Composites Science and Technology 162 (2018) 225–234

Contents lists available at ScienceDirect

Composites Science and Technology

journal homepage: www.elsevier.com/locate/compscitech

Modelling the electrical resistance change in a multidirectional laminate with a delamination

Francesco Panozzo[a], Michele Zappalorto[a,*], Lucio Maragoni[a], Stefan Klaus Nothdurfter[b], Axel Rullo[b], Marino Quaresimin[a]

[a] Department of Management and Engineering, University of Padova, Stradella S. Nicola 3, 36100 Vicenza, Italy
[b] Automobili Lamborghini S.p.A., Advanced Composites Research Center (ACRC), Via Modena 12, 40019 Sant'Agata Bolognese Bo, Italy

ARTICLE INFO

Keywords:
Structural Health Monitoring (SHM)
Damage detection
Carbon nanotubes
Electrical resistance measurement
Delamination

ABSTRACT

In this work, the electrical response of a multidirectional symmetric composite laminate with a delamination is studied analytically, numerically and experimentally.

An analytical model is initially developed to predict the electrical resistance of the composite laminate as a function of the delamination extent. The model was first validated against the results of a bulk of finite element analyses, considering different lay-ups and electrical resistivity. The model predictions were then compared to experimental data obtained through a dedicated experimental campaign performed on unidirectional and multidirectional Double Cantilever Beam (DCB) specimens. A satisfactory agreement was found in all the cases, thus supporting the accuracy of the analytical model.

1. Introduction

Damage monitoring is a fundamental aspect in the design process of composite structures where high reliability is required. The practice of monitoring composite structures during their entire in-service life is becoming more and more frequent in fields such as aerospace and wind energy production. In fact, the increasing size of load-carrying composite parts (such as wings, fuselages, and wind turbine blades) makes conventional Non-Destructing Evaluation (NDE) techniques, such as visual inspection, ultrasonic inspection and X-ray radiography, extremely time consuming and labour-intensive. In the last years, the use of composites for structural applications has been rapidly growing also in the large-scale automotive industry, and detecting pre-critical damage can play a major role in increasing the passengers' safety.

In most of their applications, structural parts made of composite materials are subjected to high static or cyclic loads, that lead to a progressive damage and a degradation of the mechanical properties (see, among others, Refs. [1–4] and works quoted therein). In addition, parts may be subjected to impacts which often lead to internal damage, difficult to be detected by visual inspection.

Different from NDE, Structural Health Monitoring (SHM) provides a continuous inspection of the part, so that damage can be detected even at the earliest stages, and preventive actions can be taken to reduce operational costs, downtime and to generally increase the reliability of the structure. Indeed, information provided by SHM systems can be used to enable a maintenance based on the actual damage state of the part, with a significant reduction of costs and a sensible increase of the safety of the structure. At the same time, they can give a thorough knowledge of the actual load-history of the part and its damage state, allowing parts to be designed in a less-conservative way and reducing the costs and weight associated with over-designed structures. Furthermore, the information coming from SHM systems can be integrated in the design process, serving as input data for models aimed at describing the damage evolution in composite laminates.

Among the different SHM methodologies, electric potential based techniques represent a valid solution, as the onset of damage leads to an irreversible increase of the Electrical Resistance (ER) of the part (see Ref. [5] and references reported therein). In this case, damage is directly associated to a variation of an intrinsic property of the material which is, consequently, self-sensing to the presence of damage. The potentialities of these methods have been successfully proven by several authors in the literature, since the fundamental contribution by Schulte and Baron [6], where, for the first time, a correlation between the ER change and the failure of the fibres in CFRP laminates was documented. The literature on this topic is so broad that a comprehensive literature review is a very challenging task and, especially, is out of the specific aim of the present work. Accordingly, in the following only few works, among those available in the literature, will be mentioned, those that in authors' opinion are more pertinent to the present paper.

Irreversible changes in the ER of unidirectional and cross-ply

* Corresponding author.
E-mail address: michele.zappalorto@unipd.it (M. Zappalorto).

https://doi.org/10.1016/j.compscitech.2018.04.031
Received 22 December 2017; Received in revised form 23 April 2018; Accepted 24 April 2018
Available online 28 April 2018
0266-3538/

specimens made of CFRPs during static and fatigue loadings were observed by Irving and Thiagarajan [7], who also noted a reversible resistance change due to Poisson effect, whereas Wang and Chung [8] measured an abrupt irreversible increase of the ER of CFRP laminates under bending. A further improvement in the damage sensing capability of conventional composite materials can be achieved by the addition of conductive nanoparticles such as Carbon Nanotubes (CNT) to polymers. Indeed, CNTs have the potential to realise electrically conductive polymers with improved or retained mechanical performances [9].

Nanomodification allows electrical SHM to be used also with insulating fibres (glass fibers), where the needed conductivity properties are obtained by loading the polymer or the fibre surface with conductive nanoparticles. Within this context, glass fibre-reinforced laminates modified with CNTs represent an innovative multifunctional material, with an increased conductivity and remarkable self-sensing properties [10–12]. The incorporation of CNTs can also remarkably increase the transversal and the out of plane conductivity of carbon fibre-reinforced laminates [12,13], thus improving their overall sensing capabilities.

In the best of the authors' knowledge, the first experimental studies about the application of electrical methods to conductive composites for delamination detection were carried out by Todoroki et al. [14]. These authors performed DCB and ENF static tests on unidirectional carbon fibre specimens and found a well defined correlation between the delamination extent and the electrical resistance of the specimens.

Wang and Chung [15] were able to sense delamination in a CFRP crossply laminate in real time during fatigue by measuring the electrical resistance of the composite in the through-thickness direction.

After these pioneering works, many other experimental and numerical studies were carried on this topic, mainly by Todoroki and co-workers who further examined in great detail the efficacy of the electrical method in monitoring delamination cracks (see among the others, Refs. [16–22]).

However, even if models are essential to quantitatively assess the damage extent and its evolution on the basis of ER measurements, as well as to understand the most influencing material and geometrical parameters, so far in the literature analytical modelling has received comparatively less attention with respect to experimental and numerical investigations.

Among the few analytical approaches available in the literature, worth of being mentioned is the orthotropic electric potential function method developed by Todoroki [23], based on the formal analogy existing with the equation fields describing the flow of a fluid. Such a method, first developed for an infinite plate, was later used by Todoroki and co-workers to analyse the electric-voltage-change caused by a delamination in CFRP laminates [24–26]. In principle, Todoroki's approach requires a strongly electrical orthotropy of the material.

A completely different analytical approach was recently proposed by the present authors to predict the electrical response of a composite laminate with a delamination [27]. The method is mainly based on the through-the-thickness discretization of the laminate into a certain number of “fictitious” sublayers, within which the electrical potential is approximated with a polynomial function. Leveraging the basic equation of the electric field, and exploiting proper boundary conditions allowed analytical expressions for the current densities to be determined and, in turn, to analytically assess the electric potential drop between two arbitrary points of the delaminated laminate. However, in Ref. [27] all the sublayers were supposed to be electrically orthotropic in the global reference system, so that only unidirectional, [0]n and [90]n, or symmetric cross-ply laminates could be treated.

The main aim of the present work is to fully overcome such a limitation, providing a new analytical model to assess the electrical resistance of generic multidirectional laminates with delamination cracks. To this end, the same modelling strategy presented in Ref. [27] is used, but the analytical framework is completely reformulated since the very beginning, in order to include generic off-axis angles for all the plies. The basic analytical steps are briefly presented and motivated in the modelling section and the new developed analytical solution is validated, first, taking advantage of the results from a bulk of Finite Element (FE) analyses carried out on multidirectional laminates with different delamination lengths. A parametric study of the influence of the layup and of the electrical properties of the laminae on the overall electrical response of the laminate is also carried out and the relevant results properly discussed.

Later on, the results of an ad-hoc experimental campaign performed on unidirectional and multidirectional DCB specimens made of CFRP are presented, documenting the irreversible increase of the ER of the specimen associated to the delamination growth.

Finally, the experimental results obtained in the present work are compared with the predictions of the new analytical model, showing a very satisfactory agreement.

2. Model development

In this section, the development of the analytical frame to assess the Electrical Resistance (ER) of a multidirectional symmetric laminate in the presence of a delamination is illustrated in detail.

2.1. Statement of the problem

Consider a symmetric laminate with a generic layup, characterized by the presence of a delamination as schematically represented in Fig. 1a. In the following, for the sake of simplicity, a delamination located in the laminate midplane is considered, so that the antisymmetric nature of the problem allows the analysis to be restricted to the upper half of the laminate. However, the modelling strategy presented can be easily extended to a generic delamination location, by simply removing skew-symmetric conditions and properly adjusting boundary conditions.

The plies composing the laminate are supposed to have an orthotropic behaviour in terms of electrical conductivity in the material coordinate system (Fig. 1b). The resistivity along the two principal directions are referred to as η_1 and η_2, respectively, and the out-of-plane resistivity as η_3.

As in Ref. [27], a ply-refinement technique was adopted, according to which the laminate is divided in an arbitrary number of *sub-layers* having the same thickness $h = \frac{t}{2N}$, where t is the laminate thickness and 2 N the total number of sublayers the whole laminate is divided in (namely the total number of plies multiplied by the number of sublayers in each ply). Each sub-layer has the same orthotropic electrical behaviour of the ply it

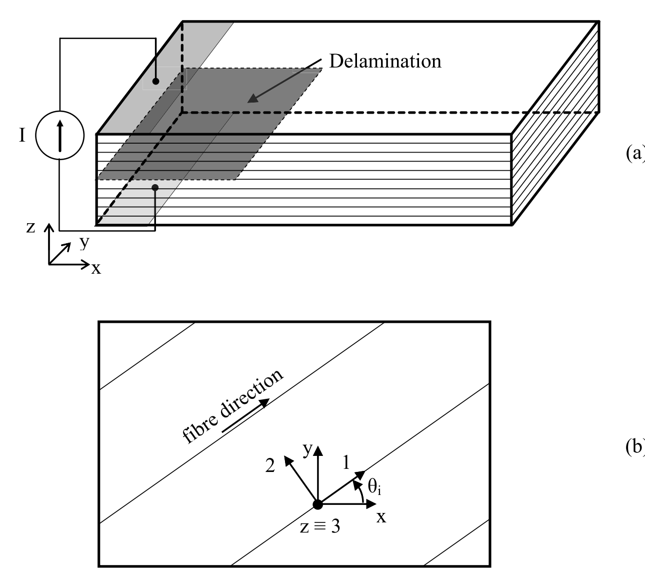

Fig. 1. Multidirectional composite laminate with a delamination between the central plies (a). Schematic representation of the generic lamina with off-axis angle θ_i (b).