MODELLING THE CORRELATION BETWEEN THE DAMAGE STATE AND THE ELECTRICAL RESISTANCE CHANGE IN SYMMETRIC LAMINATES

P.A. Carraro, F. Panozzo, M. Quaresimin, M. Zappalorto

Department of Management and Engineering, University of Padova, Stradella S. Nicola 3, Vicenza, Italy
Email: michele.zappalorto@unipd.it

Keywords: health monitoring; modelling; conductive matrix

Abstract
Fatigue damage in multidirectional laminates is characterised by a crack density evolution in the off-axis plies leading to the degradation of the laminate global stiffness, making the damage monitoring during the in-service life very important for the safe use of composite materials in advanced applications. In this view self sensing materials have a strong potential in detecting damage initiation and evolution without compromising the mechanical performance.

Self sensing composites can be obtained by nano-modification of the matrix by means of CNTs, which makes the polymer electrically conductive. It is proven in the literature that increments in the electrical resistance of statically loaded laminates resulted after the initiation of transverse cracks. In the present work a closed form solution is presented to accurately predict the variation of the electrical resistance change in conductive (CNTs doped) laminates, caused by matrix cracking in one layer. The accuracy of the proposed model is verified by comparison to a bulk of FE analyses.

1. Introduction

The static and fatigue behaviour of multidirectional laminates made of unidirectional (UD) plies is characterised by the initiation and propagation of cracks in the off-axis plies, with a continuous increasing of the crack density with the static load level [1-3] or the number of cycles [4-7] and resulting in the degradation of the composite elastic properties.

Accordingly, health monitoring for the detection of the damage is essential to improve the in service reliability and lifetime of FRP-structures. This is the reason why many types of sensors for damage sensing have been developed in the very recent years, mainly based on the use of optical fibres.

Only very recently the interest of the scientific community has moved to self sensing capability of composite parts obtained measuring the electrical conductivity of the FRP material with carbon nanotubes (CNT)- or carbon black (CB)-doped polymer matrices.

Indeed, adding small amounts of CNTs or CB in the matrix of advanced FRP can lead to electrically conductive composites, as widely reported in the literature [8-14].

Böger and co-authors [15] reported results on incremental quasi static tests on [0/45/90/-45/45/90/-45/0] glass/CB-doped epoxy laminates showing that it was possible to correlate the irreversible electric resistance increase, measured in DC during the tests, with the residual strain resulting from damage onset and growth in the laminates. However, the authors did not report observations of the damage mechanisms and their relationship with the change in the electric properties. Similar conclusions were drawn by Fernberg and Joffe [16].

Gao and co-authors [17] carried out static tests on glass/CNT-modified epoxy cross-ply laminates with lay-up $[0/90_n/0]$ and showed that damage was characterised by an evolution of the density of transverse cracks as the strain increased, followed by the onset and propagation of delaminations. It was shown

that the increase in the crack density corresponded to an irreversible increase in the electric resistance of the cross-ply laminates along the loading direction. Then, the onset and propagation of delaminations caused a further and steeper resistance increase.

Abry et al. [18] carried out static tests on cross-ply laminates made of carbon fibres and epoxy resin, without the use of CNTs or CB, exploiting the conductivity of carbon fibres for electric measurements and found that the electric resistance measured applying an AC increased with the applied strain. However they did not report correlations between these increments and the crack density. They also observed that, concerning carbon fibre composites, AC measurements were capable of detecting the onset and evolution of transverse cracks, while DC measurements highlighted the evolution of fibre-related damage [18].

Similar results were obtained by Todoroki et al. [19] who found that an AC electric resistance increase could be associated to the transverse crack density evolution in cross-ply laminates made of carbon fibres and epoxy resin.

After this brief review, it is clear that the chance of detecting damage onset and evolution in terms of off-axis cracks formation in composite laminates by means of self-sensing systems is very attractive and promising. However, at present, modelling efforts aimed at providing analytical tools for correlating the resistance increase to the state of damage in multidirectional laminates (crack density and/or stiffness degradation) are very limited.

Finite Element (FE) analyses were carried out by Todoroki and co-authors [20] to study the effect of transverse cracks and delaminations in the electric resistance of cross-ply laminates with surface probes as those tested and presented in Ref. [19].

Ogi [21] proposed an analytical model for the piezoresistance behaviour of cross-ply laminates in the presence of transverse cracks. To this aim the crack was considered as a circuital element whose resistance depends on the crack density according to polynomial functions which require the calibration of several parameters by means of experimental data fitting.

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.

As a first step toward this ambitious aim, the present authors recently proposed an analytical model 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 [22].

The main aim of the present work is to extend such a model, by proposing a close form solution able to accurately predict the electrical resistance change in conductive $[\theta_1/\theta_2]_s$ laminates, caused by matrix cracking in one layer, as a function of the crack density.

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

2. A model to assess the electrical resistance change due to off-axis cracks

Let us consider a symmetric laminate made of 4 plies, each one with generally different thickness h_1, h_2, and orientation θ_1, θ_2, with respect to the global x-axis. Due to the symmetry of the laminate, it is sufficient to study only the upper half, applying suitable symmetry conditions in the bottom of the second layer. As a further assumption, only the second ply is affected by the presence of off-axis cracks, parallel to fibre direction and regularly spaced with distance l (see figure 1).

These hypotheses allow an additional simplification to be used, restricting the study only to a representative segment of the laminate between two adjacent cracks (figure 2).
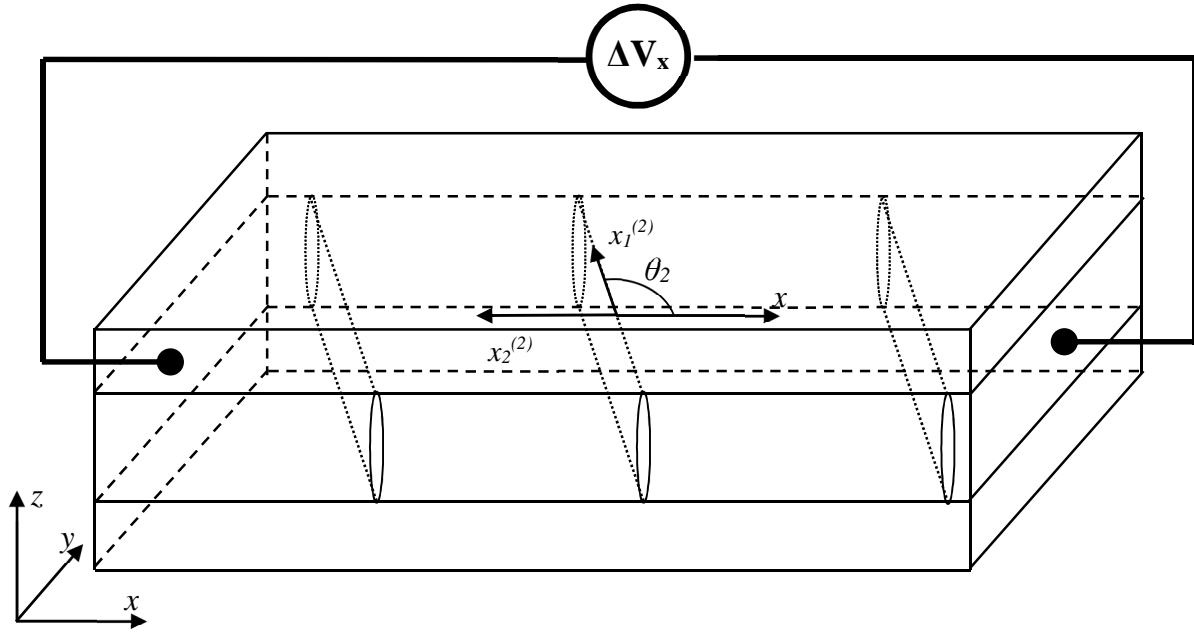
P.A. Carraro, F. Panozzo, M. Quaresimin and M. Zappalorto

Figure 1. $[\theta_1/\theta_2]_s$ laminate with off-axis cracks subjected to a potential difference ΔVx.
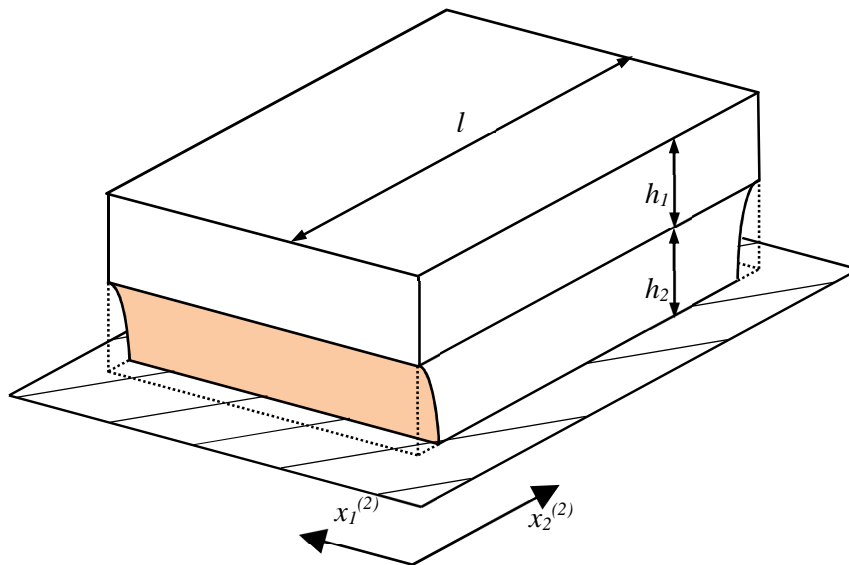

Figure 2. Representative laminate segment between two off-axis cracks.

With reference to the geometry shown in figure 2, the following analytical expression has been proposed in Ref. [23] to link the electrical resistance change to the crack density within the laminate:

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

 − where ρ is the crack density;
 − α is a parameter depending on the thickness of the plies and the electric resistivity of the plies in the through-the-thickness direction;

P.A. Carraro, F. Panozzo, M. Quaresimin and M. Zappalorto

− Ψ is a parameter depending on the thickness of the plies, the electric resistivity of the plies in the through-the-thickness direction and the angles θ_1 and θ_2;

− φ is a parameter quantifying the crack closure phenomenon.

3. Validation by comparison to numerical results

In this section, the accuracy of the analytical framework developed in the previous section is checked versus a bulk of FE analyses carried out using the commercial code ANSYS13.

Electrically conductive analyses were carried out using 20-nodes solid elements (BRICK 231 in Ansys). The analyses were carried out considering a representative laminate segment between two cracks, applying periodic boundary conditions, according to the suggestions proposed by Li et al. [24] for the mechanical problem.

An average element size of about 0.05 mm was used, small enough to guarantee accurate results in terms of global resistance, evaluated as $R_x = |(V_1 - V_0)/I|$, where I is the average current density in the half segment multiplied by the total thickness.

An example of the flow of the current density within a laminate segment is shown in figure 3, as obtained by a vector plot in Ansys.
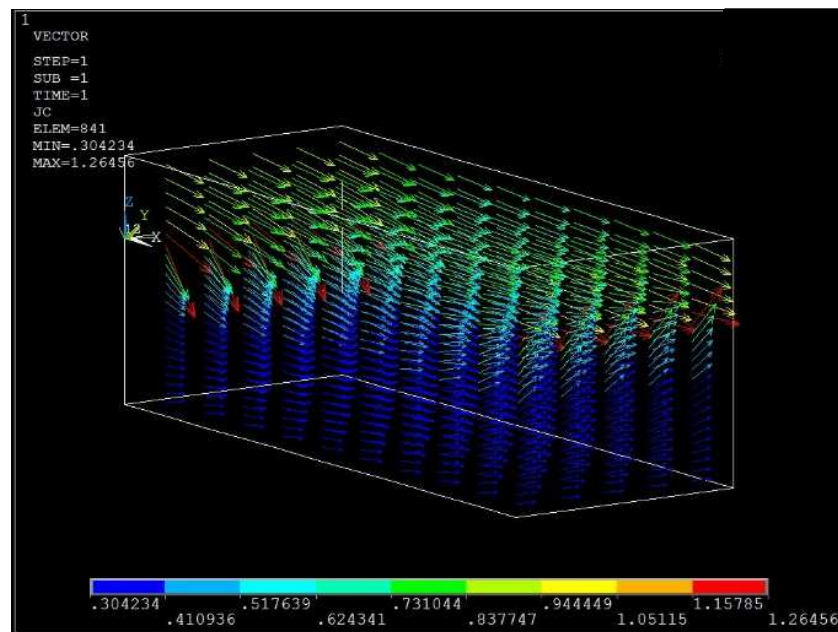

Figure 3. Example of the flow of the current density within a laminate segment.

A comparison between numerical results and the theoretical predictions based on Eq. (1) is shown in figures 4 and 5 for several layups, where a satisfactory agreement can be noted, deviations being always lower than 3%. It is also noteworthy that, as expected, the electric resistance increases while increasing the crack density.
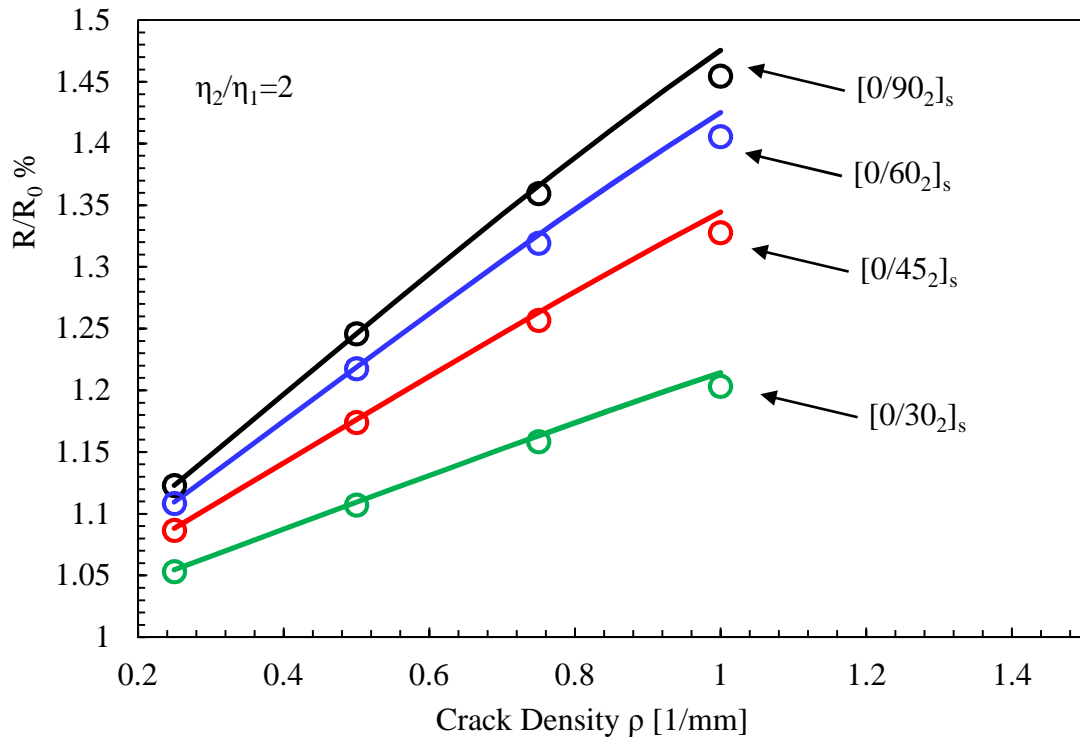
P.A. Carraro, F. Panozzo, M. Quaresimin and M. Zappalorto

Figure 4. Electric resistance ratio against crack density for $[\theta_1/\theta_2]_s$ with off-axis cracks. Symbols: FE results, lines: model prediction.
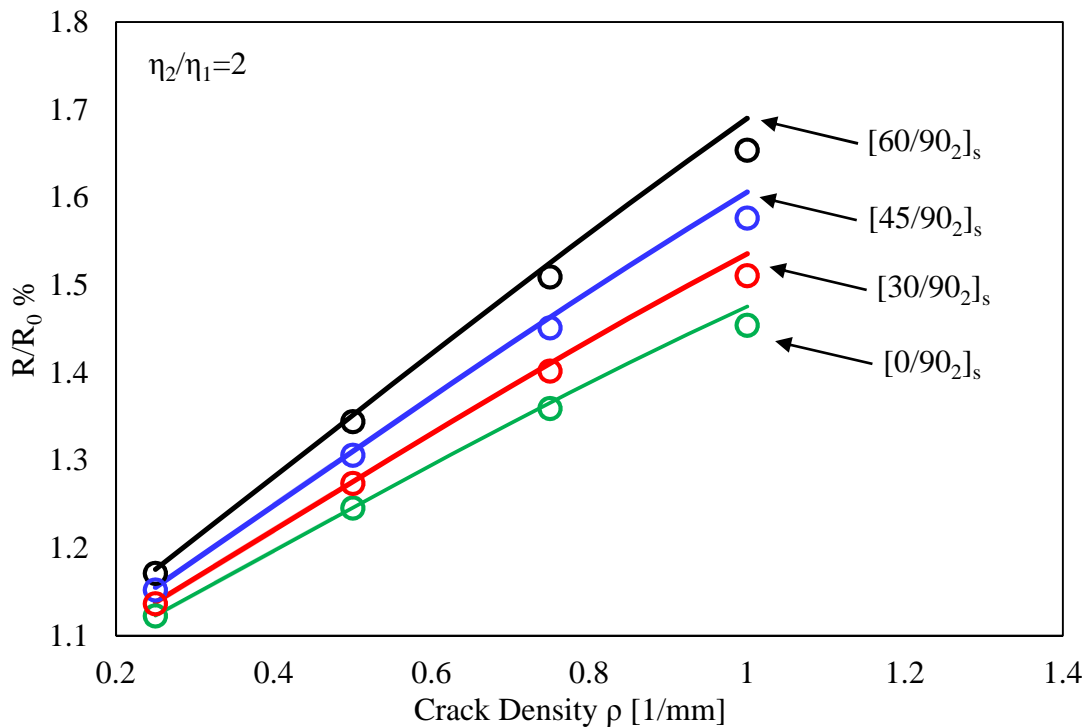

Figure 5. Electric resistance ratio against crack density for $[\theta_1/\theta_2]_s$ with off-axis cracks. Symbols: FE results, lines: model prediction.

P.A. Carraro, F. Panozzo, M. Quaresimin and M. Zappalorto

4. Conclusions

In the present work a closed form solution has been presented to accurately predict the variation of the electrical resistance change in conductive (CNTs doped) $[\theta_1/\theta_2]_s$ laminates, caused by matrix cracking in one layer. The accuracy of the proposed model is verified by comparison to a bulk of FE analyses, showing a very satisfactory agreement.

As a major conclusion, it can be stated that composite laminates manufactured with semi-conductive polymers are provided with remarkable self sensing capabilities, which also depend on parameters such as the thickness of the cracked layer and the ratio between the resistivity of the layers.

Acknowledgements

References

[1]   J. Varna, R. Joffe, N.V. Akshantala, R. Talreja, Damage in composite laminates with off-axis plies, *Composites Science and Technology*, **59**, 1999, pp. 2139-2147.

[2]   C.V. Singh, R. Talreja, A synergistic damage mechanics approach for composite laminates with matrix cracks in multiple orientations, *Mechanics of materials*, **41**, 2009, pp. 954-968.

[3]   C.V. Singh, R. Talreja, Evolution of ply cracks in multidirectional composite laminates, *International Journal of Solids and Structures*, **47**, 2010, pp. 1338-1349.

[4]   J. Tong, Three Stages of Fatigue Crack Growth in GFRP Composite Laminates, *Journal of Engineering Materials and Technology*, **123**, 2001, pp. 139-143.

[5]   Z. Sun, I.M. Daniel, J.J. Luo, Modeling of fatigue damage in a polymer matrix composite, *Materials Science and Engineering*, **A361**, 2003, pp. 302-311.

[6]   K. Tohgo, S. Nakagawa, K. Kageyama, Fatigue behaviour of CFRP cross-ply laminates under on-axis and off-axis cyclic loading, *International Journal of Fatigue*, **28**, 2006, pp. 1254-1262.

[7]   M. Quaresimin, P.A. Carraro, L. Pilgaard Mikkelsen, N. Lucato, L. Vivian, P. Brøndsted, B.F. Sørensen, J. Varna, R. Talreja, Damage evolution under internal and external multiaxial cyclic stress state: a comparative analysis, *Composites: Part B: Engineering*, **61**, 2014, pp. 282–290.

[8]   F. H. Gojny, M. H.G. Wichmann, B. Fiedler, W. Bauhofer, K. Schulte, Influence of nano-modification on the mechanical and electrical properties of conventional fibre-reinforced composites, *Composites: Part A*, **36** , 2005, pp. 1525–1535.

[9]   A. Markov, B. Fiedler, K. Schulte, Electrical conductivity of carbon black/fibres filled glass-fibre-reinforced thermoplastic composites, *Composites: Part A*, **37** , 2006, pp. 1390–1395.

[10]   M. H.G. Wichmann, J. Sumfleth, F. H. Gojny, M. Quaresimin, B. Fiedler, K. Schulte, Glass-fibre-reinforced composites with enhanced mechanical and electrical properties – Benefits and limitations of a nanoparticle modified matrix, *Engineering Fracture Mechanics*, **73**, 2006, pp. 2346–2359.

[11]   E. T. Thostenson, T. W. Chou, Carbon nanotube networks: sensing of distributed strain and damage for life prediction and self healing, *Advanced Materials*, **18**, 2006, pp. 2837–2841.

[12]   T.W. Chou, L. Gao, E.T. Thostenson, Z. Zhang, J.-H. Byun, An assessment of the science and technology of carbon nanotube-based fibers and composites, *Composites Science and Technology*, **70**, 2010, pp. 1-19.

[13]   N. Yamamoto, R. G. de Villoria, B. L. Wardle, Electrical and thermal property enhancement of fiber-reinforced polymer laminate composites through controlled implementation of multi-walled carbon nanotubes, *Composites Science and Technology*, **72** , 2012, pp. 2009–2015.

P.A. Carraro, F. Panozzo, M. Quaresimin and M. Zappalorto

[14] R. Samsur, V. K. Rangari, S. Jeelani, L. Zhang, Z. Y. Cheng, Fabrication of carbon nanotubes grown woven carbon fiber/epoxy composites and their electrical and mechanical properties, *Journal of Applied Physics*, **113**, 2013, pp. 214903

[15] L. Boger, M. H.G. Wichmann, L. O. Meyer, K. Schulte, Load and health monitoring in glass fibre reinforced composites with an electrically conductive nanocomposite epoxy matrix, *Composites Science and Technology*, **68**, 2008, pp. 1886–1894.

[16] S. P. Fernberg, R. Joffe, Damage detection in carbon fibre cross-ply laminates by aid of carbon nanotube doped resin, *In: Proceedings of the 13th European Conference on Composite Materials ECCM13*, June 2-5, 2008, Stockholm, Sweden

[17] L. Gao, E. T. Thostenson, Z. Zhang, T. W. Chou, Sensing of Damage Mechanisms in Fiber-Reinforced Composites under Cyclic Loading using Carbon Nanotubes, *Advanced Functional Materials*, **19**, 2009, pp. 123–130.

[18] J. C. Abry, Y. K. Choi, A. Chateauminois, B. Dalloz, G. Giraud, M. Salvia, In-situ monitoring of damage in CFRP laminates by means of AC and DC measurements, *Composites Science and Technology*, **61**, 2001, pp. 855-864.

[19] A. Todoroki, K. Omagari, Y. Shimamura, H. Kobayashi, Matrix crack detection of CFRP using electrical resistance change with integrated surface probes, *Composites Science and Technology*, **66**, 2006, pp. 1539–1545.

[20] A. Todoroki, M. Tanaka, Y. Shimamura, H. Kobayashi, Effects with a matrix crack on monitoring by electrical resistance method, *Advanced Composite Materials*, Vol. 13, No. 2, 2004, pp. 107–120.

[21] K. Ogi, A Model for Piezoresistance Behavior in a CFRP Cross-Ply Laminate with Transverse Cracking, *Journal of Solid Mechanics and Materials Engineering*, Vol. 1, No. 8, 2007, pp. 975-985.

[22] P.A. Carraro, M. Zappalorto, M. Quaresimin, Health monitoring of cross-ply laminates: Modelling the correlation between damage evolution and electrical resistance change. *Composites: Part A,* Vol. 82, 2016), pp. 151–158.

[23] P.A. Carraro, F. Panozzo, M. Zappalorto, M. Quaresimin, An analytical model for the health monitoring of conductive GF laminates via electric resistance measurements. Submitted for publication.

[24] S. Li, C.V. Singh, R. Talreja. A representative volume element based on translational symmetries for FE analysis of cracked laminates with two arrays of cracks, *International Journal of Solids and Structures* Vol. 46, 2009, pp. 1793–1804

P.A. Carraro, F. Panozzo, M. Quaresimin and M. Zappalorto