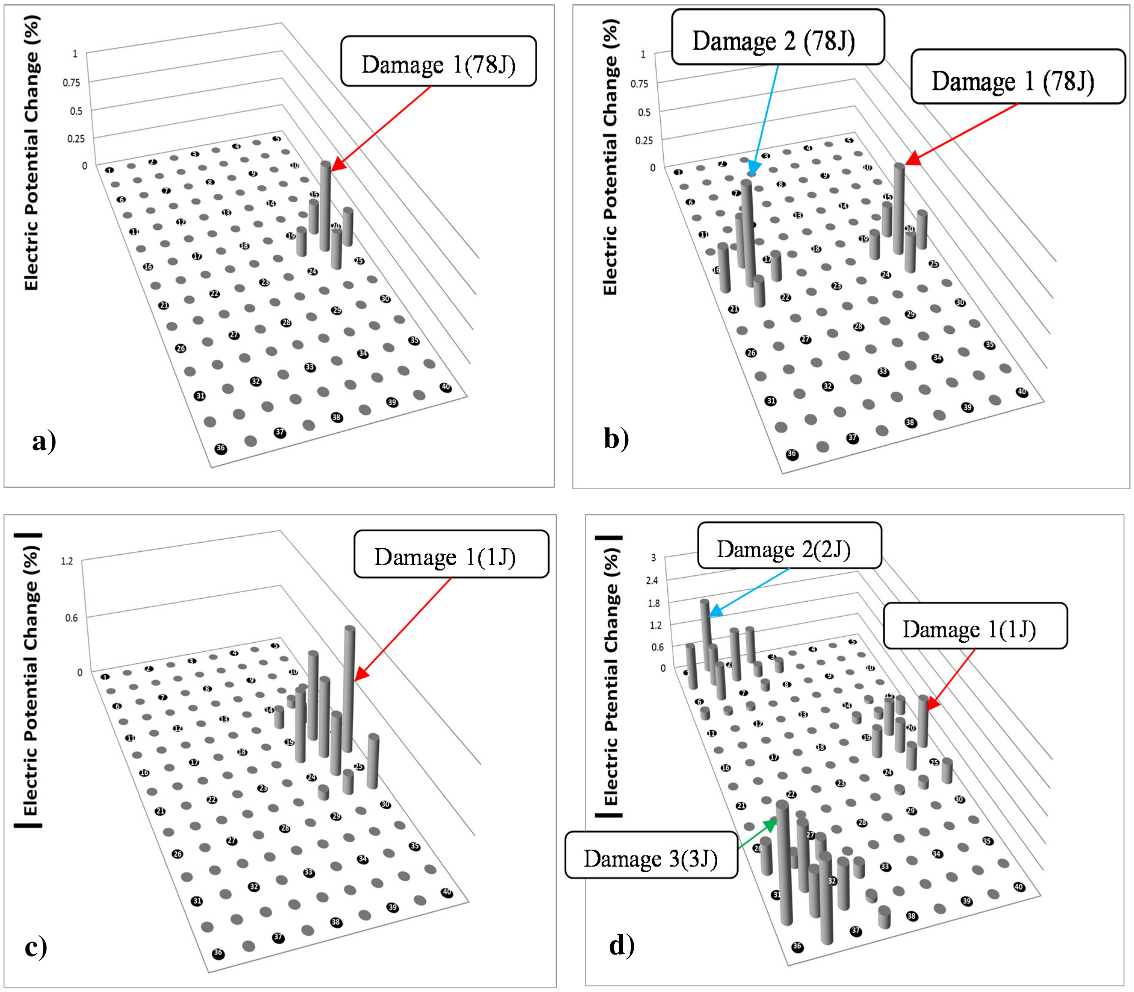

Figure 3. Electric potential change distribution of plate 2 after a) impact damage 1 (78 J) and b) impact damages 1 and 2 (78J each) , Absolute electric potential change distribution of plate 3 after c) BVI damage 1 (1J), d) BVI damage 1–3 (1, 2 and 3J)

5. Conclusion

A novel, practical and real-time structural health monitoring (SHM) technique is provided to detect, locate and quantify damages in the large polymer composite plates made of carbon fibers and CNT networks. In this technique, electric current was applied through the large plate and electric potentials were measured. This electric potential distribution in the undamaged plate was used as a reference map. Real-time monitoring of electric potential distribution over the surface of the plate was performed to provide an actual map of electric potential distribution. This map was compared against a reference map to identify significant changes in electric potential. These significant changes provide the ability for detection, location and quantification of damages and barely visible impact damages in the large plates.

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