# MULTIFUNCTIONAL COMPOSITES FOR DAMAGE MONITORING: RECENT ACTIVITIES AND OPEN ISSUES

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## Abstract

Damage monitoring is a fundamental aspect in the design process of composite structures where high reliability is required without negatively affecting the life-cycle costs of the part.

Parts made of composite materials are subjected to static and cyclic loads, leading to a progressive damage and degradation of the mechanical properties. In addition, parts may be subjected to impacts, which are in most of the cases difficult to be detected by visual inspection. Structural health monitoring (SHM) provides a continuous inspection of the part, so that these typologies of damage can be detected since the earliest stages, and preventive actions can be taken to reduce operational costs, downtime, and to generally increase the reliability of the structure. Within this frame, electric potential-based methods have been widely investigated in the literature, and their effectiveness in monitoring the stiffness reduction due to fatigue loads and, more generally, to damage accumulation has been successfully proven.

In the present work, a summary of the recent activities carried out by the authors in the field of Electrical Health Monitoring (EHM) is briefly presented.

## 1. Introduction

In the last decades, structural health monitoring of composite parts has arisen an increasing interest from the industrial and the scientific community. Several efforts have been devoted to develop techniques to reliably monitor the presence of damage in composite structures, providing real-time information on the health status of the part. In fact, due to the outstanding strength and stiffness of composite materials, in combination with their low density, their use is becoming wider for structural applications where lightweight is needed. Indeed, especially in the wind turbine, aeronautic and automotive fields, the use of composite materials can reduce significantly the weight of the structures.

Structural parts made of composite materials can be subjected to impacts during their in-service life, leading to the formation of matrix cracks and delamination between the plies [1 – 3]. Such damages do not necessarily lead to the failure of the part, however they reduce the load bearing capability and its stiffness. Therefore, being able to monitor the presence of damage would be extremely important for engineering applications, increasing the overall safety of the structure, and enabling a switch from a time-based to a condition-based maintenance, with a significant reduction of the inspection costs.

The variation of the electric potential distribution in conductive composites has proven to be a reliable parameter to monitor the presence of damage [4–5] and many authors documented experimentally [6-16] that the onset of damage in advanced conductive Fibre Reinforced Polymers (FRPs) causes an irreversible change of the electric resistance.

Instead, only few works were devoted to modelling activities on this topic. This represents the main current limitation of the electrical heath monitoring approach for composite materials. Indeed, for a successful engineering application of electrical methods for health monitoring of self-sensing composite parts there is the strong need for models capable to soundly predict the damage state and the associated performance reductions, on the basis of electrical resistance measurements. This is essential to understand the most important material and geometrical parameters influencing the phenomenon and to effectively quantify their effects, in order to design the best solution for a specific application. For these reasons, very recently, great efforts were devoted by the authors to develop analytical models able to predict the electrical resistance increase associated to a certain damage scenario. The main outcomes of such an intense modelling acitivty is briefly presented in the following sections.

## 2. Electrical resistance increase due to matrix cracks in composite laminates

The damage evolution of multidirectional laminates made of unidirectional plies, subjected to static or fatigue loads, is a complex phenomenon that involves an initial onset of transverse matrix cracks, with a continuous increase of the crack density (i.e., the number of cracks per unitary length). The propagation of matrix cracks does not necessarily lead to a failure of the part, however it can reduce the stiffness of the material, compromising the overall functionality of the structure. For this reason, initially, large attention was devoted to modelling the electrical resistance increase caused by matrix cracks in symmetric laminates [17]. In particular, considering a $[(\theta_1)_m/(\theta_2)_n]_S$ laminate made of unidirectional plies, with off-axis cracks in the $\theta_2$ layers Panozzo et al. [17] proposed a closed form solution for the laminate electrical resistance as a function of the crack density and the electrical properties of the laminae. Such a closed form expression reads as:

$$\frac{R}{R_0} = 1 + \frac{2\rho}{\alpha} \cdot \omega \cdot \tanh\left(\frac{\alpha}{2\rho}\right) \tag{1}$$

where $\rho$ is the crack density and $\alpha$ and $\omega$ are two parameters depending on the angles $\theta_i$, on the material electrical properties and on the thickness of the plies.

Panozzo et al. [17] also proposed to use Eq. (1) in combination with a mechanical model for the cracked laminate, the latter which allows to determine the laminate elastic modulus as a function of the crack density, obtaining, in this way a direct correlation between the electrical resistance increase and the elastic modulus degradation. An example is shown in figure 1, where the analytical predictions are also compared with the results of a number of numerical analyses. It is evident that a well defined correlation exists between stiffness drop and electrical resistance increase, and such a correlation is properly described by the model given in [17].

In Ref. [17] a detailed parametrical analysis was also carried out to highlight the effect of the most influencing material and geometrical parameters, which were identified to be the orientation of the plies ($\theta_1$ and $\theta_2$), the thickness of the plies ($h_1$ and $h_2$) and the ratio between the in-plane and out-of-plane conductivities. Based on the results the following main conclusions were drawn:

- the highest increase of the electrical resistance, for a given value of elastic modulus degradation, is obtained for the case of $\theta_1 = 0°$, and the sensitivity decreases for higher $\theta_1$ angles;
- for a given value of elastic modulus degradation, the electrical resistance change of laminates with low values of $\theta_2$ is low, reaching a maximum at 55°, and slightly decreases for higher values of the off-axis angle;

- laminates with lower anisotropy ratio (i.e., higher out-of-plane conductivity) are characterized by a higher sensitivity, since the increase of the electrical resistance for a given value of the elastic modulus drop is higher;
- the thicker the cracked layer, the lower the sensitivity is.

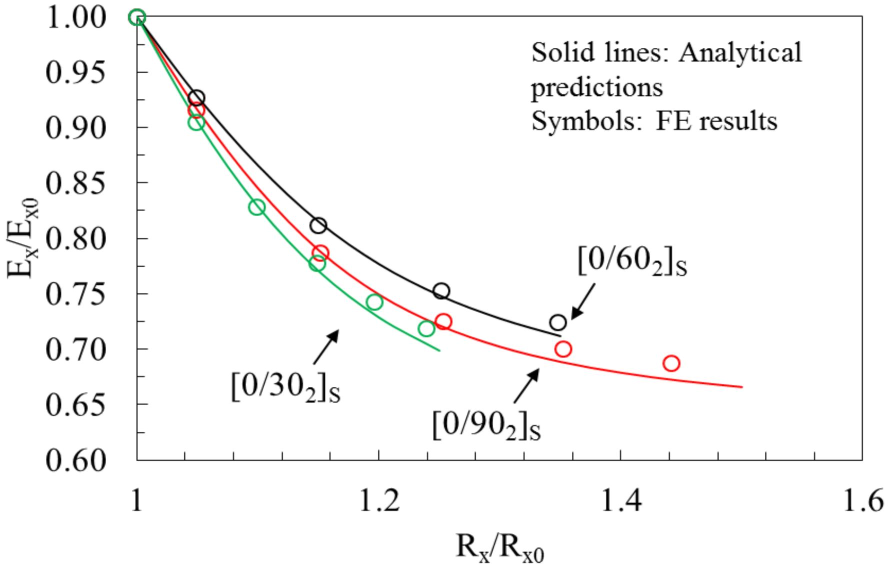

Figure 1. Influence of the orientation angle $\theta_2$ on the electrical/mechanical response of the cracked laminate [17].

## 3. Electrical resistance increase due to a delamination between the plies in a composite laminate

The initiation and growth of delamination cracks, often preceded and triggered by matrix cracking, is one of the dominant failure mechanisms in composite laminates, both under static and fatigue loadings. Accordingly, sensing the extension of delamination cracks in composites is of paramount importance.

Very recently, Zappalorto et al. [18] developed an analytical model to assess the electric potential distribution of a conductive composite plate in the presence of a delamination between the central plies. The model was validated first by comparison with finite element analyses on plates with different geometries and electrical properties, and later against the results of a dedicated combined electrical-mechanical experimental campaign carried out on CFRP DCB specimens [18] (see figure 2 for an example).

Zappalorto et al. [18] also carried out a detailed analysis to understand the role played by the main geometrical and material parameters in the resistance change and therefore their effect on the sensitivity of the method for damage monitoring. In particular, they found that:

1. the resistance change is higher for lower $\eta_z/\eta_x$ ratios, thus documenting that decreasing the resistivity ratio, for instance by modification of the resin with CNTs or other conductive particles, can lead to a higher accuracy (see figure 3, for example).
2. thinner panels provide a higher resistance change and are therefore better candidates to be monitored by means of electrical methods (see figure 4)
3. The laminate layup has a non-neglible effect on the sensitivy of the method (see figure 5).

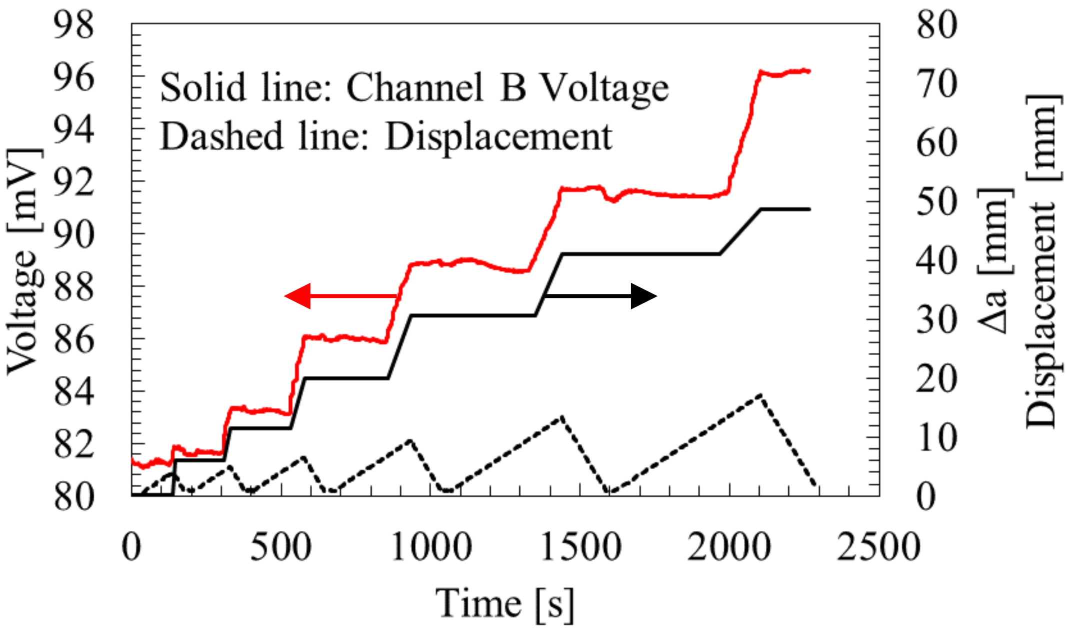

Fig. 2. Plot of the voltage, displacement and delamination length vs time of a combined mechanical/electrical DCB test. The laminate was composed of 18 pre-preg layers of T700s carbon fibres, with a layup of $[0]_{18}$ (see Ref. [18] for more details).

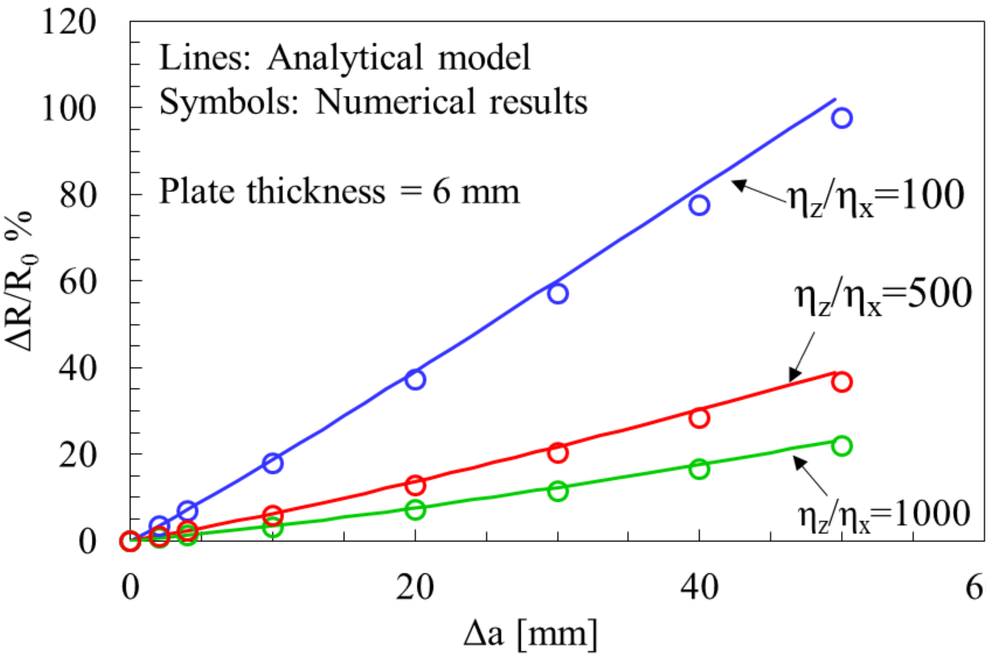

Fig. 3. Comparison between predictions and numerical results for different resistivity ratios [18]. Carbon fibre laminate with a $[0]_n$ layup.

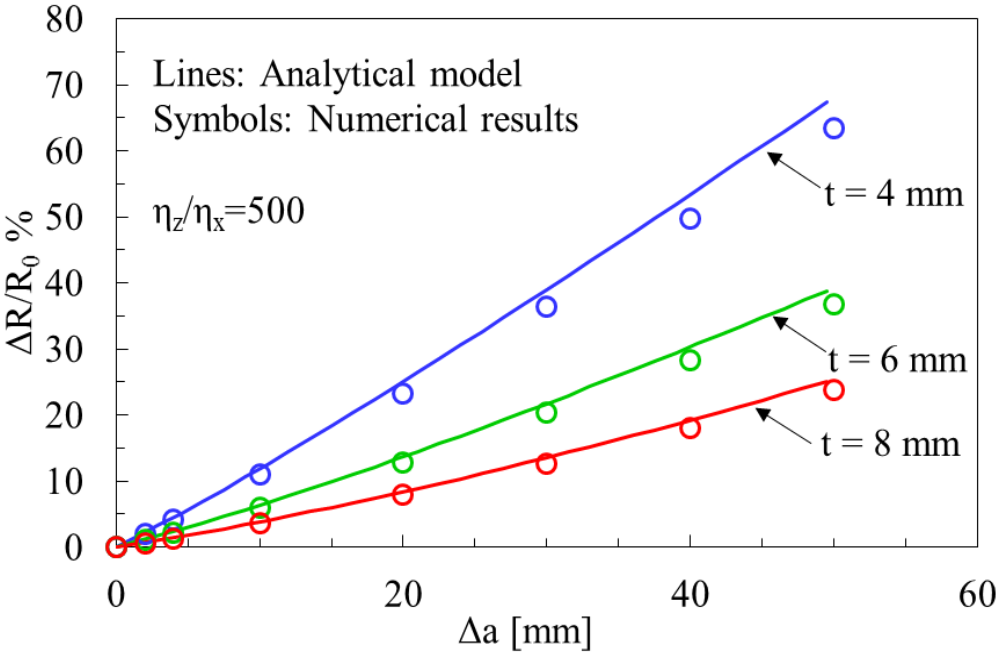

Fig. 4. Comparison between predictions and numerical results for different values of the plate thickness [18]. Carbon fibre laminate with a $[0]_n$ layup.

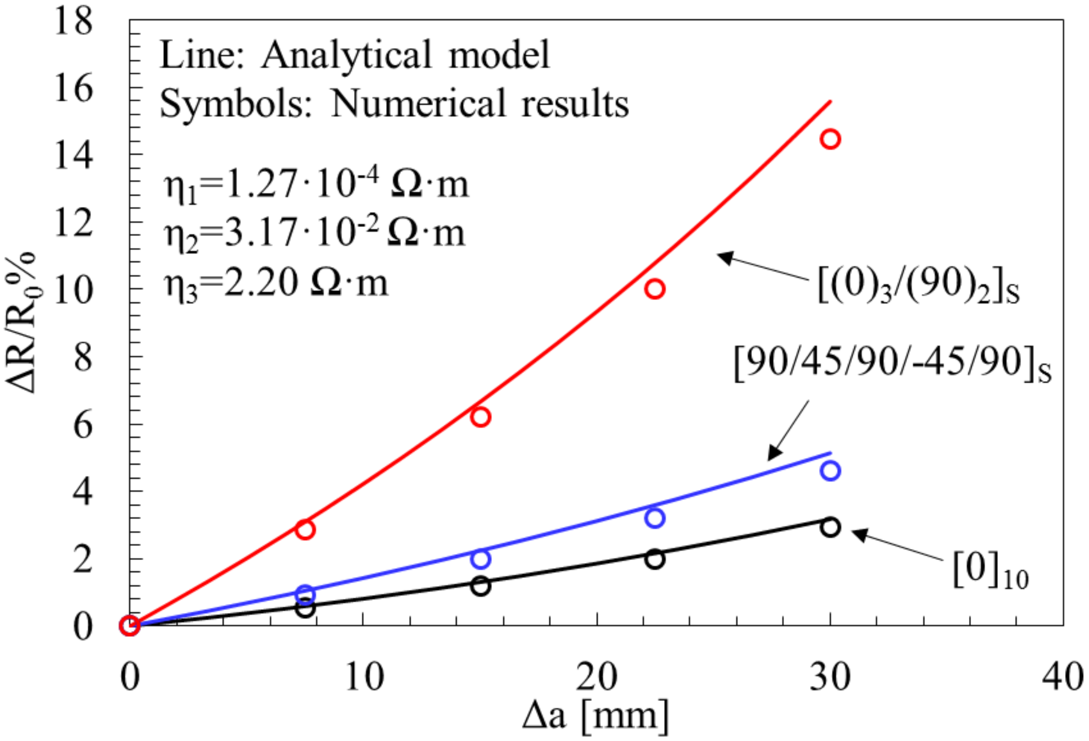

Fig. 5. Influence of the laminate layup on the ER change due to the presence of a delamination [19].

## 4. Conclusions

In this paper, a brief summary of the recent modelling activities carried out by authors within the field of Health Monitoring of composites with electrical methods has been presented. Two main damaging mechanisms have been investigated, namely matrix cracks and delamination between the plies and the main outcomes of these models have been reported and briefly discussed.

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