Electrical-based methods for locating damage in composite structures

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Abstract

Based on the assumption that structural health is directly related to electricity conduction, in the case of conductive composite structures, the electric field has been proposed as a means for damage detection in electrically conductive laminates. Studies for locating the damage and monitoring its evolution using the local variation of the electrical conductivity have been rather sporadic. Here we present a strategy to collect electrical data in 2D following tomographic approaches (Electrical Tomography - ET) and two strategies to post-process the data and locate the development of damage in conductive composite structures;

- *the Effective Dipole (ED)*
- *the Electrical Tomography Inverse Problem (ETIP)*

These approaches utilize voltage measurements on composite parts injected with electric current. ED delivers point estimates of the damage location while ET delivers conductivity maps.

Within the frame of the present work, a basic but informative description of the theoretical background of the methods and their application strategy is provided. We apply them to static cases for damage localization in CFRP. We present experimental results and predictions using both ED and ETIP. The findings are supported by Finite Element simulations. The results indicate that both methods are capable of indicating the location of the developed damage. More specifically ED suppresses the damage location prediction envelope as far down as 7% of the total inspection area. ETIP provides a comprehensive conductivity map (similar to that of a C-scan) where correlations with damage are indicated. Secondary processing steps can be implemented to provide clearer damage characterization. Both can easily be implemented for the real time in-situ damage monitoring, while ED proves to be much faster. The present work contributes in the direction of damage location in conductive composites structures, using information from the electrical field.

1 Introduction to electrical sensing approaches

Non-Destructive Inspection & Evaluation (NDI and NDE) of composites is of great importance for quality assurance as well as for Structural Health Monitoring (SHM) of composite structures. With the increasing use of composites in advanced structures, the demand for non-destructive inspections and, whenever possible, of on-line SHM will become a necessity.

Apart from the more traditional techniques such as Ultrasonics and Thermography, alternative approaches based on different physical field have been proposed for use in composites, such as X-Rays and electrical properties. In this paper, we use the electrical field for NDE of composite structures. Among the initial works proposing the use of electrical conductivity for sensing strain and damage in conductive composites was the work by Baron and Schulte [1]. The idea of electrical conductivity/resistivity for damage assessment is based on the assumption that a healthy conductive part will conduct electricity and as damage accumulates its resistance will increase. Most of the studies originating from this concept have implemented a 1D approach on specimen level. The reported results have demonstrated sensing the existence and accumulation of damage in the material. This step is related to sensing of damage, thus answering to Level 1 of SHM [2]. However, the application principle of such methods on a larger composite structure is not directly obvious. Furthermore, when considering scaling up these monitoring approaches to larger structures, eventually, the question of where the damage is located is brought up. More advanced strategies need to be developed for sensing in 2D and complex 3D geometries. These strategies would answer to Level 2 of SHM - Locating the damage - and ultimately to Level 3 - Sizing the damage. Some studies have dealt with this issue [3-6] but have remained on theoretical or very initial application level.

Answering to this need, in the present work we introduce a NDE method based on electrical fields and describe two different post-processing approaches in search to answer where the introduced damage exists.

Electrical Tomography (ET) is an experimental method originating from the geophysical sciences. It is based on injecting electrical current at several points and taking measurements of the resulting voltage distribution at specific predefined points. It organizes the application in a protocol comprised of frames based on the chosen parameters and the combinations of electrical current injection patterns and measurements frames. Here it is employed as a data collection method for NDE.

The Effective Dipole (ED) approach is a post-processing technique. It receives the recorded electrical measurements of ET as input and provides point estimates of the perturbation source location. For each injection pattern and respective frame of the protocol a point estimate is calculated . At the end of the process a group of estimated points is formed for the ET protocol used.

Electrical Tomography Inverse Problem (ETIP) approach is a post-processing imaging technique providing a map of electrical conductivity distribution. It is a mathematical calculation of the inverse problem computing an approximation of the conductivity distribution inside the body based on the measured voltages and injected currents.

2 Implementation and Post-Processing Approaches

2.1 Electrical Tomography Scanning Protocol and Setup

ET uses an array of electrodes, usually located at the boundary of an object, to inject electrical current and record induced voltages. These recording are utilized in post-processing algorithms to assess the interior of the object and in our case to identify and locate damage. To put such concept into practice, several questions arise and form the application parameters. The major application parameters identified are the number of electrodes, the positioning of the electrodes, the type of injected current, the combinations for injection, combinations of measurements etc. In our implementation the chosen parameter values are presented in Table 1 together with the philosophy behind each decision. The first two parameters are more general design parameters, whereas the last two are more related to implementation (once the first two have been decided). Further information on the application parameters can be found in [7-10].

Parameter	**Value**	**Base of Decision**
Number of electrodes	20	Maximum number of electrodes the ERT system could handle
Positioning of electrodes on structure	Peripherally positioned	Minimum invasion and perturbation of mechanical performance
Type of electrical current	DC (0.1A)	Easiness of application
Electrical Current Injection combination	Opposite protocol	Simplest hardware requirement and better field penetration
Voltage Measurement combination	Voltage on electrodes (reference: ground)	Largest amount of information for a more global investigation

Table 1. Electrical tomography application parameters for this study

The application protocol for our study runs as follows: electrical current is injected between pair 1-11 positioned at opposite sides; high voltage on electrode 1 and ground connected on electrode 11. This represents a current pattern. Voltage measurements are taken for all the electrodes with reference to the ground (V@1,2,3,...,20). This represents a frame. Then current pattern 2-12 is applied at the next pair of opposite electrodes and the respective frame of voltage measurements (V@1,2,3,...,20) is taken. This continues until the measurements of current pattern on pairs of opposite electrodes cover all the available opposite pairs and the last pair of 10-20 electrodes is used. Due to reciprocity the protocol does not continue with current patterns 11-1, 12-2,…20-10. Excluding current bearing electrodes as a common practice this gives a total of 160 measurement for each “photograph”. No_Measurements_Opposite = No_Electrodes * (No_Electrodes - 4) / 2 = 160. This “photograph” characterizes the state of the material/structure at a given moment.

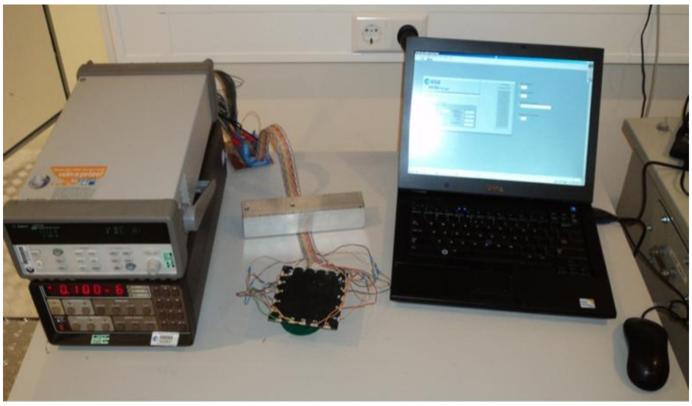
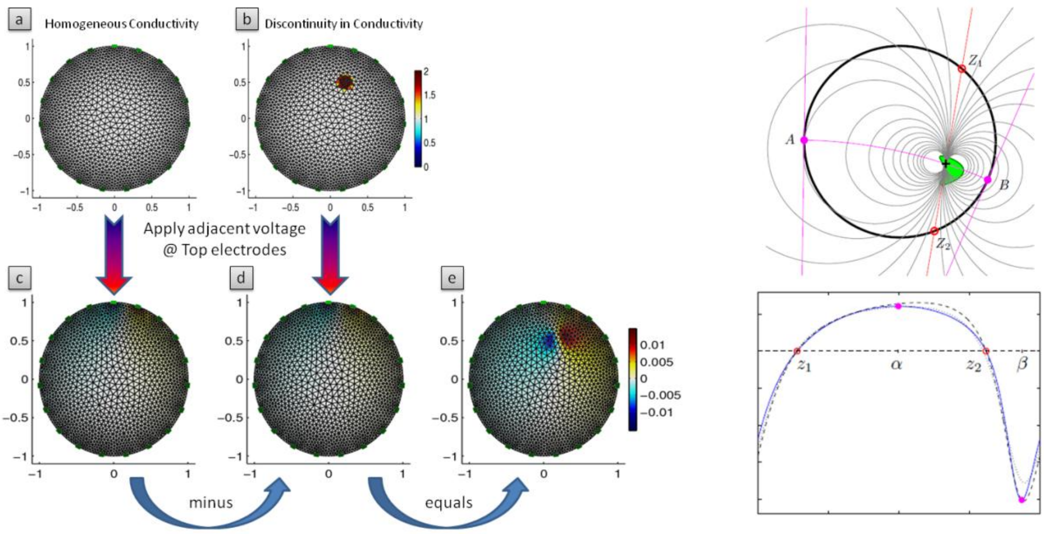


Figure 1. Electrical Tomography System architecture: the DC source (left bottom), the switching matrix (left top), the material-structure under test (middle) and the software/handling unit (right)

To apply the described protocol in our structure, meaning to deliver the electrical current at the desired electrodes and record the desired voltages, an ERT system was setup. The system is presented in Figure 1. Three major parts can be identified; the composite specimen under investigation, the ERT system and the software/handling unit. The ERT system consists of a programmable DC source (KEITHLEY 224) and a data acquisition switch board unit with an internal digital multi-meter (AGILENT 34970A). The ERT system is controlled through dedicated software routines (LabView). All post-processing is performed using MatLab and EIDORS toolkit [7,11].

2.2 Effective Dipole approach

The concept of the Effective Dipole approach (or location search method) is visually presented in Figure 2a. It is based on the observation that a discontinuity in a conductive structure will create an additional potential field similar to a dipole. We start by assuming a homogeneously electrically conductive structure; in this example a circular part (top left). We select to electrodes to inject the electrical current; in this case the top two. When the system is injected with current a potential field is created in it (bottom left). Then a discontinuity (an area having a different value of electrical conductivity) is introduced to the material (top right). When the new system is injected with current a potential field is developed (bottom centre). On first view the two distributions seem rather similar. By subtracting the two voltage distributions we see that the difference between the two distributions is significant and that the voltage field similar to a dipole positioned at the location of the discontinuity (bottom right).



(a-e) (f)

Figure 2. (a-e) Effective Dipole observation of principle [11] , (f) Effective Dipole application in ET [12]

Thus, if we take two frames (one reference and one after a certain time of service), we may be able to identify the development and location of damage by comparing the two distributions. The difficulty with such a process is that we do not have access to the whole potential distribution. Rather, we only can see whatever is expressed at the boundary of the structure where our electrodes are located. To visually express this the example of Figure 2b is presented [12]. Here a dipole is located at a certain point (Figure 2b top) creating a potential field as indicated by the equipotential lines. The resulting profile on the boundary of the object is shown below (Figure 2b bottom). In real ET applications it comprises of points (for each electrode) rather than a curve. The available information is directly related to the topology selected and so it can be considered as a design parameter of the NDE system.

To inversely locate the position of the dipole based on ET data several algorithms have been proposed [10,12-13]. In this work we implemented the simplest technique [10] in terms of application for plate specimens compared to more strictly mathematically grounded methods. The application of the geometric method to describe the centre and moment of the dipole is as follows.

For each frame of the Reference state we subtract the respective one of the Damaged State. For each resulting profile (Figure 2b-bottom), we identify 4 points; the two zeros and the two global extrema. The x-axis here corresponds to the polar angle on the boundary. The centre of the dipole lies on the straight line connecting the two points corresponding to zero potential change (the Zero Line). Theoretically the two extreme points, A and B, lie on a circular arc, the centre of which is defined by the intersection of tangents of the object at A and B. Assuming that the curvature of these arcs is extremely large, we can approach the arc with a straight line (the Moment Line). The intersection of the Zero and the Moment Line describes the approximate centre of the effective dipole. Despite the observational nature of the geometric technique, the outcomes already show the capabilities of such location methods. Certainly there is error induced by this described assumption, nevertheless the practicality of this assumption will be counterbalanced by the effectiveness of the implementation.

Using the described technique, for each frame of a photograph a point estimate can be elaborated. Thus a photograph will consist of a swarm of 10 points for the protocol used in this study.

2.3 Electrical Tomography Inverse Problem approach

Electrical Tomography Inverse Problem (ETIP) is the recovery of the conductivity of the interior of a body from a knowledge of currents and voltages applied to its surface. The aim is to compute an approximation for the conductivity distribution inside the body based on the measured voltages and injected currents. Any increase or decrease of conductivity at regions of the structure is expected to correlate with the presence and evolution of damage.

The inverse conductivity reconstruction problem is severely ill-posed. To tackle this issue minimization schemes are employed. In this work, we use the Tikhonov Regularization scheme which is one step further from typical Least Squares approach. The problem is formulated according to Equation 1:

$$d\sigma_{Tikhonov} = \min_{d\sigma}\left(\left\| dV - U(d\sigma)\right\|^2 + \lambda \left\| L\ d\sigma \right\|^2\right) \tag{1}$$

where: $d\sigma_{(Tikhonov)}$ is the change in conductivity distribution (x,y), dV is the change in the experimental voltage measurements expressed between a State 1 (Reference state) and State 2 (Damaged state), U(dσ) is the calculated voltage changes corresponding to a dσ change. The parameter λ is a trade-off between having a good fit of the experimental data and excluding the data errors induced by the noise. The choice of λ is difficult without trial of different values. In our work, we followed a heuristic approach by inputting different values for λ-parameter and calculating different solution maps [16]. Furthermore, L was the identity matrix. For the calculation of U, FEM formulations are used. Further details can be found in [8, 9, 14-16].

For each map, we define the Centre of Interest (CoI) as the centre of weighted conductivity changes and the Region of Interest (RoI) as the region enclosing the 1-σ weighted standard deviation in the X and Y directions.

3 Experimental Campaign

The described strategies were experimentally applied on commercially available Carbon Fiber Reinforced Polymer (CFRP) plates supplied by R&G GmbH, Germany. The plates are made by 3 layers of carbon fibre woven twill 2x2 fabric and a moderate Tg epoxy. The thickness of the plate is 1.5mm. Square 10cm specimens were cut with the fibres having a $0^o/90^o$ orientation.

The electrical conductivity of the material was experimentally determined for the development of the material model. For this, the in-plane electrical conductivity of the material was measured in different directions (0^o, 30^o, 45^o, 60^o, 90^o). From the electrical point of view, the woven CFRP showed a nearly isotropic behavior having in-plane conductivity of 10^3S/m. Thus an electrically isotropic and homogeneous material was used in the initial FE models.

Two damage case scenarios were considered according to commonly employed approaches; a drilled hole [3] and an indentation [4]. A drilled hole is considered as a first approach to simulating damage in a composite as it can serve a dual role; decrease the mechanical performance of the material and creates a discontinuity in the electrical field. A small size hole of 3mm diameter was drilled to the specimen at (X, Y)=(2.90, 5.00)cm. The damage size corresponds to less than 0.1% of the total specimen's surface. Indentation damage represents a first step to simulate impact damage, a common and important damage mode in composites. A modified Quasi-Static Indentation (QSI) setup was developed based on ASTM-D6264 and employed for this damage case. A hemispherical indenter is pushed against a specimen, simply supported by a metal base having a circular cut-out under the specimen. The indentation was done at a centrally located position (X, Y)= (5.2, 5.6)cm.

The experimental test procedure of this work was as follows. The specimen is ERT-scanned to get the reference "photograph" - Reference State. Then, damage is introduced to the specimen simulating the degradation that occurs over some service time of the structure. The specimen is ERT-scanned to get the "photograph" of the damaged state – Damage State. Ultrasonic inspection is also performed after the ERT-scanning for direct comparison and verification. The electrical "photographs" before and after the damage are used for post-processing.

4 Results and Discussions

4.1 Damage Case 1: Drilled Hole

Figure 3 shows the gathered results for Damage Case 1. On the left, the damaged specimen is presented, while at the centre and the right the results of the ED and ET post-processing, respectively.

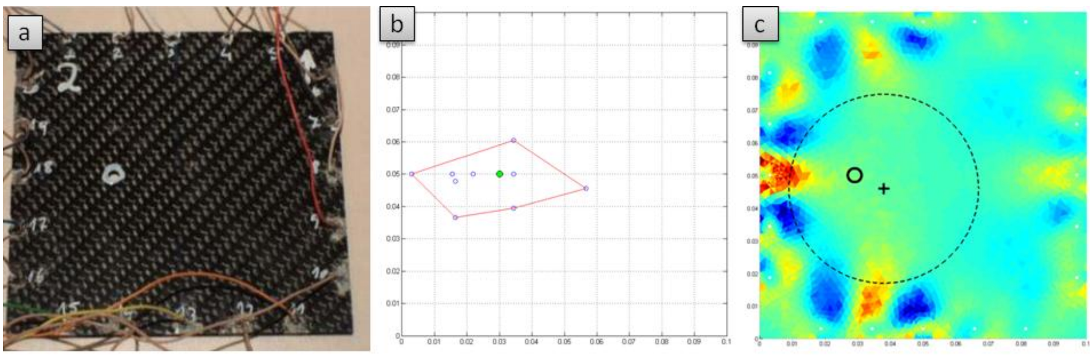


Figure 3. Damage Case 1: (a) Damaged specimen, (b) Estimated Effective Dipoles, (c) Electrical Tomography Map with CoI (+) and RoI (dashed ellipse)

The drilled hole induces a very localized damage and severe electrical conductivity change. However, the size (3mm diameter for a 10x10cm plate) is very small and thus the effectiveness of the electrical techniques can be assessed.

The ED estimation points are shown in Figure 3b. All the points are spread in the vicinity of the real damage. The largest distance from the real damage location is 2.5cm. The convex envelope of the prediction points is shown in red and represents 7% of the total area under inspection. The real damage falls within the convex envelope very close to its centre, showing the effectiveness of the method to point to the area of the damage. Assuming that initially one would have to inspect the whole component for damage, this technique results in a larger than 90% suppression of the inspection area.

The ETIP Map showing the conductivity distribution is presented in Figure 3c. The maps shows symmetry about the horizontal axis at the middle of the composite plate. In addition, interesting changes are only indicated on the left side of the plate. The CoI is calculated to be at (3.79, 4.59) cm as compared to the position of the real damage is at (2.90, 5.00) cm. The CoI is within 1cm apart from the real damage (d=0.98cm). Comparing this to the size of the specimen, a rough localization error of ~10% may be concluded for the predicted point. The area of the RoI is 26.4% of the specimen's area which means that the process has helped suppressing the inspection area by nearly 75%, while successfully locating the point of damage.

4.2 Damage Case 2: Indentation Damage

The damaged composite plate with the indentation imprint are shown in Figure 4a. Visual inspection showed a permanent imprint on the indentation side and small damage (fiber bundle breakage) on the opposite side. Ultrasonic C-scan (Figure 4b) as an already established NDI method was used for verification and cross-correlation of the findings. The revealed damage is rather small and localized as seen visually. Based on these findings it is expected that the electrical properties might not be so severely affected.

Using the gathered recordings, the ED estimations are calculated and are shown in Figure 4c. The point estimates are indicated in blue circles. The real damage is indicated with the green circle. The convex envelope of the point estimates is given in red. It is noticed that the size of the convex envelope is enlarged by several point estimations located on electrodes. This is a attributed to the software implementation of the geometric approach and the transition from circular to square object. This may have introduced geometrical systems that the algorithm could not address. Nevertheless, the envelope of the points located within the plate (blue envelope) are located very close to the real indentation position. The area of the blue convex envelope is nearly 5% of the total plate area which leads to a larger than 90% suppression of the inspection area. Considering that the induced damage was rather minimal according to NDI, the findings give confidence for the effectiveness of the method. Thus, it is expected that by implementing more sophisticated algorithms or fixing possible bugs in the available codes more accurate results can be expected even for such small damages.

The calculated ETIP Map giving the conductivity distribution is shown in Figure 4d. The map shows symmetry about the middle horizontal axis and the vertical centre line. This observation is confirmed by the calculated CoI at (5.14, 4.72)cm. The standard deviations forming the RoI were calculated 2.18cm and 2.68cm for X and Y respectively, forming an elliptical curve. The area of the RoI is 18.3% of the plate's area, suppressing the inspection area more than 80%. The damage at (5.20, 5.60) cm falls within the RoI and is located 0.89cm away from the CoI giving a predicted location error ~9%.

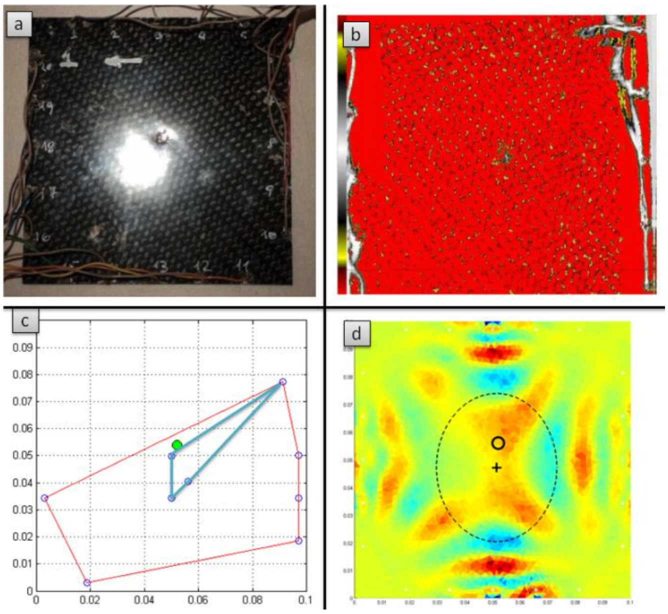


Figure 4. Damage Case 2: Indentation - (a) Indented Specimen, (b) Ultrasonic C-scan Map, (c) Electric Dipole Technique, (d) Electrical Tomography Map with CoI (+) and RoI (dashed ellipse)

5 Conclusions and Future directions

The non-destructive inspection and structural evaluation of composites is of great importance for their ever increasing use in advance structures. Electrical-based methods have been proposed for use in NDE. This work presented some ideas in the utilization of electrical fields for the non-destructive evaluation of composite materials targeting damage identification and localization. Electrical Tomography was described as a method for collecting electrical data from a composite system. Two post-processing techniques were described and experimentally validated; the Effective Dipole (ED) and the Electrical Tomography Inverse Problem (ETIP). The advantage is that both techniques use the same set of data. ED provides a group of point estimations of the location of damage, while ETIP delivers an estimation of conductivity distribution in the form of a map.

From the experimental findings it can be concluded that:

- Electrical sensing methods based on ET are capable of sensing changes caused by damage in composite materials as small as 0.1% of the inspected area.
- Both techniques could successfully predict the location of the induced damage with a deviation error less than 10%.
- Both the convex envelope of ED group and region of interest of ETIP can achieve significant suppression of the inspection area reaching up to more than 90%.
- ED is a much faster and simpler post-processing method that can be utilized online. The post-processing algorithm can deliver results very fast and thus on-line NDE could be envisioned.
- ETIP requires more time both for data acquisition and post-processing.

Some future development directions are proposed here to assess unanswered questions:

- Detailed assessment of sensitivity and distinguish-ability of the two techniques.

- As ED is much faster than ETIP in terms of processing time, it can be used to forward feed initial estimations for making more accurate ETIP predictions.
- Study and Development for different geometries e.g. cylindrical composite parts.
- As all results till now are qualitative, quantification through cross-property relations between electrical conductivity and structural performance is envisioned for sizing of the damage and moving on to Level 4 SHM - Remaining life prediction.

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