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Health monitoring of cross-ply laminates: Modelling the correlation between damage evolution and electrical resistance change

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ABSTRACT

In this work an analytical solution is developed to accurately predict the stiffness reduction in conductive cross-ply laminates, caused by matrix cracking in the transverse layers, as a function of the electrical resistance change of the laminate itself.

To this end a closed form solution is initially developed with the aim to link the density of transverse cracks to the electric resistance of the cross-ply laminate. Such an expression is later used within a further model which allows the stiffness degradation associated to a given crack density to be estimated.

The accuracy of the proposed model is verified by comparison with a bulk of FE analyses.

1. Introduction

Fibre reinforced polymers (FRPs) are outstanding materials for advanced applications, characterised by excellent lightness and mechanical properties, of which the performances are, however, affected by the intrinsic damage occurring during the in service life. In the development of composite products it has to be considered that most of the structural parts produced from FRPs, like car frames, aircraft wings or wind turbine blades, are designed for high load levels possibly leading to a progressive damage, such as matrix cracking, delaminations and fibre breakage, which in turn leads to the degradation of the mechanical properties during the product life.

In the literature it is acknowledged that the early stages of the static and fatigue behaviour of multidirectional laminates made of unidirectional (UD) plies are characterised by the initiation and propagation of cracks in the off-axis plies. The density of transverse cracks (measured as the number of cracks per unit laminate length) increases progressively with the static load level [1–3] or the number of cycles [4–8], leading to the degradation of the global elastic properties and, in turn, to larger deformations and lower load bearing capabilities with respect to the design assumptions.

Within this scenario, health monitoring for the detection of the intrinsic damage is essential to improve the in service reliability and lifetime of FRP-structures. This is the reason why many types of sensors and techniques for damage sensing have been developed in the very recent years.

A comprehensive literature review on this topic is far from easy to be drawn and is out of the specific aim of the present work which is focused, instead, on self sensing fibre reinforced polymers where the detection of damage is achieved by using electrical conductivity methods.

Within this context, worth of mentioning is the pioneering work by Schulte and Baron [9] where, for the first time, the electrical conductivity of carbon fibres was used to monitor damage, related to fibre breakage, in Carbon Fiber Reinforced Polymers (CFRPs).

Starting from these bases, several alternating current (AC) and direct current (DC) methods have been widely used to study damage mechanisms, such as delaminations and matrix cracking in composites under different loading conditions.

Todokori et al. [10] developed an electrical potential method for the real time non-destructive evaluation of the evolution of delaminations by measuring the electric resistance change during Mode I and Mode II tests.

Abry et al. [11] carried out static tests on cross-ply laminates made of carbon fibres and epoxy resin and found that the electric resistance measured applying an AC current increased with the applied strain. They also noted that, concerning carbon fibres composites, AC measurements were capable of detecting the onset and evolution of transverse cracks in CFRPs, whereas DC measurements highlighted the evolution of fibre-related damage, only.

Further analyses on this topic were carried out by several authors [12–18] whereas an overview on the possible applications

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of electrical methods to fibre reinforced polymers can be found in Kupke et al. [19] and Wen et al. [20].

Moving to modelling activities in the field of conductive fibre composites, comparatively few works can be found in the literature. Finite Element (FE) analyses were carried out by Todoroki et al. [14] to study the effect of transverse cracks and delaminations on the electric resistance of cross-ply laminates with surface probes. Ogi [21] proposed an analytical model for the piezo-resistive behaviour of CF cross-ply laminates in the presence of transverse cracks which requires the calibration of several parameters from experimental tests.

The extensive research activity on this topic carried out by several scientists over the most recent years is a consequence of the large interest in the scientific community to explore the possibility to use the resistance change as a quantitative damage parameter for composite parts.

All the investigations above mentioned were focused on damage sensing with conductive fibre-based composites. Moving to non-conductive fibres, electrical conductivity methods can still be effective for damage monitoring whenever nanomodified polymers are used as matrices.

Nanotechnology has recently emerged as a suitable tool to optimise properties of materials by designing their internal structure at the very nanoscale, thus assisting in the achievement of multi-functional materials with outstanding physical and mechanical properties [22].

As widely documented in the recent literature [23–33], the addition of small amounts of carbon nanotubes (CNT) or larger amounts of carbon black (CB) particles in the polymer matrix of advanced non-conductive fibre composites can lead to electrically conductive FRPs, where the onset of off-axis cracks and delaminations causes an irreversible change of the electric resistance.

Dealing with this topic, Boger et al. [34] reported the results from incremental quasi static tests on [0/45/90/−45/45/90/−45/0] glass/CB-doped epoxy laminates, where a direct correlation was evident between the irreversible electric resistance increase, measured in DC current during the tests, and the residual strain resulting from damage onset and growth in the laminates.

Similar results can be found in the paper by Fernberg and Joffe [35] reporting incremental static tests on glass/epoxy cross-ply laminates.

Gao et al. [36] carried out static tests on [0/90$_n$/0] glass/CNT-modified epoxy laminates (with $n = 1$, 2 and 5) and documented that, increasing the strain level, damage was characterised by an evolution of the density of transverse cracks, followed by the onset and propagation of delaminations. It was proved that the increase of the crack density was associated to an irreversible increase of the laminate electric resistance measured along the loading direction. The onset and propagation of delaminations caused a further and steeper resistance increase. The same authors also documented that the variation of the laminate electrical resistance was higher as the number of transverse layers, n, increased.

Gao et al. [37] proved the existence of a direct bi-linear relationship between the laminate electric resistance increase and the cumulative number of acoustic emission events, implicitly proving the reliability of the self sensing system in detecting damage onset and evolution.

Viets et al. [38] developed a technique for the damage detection in nanoparticle-modified glass fibre reinforced polymers (GFRPs), using in-plane and through-the-thickness electrical resistance measurements.

In the best of the authors knowledge, far less attention has been paid to modelling activities on this topic, with the only exception of a very recent paper by Selvakumaran et al. [39], where the effect of the different geometrical and material parameters on the resistance increase due to transverse cracking was studied by means of FE analyses.

A successful engineering application of electrical methods for health monitoring of self-sensing laminates requires models capable to soundly predict the damage state, in terms of matrix cracking or delamination extents, and the associated performance reductions, on the basis of resistance measurements. In the best of the authors' knowledge such a predictive tool is not available in the literature yet.

The main aim of the present work is to partially fill this gap, by proposing a close form solution able to accurately predict the stiffness reduction in conductive cross-ply laminates, caused by matrix cracking in the transverse layers, once the associated electrical resistance change is known from experimental measurements. More precisely:

- initially an analytical solution is developed with the aim to link the density of transverse cracks to the DC electric resistance of the cross-ply laminate;
- subsequently, this expression is substituted into a further model which allows the stiffness degradation to be estimated as a function of the crack density;
- In this way it has been obtained an analytical expression capable of predicting the laminate stiffness degradation as a function of the electrical resistance increase.

The accuracy of the proposed model is verified by comparison with a large bulk of FE analyses.

2. Preliminary remarks

The aim of this section is to better clarify terms, methods and topics used and addressed in the work. Briefly:

- First of all, we would like to focus the readers' attention on the term "*damage*", which is meant here as matrix cracking in the transverse layers, namely the initiation and multiplication of transverse cracks, perpendicular to the loading direction. In agreement with the experimental observations this represents the first stage of damage evolution in cross-ply laminates made of UD plies under static and fatigue tension loadings. Accordingly the model cannot be applied, as it stands, to woven composites, where the damage scenario is different, nor in the presence of delaminations and splits.

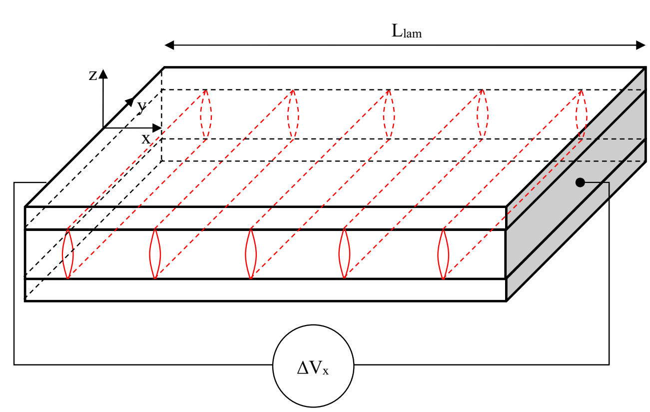

Fig. 1. Cross-ply laminate with transverse cracks subjected to a potential difference ΔV_x.