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Sensing Uniaxial Tensile Damage in Fiber-Reinforced Polymer Composites Using Electrical Resistance Tomography

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Abstract. This work describes the application of Electrical Resistance Tomography (ERT) in sensing damage in fiber-reinforced polymer composites under uniaxial quasi-static tension. Damage is manifested as numerous matrix cracks which are distributed across the composite volume and which eventually coalesce into intralayer cracks. Hence, tensile damage is distributed throughout the volume, and could be more significant outside the sensor area. In this work, tensile damage of unidirectional glass fiber-reinforced polymer composites (GFRP) and plain weave carbon fiber-reinforced polymer composites (CFRP) is sensed by utilizing a spray-on nanocomposite sensor, which is then instrumented by boundary electrodes. The resistance change distribution within the sensor area is reconstructed from a series of boundary voltage measurements, and ERT is implemented using a maximum a posteriori approach and assumptions on the type of noise in the reconstruction. Results show that this technique has promise in tracking uniaxial damage in composites. The different fiber architectures (unidirectional GFRP, plain weave CFRP) give distinct features in the ERT, which are consistent with the physical behavior of the tested samples.

1 Introduction

Electrical impedance tomography (EIT) techniques have been developed for many years to investigate subsurface or externally inaccessible objects, especially for medical imaging [1]. In EIT, small electrical currents are injected into electrodes positioned along the boundary of a body under exam, and the internal

conductivity or conductivity changes of the body are computed. This technique offers an attractive option that is cost-effective and available in real time. Moreover, electric current can penetrate through a variety of materials without damaging them. Advances in sensor technology and image processing open the possibility to use EIT techniques not only in medical imaging, but also in other applications, such as nondestructive evaluation and structural health monitoring (SHM) of heterogeneous structures (for example, fiber-reinforced polymer composites, which are of interest for this paper).

Fiber reinforced polymer (FRP) composites have been widely used for primary structural components in aircraft and spacecraft, automobiles, wind turbine blades, naval and civil infrastructure, because of properties such as their tailorability, high strength-to-weight ratio, and corrosion resistance. However, FRP composites have more complex damage mechanisms than conventional metallic materials, e.g. matrix cracking, fiber breakage, fiber/matrix interface debonding, delaminations, which can be caused by manufacturing defects and in-service damage. In some cases, these damage types are barely visible. Since the degradation of mechanical and other properties can impact structural durability, it is important to monitor these damages, estimate the service life, and avoid catastrophic failures with condition-based maintenance.

A number of damage detection and monitoring methods have been investigated and developed with various degrees of success and limitations. In all detection methods, the basic principle of the approach is to correlate a damage or physical change to a measured entity. The methods include ultrasonic wave propagation, acoustic emission, vibration-based methods, electrical resistance/impedance methods, shearography, eddy currents, radiography (e.g. [2]-[4] for recent reviews).

The work in this paper focuses on a direct current electrical resistance-based method for structural health monitoring of FRP composites, known as electrical resistance tomography (ERT). Through boundary voltage measurements and the ERT algorithm, the conductivity map within the region of interest can be reconstructed. The use of strain gauges allows labeling the conductivity maps to strain values during the loading process. The implementation of this technique for SHM of FRP composites has already been established by authors of this paper in [5], where damages from a drilled hole and from low-velocity impact were successfully identified on fiberglass composite specimens with a conductive nanocomposite sensor applied to it. These damages were controlled and clearly localized: they were created after the manufacturing of the samples, and had known location, size and severity. Hence, the conductivity map could be easily validated.

This paper presents the application of ERT to identify quasi-static uniaxial tensile damage on glass fiber-reinforced polymer (GFRP) and carbon fiber-reinforced polymer (CFRP) composites. There are two significant differences with respect to the previous work [5], which result into increased complexity of processing and interpretation of the results of the mapping. First, uniaxial tensile damage may be distributed across the volume, since it starts in the form of numerous matrix cracks with spacing dependent on the local stress field. Eventually, the matrix cracks coalesce into intralayer cracks, in

agreement with the well-established characteristic damage state model. Hence, the damage is not a single crack whose location and growth can be controlled, and is not confined to a small area. There is a concrete possibility that the intralayer cracks eventually leading to the sample failure occur outside the sensor area. Second, the electrodes move and deform due to stretching of the samples during loading. At this stage, our objective is to examine the ability of ERT to capture reasonably well the onset and progression of uniaxial tensile damage in FRP composites. Therefore, as first approximation, the movement and the deformation of the electrodes are assumed to be small, and these effects on conductivity changes are neglected.

2 Materials and Methods

2.1 Materials and mechanical testing

For the experimental part of this work, GFRP samples were manufactured with 8 layers of quasi-unidirectional fiberglass (type 7715, Applied Vehicle Technology), and layup $[0]_8$. The CFRP consisted of 8 layers of T300 carbon plain weave (type PC136, 3k tows, Sigmalex), with quasi-isotropic in-plane properties before damage. The dry preforms were infiltrated with epoxy (LAM125/LAM237, Pro-Set), and were manufactured using Vacuum Assisted Resin Transfer Molding. After resin infiltration, the composites were cured for 14 hours at 25 deg. C, and for 8 more hours at 82 deg. C. Successively, fiberglass tabs were bonded, and the plates were cut into samples, with gauge length nominally equal to 152 mm and width equal to 25.4 mm (the dimensions are selected according to the relevant ASTM standard, D3039). The nominal thickness of the GFRP and CFRP samples was respectively 1.5 mm and 2 mm.

A spray-on conductive sensor with dimensions 26 mm width x 50 mm length was deposited on the surface of the composite samples. The sensor consisted of a film containing an electrically percolated distribution of functionalized multiwalled carbon nanotube in a polyvinylidene fluoride (PVDF) latex, manufactured with the process described in [5]. Prior to spraying the nanocomposite sensor, the surface of the CFRP sample was coated with a layer of epoxy which was then cured. This step ensured that the carbon fibers, also conductive, would not interfere with the conductive nanocomposite sensor. On the other surface of the sample, two strain gauges were applied to measure axial and transverse strains around the nominal center of the samples.

A round robin test was conducted between Embry-Riddle Aeronautical University (ERAU) and the University of California, Davis (UCD): two sets of samples were prepared, where each set consists of CFRP and GFRP tensile beams. The first set, tested at ERAU, consisted of three CFRP samples and three GFRP samples, indicated as C1, C2, C3 and G1, G2, G10, respectively. The second set, tested at UCD, consisted of four GFRP samples, identified as G11, G15, G16 and G17. The CFRP samples in the UCD batch were not tested, due to inconsistencies of the resistance distributions within the nanocomposite sensor surface, prior to testing.

During the tensile tests, the testing machine at either laboratory was operated in displacement control, and data was collected every 1.27 mm displacement until the sample broke, with the exception of the first samples to be tested, where the acquisition interval was larger (for example, in C2). The strains and the differential voltages at the boundary were collected, by using a LabView data acquisition system. A thermocouple was also used to monitor temperature changes of the nanocomposite sensor. Moreover, two-point resistive tests were performed, to verify the reliability of the nanocomposite sensors. The experimental setup is shown in figure 1.

2.2 Conductivity mapping

Sixteen electrodes were created along the perimeter of the sensor, with four electrodes uniformly spaced on each side. The electrodes had size equal to 2 mm x 2 mm, and were made with silver paint (Ted Pella). Then, silver epoxy (MG Chemicals) was used to attach 30 AWG wire leads to the electrodes. A specific pattern of current injections, shown in figure 1d, was adopted to mimic the so-called pseudo-polar pattern discussed in [6], which results in improved EIT results in the field of brain medicine. During data collection, the axial testing machine was paused, and a current of 10 ± 0.1 mA DC was injected into one electrode, setting another electrode to ground. Then, the boundary electrode voltages between the remaining adjacent electrodes were recorded.

Figure 1 (a) Experimental set-up for tensile tests in ERAU laboratory, (b) CFRP sample at zero load, (c) 25.4 mm wide GFRP samples with wired nanocomposite sensor (black), and (d) current injection pattern in a nominal 26 mm W x 50 mm L nanocomposite sensor.

This procedure was repeated several times with different permutations of the injection current electrode. In total, there were 12 current injections, and for each injection 12 boundary voltages were recorded. Hence, 144 voltage data were collected for each load step.

The ERT map reconstructed from measured boundary voltages provides information on conductivity

changes within the nanocomposite sensor applied to the FRP composite sample, between the initial “no strain” step and the current time step. ERT is based on a formulation of Maxwell’s equation, where for a conductive medium that does not generate current, the voltage within the medium is governed by the following Laplace elliptical equation:

$$\nabla \cdot (\sigma \nabla u) = 0 \quad (1)$$

where σ is the DC conductivity at a point in the medium and u is the corresponding voltage at that point. The boundary conditions dictate the current injection at the electrodes being normal to the surface of the electrodes, and the electrode voltages in the presence of contact resistance (equations (3) and (4) of [5]). The solution requires two major steps, which were implemented in this work with the commercial software MATLAB (Mathworks): a) the solution of the forward problem, where a known internal conductivity field leads to the computation of the boundary electrode voltages through the use of the Finite Elements Method (FEM); b) the solution of the inverse problem (equation (1)), which is ill-posed and nonlinear, and requires additional constraints (regularization techniques). Regarding the forward problem and the FEM mesh, three constant mesh densities were studied: mesh 1, with 1 element per electrode, mesh 2, with 2 elements per electrode, and mesh 3, with 4 elements per electrode. The current algorithm does not allow an adaptive mesh refinement, or a convergence study similar to that of a commercial FEM structural analysis code. Hence, the size of the mesh is uniform throughout the area of interest.

In the current paper and in [5], the regularization algorithm is called *maximum a posteriori*, and was introduced in [7]: it computes the conductivity changes $\Delta\sigma$, between those of the current step and an initial value, σ_o , as a function of the electrode voltage difference ΔV , as well as the vector of initial electrode voltage values, V_o :

$$\left\{ \begin{array}{c} \Delta\sigma \\ \sigma_o \end{array} \right\} = \left[\left(H^T W H + \lambda R \right)^{-1} H^T W \right] \left\{ \begin{array}{c} \Delta V \\ V_o \end{array} \right\} \quad (2)$$

In equation (2), H is the Jacobian (also called sensitivity matrix) computed in the forward problem solution, which was based on a Delaunay triangular mesh; W is a diagonal matrix reporting the inverse of the variance values from the measurements, based on the assumption of Gaussian white noise; R is a regularization matrix based on a Gaussian high-pass filter, which is independent of the mesh size; λ is the regularization hyperparameter, which depends on the amount of smoothing implemented, [5], [7]. In this paper, λ is computed as the value corresponding to a particular selection of the so-called noise figure NF . NF is defined as the ratio between the signal-to-noise ratio of the electrode voltage measurements and that of the reconstructed conductivity. Here, $NF = SNR_V / SNR_\sigma = 1$ and the corresponding λ , say $\lambda_{NF=1}$, is selected to reduce user bias [8]. In this project, because of the need to compare conductivity maps at different load steps in the same sample, it was important to use the same value of λ for each load step.

Therefore, as first approximation, the average of all the values of $\lambda_{NF=1}$ from the individual load steps was calculated, as λ_{ave} , and the conductivity maps were reconstructed again with λ_{ave} . Because the NF corresponding to λ_{ave} is typically not 1 anymore, this choice will be revisited in future work.

3 Results and Discussion

3.1 Two-point electrical resistance tests

Two-point electrical resistance was measured for selected samples under static and fatigue axial tests, to assess the reliability of the nanocomposite sensors under uniaxial tension, figures 2 and 3. The tests show that the normalized changes of sensors' resistance ($\Delta R/R_0$) are physically meaningful and reasonably repeatable within experimental scatter. The results from the GFRP tests are comparable to those of other researchers [9], and confirm the reliability of the nanocomposite sensor as a piezoresistive sensor. The gauge factor was computed for the linear part of the static curves, between 0.25% and 1% strain, and ranged from 3.235 for GFRP to 6.225 for CFRP. By comparison, the gauge factor of commercial strain gauges is typically equal to 2.

Figure 2 Measurements of two-point electrical resistance changes during static uniaxial tension tests: (a) CFRP samples and (b) GFRP samples. The box in the plots shows the initial resistance R_0 ; (c) picture of specimens.

Figure 3 Measurements of two-point electrical resistance changes during cyclic uniaxial tension tests.

3.2 ERT results

Representative conductivity maps for a GFRP sample, G15, and a CFRP sample, C2, are in figures 4 and 5, respectively. Their displacement/load plots are shown in figure 6. Although there are variations of ERT maps from sample to sample, due to the nature of the algorithm as well as to experimental scatter and noise, there are some common features to highlight among samples of the same material and fiber architecture. The two groups of samples fail in very distinct ways (figure 7): the quasi-unidirectional GFRP samples separated in axial strips of different widths. On the other hand, all CFRP samples, nominally quasi-isotropic before irreversible damage, broke in the direction perpendicular to the loading. The ERT maps are computed with respect to the baseline maps at no strain. Changes of electrical conductivity of the nanocomposite sensor can be due to the 2D deformation and damage of the sensor, which is bonded to the host FRP composite. The sensor contains anisotropic fillers (carbon nanotubes) in a reasonably homogeneous distribution prior to loading. Axial/transverse strains and damage may cause interruption of the electrical paths among the carbon nanotubes, or increased proximity of carbon nanotubes and improved electrical paths. Before testing the samples, the electrical resistance measured at electrodes positioned along the length direction was approximately twice as much as the resistance measured along the width direction, consistently with the aspect ratio of the sensor prior to testing, table 1. Axial and transverse deformations change the resistance distribution pattern. To validate that the ERT maps are physically meaningful, they should reflect the samples' failure pattern and the fiber architecture.

Figure 4 Electrical conductivity map for GFRP sample G15 for varying levels of strain and damage.

Figure 6 shows the “location” of these images on the load/strain plots.

Figure 5 Electrical conductivity maps for CFRP sample C2 for varying levels of strain and damage.

Figure 6 shows the “location” of these images on the load/strain plots.

Figure 6 Displacement-load plot for G15 samples (run at UCD), and C2 (run at ERAU). (a)-(d) refer to specific plots in figures 4 and 5.

The changes of resistance in the sensor due to tensile damage are more complex than the ERT changes observed in other studies, e.g. [5]. In general, the conductivity within the area of the sensor can be seen as a combined conductivity of numerous electrical paths between the electrodes [10]. These electrical paths can be broken or strengthened due to damage and deformation. The tensile load causes matrix cracks and fiber breakages that disconnect some electrical paths between the electrodes, which result in a decrease of conductivity. At the same time, other electrical paths are strengthened by fiber bundling of the host structure and the attached sensor, due to compressive load caused by Poisson’s effect. Hence, the conductivity between these electrodes may increase. Complex conductivity patterns can be seen in the above images, figures 4 and 5. In the GFRP unidirectional sample, the largest change is concentrated on the top right edge of the figure, which corresponds to the physical top right edge of the sample. It extends partially in the axial direction. Sample G15 failed by breaking in wide strips along the length of the sample (figure 7), with a failure pattern that appears consistent with its ERT map in figure 4.

Figure 7 Broken samples: (a) detail of failure of GFRP G15 sample, (b) unidirectional GFRP samples broken in the axial direction, and (c) CFRP samples broken in transverse direction.

Table 1 Measured resistance of the sensor before the tensile tests. “L” is the length direction, “W” the width direction of the nominal 50 mm L x 26 mm W sensor.

Samples	Resistance-L (Ohm)	Resistance-W(Ohm)	Ratio of means
G1	1197.06 ± 90.65	584.32 ± 62.14	2.05
G2	1443.90 ± 87.87	735.09 ± 42.07	1.96
G10	1482.50 ± 117.39	733.11 ± 92.16	2.02
G11	1372.33 ± 142.62	728.06 ± 36.28	1.88
G15	1703.67 ± 128.34	879.01 ± 56.72	1.94
G16	1456.08 ± 88.15	835.10 ± 33.67	1.74
G17	1260.49 ± 62.93	604.20 ± 26.09	2.09
C1	1163.75 ± 59.03	590.36 ± 62.93	1.97
C2	905.96 ± 70.82	461.30 ± 99.46	1.96
C3	920.60 ± 114.45	516.35 ± 124.98	1.78

The interpretation for the ERT map of the CFRP sample is not as straightforward. We compare this map to the results from grating shearography experiments applied to a section of one ply of plain weave CFRP (T700S/M10 with 12k tows) under axial tension [11]: the three images presented with permission in figure 8 show that, for that particular CFRP ply, there are axial, transverse and shear strains, both tensile and compressive, with distinct features across the surface of interest. Although the material of [11] is stiffer (12k tows and T700 carbon) and the algorithms are based on different methods and different

resolution, a superposition of these three images in a single plot would lead to patterns that appear similar to those in the ERT map in figure 5. Therefore, we argue that the two ERT maps presented in this paper are physically meaningful, and exhibit features consistent with the fiber architectures of the host structures.

Although the results are consistent with other published findings, validation of the reconstructed conductivity images using other methods is essential. The authors plan to continue this work and include validation through a digital image correlation technique. Additionally, the effect of the electrodes' motion and deformation needs to be included as well, especially if the ERT is to be implemented for more ductile/flexible materials. Some ERT maps show artifacts at the boundaries, in the form of high changes of conductivity in individual FEM elements. Artifacts appear in the EIT literature, e.g. in [7], [8], [12] and [13], and may be due to electrode motion, noise and the reconstruction algorithm itself. Artifacts may be alleviated by a refined mesh [12] or algorithms that take into account electrode motion, see for example [13]. Findings from the refined mesh study are reported below.

Figure 8 From top to bottom: axial, transverse and shear strains of one layer of plain weave CFRP sample under axial tension, obtained with grating shearography [11].

3.3 Results from the FEM mesh refinement

As explained in Section 2.2, the reconstruction of the image requires the relationship between the conductivity changes and the measured voltage that is also known as the sensitivity matrix, H . Therefore the quality of the ERT solution depends on the accuracy of H . Current density near the edges of the electrodes increases due to the high conductivity of the electrodes. Hence, sensitivity is very high in the immediate vicinity of the electrode and rapidly decreases away from them. To capture this phenomenon, it is recommended to use at least four elements per side to model any electrode [12].

Figure 9 Study on FEM mesh for GFRP sample G17. From left to right, the three different FEM meshes are shown, i.e.: 2 mm, 1 mm, and 0.5 mm. Values of the sample axial strain and of the hyperparameter λ are shown on the left. The mesh lines have been removed for clarity.

The initial mesh for calculating the sensitivity matrix used one element per electrode. This meant that the sensor area was modeled using 2 mm base x 2 mm height triangular elements, with a total of 672 elements. The images in figures 4 and 5 were constructed using the initial model. As explained in the previous section, the element size was uniform throughout the whole area. The refined two meshes had respectively two and four elements per electrode, leading to a much higher number of elements (table 2). As it can be expected, the CPU cost of these analyses increased exponentially as the size of the element decreases, as shown in table 2. The analyses were performed using a Window based computer with Intel Core i7-4790 processor, 16 GB memory and 64 bit operating system. The images of the three models for the first and the last load steps of GFRP sample G17 are presented in figure 9.

Table 2 Summary of the models and their calculation time.

	Model 1	Model 2	Model 3
Element size (mm)	2	1	0.5
Number of elements	672	2688	10752
Calculation time (min)	3.26	11.09	129.33

The conductivity maps of the three models show the same qualitative patterns: there is a large change along the axial direction, which is again consistent with a sample breaking in strips (similarly to sample G15 discussed above). As the mesh is more refined, the smoothness of the color map increases, and the numerical artifacts along the boundary reduce. Grychtol and Adler [12] observed a similar reduction of artifacts in their work. That paper also shows that the use of an adaptive meshing model can lower the CPU time, while still maintaining high accuracy or low sensitivity error.

Since the sensitivity matrix is indirectly a function of the element area, the magnitude of the conductivity change images is different for the different mesh size. Therefore, for clarity, the scale in the image for the finest mesh model is lower than the other two models. Additionally, we found that the regularization parameters of the refined mesh model are lower than the initial model. This means that the SNR of the reconstructed conductivity reaches the SNR of the collected data much sooner when the mesh is refined. To reduce the calculation time, we recommend using adaptive meshing method, where the mesh in the vicinity of the electrode can be refined.

4 Conclusions

Electrical Resistance Tomography (ERT) was applied to GFRP and CFRP samples to investigate the samples' damage behavior under quasi-static uniaxial tension. The sensor consisted of a nanocomposite film sprayed in the samples' gauge section. Within the limits of the study (i.e. scatter and noise from experimental data, uniform meshing, noise model and choice of hyperparameter, etc.), the ERT maps exhibit features that are consistent with the damage mode of unidirectional GFRP samples and with another work in the literature on plain weave CFRP. A study on the mesh refinement demonstrates improvement in the quality of the reconstructed conductivity image, leading to a smoother conductivity distribution smoother and reduced numerical artifacts around the boundaries. In summary, ERT shows promise as an SHM tool able to detect distributed damage in CFRP and GFRP samples under uniaxial tension.

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