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Piezoresistive nanocomposites for sensing the effectiveness of composite patch repair

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ABSTRACT

In this paper, piezoresistive nanocomposite is used to detect the effectiveness of bonded composite repair. The hybrid nanocomposites fabricated using wet-layup method with carbon nanotube sheet and graphite platelets as fillers exhibits enhanced piezoresistivity. The nanocomposite is incorporated as outer ply of repair patch in a scarf-repair process of damaged carbon fiber composite. Flexural test of repaired composite with intentionally placed disbond exhibits a different electromechanical response compared to defect-free repair; this concept can be used to detect the repair quality.

1. Introduction

High strength composites are increasingly being used for applications in aerospace, civil-infrastructure and renewable energy systems [1,2]. For example, most of the airframe of aircrafts like F35, Boeing 787 and Airbus A350 are made out of composites because of their superior performance and reduced weight [1]. There are numerous sources of damage to composite structures incurred during manufacturing, service and maintenance. E.g., a composite aircraft structure can suffer damage due to ground handling (blunt impact), lightning-strike, bird-strike, battle damage, environmental damage and fatigue cracks. The ubiquitous use of composites necessitates the development of effective repair methods and approaches to detect repair quality to address the structural damage.

Bonded repair methods provide the best structural repair option for composite structures and have several advantages over mechanically fastened repairs [3]. Adhesive bonding facilitates continuous load flow and smoothness (for aerodynamics) while avoiding bearing stresses, stress concentrations and fastener holes. Despite advantages, some problems persist with bonded repair. Aerospace composites are typically cured with simultaneous application of heat and pressure in an autoclave. During in-service repair however, only heat is provided through sources like heat-blankets. This can lead to defects like porosity and delaminations in an already weakened structure [4]. Therefore, it is vital to have efficient methods to gauge the effectiveness of the repair which is the focus of this study.

The ability of carbon nanostructures such as graphene nanoplatelets (GNPs) and carbon nanotubes (CNTs) to impart electrical conductivity and strength to polymeric materials, has made them an excellent choice as fillers for next generation of functional composites [5]. Large improvements in electrical conductivity are obtained by dispersing CNTs into insulating polymer matrices [6]. Additionally, CNT based nanocomposites exhibit a change in electrical resistance when subject to mechanical loading. While it is known that CNT's exhibit intrinsic piezoresistivity [7], given the large difference in elastic moduli between CNT and matrix, the deformation is expected to be concentrated in the matrix leading to changes in the tunneling network. This modification of the tunneling network is reported to be the primary mechanism for piezoresistivity in nanocomposites [8–10]. Both experimental and modeling studies indicate that combining two fillers like GNPs and CNTs to form a hybrid nanocomposite leads to increased conductivity and piezoresistivity [13,14]. The resistivity change of nanocomposites has been used for applications such as strain-sensing [8,9] and health-monitoring [11,12].

The objective of this communication is to develop an embedded approach to detect damage and bond-line integrity of composite patch repair using the CNT- graphite platelet hybrid nanocomposite as an outer ply. We show that the piezoresistivity exhibited by the nanocomposite outer ply can be used to detect a pre-existing disbond in the patch repair of a carbon fiber composite plate.

2. Experimental

2.1. Specimen fabrication

The carbon fiber composite 8 ply quasi isotropic laminate of dimensions 152.4 × 152.4 mm (6 × 6 in.) is fabricated from the bidirectional carbon fiber prepreg CF3327-1 EPC: SE-019K using Wabash

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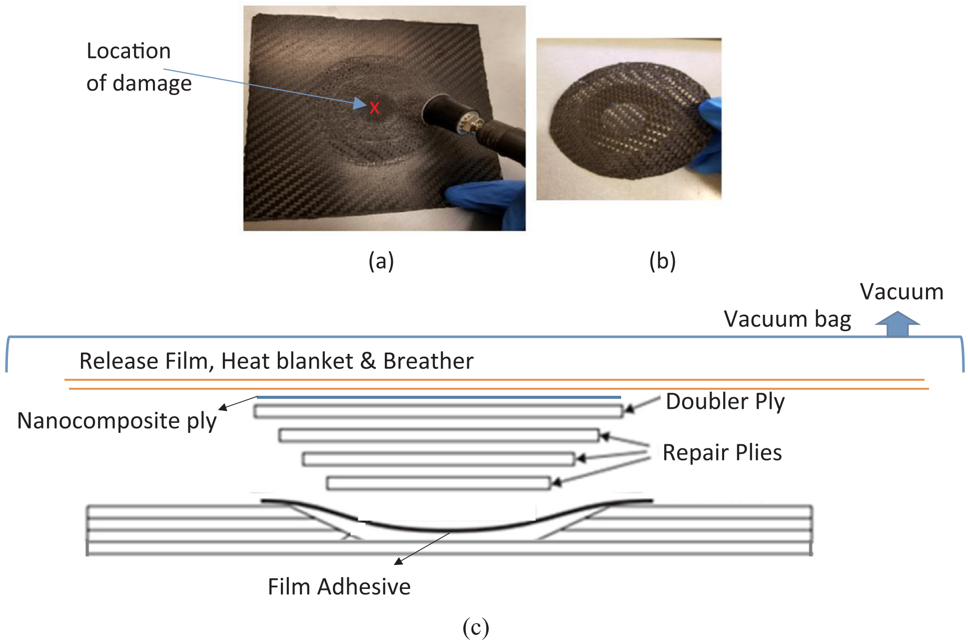

Fig. 1. (a) Grinding of composite panel before repair (b) repair patch (c) schematic of the composite repair including nanocomposite outer-ply.

hydraulic compression press to replicate the pressure-temperature cycle of an autoclave cure (121 °C for 90 minutes and 35 psi pressure). A 6.35 mm^2 (0.25 in^2) surface damage was inflicted on the composite sample using a knife. For repairing this damage, traditional scarf repair procedure was followed. Three plies with differing depths and diameters (75, 50 & 25 mm) were ground out near the damage as shown in Fig. 1(a). A corresponding repair patch was fabricated as described above with the same dimensions and layup of the ground out plies and an additional doubler ply of 89 mm (3.5 in) diameter as shown in Fig. 1(b).

2.2. Nanocomposite fabrication

The CNT sheet composed of freestanding multiwall carbon nanotubes procured from nanotechlabs is cut into 63.5 × 12.7 mm (2.5 × 0.5 in.) strip samples for tensile test samples and 89 mm diameter circles for repair samples. The graphite platelets used as the second filler were prepared by finely chopping (300–600 µm) low resistance (2.8 × 10^{-2} Ω/Sq) conductive graphene sheet using scissors. The sheet procured from 'Graphene Supermarket' is made out of multiple layers of graphene nanoplatelets adhesively bonded together. The nanocomposite samples are fabricated using wet-layup method. The graphite platelets are mixed into the epoxy resin and the mixture is thoroughly stirred before the hardener is added. Because of the large micrometer size of the coarse platelets we do not observe agglomeration of these particles. After adding the hardener, the epoxy is applied to both the surfaces of CNT sheet strips on a flat aluminum mold. The setup for making nanocomposite ply is similar to that shown in Fig. 1(c), but the layup in this case consists of only the nanocomposite ply. The electromechanical response of the nanocomposite specimen is established using tensile tests while simultaneously measuring the electrical resistivity passing a current of 0.5 A through the sample (Fig. 2c). The nanocomposite has a nanotube concentration between 17–18 wt% with additional second filler content. After considerable testing reported elsewhere [13] samples with 5 wt% graphite platelets used here were found to give the highest piezoresistive response and a gauge factor of 10.2.

2.3. Patch repair and testing

The schematic of the repair is shown is Fig. 1c. the nanocomposite outer ply was co-bonded with the repair patch and the composite plate under vacuum as shown. We incorporate a preexisting disbond in the repair samples using a 12.7 mm (0.5 in.) circle shaped Teflon tape at the center of the repair. The in-field repair procedure typically involves the use of heat blanket. Here, because of the composite plate dimensions and uniform heating requirements, the entire setup in Fig. 1c was heated under vacuum inside an oven at 121 °C. The repaired samples were tested in flexure in a specially fabricated three-point bending test fixture (Fig. 2a). Copper electrodes were attached to the nanocomposite outer-ply using silver-epoxy adhesive. The resistance of the nanocomposite is monitored while the composite specimen is subject to mechanical deformation by a passing controlled current of 0.5A and recording the corresponding voltage drop (Fig. 2b).

3. Results and discussion

It is well established through multiple studies that CNT monofiller nanocomposites exhibit a change in resistance when subject to deformation. We find that this effect is significantly enhanced when graphite platelets are added as a second filler. In the monofiller CNT sheet composites, we see an increase in electrical resistivity 35.2 × 10^{-5} Ω·m to 36.03 × 10^{-5} Ω·m (35.8–36.2 × 10^{-5} Ω·m in different samples) with an applied strain of 5%. When the matrix is modified with 5 wt% graphitic platelets the resistivity increases on an average from 18.4 × 10^{-5} Ω·m to 29.3 × 10^{-5} Ω·m resulting in a gauge factor increase from 0.48 to 10.2. Fig. 3(a) shows the resistivity strain response (average of four specimen) of the hybrid nanocomposite with 5 wt% graphite platelets subject to tensile deformation. Note that, there is an inherent uncertainty in the resistance strain response due to processing conditions and microstructural variations. Table 1 shows the change in gauge factor for different compositions of graphite platelets for the nanocomposite. When the nanocomposite is deformed, the deformation is expected to be concentrated in matrix leading to changes in the contact network of the filler particles. The piezoresistivity of the nanocomposites can be explained by these modifications to the tunneling-percolation filler network. Addition of planar graphitic platelets as second filler increases the number of tunneling junctions. SEM