TOWARDS MESO SCALE IMPEDANCE-BASED MONITORING OF DEGRADATION IN LAMINATED COMPOSITES

Gilles Lubineau, Harilal Remesan, Khaled Almuhammadi, Lakshmi Selvakumaran, and Tushar Kanti Bera

King Abdullah University of Science and Technology (KAUST),
Physical Science and Engineering Division, COHMAS Lab.
KAUST Campus, Bldg 4 Room 2216
23955-6900 Thuwal, Kingdom of Saudi Araia
Email: gilles.lubineau@kaust.edu.sa, Web Page: https://cohmas.kaust.edu.sa

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Abstract

A practical way to track the evolution of damage in laminated composites is to monitor the change of its electrical resistance. Such measurements can be conveniently processed at the meso scale by using recently developed rigorous micro meso relations for electrical conductivity. Yet, pure resistive monitoring is limited due to small penetration without the material. Electrical impedance spectroscopy (EIS) of carbon fiber reinforced polymer (CFRP) has been conducted with ECG electrodes directly pasted on the CFRP samples without removing the resin layer. The impedance and phase angle variations obtained for a CFRP composite plate with delamination is compared to the data obtained from a sample without delamination. Results demonstrate that the impedance and phase angle profiles change for a CFRP plate with delamination from a sample without delamination. The delamination induced impedance variation in CFRP composites can be utilized for nondestructive damage evaluation.

1. Introduction

Carbon Fiber Reinforced Polymer (CFRP) [1-2] laminates with excellent mechanical properties are being applied for structural design and development in different fields of engineering and technology including aerospace engineering, automotive engineering, civil engineering and so on.

Like any other material, efficient structural health monitoring techniques are required for proper design, fabrication and operation of CFRP structures. Non-destructive testing (NDT) methods like X-Ray Scanning [3], ultrasonic evaluation [4], eddy current testing [5], vibration analysis [4], phased array analysis [4], shearography [4], thermography [6], sampling phased array (SPA) [7], acoustic emission monitoring [8], etc. have been applied for structural health monitoring of CFRP composites. Compared to the above conventional techniques, electrical measurement methods [9-13] have a number of advantages electrical such as fast data acquisition, simple sensor installations, portable and standalone instrumentation and on-field measurement process.

Such techniques provide a large quantity of information, from which the challenge is to reconstruct the conductivity map within the domain based on partial measurements of the electrical potential over the boundary of the domain. Yet, the relations between the global modification of resistivity and the exact underlying damage map is still unclear that makes difficult to interpret these non-destructive-testing results. This is even more difficult due to the numerous underlying damage mechanisms that can take place either at the inter laminar of inter laminar level. A strong improvement has been done concerning the observation of transverse cracking. We introduced the homogenization process that defines at the meso scale an equivalent homogeneous ply that is energetically equivalent to the cracked one. It is shown that this equivalent ply mainly depends on the cracking level while it

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can be considered independent on the rest of the laminated structure [16,17]. The direct consequence is that the meso scale is a pertinent one to perform the homogenization.

Yet, the above techniques have been mainly developed for DC. Considering the dielectric nature of the insulating polymer, switching to spectroscopy and higher frequency AC measurement might also be of interest. Surface electrodes, which are essentially required for interfacing the electrical measuring instrument with the CFRP sample, are one of the crucial components in electrical measurement. Sand polishing [14], laser ablation [15], and other resin removal techniques for electrode fabrication are time-consuming and may damage the surface layer of the structure. In this direction, electrical impedance spectroscopy (EIS) on CFRP laminates are conducted by pasting the adhesive electrodes on the composite surface without removing the top resin layer. In the proposed study, the standard Ag/AgCl based ECG electrodes are used for AC current injection and voltage measurement and are found efficient for impedance sensing.

2. Materials and methods

The experimental samples with square geometry (150x150 mm) are developed with T700-M21 prepreg CFRP lamina arranged in $[0/90/45/-45]_s$ layup sequence. A circular Teflon sheet (diameter 60mm) is placed in between first and second layers to replicate the presence of delamination. All the samples with and without delamination are developed with same curing cycle. A 4x4 electrode array (Figure 1a) made up of sixteen ECG electrodes (Figure 1b) are attached to the top of the specimen and numbered as shown in the schematic shown in figure (Figure 1c). A reference electrode (Figure 1a) is pasted at one of the corners of the sample and connected to the ground point of the instrumentation. The square shaped conductive gels on electrodes ensure equal effective contact areas with low resistive and smooth contacts in the electrode-sample interface.

The EIS studies are conducted with Agilent E4980A LCR meter and the impedance and phase angles of CFRP samples are measured with a sinusoidal current (50 mA rms) from 20 Hz to 2 MHz. The current signal is injected across the electrodes in different electrode pairs and the impedance and phase angle responses are studied. The impedance data are collected by injecting the current signal along the zero degree fiber direction as well as along the 90 degree fiber direction. For 0 direction, the measurements are conducted across the electrodes (1-4), (5-8), (9-12), (13-16), (6-7) and (10-11), whereas for the 90 degree direction, the data are collected from the (1-13), (2-14), (3-15), (4-16), (6-10) and (7-11) electrodes pairs. An unexpected measurement error is found for the current injection across (3-15) and further study is required to troubleshoot the issue. The measurements are obtained using two-probe configuration. As the impedance measurement process was conducted with ECG electrodes directly pasted on the CFRP samples, the load impedance was found to be much larger than the cable impedance and hence the two-probe method was justified. In future, four-probe measurement will be conducted for enhancing the measurement accuracy. The impedance data collected from two different samples without delamination and two samples with delamination are averaged and compared.

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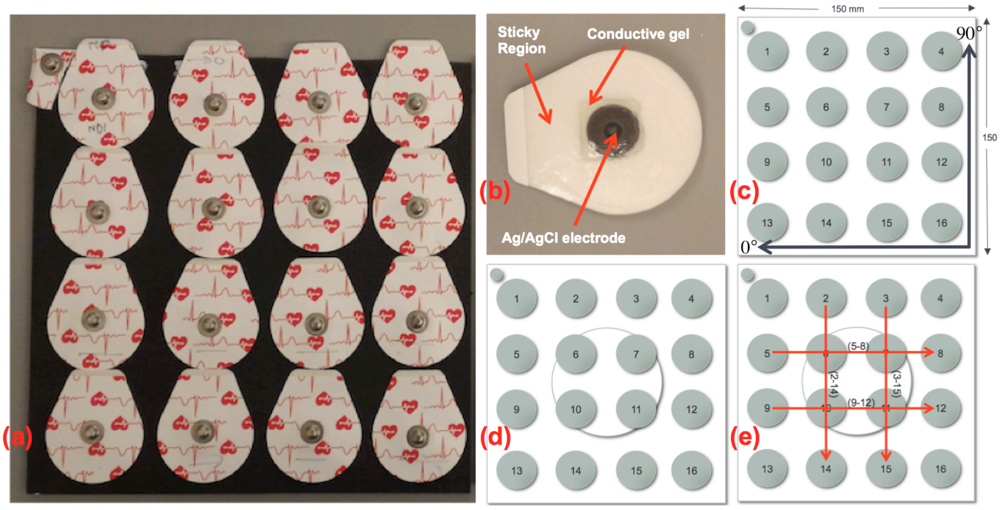

Figure 1: ECG electrode arrangements on CFRP samples for their EIS studies (a) 4x4 electrodes array made up of sixteen electrodes (b) a single ECG electrode with Ag/AgCl electrode and conducting gel, (c) geometrical dimension of the samples with electrode positioning, (d) schematic of a sample with a circular delamination, (e) electrode combinations through with the EIS studies are conducted.

3. Results and discussions

The impedance and phase angle are measured over the frequency range of 20 Hz to 2 MHz for all injection sequences along 0 degree and 90 degree directions. EIS studies across the electrodes (5-8) and (2-14) are conducted on the CFRP sample with delamination and the impedance and phase angle variations are compared with the data collected for the sample without delamination. A measurable difference in impedance response for specimens with and without delamination is found due to presence of the structural dissimilarity at the region in between the injection electrodes. Figure 2(a) and Figure 2(b) respectively represents the impedance and phase angle responses for the injection through (5-8).

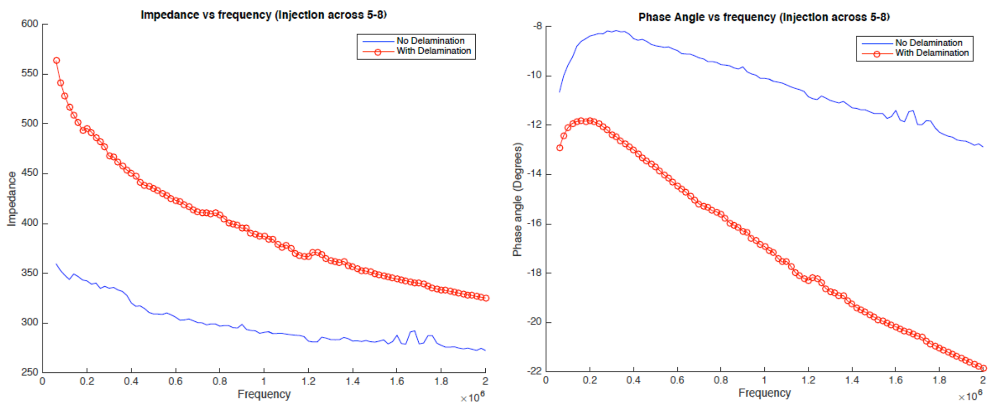

Figure 2: Impedance and phase profiles of CFRP samples obtained from the EIS measurements conducted with a current injection along the fiber direction (0°) using **electrode** pair 5-8 (a) impedance variation, (b) phase angle variation.

The impedance and phase angle variations for the injection through (2-14) have been shown in Figure 3(a) and Figure 3(b) respectively. A considerable difference between the impedance response for sample without delamination and sample with delamination is found for both the current injection (5- 8) and (2-14) and which can be utilized for CFRP damage detection noninvasively.

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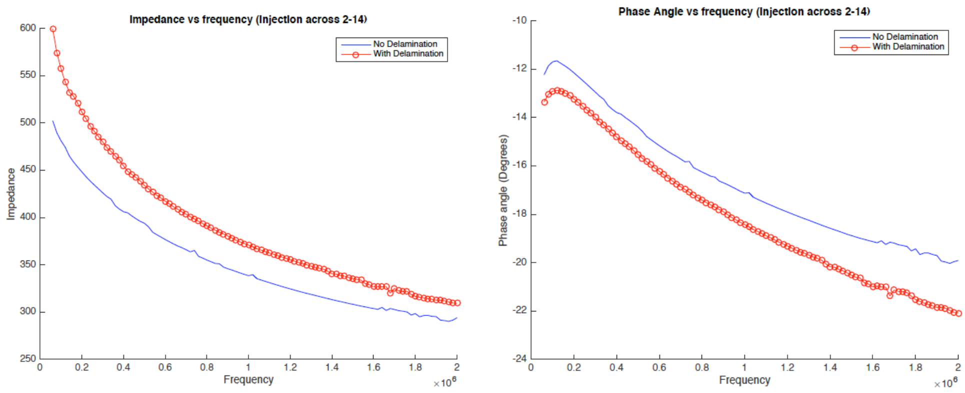

Figure 3: Impedance and phase profiles of CFRP samples obtained from the EIS measurements conducted with a current injection perpendicular to the fiber direction using electrode pair 2-14 (a) impedance variation, (b) phase angle variation.

4. Conclusions

EIS studies are conducted on CFRP samples with and without artificial delamination and the frequency dependent impedance variations are compared. Results demonstrate that the impedances of the samples with delamination are higher compared to samples without delamination. Phase angle variations of the samples with delamination are also found to be more capacitive except for the studies conducted across the electrodes on the delamination region.

Acknowledgments

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References

[1] P.K. Mallick (2007). Fiber-reinforced composites: materials, manufacturing, and design. CRC press.
[2] U. Meier (1992). Carbon fiber-reinforced polymers: modern materials in bridge engineering. Structural Engineering International, 2(1), 7-12.
[3] D.J. Bull, L. Helfen, I. Sinclair, S.M. Spearing, & T. Baumbach (2013). A comparison of multi-scale 3D X-ray tomographic inspection techniques for assessing carbon fibre composite impact damage. *Composites Science and Technology*, *75*, 55-61.
[4] J.H. Heida, D.J. Platenkamp , Evaluation of Non-Destructive Inspection Methods for Composite Aerospace Structures, 6th NDT in Progress 2011, International Workshop of NDT Experts, Prague, 10-12 Oct 2011.
[5] R. Lange & G. Mook (1994). Structural analysis of CFRP using eddy current methods. NDT & E International, 27(5), 241-248.
[6] C. Toscano, A. Riccio, F. Camerlingo, C. Meola, Lockin thermography to monitor propagation of delamination in CFRP composites during compression tests, 11th International Conference on Quantitative InfraRed Thermography, 11-14 June 2012, Naples Italy.
[7] S.V. Ramanan, A. Bulavinov, S. Pudovikov, C. Boller & T. Wenzel (2010, November). Quantitative non-destructive evaluation of cfrp components by sampling phased array. In Proceedings of the International Symposium on NDT in Aerospace, Hamburg, Germany.
[8] A. R. Bunsell, The Monitoring of Damage in Carbon Fiber Composite Structures by Acoustic Emission, Composite Structures 2, 1983, pp 1-20
[9] K. Schulte & C. Baron (1989). Load and failure analyses of CFRP laminates by means of electrical resistivity measurements. Composites science and technology, 36(1), 63-76.
[10] M. Kupke, K. Schulte & R. Schüler (2001). Non-destructive testing of FRP by dc and ac electrical methods. Composites Science and Technology, 61(6), 837-847.
[11] J.C. Abry, S. Bochard, A. Chateauminois, M. Salvia & G. Giraud (1999). In situ detection of damage in CFRP laminates by electrical resistance measurements. Composites Science and Technology, 59(6), 925-935.
[12] A. Todoroki, M. Tanaka & Y. Shimamura (2002). Measurement of orthotropic electric conductance of CFRP laminates and analysis of the effect on delamination monitoring with an electric resistance change method. Composites Science and Technology, 62(5), 619-628.
[13] J. Wen, Z. Xia, & F. Choy (2011). Damage detection of carbon fiber reinforced polymer composites via electrical resistance measurement. Composites Part B: Engineering, 42(1), 77-86.
[14] A. Todoroki, K. Omagari, Y. Shimamura and H. Kobayashi, H. (2006). Matrix crack detection of CFRP using electrical resistance change with integrated surface probes. Composites science and technology, 66(11), 1539-1545.
[15] K. Almuhammadi, L. Selvakumaran, M. Alfano, Y. Yang, T.K. Bera & G. Lubineau (2015). Laser-based surface preparation of composite laminates leads to improved electrodes for electrical measurements. Applied Surface Science, 359, 388-397.
[16] L. Salvakumaran and G. Lubineau (2013), Electrical behavior of laminated composites with intralaminar degradation: A comprehensive micro-meso homogenization procedure. Composite Structures. V. 109, 178-188.

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