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Application of electrical impedance tomography to an anisotropic carbon fiber-reinforced polymer composite laminate for damage localization

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ABSTRACT

Electrical impedance tomography (EIT) is an emerging method for assessing the structural condition of composite structures. In this work, EIT's damage localization capability is investigated through its application upon a commercial laminated anisotropic carbon fiber reinforced polymer plate. Aluminum rivets were used as electrodes. EIT reconstructs the spatial conductivity within a defined space by using its boundary voltage response. The algorithm starts with a forward simulation of the voltage distributions within the boundary, hence the orthotropic conductivity of the CFRP plate was first characterized experimentally. It was found that the inhomogeneous fiber contacts through the thickness are influencing the reconstruction results. A detailed 3D finite element simulation was built to model the conductivity distribution. Different current injection patterns were attempted with their reconstruction results being evaluated via four criteria. It was found that the diagonal current injection and the difference evaluation lead to the best results.

1. Introduction

Carbon fiber reinforced polymers (CFRP) are increasingly utilized for aerospace, automotive and wind energy structures due to their high strength- and stiffness-to-weight ratio. However, this potential is generally reduced by high safety factors, since failure prediction is not reliable so far. Structural health monitoring (SHM) can help exploit the full lightweight potential of CFRPs by enhancing this reliability. Different SHM methods are investigated for a potential application on CFRP, as for example guided waves [1] or fiber optical sensors [2].

Sensors have to be applied on the structures for most SHM techniques. Especially CFRP can be a smart material, due to the good electrical conductivity of the carbon fibers. The structure itself is the sensor. Based on this characteristic it was proposed for damage detection and strain sensing [3,4].

Direct electrical resistance measurements are, for example, applied to polymers, doped with conductive nano-particles such as carbon nanotubes, graphene or silver. They are, for example, used as surface sensors or matrix material for glass fiber reinforced polymers. Their quasi-isotropic electrical conductivity is usually optimized for the SHM application [5]. In contrast to this, the highly anisotropic and sometimes inhomogeneous conductivity of the unidirectional (UD) CFRP ply is a great challenge. Laminates are not optimized for their electrical properties but for their structural application, for instance, for their load carrying capacity. Different methods for damage detection based on resistance measurement and piezoelectricity, for example, in UD specimens during tensile tests, were investigated by different research groups [6–10]. A methodology for damage localization based on neural networks was also proposed for orthotropic material [11]. However, the methodology is based on extensive simulated training data and the experimental results do not correspond well to the training results on isotropic specimens.

The electrical impedance tomography (EIT) can be used as a tool for damage localization and identification in structures. EIT was recently applied for damage localization in quasi-isotropic CFRP material [12,13]. However, the anisotropy and inhomogeneity of the composite laminate remains a challenge.

Electrical contacts are necessary for current introduction and resistance or voltage measurements. They are an additional challenge for CFRP, since contact resistances are usually in the same order of magnitude as the resistances to measure. However, contact resistances are not that important for damage detection as long as they are constant over time, since often the resistance change is compared to an initial baseline measurement. But as they influence the measurement accuracy, it is necessary to keep them as small as possible compared to the resistances to measure [8]. An obvious contact solution for CFRP

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structures are rivets, since they are often used as fail safe elements in aircraft structures in addition to adhesive bondings [14,15]. In contrast to standard laboratory solutions as silver paint and silver epoxy or blades which are driven in the material, rivets are robust and additional contact elements can be avoided [9,15].

In this work the damage localization potential of direct resistance and voltage measurements for anisotropic CFRP material is investigated. In a preliminary study the one dimensional damage localization was shown to be applicable to a UD specimen [16]. Here, the potential of the EIT method for two dimensional damage localization in an anisotropic CFRP laminate is examined. For this study, first, the homogenized anisotropic conductivity tensor of the considered CFRP material is determined experimentally. Second, two different contact solutions are applied on two square CFRP plates, blades and rivets. Third, different measurement patterns are used for the EIT. Finally, the results are compared to finite element simulations.

2. Material and methods

2.1. Material

The composite laminate material used in this study is commercially available and consists of the UD fiber/epoxy prepreg FT 109 with an areal weight of 600 g/m^2 (CG-TEC GmbH, Germany). The fiber volume fraction is 55.5% and the anisotropic layup is [0°/90°/0°]. Each square-shaped plate has a thickness of 1.8 mm and a width of 250 mm.

2.2. Electrical anisotropy of CFRP

Each UD CFRP ply has an anisotropic electrical conductivity, resulting from the one-dimensional highly electrically conductive carbon fibers and the isolating polymer matrix. The homogenized conductivity of a ply in fiber direction (1-direction) can be calculated by the rule of mixtures [17]. In the directions perpendicular to that (2- and 3-direction) the conductivities are caused by percolation through contacts between fibers and are therefore up to 2000 times lower depending on fiber volume fraction and fiber waviness [15,18]. The conductivity between plies of different orientation within a laminate is lower than that of the 2- and 3-direction homogenized conductivities within a ply, since this interface has a lower amount of fiber contacts. In Fig. 1(a) the fiber contacts are illustrated in case of the highest theoretically possible packing. The minimum distance between two fiber contacts within a ply transverse to the fibers is the fiber radius *r*. In fiber direction, such contacts are continuous, as shown in the red lines in Fig. 1(a). Between two plies the minimum distance is 2*r* in both directions, as indicated by the red points. In Fig. 1(b) a microscopic image of the contact zone between a 0°- and a 90°-ply of the investigated laminate is shown.

Assume that the UD CFRP ply has an orthotropic electrical conductivity, the conductivity tensor in the principal directions can be formulated as

$$\Sigma = \begin{bmatrix} \sigma_{11} & 0 & 0 \\ 0 & \sigma_{22} & 0 \\ 0 & 0 & \sigma_{33} \end{bmatrix}. \tag{1}$$

A homogenized conductivity tensor could be determined according to the classical laminate theory, if the layers were homogeneous and without electric gradient through the thickness present [18]. For the single ply it is assumed that σ_{22} and σ_{33} are equal due to the ply's transverse isotropy. It is necessary to determine the components of the ply's conductivity tensor to understand a CFRP's electrical behavior for the purpose of modeling and analysis.

However, since only laminated material is available in this study only the in-plane conductivities σ_{11} and σ_{22} of a unidirectional laminate as well as the homogenized in-plane conductivities of the anisotropic laminate under investigation are determined.

Direct determination of the conductivity tensor components by measuring the gauge resistance of a specimen is not possible due to the very low resistivity of individual carbon fibers. The contact resistance of a conventional electrode attachment can be of higher magnitude than that of the carbon fibers, resulting in an extremely low signal-to-noise ratio. Four-probe measurements with varying specimen lengths may provide accurate measurements, but are time-consuming [6]. This method was applied to UD specimens. A more simple procedure for determining the electrical conductivity of anisotropic materials was proposed by Montgomery [19,20] and adopted in this study to determine the homogenized two-dimensional conductivity tensor of anisotropic CFRP laminates. The application of this method for CFRP laminates was validated by the four point measurements and finite element (FE) simulation. The required specimen is a rectangular prism with faces orthogonal to the principal axes (1- and 2-direction) and four electrodes on the corners of one face. Therefore, the Montgomery-method can be directly applied on the specimen plates. Razor blades were used as contacts at the edges. Current is applied through the contacts on two neighboring corners and the voltage is measured between the other two corners. A similar measurement is made with contacts rotated by 90°. These measurements permit the calculation of the in-plane components of the resistivity tensor. The measured components of the homogenized conductivity tensor of the UD specimens are $\sigma_{11} = 31.25$ (Ωmm^{-1}) and $\sigma_{22} = 0.015$ (Ωmm^{-1}) with a conductivity ratio of $\sigma_{11}/\sigma_{22} = 2083$ [16]. The measured homogenized components of the laminate are $\sigma_{11} = 11.77$ (Ωmm^{-1}) and $\sigma_{22} = 6.35$ (Ωmm^{-1}) with a conductivity ratio of $\sigma_{11}/\sigma_{22} = 1.85$, which is close to the theoretical value of 2 (classical laminate theory), for the stacking sequence of the considered laminate.

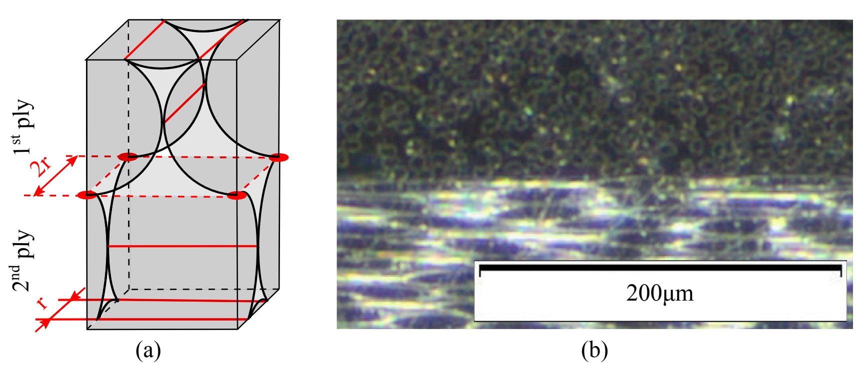

Fig. 1. Fiber contacts: (a) The sketch illustrates the maximum possible fiber contacts within (distance is fiber radius r) and between two perpendicular plies (distance 2r); (b) An optical microscopic image shows a cross-section of the [0°/90°] ply interface of the considered laminate.