

Damage Detection in Complexly Shaped Carbon Fiber Pre-Preg via Segmented Electrical Impedance Tomography

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Abstract

The rise of fiber-reinforced composites in structural and load-bearing applications necessitates effective nondestructive evaluation (NDE) methods for inspection. However, many existent NDE methods struggle with factors such as complex shapes, internal geometries, in-service monitoring, etc. Electrical impedance tomography (EIT)—owing to strengths such as sensitivity to a wide variety of deleterious effects, applicability to complex shapes, and potential for continuous in-service monitoring—has recently attracted attention as an inspection modality for conductive composites, especially carbon fiber composites. Despite growing interest in EIT, it is a comparatively new NDE modality and therefore requires additional rigor before it can be accepted as a trusted inspection tool. In particular, we herein make three important contributions that address bottlenecks to using EIT as a composite inspection tool: First, EIT is applied to a carbon fiber/epoxy pre-impregnated (pre-preg) composite. This is important because pre-preg is the standard for high-strength composites, and little-to-no work has been done to validate EIT on this material. Second, a novel *segmented* approach is used. This approach uses only a subset of the total EIT electrodes to image just one section of the component at a time, which reduces the computational cost of EIT and consequently makes it more amenable to in-service inspections. And third, this work validates the effectiveness of EIT on a complex shape with internal geometry. Our results show that EIT, combined with the mixed prior regularization method, is able to adeptly detect and localize multiple damages in a stiffened tube structure produced out of carbon fiber/epoxy pre-preg with no non-relevant or false-positive indications. Further, by using the segmented approach, EIT is able to independently image the inner and outer parts of the geometry.

Keywords: pre-preg composite, electrical impedance tomography, nondestructive evaluation, damage detection, electrical properties

1. Introduction

Electrical impedance tomography (EIT) is the process of spatially mapping the internal conductivity distribution of a domain [1, 2]. This imaging modality has recently attracted much attention as a potential inspection and nondestructive evaluation (NDE) tool for conductive composites because of its unique advantages: it offers full-field, sub-surface, and radiation-free imaging with only surface-mounted electrodes; it is sensitive to many variables of interest (i.e., anything that changes how current flows through the composite can potentially be detected, including damage or material breakage and the evolution thereof [3–9], strain and deformation [10–13], temperature changes [14], chemical condition [15], and among other examples, moisture flow [16, 17]); it is low cost, easily multiplexed, and amenable to in-service use; it works on complex shapes with internal geometries [18–21]; and it is scalable to large domains (e.g., geospatial applications of EIT can generate images

on the order of hundreds of meters or greater [22–25]. Carbon fiber composites in particular are prime candidates for inspection via EIT because, unlike nanocomposites, they do not need to be modified and are already extensively used in real applications.

Composite NDE is of course not a new problem, and a wide variety of standardized and highly trusted tools exist for composite inspection. As a non-exhaustive list, these include ultrasonic methods, active thermography, and radiography. The intent of EIT research is not to replace these tools. Rather, the intent is to see how the unique strengths of EIT, as summarized in the previous paragraph, can supplement existing composite inspection tools to provide a more complete picture of the condition and health of composite components. For example, ultrasonic methods generally struggle with complex shapes with internal geometries due to geometry-induced reflections obscuring defect-induced reflections. Further, ultrasonic methods such as A-, B-, or C-scans are difficult to scale for large components and often require the component be taken offline. Active thermography likewise can have trouble with complex shapes containing internal geometries and generally cannot be done during in-service conditions (though it can rapidly inspect large areas). And lastly, radiographic methods are not adept at finding zero-volume defects such as tight delaminations, extra safety precautions are required due to the use of ionizing radiation, and it cannot be used in service.

Unlike ultrasound, thermography, and radiography, EIT is a comparatively immature NDE method and therefore still requires verification as a robust damage-sensing modality to become a trusted inspection tool. A few representative studies in this area (i.e., limited to just carbon fiber composites) include the work of Schueler et al. [26] who used EIT to extract damage size and position for unidirectional carbon fiber reinforced polymer (CFRP) composites. While their method was successful, it relied on an equivalent resistor network formulation of EIT rather than the more traditional approach that reproduces electrical conductivity as an elemental property on a finite element mesh. Baltopoulos et al. [27] later applied a more traditional EIT formulation to a commercially purchased CFRP plate subjected to through-hole and indentation damage. Their results were somewhat mixed in the sense that the EIT images do not unambiguously show the damage, even when considering the inherent blurriness of EIT. Later yet, Nonn et al. [28] applied EIT to CFRP plates to find through-hole damage. Like Baltopoulos et al. [27], their EIT images were rather indistinct compared to the clearly defined size and shape of the damage. This trend of relatively difficult-to-decipher EIT images of well-defined damage persisted with Rocha et al. [29] who used EIT to find hole and impact damages to carbon fiber composites and Cheng et al. [30] who used EIT for damage process monitoring on carbon fiber composites subject to quasi-static indentation. It should also be noted that, strictly speaking, these and the forthcoming studies used electrical *resistance* tomography (ERT) since they employed DC. EIT implies the use of AC and can reconstruct both conductivity and permittivity. We herein use the term EIT to describe DC imaging since this has become the norm in this field.

Nomenclature clarifications aside, much work has also been done to improve EIT’s imaging performance. For example, numerous groups have endeavored to improve EIT by looking at different injection-measurement patterns (i.e., the sequence of electrodes between which current is injected and voltages are measured) [28, 31, 32]. However, the benefit of different injection-measurement patterns is generally modest at best. Different injection-measurement patterns can improve sensitivity, but they do little to actually improve image quality. Work has also been done to solve the EIT inverse problem via AI/ML [33–37]. These methods have generally shown better image quality (i.e., tighter localization of damaged region, reduced non-relevant background indications, etc.), but like most AI/ML methods, they are severely limited by the availability of training data and the inability to be generalized beyond the training data (e.g., application to different shapes, damage types, loading conditions, etc.). Beyond AI/ML, more classical approaches to improving

EIT have also been explored, such as incorporating advanced regularization techniques into the inverse problem; Homa and colleagues developed and implemented a mixed regularizer that has shown excellent performance for the detection of small, highly localized defects [38, 39]. Work has also been done to separate out combined signals (e.g., separating conductivity changes due to simultaneous damage and strain conditions) via novel source-separation algorithms [40].

The preceding discussion is meant to illustrate that EIT does indeed have potential for carbon fiber composite inspection, numerous proof-of-concept studies have been conducted, and work is ongoing to improve EIT’s performance. However, much work remains to be done in demonstrating EIT’s effectiveness before it can become a trusted inspection tool for carbon fiber composites. First, greater exploration of the applicability of EIT to complex shapes is needed. Existent studies *overwhelmingly* study EIT applied to simple flat plates. If the potential of EIT for in-service monitoring is to be leveraged, we must acknowledge that real components and structures are generally *not* flat plates. Some work has been done in this area (interested readers are directed to references [41–45]), but more is needed. Second, to our knowledge, little-to-no work has been done to validate EIT on pre-impregnated (pre-preg) carbon fiber composites. This might seem like a trivial exercise (i.e., if EIT works on non-pre-preg carbon fiber, it surely must work on pre-preg too); however, because pre-preg is the standard for high-strength composites in potentially safety-critical applications (e.g., aerospace), explicit validation is essential. And third, an oft-cited limitation of EIT is its computational burden. That is, unlike strength-of-signal NDE methods, EIT requires finite element solvers, optimization-based inversion techniques, etc. This assertion is largely a misconception. Although it is true that EIT as a whole is more computationally burdensome than some methods, in reality, the vast majority of the computations can be done offline, stored, and simply recalled during the imaging process. In fact, optimized EIT algorithms can solve the inverse problem in seconds using off-the-shelf laptop computers and written in relatively slow languages like Matlab [46]. Nonetheless, finding ways to further reduce the computational burden of EIT is a worthwhile endeavor.

In light of the above-described opportunities to advance EIT (i.e., continued application to complex shapes, validation on carbon fiber pre-preg, and reducing computational burden), this manuscript makes three contributions: First, our methods are studied on a shape of representative “real-world” complexity, an annulus-stiffened tube. Second, the stiffened tube is produced out of commercially available, unmodified (i.e., no nanofillers), out-of-autoclave carbon fiber pre-preg. And third, we present a novel *segmented* approach to EIT. To clarify, the stiffened tube has two distinct areas: the shell and the annulus. Both of these areas are instrumented with electrodes, but only one set of electrodes (i.e., either the shell or the annulus electrodes) are used at a time. This means that we are effectively only imaging one section of the stiffened tube at a time, which reduces the inspection burden by focusing the inspection on only specific areas of concern.

The remainder of this manuscript is organized as follows. First, we describe our experimental methods, including manufacturing the stiffened tube, damaging it, and EIT measurements. Second, we present the anisotropic EIT formulation. Third, we discuss the segmentation procedure used in this work. Fourth, the results are presented and discussed. And lastly, we end with a summary and conclusions.

2. Experimental Methods

2.1. Stiffened Tube Manufacturing

The stiffened tube geometry used in this work consists of an outer cylindrical shell with a bonded internal annulus at the mid-plane. This geometry was motivated by the extensive use of thin-walled aerospace structures and the common use of tubes as structural members. No specific

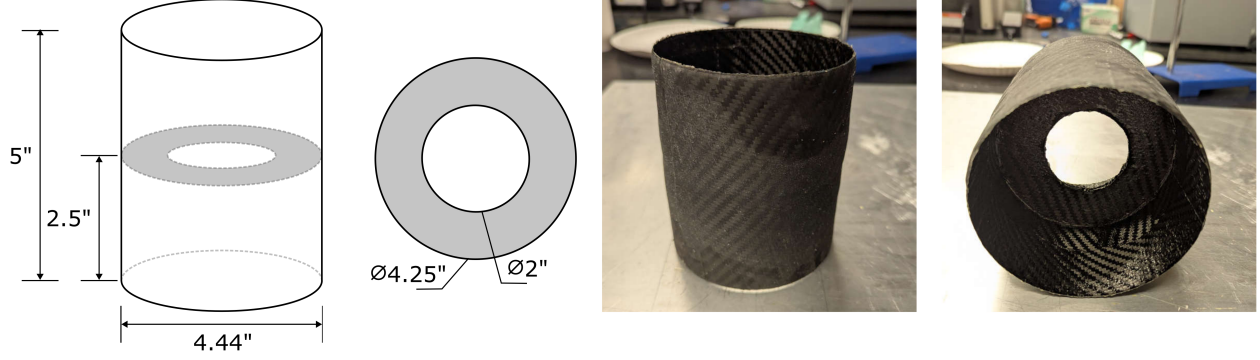


Figure 1: Left: Dimensions of the annulus-stiffened tube. Middle and right: Images of the stiffened tube.

load-bearing environment influenced aspects about the shape. Rather, a stiffened tube was selected because the shape may reasonably represent a section of a larger composite support structure.

The layup sequence was defined as $[(0^\circ/90^\circ)_2/\pm 45^\circ]_S$ for both the shell and annulus regions, resulting in a balanced and symmetric laminate. This layup sequence was selected because it is mechanically quasi-isotropic and balances the residual stresses from the curing process. Optimization of laminate strength and fiber orientation was not the focus of this study and therefore a simple layup was desirable. A 3K tow, 2×2 twill weave carbon fiber pre-preg material system was purchased from FibreGlast (Brookville, OH, USA). This material was selected because it could be stored at room temperature for six months and could be cured without an autoclave. The geometry can be seen in to the left in Figure 1, where all dimensions shown are in inches. The final stiffened tube can be seen in the middle and right of Figure 1. The overall height of the stiffened tube was 5". The shell and annulus outer diameters were 4.44" and 4.25", respectively. Both regions had the same nominal thickness of 0.096". The inner diameter of the annulus region was 2".

Producing the stiffened tube did not involve novel composite manufacturing techniques, but the process did require considerable planning to make an acceptable test specimen. The shell and annulus regions of the stiffened tube were joined during the same layup and curing cycle. A single cure cycle ensured that the fibers between both regions were in contact to establish electrical connectivity. For the annulus, the plies were cut to larger diameters with slits so that the extra lengths could be draped symmetrically to form right angles. The plies conformed to a sacrificial foam mold in the shape of a cylinder. The shell plies were subsequently laid across the mold because the foam occupied the negative space of the stiffened tube. The draped plies provided large contact areas for the shell-to-annulus interface and allowed electrical conductivity between the two regions. This connectivity was verified with continuity checks and resistance readings with a digital multi-meter (DMM) between the shell and annulus regions.

Since the stiffened tube had specific desired geometries (i.e., height, diameters, right angles, etc.), tooling was necessary to reliably make it. Precisely cut plies were required to ensure the fabric could conform to non-planar surfaces without excess material. To that end, cutting templates made from acrylic were designed and laser-cut using a Trotec Flexx 400 in order to have plies with the correct size and fiber orientations. The foam core was made from high-temperature polyisocyanurate (PIR) (ITW/Grainger) because it was dimensionally stable at the CFRP's curing temperature. A consequence of using this particular foam was the material's brittleness and tendency to produce dust from light surface abrasions. Therefore, to prevent debris from contaminating the CFRP sheets, an adhesive-backed, low-friction flourinated ethylene propylene (FEP) film (McMaster-Carr, 5805T11) was applied to the mold. This FEP film was wrapped along all exterior surfaces of the foam before beginning the layup process and allowed handling without

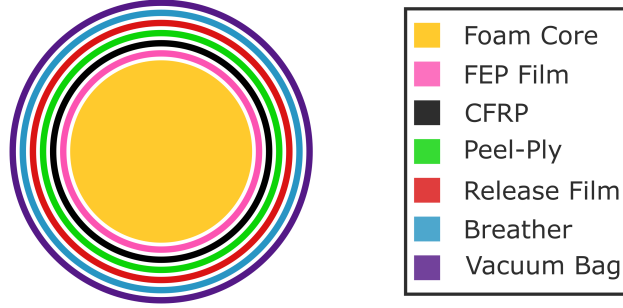


Figure 2: A top-down schematic of the layers and materials used in the vacuum bagging process.

generating debris. Having the FEP film also created a barrier between the resin and foam, allowing for easier removal after curing. Because the PIR foam came in thin sheets, multiple pieces of the foam were concentrically stacked to the required height needed for the stiffened tube. Additionally, the cylindricity of the mold was essential for achieving the desired form. Therefore, an aluminum 6061-T6 tube (McMaster-Carr, 9056K991) was used as a stamp die cutting tool for cutting out and stacking alignment of the foam layers.

The layup consisted of two phases; first, the annulus plies were assembled onto the sacrificial foam mold to create the inner geometry (i.e., annulus with draped edges) of the stiffened tube. The second phase involved assembling the shell plies onto the annulus and mold to produce the final desired geometry. Throughout the process, common CFRP manufacturing materials and techniques were used. Figure 2 shows the sequence of materials used in the layup. Debulking the laminate was essential throughout the layup process; debulking eliminated plies from shifting out of alignment between layers, preventing bunching. Ply wrinkles were removed at these steps to ensure smooth, consistent surfaces. A debulk was performed at the start of each phase and then after laying two subsequent layers. The initial debulk ensured that the ply conformed to the shape of the mold and the additional debulk steps ensured high quality of the cured laminate. Each debulk placed the laminate under vacuum pressure for at least 15 minutes at room temperature. Once the layup sequence was complete, the laminate was placed in an oven at 290 °F for two hours per the manufacturer's instructions. The inner foam core was removed, assisted by the FEP film, after the curing process was completed.

Surface-mounted electrodes were placed throughout the annulus and shell regions. The general locational areas were first marked by paperboard (McMaster-Carr, 3659N11) templates, and subsequently wet-sanded using 600 grit sandpaper, followed by 1200 grit sandpaper to expose the conductive fibers beneath the cured resin. All surfaces were next cleaned using acetone and allowed to air-dry. The same templates were used again to paint 0.25" square electrodes using two coats of conductive silver paint from Ted Pella Inc. (Redding, CA, USA). Off-the-shelf right-angle jumper pins were used as contact points between the electrodes and test measurement equipment. These pins were joined to the electrode surfaces using silver conductive epoxy H20E EPO-Tek (Ted Pella Inc.) and reinforced with high heat epoxy putty from J-B Weld (Marietta, GA, USA). The epoxy and putty both required an additional oven cure of 1.5 hours at 176 °F. The use of pins provided solid electrical connections and allowed the convenient use of lead wires. Figure 3 shows the stiffened tube with electrodes attached.

As mentioned in the previous paragraph, electrodes were applied along surfaces of the stiffened tube. Figure 3 also shows a schematic where these electrodes were placed. A total of 32 electrodes were used; 16 electrodes were allocated to the shell and annulus regions, respectively. These electrodes were placed equidistantly along the circumference of the top and bottom sections of

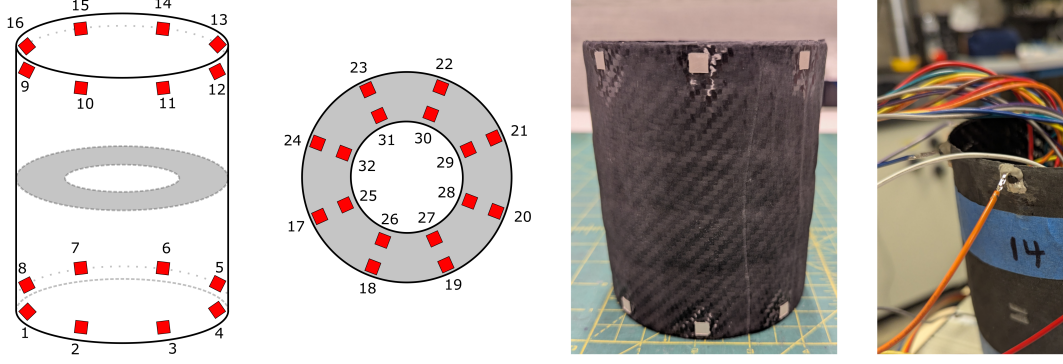


Figure 3: Left: Schematic of electrode locations on the shell and the annulus. Middle: A picture of silver paint electrode patches on the shell. Right: A close up picture of pins adhered to electrode patches and jumper wires attached.

the shell. The annulus electrodes were arranged in two concentric rings in addition to being aligned to the shell electrodes.

2.2. Impact and Notch Damage

The stiffened tube was subjected to two different damage modes: notch and impact damage. Notch damage commonly propagates from areas of high stress concentrations. In notch damage, because material is being removed, there is a total cessation of conductivity. Hence, the accuracy of the EIT results (i.e., damage location, size, and shape) can be verified directly against the test specimen. The second damage mode, impact damage, can be the result of maintenance tools, loose hardware, or debris impacts during service. Consequently, indentations from impacts may be visible on the surface or barely visible impact damage (BVID) can manifest through fiber breakage, matrix cracking, and delamination within sub-surface layers of the composite. In general, conductivity changes from impact damage are expected to be less than notch damage due to remaining fiber connections at the impact site.

The inner diameter of the annulus was chosen for notch damage because it is a reasonable place this damage could occur in a real composite structure. As seen in the right of Figure 4, the notch was placed at the midpoint between electrodes 30 and 31. Sizing of the notch damage was approximately $0.36'' \times 0.15''$ —comparable in size to the electrodes—extending lengthwise into the annulus. Figure 4 also shows the actual notch damage on the annulus. There is a slight angle to the notch, which is a consequence of using a cutting wheel tool to make the notch damage by hand. However, the shape deviations are relatively small and ultimately an insignificant factor to the final EIT results.

The impact damage location was chosen to be on the shell's surface because it is the most likely part of the component to suffer impact damage. The location of impact was between electrodes 9 and 10, near the top edge of the shell, as seen in the middle of Figure 4. Impacting the shell near the electrodes was a consequence limitations regarding how the tube had to be secured in the impact machine. The surface of the shell had clear indicators of an impact strike; an indentation was present on both the front and back sides of the shell. Fiber breakage on the topmost layers was also observed. To perform the impact test, a CEA 9340 drop tower was programmed to deliver the required impact energy. The impact surface of the test specimen was placed at the designed impact plane of the drop tower using an adjustable jack stand. A V-block supported the cylindrical test specimen and provided clearance for the electrode pins. An aluminum 6061-T6 slug was machined and inserted into the stiffened tube to prevent it from collapsing. Finally, steel blocks

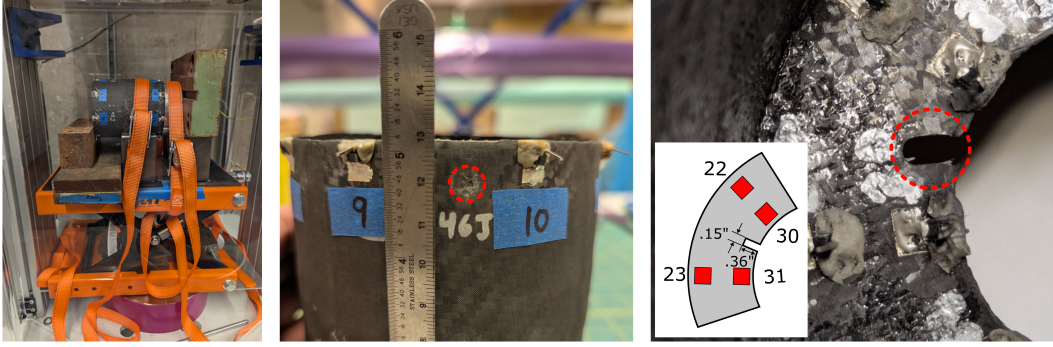


Figure 4: Left: A close up picture of the tube secured in the drop tower for impact testing. Middle: The post-impacted shell. The impact happened between electrodes 9 and 10 and is in the center of the red circle. Right: The notched annulus, with the notch in the center of the red circle. The inset shows that the notch was induced between electrodes 30 and 31.

and tie-down straps were used to restrain lateral movement and rebounding of the test specimen. The drop tower and impact test setup can be seen to the left in Figure 4.

2.3. Electrical Impedance Tomography Measurements

The EIT experiment involves the process of injecting current into an electrode, grounding an electrode, and measuring the voltages from all remaining electrodes. An injection scheme is used to define the order for injecting and grounding electrode pairs. Details about this injection scheme are provided in §4. A DC of 500 mA was injected into each electrode pair using a BK Precision 9131B power supply. Preliminary testing showed that this current value provided the largest voltage measurements without appreciable Joule heating at the injected electrode, thereby improving the signal-to-noise ratio (SNR) for measurements. Injection and grounding wires were attached to electrode pins using hook-style leads. Every electrode pin had an attached lead wire connected to four National Instruments (NI) SCB-68A input-output boxes. These signals were then captured using NI PXIe-6368 data acquisition system (DAQ) cards. A LabVIEW program recorded the data for 1 second at 200 Hz. All data reduction was performed using Matlab.

3. Anisotropic Electrical Impedance Tomography Formulation

EIT consists of two parts—the forward problem and the inverse problem. The former seeks to predict the voltage on each electrode given a conductivity distribution, and the latter seeks to determine the conductivity distribution given the electrode voltages. The forward problem is typically solved on a finite element mesh. This is known as the EIT reconstruction mesh. The EIT inverse problem then seeks to find the element-wise conductivity of that mesh. In the remainder of this section, we describe the forward problem for electrically anisotropic materials, demonstrate how the conductivity tensor was transformed to account for the curved surface of the stiffened tube, and then detail the inverse problem for anisotropic conductivity.

3.1. Forward Problem

The forward problem is governed by Laplace’s equation for steady-state diffusion as shown in equation (1).

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

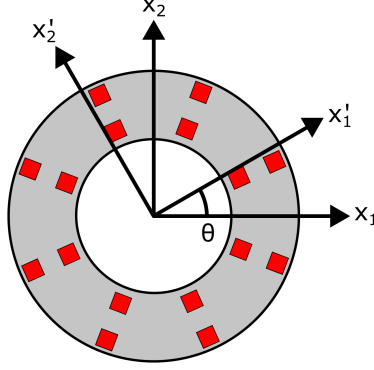


Figure 5: Schematic representation of the coordinate systems used for conductivity transformations. For every element in the shell, θ is calculated using its centroid. The conductivity tensor for that particular element is then transformed by θ using standard second-order transformation laws. Note that only shell elements (i.e., not annulus elements) are transformed due to the curvature of the shell. Note also that x_3 and x'_3 align in the out-of-plane direction.

Above, σ is the symmetric, second-order electrical conductivity tensor, and ϕ is the domain potential. This governing equation is subject to boundary conditions known as the complete electrode model (CEM) boundary conditions [47]. These are shown in equations (2)–(4).

$$\phi + z_l \sigma \nabla \phi \cdot n = V_l \quad (2)$$

$$\sum_{l=1}^L \int_{E_l} \sigma \nabla \phi \cdot n \, dE_l = 0 \quad (3)$$

$$\sigma \nabla \phi \cdot n = 0 \quad \text{on} \quad x \in \partial\Omega \setminus \bigcup_{l=1}^L E_l \quad (4)$$

Above, L is the total number of electrodes, z_l is the contact impedance between the domain and the l th electrode, n is an outward-pointing normal vector, V_l is the voltage on the l th electrode, E_l is the size of the l th electrode, and $\partial\Omega$ is the boundary of the domain. Physically, these boundary conditions enforce a voltage drop between the domain and the electrodes due to contact impedance, conservation of charge, and that current only passes through electrodes, respectively. The finite element-discretized forms of these equations can be found in references [1, 2]. A three-dimensional mesh of linear tetrahedral elements was used in this work. A total of 25,093 tetrahedral elements were generated using Corefoam Cubit, a commercialized finite element meshing software originally developed by Sandia National Laboratories.

3.2. Conductivity Tensor Transformation

Because of the anisotropic conductivity of the carbon fiber laminate and the curved surface of the stiffened tube, the conductivity tensor of each element in the EIT reconstruction mesh must be transformed. That is, the electrical conductivity of the laminate can be measured in its principle directions, x_1 , x_2 , and x_3 , as drawn in Figure 5. This principal state can then be transformed based on how a particular element is rotated about the out-of-plane axis, x_3 , by θ , which is also shown in Figure 5.

Procedurally, the centroid of each tetrahedral element within the shell was first calculated. Next, from the centroid location, the angle θ was calculated and used to construct a standard

transformation tensor, R , about the x_3 -axis. Using the transformation tensor, the transformed conductivity can be calculated as

$$\sigma' = R\sigma R^T. \quad (5)$$

In equation (5), the prime denotes the conductivity tensor in the transformed or primed coordinate system (i.e., the x'_1 - x'_2 - x'_3 system defined in Figure 5). This process was repeated for every element in the shell region of the stiffened tube. No transformations were done in the annulus because this part is aligned with the principal directions of the laminate (i.e., aligned with the x_1 , x_2 , and x_3 -directions) and has no curvature.

3.3. Inverse Problem

A challenge with anisotropic EIT is that the inverse problem goes from seeking one unknown per element (i.e., scalar conductivity) to six (in three-dimensional meshes) unknowns per element (i.e., six independent components of the conductivity tensor). This is problematic because EIT is already a challenging inverse problem, and increasing the number of unknowns per element only exacerbates this challenge. To overcome this challenge, it is common to normalize the conductivity tensor by a scalar value such that $\det|\sigma| = 1$ and then use EIT to find the distribution of these scalar values for each element [48]. More precisely, define the conductivity tensor for a particular element as

$$\sigma = \kappa \tilde{\sigma}, \quad (6)$$

where

$$\kappa = \sqrt[3]{\det|\sigma|}. \quad (7)$$

Thus, the EIT inverse problem ultimately seeks κ for each element. This approach has the benefit of reducing the number of unknowns per element back down to one, but it has the drawback of preserving the eigenvectors of the conductivity tensor before and after damage—a damaged conductivity tensor is physically under no obligation to have the same eigenvectors as its undamaged counterpart. Nonetheless, this is a tradeoff we make in order to render the anisotropic inverse problem as tractable.

Having described the conductivity tensor normalization process, we next proceed to the actual inverse problem. In this work, we opted to use a time-difference formulation. This means that EIT measurements are collected twice—before damage and again after damage. EIT then seeks to find the *change* in κ between states. With this in mind, we define y as the voltage difference vector, where V_m is a vector of inter-electrode voltage differences measured at times t_1 and t_2 .

$$y = V_m(t_2) - V_m(t_1) \quad (8)$$

This vector can also be defined computationally using the forward model as

$$W = F(\kappa + x) - F(\kappa). \quad (9)$$

Above, $F(\kappa)$ is a vector of inter-electrode voltages as predicted by the forward model for a given set of element-wise κ values, and x is the change in κ that we seek (i.e., $x = \delta\kappa$). We use x rather than $\delta\kappa$ in the forthcoming formulation because we solve the EIT inverse problem using an iterative method, and using $x = \delta\kappa$ eliminates the need for cumbersome $\delta(\delta\kappa)$ terms. $F(\kappa + x)$ is next linearized as $F(\kappa + x) \approx F(\kappa) + \frac{\partial F(\kappa)}{\partial \kappa} x$ about some initial estimate of κ , κ_0 (see §5.1). The

316 sensitivity matrix is then defined as $J = \frac{\partial F(\kappa)}{\partial \kappa}$. More explicitly, the value of the sensitivity matrix
 317 for the e th element due to an injection on the M th electrode pair and a measurement on the N th
 318 electrode pair can be calculated as

$$J_{MN}^e = - \int_{\Omega_e} \nabla \phi_M \cdot \tilde{\sigma} \cdot \nabla \bar{\phi}_N \, d\Omega_e. \quad (10)$$

319 In equation (10), MN is a single index of J referring to the integral of the product of the
 320 gradient of the voltage on the e th element due to current supplied by the M th electrode injection
 321 pair and the gradient of the voltage on the e th element due to the N th adjoint field. The adjoint
 322 field is the domain solution due to a unit current injection being supplied to the N th electrode
 323 measurement pair. It should also be remarked that the anisotropic sensitivity matrix returns to
 324 the isotropic form if $\tilde{\sigma}$ is the identity matrix, as is the case for isotropic conductivity.

325 Thus, equation (9) can be expressed as $W \approx Jx$. We then seek an x that minimizes the
 326 difference between W and y , as shown in equation (11).

$$x^* = \min_{x \leq 0} \|Jx - y\|_1 + \alpha \|Rx\|_2^2 \quad (11)$$

327 Above, x^* is the change in κ satisfying the minimization, α is a hyperparameter dictating the
 328 amount of regularization, and R is the regularizer. Because damage is expected to decrease con-
 329 ductivity, a negative constraint is also enforced.

330 Herein, we use the ℓ_1 -norm on the error term. The ℓ_2 -norm is typically used on the error term in
 331 EIT, but this approach is notoriously sensitive to outlier data. The ℓ_1 -norm, on the other hand, is
 332 much more robust to outliers; we therefore strongly recommend it as a best practice in experimental
 333 EIT. To minimize the ℓ_1 -norm of the error, we use the primal-dual interior point method (PDIPM)
 334 [49–51], shown in equation (12).

$$z^* = \max_z \begin{cases} z^T (Jx - y) + \alpha \|Rx\|_2^2 & : |z_i| \leq 1 \\ J^T z + \alpha R^T R x = 0 \end{cases} \quad (12)$$

335 In these equations, x is the primal variable, and z is the dual variable. They are calculated
 336 simultaneously in an iterative fashion as $x^{n+1} = x^n + \delta x$ and $z^{n+1} = z^n + \min(1, \xi) \delta z$. ξ is selected
 337 such that $\xi = \sup(\xi : |z_i^n + \xi \delta z_i| \leq 1)$ for the $n + 1$ iteration by solving equation (13), where E
 338 and G are defined in equations (14–15), respectively. $(Jx - y)_i$ is the i th value of the error vector,
 339 z_i is the i th value of the dual vector, and β is a small scalar value.

$$\begin{bmatrix} 2\alpha R^T R & J^T \\ GJ & -E \end{bmatrix} \begin{bmatrix} \delta x \\ \delta z \end{bmatrix} = - \begin{bmatrix} J^T z + 2\alpha R^T R x \\ (Jx - y) - Ez \end{bmatrix} \quad (13)$$

$$E = \text{diag} \left(\left((Jx - y)_i^2 + \beta \right)^{\frac{1}{2}} \right) \quad (14)$$

$$G = \text{diag} \left(1 - \frac{z_i (Jx - y)_i}{\left((Jx - y)_i^2 + \beta \right)^{\frac{1}{2}}} \right) \quad (15)$$

340 As shown in reference [52], selecting the appropriate regularization term is essential to effective
 341 EIT. Because we are seeking to detect small, highly localized damages (i.e., impact and notch
 342 damage), we herein use the mixed prior. First developed by Homa and colleagues [38, 39], this
 343 approach combines two regularization terms: a smoothness prior and a focal prior as $R = L + \Lambda$.

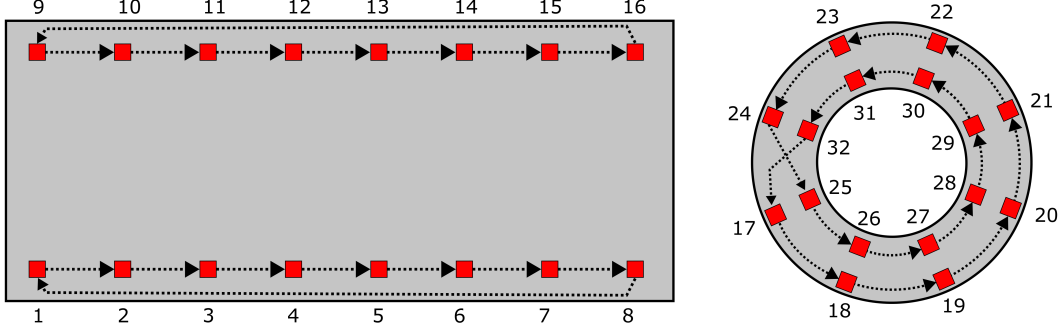


Figure 6: Schematics of the electrode locations and injection-measurement patterns for the shell (left) and the annulus (right). The shell is “cut open” along its length and flattened here for ease of visualization. The arrows indicate the movement of the injection/ground source, for example on the bottom row of electrodes on the shell, from 1–2, 2–3, 3–4, 4–5, etc.

The smoothness prior, L , is the discretized form of the discrete Laplace operator, $\nabla^2 x$, and promotes spatially smooth solutions. The focal prior, Λ , only allows κ changes to occur corresponding to statistically significant variations in the voltages. Consequently, the focal prior is very good at eliminating non-relevant background conductivity changes that may arise from noise. However, it does not require that conductivity changes be connected (i.e., it can give rise to “jagged” conductivity distributions that are decidedly not physical). Combined, these two terms only permit conductivity changes arising from significant variations in the measurement data while also enforcing that elemental conductivity changes are smoothly grouped together. Deriving the mixed prior is outside the scope of this work and is well documented elsewhere. Interested readers are directed to the works of Homa and colleagues [38, 39].

4. Segmentation Procedure

A novel aspect of this work is the *segmented* approach to EIT. To reiterate, this means that only a subset of the total electrodes are used at any given time—just the shell electrodes or just the annulus electrodes. By using only one subset of electrodes, we are effectively only imaging the part of the stiffened tube related to the electrode subset. This has the benefit of reducing inspection burden (i.e., fewer operations in the EIT inverse problem, fewer measurements to take, etc.), but with the consequence of omitting possible damage information on parts of the component not actively being interrogated.

The stiffened tube had a total of 32 electrodes, 16 on the shell and 16 on the annulus. The electrode locations and injection order are shown in Figure 6. In this figure, the shell is “cut open” and flattened out to better see the electrodes. Both the shell and annulus used an adjacent-adjacent injection-measurement scheme, meaning that current was injected between adjacent electrodes and voltages due to any particular injection were likewise measured between adjacent electrodes. For example, considering the bottom row of electrodes labeled as 1–8 in Figure 6, current is first injected on electrode 1 and grounded on electrode 2. During this injection, voltage is measured between all adjacent pairs not involved in the injection/ground process—between electrodes 3 and 4, between electrodes 4 and 5, between electrodes 5 and 6, etc., until the pattern circles back around to measuring voltage between electrodes 8 and 1. More specifically, the shell used two adjacent-adjacent injection-measurement schemes, one on the bottom row of electrodes and a second on the top row of electrodes. That is, for current injected between electrodes on the bottom row (i.e., electrodes 1–8), voltages were only measured between electrodes on the bottom

row. And for current injected between electrodes on the top row (i.e., electrodes 9–16), voltages were only measured between electrodes on the top row. Current was never injected between rows nor was voltage measured between rows. This was done because inter-row electrodes, by virtue of being further apart than intra-row electrodes, will have a larger resistance, which can skew the imaging results. This resulted in two sensitivity matrices, J_{bottom} and J_{top} , and two sets of voltage measurements, V_{bottom} and V_{top} . These were concatenated into a single set of equations as $J = [J_{\text{bottom}}^T \ J_{\text{top}}^T]^T$ and $V_m = [V_{\text{bottom}}^T \ V_{\text{top}}^T]^T$.

The annulus consisted of two rings of electrodes, labeled as 17–32 in Figure 6. The adjacent-adjacent injection-measurement scheme was again used on the annulus. However, unlike the shell, inter-ring injections and measurements (i.e., between electrodes 17 and 32) were allowed because the distance between these electrodes was not much different than the distance between intra-ring electrodes (i.e., electrodes constrained to just one ring).

5. Results and Discussion

5.1. Best-Fit Homogeneous Conductivity

Rather than directly measuring the baseline conductivity of the composite, we instead performed a homogeneous best fit on the stiffened tube. This means that we supplied a range of homogeneous conductivity values to the forward model, used the forward model to calculate the inter-electrode voltages, compared the model-predicted voltages to the experimentally measured voltages, and picked the homogeneous conductivity that minimized the error between the model and the experiment. The shell and annulus electrodes sets were considered simultaneously by concatenating both data sets into a single experimental voltage vector.

A complicating factor with this approach is that the conductivity is not scalar, meaning that we cannot simply loop over a single value for the conductivity. To overcome this challenge, we embedded this best-fit process into three nested *for loops*, one loop for each principal direction of the conductivity tensor. Each loop ran over a range of conductivity values, and then for a given set of principal conductivity values, the principal-state conductivity tensor was transformed based on the orientation of each element in the mesh as described in §3.2. This process resulted in a best-fit homogeneous conductivity of

$$\sigma = \begin{bmatrix} 89.17 & 0 & 0 \\ 0 & 5583.33 & 0 \\ 0 & 0 & 5291.67 \end{bmatrix} \text{ S/m} \quad (16)$$

in the principal state, thereby suggesting that the conductivity is indeed approximately transversely isotropic (i.e., $\sigma_{11} \neq \sigma_{22} \approx \sigma_{33}$, where x_1 is the through-thickness direction and x_2 and x_3 are the in-plane directions). These values are also in line with previously published conductivity values for carbon fiber composites (cf. reference [42]). As previously mentioned in §3.2, transformations were not performed on the annulus part of the component because it is not curved and is aligned with the principal directions. This conductivity tensor was used as the linearization point for calculating the derivative term, $J = \frac{\partial F(\kappa)}{\partial \kappa}$, in the EIT inverse problem and for calculating the baseline value of κ , $\kappa_0 = 1381.11$ S/m.

5.2. Damage Detection

The damage detection results for this study are shown in Figures 7 and 8. The former shows the shell impact and annulus notch damage plotted on the same color scale, whereas the latter shows the shell impact plotted individually on a separate color scale. In order to make it easier

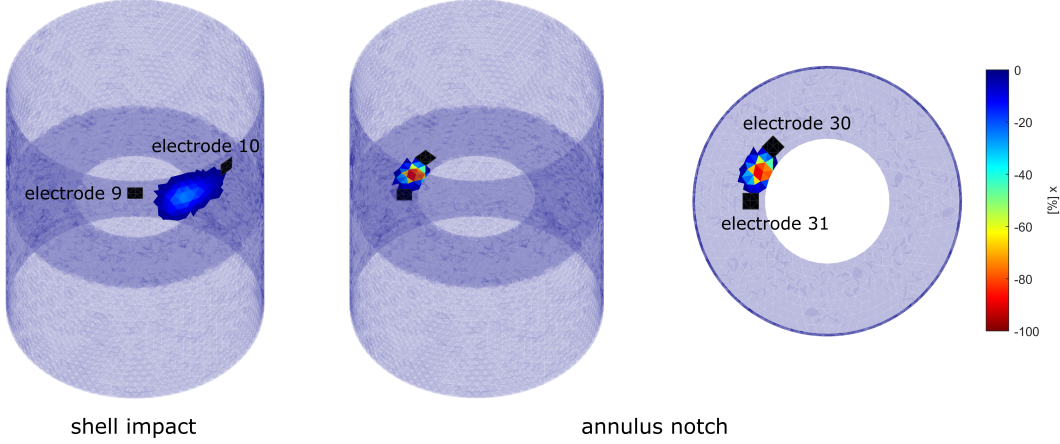


Figure 7: EIT results for impact detection on the shell (left) and notch detection on the annulus (middle and right). Undamaged elements are plotted as being transparent. Damaged elements (corresponding to at least a 1% loss) are opaque. “Fuzziness” in the images is simply a consequence of overlapping transparent regions. Note that x denotes the percent change in κ relative to the baseline value, κ_0 , as calculated from the homogeneous best-fit conductivity. The black squares designate electrode locations. Recall that the impact damage is between electrodes 9 and 10, and the notch damage is between electrodes 30 and 31.

to see that the mixed prior is suppressing non-relevant indications (i.e., conductivity changes only appear corresponding to damage), the element-wise conductivity was plotted as transparent. The exception is for elements having conductivity (more specifically κ) losses greater than 1%; such elements are plotted as entirely opaque. Relevant electrodes near the damage are colored black. Recall that the impact damage occurred between electrodes 9 and 10, and the notch damage was induced between electrodes 30 and 31.

Based on the results shown in these figures, we can draw several conclusions that are worth discussing. First, and perhaps most obviously, it is clear that EIT does accurately detect and localize both the impact damage on the shell and the notch damage on the annulus. This shows that EIT does indeed work on carbon fiber pre-preg composites.

Second, it should be noted that these damages are not detected simultaneously (i.e., both in a single EIT image). Both post-damage voltage sets (i.e., the shell set and the annulus set) are references against a healthy or undamaged state for difference imaging. However, when using only the shell electrodes, we are effectively blind to annulus damage and vice-versa when using the annulus electrodes. This is a consequence of the segmented approach. The segmented approach has the benefit of simplifying the EIT inverse problem by interrogating only one set of electrodes at a time, but it does necessarily come at the cost of no sensitivity to non-interrogated parts of the component. Hypothetically, however, one could “stitch together” the images from each segment to produce an image of the entire stiffened tube. This limitation of the segmented approach is essential to keep in mind when using EIT in practice; an unaware operator may errantly miss defects or other damages on the non-interrogated part of the component resulting in a Type II error (i.e., missed defect).

Third, consistent with previous work using the mixed prior [38, 39], non-relevant conductivity changes (i.e., away from the damage locations due to noise, electrode misalignment, etc.) are entirely suppressed. This is an especially useful property of the mixed prior, especially with regard to avoiding Type I NDE errors (i.e., false positives).

And fourth, considering Figure 7, the notch-induced conductivity loss on the annulus is significantly larger than the impact-induced conductivity loss on the shell. This is an expected result

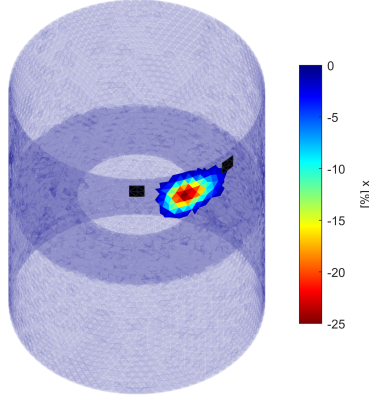


Figure 8: EIT results for impact detection on the shell only. Undamaged elements are again transparent. Elements with a 1% loss are opaque. x again denotes the change in κ relative to the baseline value. Note that the impact damage is much more evident when plotted individually. The black squares again indicate electrode locations.

and makes intuitive sense. That is, the notch, by virtue of entirely removing material, represents a total cessation of conductivity. Hence, we physically expect a 100% conductivity loss, which is roughly what we see in the EIT results. The impact, on the other hand, results in a complicated network of fiber breakage, delamination, matrix cracking, etc., the totality of which does not entirely prevent current flow (i.e., there are residual intact fibers after the impact that give rise to non-zero conductivity). Hence, we do not necessarily expect a 100% conductivity loss. Instead, we observe a roughly 25% conductivity loss.

6. Summary and Conclusions

In summary, this manuscript has studied the effectiveness of EIT for damage detection in carbon fiber composites. This work was motivated by the potential of EIT for the inspection of carbon fiber composites and the need for further validation of this modality. More specifically, three novel contributions were targeted: First, this study represents, to our knowledge, the first application of EIT to a pre-preg carbon fiber composite. Validating EIT on a pre-preg carbon fiber composite (as opposed to a carbon fiber composite produced by methods such as resin infusion and hand layup) may seem trivial, but considering that pre-pregs are the standard for real, structural-grade composites, explicitly confirming that EIT does indeed work on them is essential.

The second novel contribution of this paper was a segmented approach to EIT. Many real structures and components consist of multiple parts or shapes each representing areas of concern. In the case of this study, the stiffened tube is made up of an outer shell and an inner annulus. Rather than interrogating the entire component during each EIT inspection, it may be desirable to interrogate just one part of the component at a time, which has benefits such as reducing computational burden and focusing/narrowing the scope of the inspection. To this end, we presented a segmented approach to EIT in which only one subset of the entire domain was inspected at a time. Further, the EIT inverse problem was solved using the ℓ_1 -norm on the error term and the mixed prior for regularization. The authors strongly recommend the use of the ℓ_1 -norm on the error term in experimental EIT due to its demonstrated robustness to outlier data. And similar to observations made in previous studies [38, 39], the mixed prior showed that it is quite adept for imaging small, highly localized damages such as impacts and notches.

And third, we demonstrated these techniques on a complexly shaped component, an annulus-stiffened tube. EIT has been exhaustively validated on simple shapes such as flat plates that do not represent the reality of composite designs. The authors therefore strongly encourage others to likewise validate their techniques and instruments on shapes of representative complexity.

Having summarized our contributions, we can draw the following conclusions.

- EIT does indeed work on pre-preg carbon fiber composites. This may seem like a self-evident conclusion, but as described previously, given the prominence of pre-preg in real engineering applications, especially for load-bearing components and structures, validating the effectiveness of EIT as an inspection and NDE modality is an essential and necessary step.
- Segmented EIT formulations are effective at finding damage in their respective sections, but they entirely miss damage in other sections. Segmented EIT formulations should therefore be used with this understanding. If the operator is unaware of the limitations of a particular subset of electrodes, they may accidentally conclude that the component is damage free, resulting in a Type II error.
- A 46 J impact produced an estimated 25% loss in conductivity, whereas a comparable study using dry fabric CFRP had a 10% loss from a 12 J impact [42]. Because pre-preg CFRPs have superior material properties (e.g., toughness), EIT practitioners should be aware that an impact energy in a dry fabric laminate may not be sufficient to induce damage in a similar pre-preg laminate and test parameters may need to be adjusted accordingly.

Lastly, we can make a few recommendations for future research. First, even though the material herein studied exhibited mild electrical anisotropy, real structural-grade carbon fiber composites are typically produced out of unidirectional tapes, which are *highly* electrically anisotropic. The anisotropic formulation used in this work is unlikely to work on such materials; highly anisotropic EIT formulations are therefore needed. Second, electroding remains an unsolved challenge for this field. Silver paste-based electrodes such as used in this study work well enough in laboratory conditions, but they are utterly unsuitable for field use. And third, we used a three-dimensional reconstruction mesh in this work. However, especially for relatively thin-walled components, it would be much more computationally efficient to use shell elements. Future work on thin-walled EIT should therefore prioritize this. Work by Jauhiainen et al. [43] is an excellent starting point.

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