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On the detectability of transverse cracks in laminated composites using electrical potential change measurements

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ABSTRACT

Real-time health monitoring of structures made of laminated composites is necessary as significant damage may occur without any visible signs on the surface. Inspection by electrical tomography (ET) seems a viable approach that relies on voltage measurements from a network of electrodes across the inspected domain to infer conductivity change within the bulk material. If conductivity decreases significantly with increasing damage, the obtained conductivity map can be correlated to the degradation state of the material. We focus here on detection of transverse cracks. As transverse cracks modify the in-plane transverse conductivity of a single ply, we expect them to be detectable by electrical measurements. Yet, the quality of detection is directly related to the sensitivity of the measurements to the presence of cracks. We use numerical experiments to demonstrate that the sensitivity depends on several material and geometrical parameters. Based on the results, the applicability of ET to detect transverse cracks is discussed. One conclusion from the study is that detecting transverse cracks using ET is more reliable in some laminate configurations than in others. Recommendations about the properties of either the pristine material or the inspected structures are provided to establish if ET is reliable in detecting transverse cracks.

1. Introduction

Laminated composites possess superior mechanical properties, such as a high strength-to-weight ratio, corrosion resistance, and better fatigue properties in comparison with metallic solutions, which make them good candidates for long-term structural applications [10]. In spite their proven advantages, composites are complex when compared to classical metallic materials, due to the wide range of possible degradation mechanisms, including intralaminar degradation, which includes fiber breakage [8,12], diffuse damage [59,29], transverse cracking [26,39,32], and local delamination [36,40,60,27,28], and interlaminar degradation, which mainly includes delamination. Furthermore, significant damage can occur in such materials without being visible on the surface, which in turn makes real-time monitoring crucial. Being able to track and monitor the appearance and evolution of degradation in composites is key to the successful use of such complex materials while increasing the level of confidence.

Techniques to evaluate the degradation state can be broadly classified as non-destructive testing (NDT) and structural health monitoring (SHM) techniques. While most NDT techniques can only be used offline and often require dismantling of the part to be tested, SHM can ideally be used *in situ* to obtain *real-time* information about the degradation [11]. NDT techniques, which usually require heavy and expensive instruments but provide more detailed results (such as X-ray inspection, for example), are therefore suitable for refined inspection of parts that have been clearly identified as damaged. SHM techniques, which are supposedly fast, efficient, and cost-effective, are on the other hand needed for detecting the initiation and location of such damage within a system during operation [11].

SHM techniques that are currently available include optical fibers [30], acoustic emission [14], ultrasonics [5], modal analysis [13], lamb waves [13,37,47], the strain memory alloy method [13], and eddy current techniques [17]. However, most of these techniques require sensors/actuators that are sometimes expensive and often require shutting down the system. Moreover, these techniques necessitate the intervention of skilled personnel on site, which is not desirable for structures that are out-of-reach during operations such as in flight or underground structures [24].

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Nomenclature

u	electric potential
$\mathbf{E}$	electric field
$\mathbf{J}$	current density
Ω	domain
$\delta\Omega$	boundary of domain Ω
z_{el}	contact impedance
I_{el}	current applied between two electrodes
V_{el}	electric potential obtained from electrode *el*
$\mathbf{n}$	outward unit normal vector
S_{el}	surface area of electrode
n_{el}	total number of electrodes
λ	conductivity ratio
$\mathbf{\Sigma}$	electrical conductivity
e_1	fiber direction
e_2	transverse direction
e_3	through-thickness direction
ρ	dimensionless cracking density
H	thickness of cracked ply
L	average length between cracks
Σ_2	transverse conductivity of ply
$[\,]^\circ$	parameter of interest when there is no damage
d_e	mesoscale damage indicator
m	thickness ratio
n	number of layers in cracked ply
Σ_3	through-thickness conductivity of ply
Σ_1	longitudinal conductivity of ply
V	set of electric potential obtained from the electrodes
S	sensitivity
p	ply number
J_x^p	current density of ply p in x-direction
A_p	cross-sectional area of ply p
θ_p	orientation of ply p
π	cross-section of a composite laminate
A	total area of cross-section π
h	total thickness of laminate
w	width of laminate
h_p	thickness of ply p
Σ^{eq}	equivalent conductivity of the laminate
l	length in x-direction between two current injection electrodes
$\triangle V$	potential difference between length l
t^{cr}	total number of cracked plies
Σ_x^{cr}	conductivity of the cracked ply in the x-direction
h_{cr}	thickness of cracked ply
el	electrode

One method that is gaining interest as a potential SHM method is electrical tomography. Electrical Resistivity Tomography (ERT), which uses DC currents, or Electrical Impedance Tomography (EIT), which uses AC currents, aim at reconstructing the conductivity field within the inspected part based on a set of electrical measurements on the surface. This method has the advantage of providing *real-time* and in situ information about the health of the material without being invasive and without the need for expensive sensors/actuators. It is a technique that provides structural information at the global scale and has been shown to be sensitive towards capturing delamination and impact damage [51,58]. Identifying damage in composites via ET can be viewed as a two-step process, involving two inverse problems. The first one is a global inverse problem in which the conductivity map of the material is recovered from a finite number of voltage measurements obtained on the surface. The measurements themselves are obtained by applying current through pairs of electrodes and measuring the difference in voltage through all other subsequent pairs of electrodes. This inverse problem always constitutes an ill-posed problem due to the limited amount of information provided by the data to describe the complex state of the material in the bulk [41,9]. The second one is a local inverse problem that involves using the conductivity map obtained from the reconstruction process to locally correlate the conductivity values to the various damage mechanisms in the composite. The solution of this inverse problem is also non-unique as the obtained conductivity can be interpreted in multiple ways in terms of the different underlying possible damage mechanisms. In addition, the fact that composite materials are anisotropic makes both inverse problems highly ill-posed. Much progress has been made in solving these inverse problems: (i) specific regularization methods have been proposed in the literature (see [42,20,16,56,31,23,54,3,38]) to make the global inverse problems well-posed, although to our best knowledge, methods for highly anisotropic materials are yet to be developed, and (ii) various experimental studies and numerical studies [44,1,55,21,52,51,46,45,33] have been done to understand how the different mechanisms modify the conductivity of the laminate. However, these methods can only be applied if the damage is detectable, i.e., the measurements are sensitive to the different damage mechanisms.

Since conductivity of composites is anisotropic, the sensitivity of the measurements with respect to the various damage mechanisms is dependent on the direction. It was shown in [48] that indeed for a typical Carbon Fiber Reinforced Plastic (CFRP), the change in the electrical potential measured at the electrodes due to transverse cracks was very small, i.e., the sensitivity was minimal. Also, unlike experiments that are carried out in a controlled environment, the nature of the loading in actual applications is often unknown and the degradation profile is complex due to multiple mechanisms occurring simultaneously. Thus, the effect of transverse cracks is difficult to isolate from the other conductivity changing mechanisms such as piezoresistivity, plasticity and delamination if the sensitivity is too small. Yet, the various factors that influence the sensitivity of the measurements to transverse cracks are poorly understood. An understanding of the following aspects is thus required: (i) whether the damage is detectable through the voltage measurements, i.e., whether the change in the conductivity can be separated from noise; (ii) how sensitivity varies for different material and geometrical parameters, such as the conductivity ratio, the thickness ratio, and current injection patterns, and (iii) how the sensitivity towards transverse cracks compares with other conductivity-changing mechanisms. Since the anisotropy in electrical conductivity of a single ply largely varies depending on the nature of the primary constituents (as shown in Section 2.2), this study will show the range of applicability of electrical tomography for detecting transverse cracks.

The paper is organized as follows: in Section 2, we recall the continuum formulation that describes the response of the structure when subjected to electrical tomographic conditions. Also, some key points on the electrical behavior of a single composite ply, such as the level of anisotropy depending on the raw constituents, are emphasized. Also, the effect of transverse cracking on electrical conductivity at the mesoscale and the definition of sensitivity are outlined. Section 3 presents the effect of the various parameters outlined before on the sensitivity of the measurements to transverse cracks. In Section 4, an analytical model that can