Damage Detection Via Electrical Impedance Tomography in a Filament Wound Glass Fiber/Epoxy Composite Tube with Carbon Black Filler

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ABSTRACT

Fiber reinforced polymer composites are increasingly being used in the automotive, aerospace, and many other sectors owing to their superior specific stiffness and strength. Filament winding provides means to manufacture cylindrical fibrous composites finding applications in building stronger pressure vessels and corrosion-resistant piping systems. With the expanding use of composites to build vital structural components, there arises the need to monitor the health of these structures. The primary challenge in health monitoring of composites involves the detection of non-visible and sub-surface damage. Current methods to address this issue in filament wound composites include embedding optical fiber or piezoelectric sensors during the manufacturing process. Apart from introducing weak spots in the structure, embedding these sensors make the manufacturing process difficult and time consuming. Nanofiller modified matrix composites impart conductive properties to the composite which can be leveraged for health monitoring with minimal changes to the manufacturing process. The self-sensing capability of these composites can be combined with conductivity imaging modalities such as electrical impedance tomography (EIT) for damage identification and localization. EIT is a low-cost, real-time imaging technique in which the electrical conductivity of the body is inferred from boundary voltage measurements. To date, however, EIT has been primarily used on planar geometries such as rectangular composite coupons. Therefore, this work demonstrates the potential of EIT for damage detection in non-planar, multiply connected domains – a carbon black (CB)-modified glass fiber/epoxy filament wound composite tube. The results show that multiple through holes as small as 7.94 mm can be detected for tubes with a diameter-to-length ratio of 1:2. It was also observed that the sensitivity of this method improved as the aspect ratio of the tube decreased. These preliminary findings strongly indicate the potential of using EIT for damage detection in more complex geometries such as self-sensing filament wound composite tubes.

INTRODUCTION

Fiber reinforced composite materials are increasingly being used in the aerospace, automotive, renewable energy, and oil industries owing to their light weight, high strength, and corrosion-

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resistance properties. Cylindrical composites find applications in building lighter pressure vessels [1] and stronger, corrosion-resistant piping systems [2]. Safety factors are an important concern with the use of composite materials since damage detection remains a challenge. Composite structures can therefore benefit from robust structural health monitoring (SHM). Current SHM methods to detect damage in composites include embedding optical fiber sensors [3] [4] or piezoelectric sensors [5] in the composite. These methods not only introduce foreign elements into the composite, which act as weak spots, but also make the manufacturing process complex and time consuming.

As an alternative, nanofiller-modified composites have recently received much attention due to self-sensing capabilities (i.e. the structure itself acts as a sensor). Adding nanofillers like carbon nanotubes to the insulating matrix phase of a composite imparts conductive properties to the structure [6] thereby causing the structure to exhibit piezoresistivity. Piezoresistivity is the property by which mechanical strain or damage cause conductivity changes in the material. These conductivity changes can be leveraged for damage detection in the composite [7] [8].

In light of the piezoresistive effect, we need a method of localizing damage-induced conductivity changes in the structure. To that end, electrical impedance tomography (EIT) has recently emerged as a promising SHM tool. EIT is a low-cost, real-time imaging modality where the conductivity throughout a domain can be inferred from boundary voltage data. EIT can be used to localize damage in nanofiller-modified composites since damage directly corresponds to a local change in conductivity. This method has been abundantly demonstrated in composite materials [9] [10] [11] [12] [13] [14] [15] [16] [17] [18] [19]. Despite of the success of the preceding studies in finding damage using EIT, these studies have considered only planar coupons (i.e. thin rectangular plates). Therefore, for EIT to be a viable SHM modality, much work remains to be done in order to transition it from these simple shapes to complex geometries representative of real structures. Hence, the current study looks into damage detection of a glass fiber/epoxy composite tube which has been modified with carbon black filler to be piezoresistive.

The remainder of the paper will be organized as follows. First, an overview of EIT is discussed followed by the experimental methods used. Next, the experimental results for a glass fiber/epoxy specimen with carbon black (CB) filler are presented. Finally, the manuscripts concludes with a brief summary and conclusions.

ELECTRICAL IMPEDANCE TOMOGRAPHY

EIT aims to reproduce the conductivity distribution of a domain from current-voltage relationships observed at the domain's boundary. Mathematically, this is achieved by minimizing the difference between a set of experimentally measured voltages and a set of predicted voltages.

$$\boldsymbol{\sigma}^* = \arg\min_{\boldsymbol{\sigma}} \|\boldsymbol{V}_m - \boldsymbol{F}(\boldsymbol{\sigma})\|^2 \qquad (1)$$

In equation (1), $\boldsymbol{\sigma}^*$ is the conductivity distribution we aim to reconstruct from experimental data, $\boldsymbol{V}_m$ is the set of experimental boundary voltages, and $\boldsymbol{F}(\sigma)$ is the set of voltages predicted via a numerical simulation. The numerical simulation is carried out by discretizing the domain via the finite element method. The finite element simulation predicts boundary voltages based on the conductivity σ provided to it, which is written as $\boldsymbol{F}(\sigma)$ in the equation above. In practical systems, EIT generally makes use of conductivity changes rather than absolute conductivity (e.g. the conductivity change before and after damage). To do so, a one-step linearization is carried out by approximating $\boldsymbol{F}(\boldsymbol{\sigma})$ with a Taylor series expansion centered about an initial conductivity estimate $\boldsymbol{\sigma_0}$ and keeping only the linear terms [14] as shown in equation (2).

$$\boldsymbol{F}(\boldsymbol{\sigma}) \approx \boldsymbol{F}(\boldsymbol{\sigma_0}) + \frac{\partial \boldsymbol{F}(\sigma_0)}{\partial \sigma} (\boldsymbol{\sigma} - \boldsymbol{\sigma_0}) \tag{2}$$

From equation (2) we see that $\boldsymbol{\sigma}$ has been taken out of the argument of $\boldsymbol{F}$ and $(\boldsymbol{\sigma} - \boldsymbol{\sigma_0})$ is the change in conductivity, $\delta\boldsymbol{\sigma}^*$, that we aim to find. Difference imaging is necessary because even small errors from electrode placement and noise between the finite element model and actual experiment can cause large errors in conductivity estimations. Thus, difference imaging subtracts these common errors out. It also noteworthy that the voltage difference vector does not have to be the difference between a damaged and an undamaged state. It can be the difference between the current damage state and a previous damage state from which further occurrence of damage needs to be ascertained. Finding the damage-induced conductivity change in the domain is a severely ill-posed problem and requires regularization to obtain physically meaningful results. We employ Tikhonov regularization to stabilize the inverse problem. Mathematically, this is written out as a damped least square problem as shown in equation (3).

$$\delta\boldsymbol{\sigma}^* = \min_{-\mathbf{1.01}\boldsymbol{\sigma_0} < \boldsymbol{\delta\sigma} < \mathbf{0.01}\boldsymbol{\sigma_0}} \left(\left\| \begin{bmatrix} \boldsymbol{J} \\ \alpha \boldsymbol{L} \end{bmatrix} \delta\boldsymbol{\sigma} - \begin{bmatrix} \delta \boldsymbol{V} \\ \mathbf{0} \end{bmatrix} \right\|_2^2 \right) \tag{3}$$

In equation (3), $\boldsymbol{J} = \partial \boldsymbol{F}(\boldsymbol{\sigma_0})/\partial \boldsymbol{\sigma}$ and is called the sensitivity matrix, $\boldsymbol{L}$ is a regularization term, α is called the hyper parameter and controls the contribution of the regularization matrix, and $\delta \boldsymbol{V}$ is the experimental voltage difference between the undamaged and damaged state. The minimization problem is a constrained linear least squares problem with $-1.01\boldsymbol{\sigma_0} < \boldsymbol{\delta\sigma} < 0.01\boldsymbol{\sigma_0}$. These bounds are chosen with the motivation that damage causes a loss in conductivity and the change in conductivity will be negative. A 1% tolerance has been specified for both the lower and upper bounds to account for the presence of noise in experimental data. For more details about the mathematical formulation, the readers are directed to [20].

For the inverse problem, the domain was discretized using linear tetrahedral elements. Sufficient number of elements were used to capture the domain curvature of the cylindrical body. Figure 1 shows the mesh used for EIT.

EXPERIMENTAL DETAILS

The composite tube under study was made by Dr. Charles E. Bakis and his graduate student Jeff Kim of Penn State University using epoxy and S-glass fibers with a layup sequence of $[\pm 55°]_3$. Piezoresistivity was imparted with CB added at 1.0 wt.%. The tube had an inner diameter of 2.5" and a wall thickness of 0.085"

For EIT, current is injected from an electrode on the top edge to the electrode on the bottom edge of the tube. Voltages are measured between adjacent electrodes on the same edge for each current injection. One such current injection is shown in Figure 1. The current injection is repeated until every top-down pair receives an injection. The top down injection pattern was used to make sure current intercepts damage in the domain and the adjacent voltage scheme is used to prevent mirroring of damage during the conductivity reconstruction.

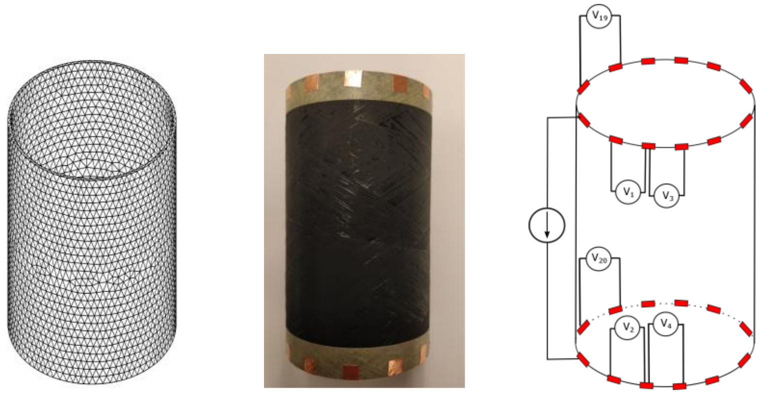

Figure 1. Left: FEM mesh used for EIT reconstruction. Middle: Actual specimen for EIT. Right: Schematic showing injection and measurement scheme.

DAMAGE DETECTION

Two specimens were studied to understand the capability of damage detection via EIT on non-planar multiply connected domains. The first specimen has a length-to-diameter ratio of 2:1. Voltage is collected before introducing any damage into the structure and this is used as the baseline for further image reconstructions in the presence of damage. Here, damage is introduced by drilling holes of various sizes. The first hole, of diameter 4.76 mm, is drilled approximately near the center of the specimen. This hole is subsequently bored out to larger diameters of 7.94 mm and then 9.53 mm. EIT images are produced after each new hole. This is done for a total of three different locations. The schematic in Figure 2 shows the three damage locations.

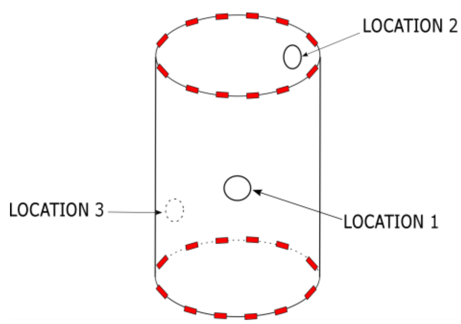

Figure 2. Schematic showing hole locations. Note that solid lines are used when the hole is visible from the current line of sight and dashed lines are used when the hole is not visible.

EIT images of the damage can be seen in Figure 3. We can make some interesting observations from Figure 3. First, the smallest hole of size 4.76 mm goes undetected in almost all the cases, except at location 2, where we see a very small change in conductivity. This may indicate the lower limit of detectability for EIT on this shape. Second, it seems that sensitivity is lost to damage near the center of the specimen. That is, as shown in the top row of Figure 3, no appreciable change in conductivity can detected for any size hole in location 1. This could be attributed to the fact that EIT is well-known to lose sensitivity away from measurement electrodes. EIT also seems to lose sensitivity to the damage at location 3 which is closer to the center of the specimen than location 2. This is inferred from the observation that EIT produces a smaller change in magnitude of conductivity for damage at location 3 than at location 2.

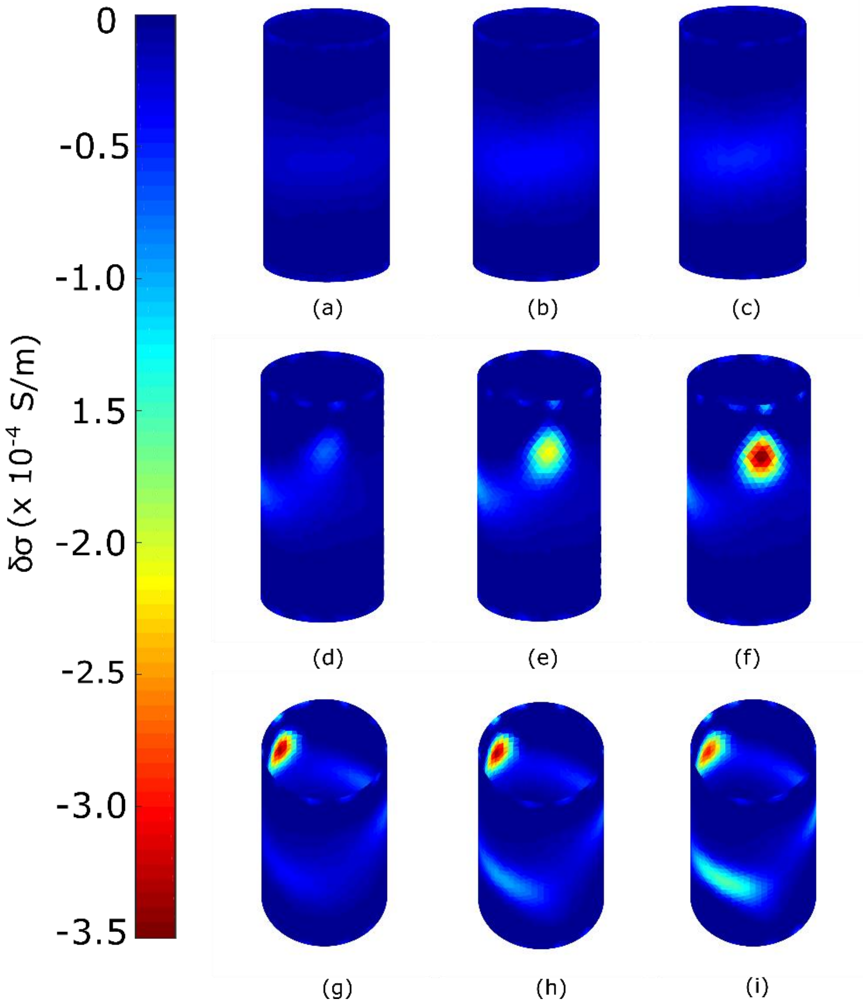

Figure 3. EIT reconstructions of (a) 4.76 mm hole at location 1 (b) 7.94 mm hole at location 1 (c) 9.53 mm hole at location 1 (d) 4.76 mm hole at location 2 (e) 7.94 mm hole at location 2 (f) 9.53 mm hole at location 2 (g) 4.76 mm hole at location 3 (h) 7.94 mm hole at location 3 (i) 9.54 mm hole at location 3.

To further explore the extent to which EIT loses sensitivity near the center for long specimens, we conduct another set of experiments for a tube of identical construction but now with a length-to-diameter ratio of 1:1. A hole of diameter 4.76 mm is drilled out approximately near the center of the specimen. And again, this hole is subsequently bored out to larger diameters of 7.94 mm and 9.53 mm.

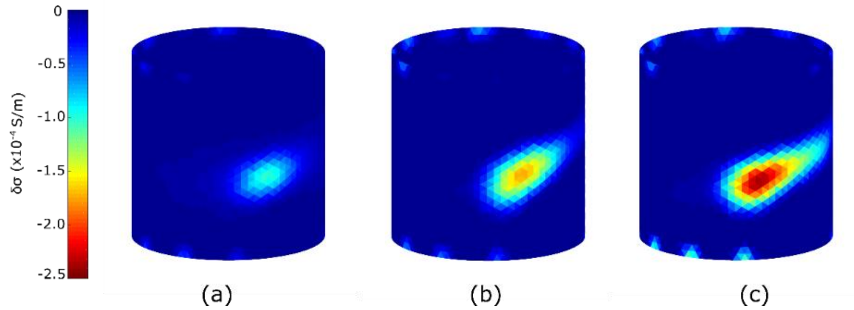

Figure 4. EIT reconstructions of (a) 4.76 mm hole (b) 7.94 mm hole (c) 9.53 mm hole.

The results in Figure 4 show that for shorter specimens, EIT is indeed able to capture damage near the center of the specimen. Further, EIT is even able to clearly localize the smallest damage case (4.76 mm) which could not be detected at all in the previous 2:1 tube.

SUMMARY AND CONCLUSIONS

The present study aimed to find damage in a filament-wound composite tube via EIT. Applying EIT to a tube represents a substantial departure from prevailing studies in the state of the art in which EIT has been limited to simple, planar geometries. The first specimen studied had a length-to-diameter ratio of 2:1. Holes of increasing diameters were introduced into the specimen at multiple locations. EIT was able to adeptly locate holes near the edges of the tube but seemingly lost sensitivity to holes at the center of the tube. In order to better understand how the tube's aspect ratio affected sensitivity, a second set of EIT experiments was conducted on a shorter tube with a 1:1 length-to-diameter ratio. In this second tube, all through holes could be clearly located in the center of the specimen.

Based on this preliminary study, it appears that EIT has considerable potential for application to non-planar geometries. Considering the abundance of EIT literature and the fact that it has overwhelmingly been relegated to simple plate-like shapes, this preliminary work is potentially of enormous consequence in transforming EIT into a powerful SHM modality. However, this preliminary work also did not make any alterations to the underlying mathematical framework of EIT. Therefore, future work should seek to refine the mathematics of EIT to make it even better suited for complex, structurally realistic shapes.

ACKNOWLEDGEMENTS

The authors gratefully thank Professor Charles E. Bakis and his graduate student Jeff Kim for making the composite tube used in this study.

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