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Multiscale Damage Detection in Conductive Composites

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Abstract: Conductive Composites such as carbon fiber reinforced composites are increasingly used in safety critical aerospace applications. The catastrophic macro structural failure of composite structures initiates from a micro level failure event such as fiber breaks. The ability to detect damage early on can improve the safety level and reliability of composite structures. A multilevel self-sensing damage detection techniques ability to detect damage at various length scales are numerically explored using COMSOL multiphysics software. The simulation methodology and results are reported highlighting the multilevel damage detection capability. The electrode configuration and detection sensitivity is also reported.

Keywords: Composites, Conductive composites, electrical resistivity, anisotropic conductivity, carbon fiber, damage, fiber breaks, matrix cracks, delamination, electrical simulation.

1. Introduction

Composite are considered as one of the technology breakthrough and enables us to design the materials also. The anisotropic nature of composites adds to the complexity and reliability of composite structures. Damage detection techniques are used to improve the reliability and safety of composites. Various damage detection techniques based on fiber optical, vibration, ultrasonic, acoustical and electromagnetic signature are used to characterize damage in composite structures. The focus of this paper is about the self-sensing technique which leverages the electrical conductive properties of the composites. This investigation can help to improve the reliability of carbon fiber composites use in aircraft fuselage and wind turbine applications for cost effective implementation and growth.

Overall specific performances of composites are better than conventional materials. However, the static, dynamic and fatigue failure pattern are different from conventional materials. For example, some of the composite failure can be catastrophic and sudden especially during fatigue loading. Ability to predict the damage initiation can improve the safety and reliability of composite structures for long term applications. Major, Composite failures include fiber breaks, matrix cracks and delamination. The initiation and growth at multiple length scale govern the overall performance of the composites.

This paper will focus on the multilevel damage detection capability of carbon fiber composite using COMSOL multiphysics simulation. The electrical conduction mechanisms in carbon fiber composite are reviewed. Typical defects and its electrical response are simulated. A multilevel damage sensing capability is numerically explored for the damage sensitivity detection. The local and global damage sensing ability is explored. The effect of electrode location and configuration is also studied and reported.

2. Damage modes and damage detection techniques in composites

Damage in laminated composites can be classified into three types; fibre damage, matrix damage and interfacial damage. Fibre breaks, matrix cracking, longitudinal splitting and delamination are the major damage modes generally observed in carbon fibre reinforced polymer composites [1]. Figure shows a schematic illustration of the major damage modes of a unidirectional laminate. The final failure of a composite structure is linked to part to laminate to lamina to constituents. Understanding and prediction of damage modes at fibre level to part level will help to improve the reliability and safety of composite structures.

A schematic illustration of fibre breaks is shown in Figure 1a. Fibres are the major load carrying members in a laminated composite. The final catastrophic failure of composite structure is due to failure of these fibres. Moreover, fibre breaks are the major damage mechanism controlling the life of the laminates subjected to mechanical loading. Matrix cracking is a form of matrix damage (refer figure 1b). Matrix cracks are the initial damage mode in multi-ply laminated composites. Matrix cracks can act as a source of initiation of other damage modes such as delamination, fibre breaks and longitudinal splitting. Longitudinal splitting is a damage mode observed in unidirectional composites (refer figure 1c). Delamination is another major mode of failure in composites. The schematics of delamination failure mode are shows figure 1d. The delamination growth can lead to loss of stiffness properties and ultimate failure.

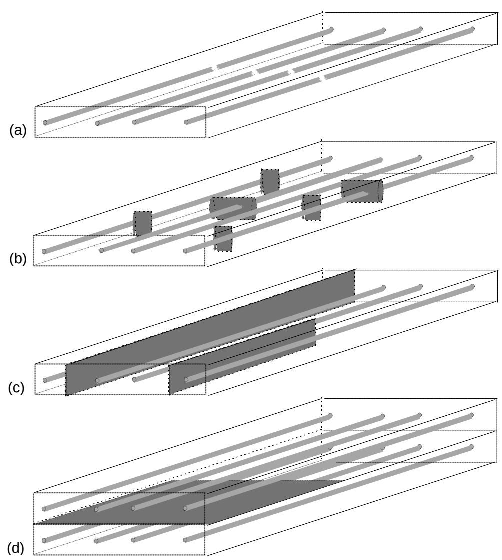

Figure 1. Schematic illustration of damage modes in a unidirectional composite: (a) fibre breaks, (b) matrix cracks, (c) longitudinal splits and (d) delamination.

The damage mechanisms of composite materials are complex and depend on many material, load and environmental parameters. It is necessary to develop a damage monitoring method that can define just the damage on the ordinate.

2.1 Damage Detection

Electrical Resistivity measurement of carbon fiber composites is a self-sensing damage monitoring technique [2]. The measured quantity in an electrical resistivity measurement technique is the resistance. The change in resistance is mainly due change of conductivity paths in the material due to the effect of damage. The electrical properties of unidirectional CFRP are orthotropic. The change in electrical resistivity can vary with the direction of current flow and the direction of resistance measurement. This is a major factor in determining the sensitivity of electrical resistivity measurement technique for characterizing different damage mechanisms. Also, this is very important in determining the location of the electrode for current injection and measuring the potential distribution.

All the composite damage mechanisms whether caused by impact, fatigue or any other loading conditions affect the longitudinal and or the transverse electrical conduction process. The analogy between the damage mechanisms and electrical conduction mechanism can provide more information to investigate the effects of damage mechanisms on electrical resistivity.

3. COMSOL Simulation

The electrical conduction mechanism and the effect of damage in CFRP composites were simulated in COMSOL using AC/DC Electric Currents Interface [3]. In a stationary coordinate system with stationary electric currents in conductive media, the point form of Ohm's law states that,

$$\mathbf{J} = \sigma \mathbf{E} + \mathbf{J}_e$$

Where σ is the electrical conductivity (S/m), and $\mathbf{J}_e$ is an externally generated current density (A/m^2). The static form of the equation of continuity then states

$$\nabla \cdot \mathbf{J} = -\nabla \cdot (\sigma \nabla V - \mathbf{J}_e) = 0$$

The generalized form with current sources can be written as follows.

$$-\nabla \cdot (\sigma \nabla V - \mathbf{J}_e) = Q_j$$

In an electrical resistivity measurement technique the measured resistance is a direct consequence of the effects of complex damage mechanisms. The change in resistance is a measure of all types of damage. In order to understand the resistance change from complex damage mechanisms and to distinguish the effects of individual damage mechanisms, experimental simulations are essential.

The fiber breaks, matrix crack and delamination mechanism was simulated using Electric Currents Interface. Homogenized anisotropic electrical properties are used for fiber breaks simulation. Representative carbon fiber and dielectric matrix properties are used for fiber breaks and delamination simulation. Figure 2 and 3 shows a typical CAD model with electrode configuration. The changes in resistance due to damage mode was measured and reported.

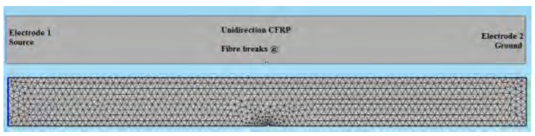

Figure 2. Typical CAD and FEA mesh along with electrode configuration used for fiber breaks simulation.

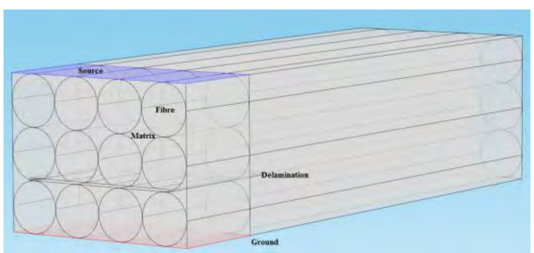

Figure 3. Typical model used for delamination and matrix cracks along with electrode configuration.

4. Results and Discussion

The simulation result on the changes in the electrical resistance or the resistivity is reported. The fiber break results are compared with experimental results. The effect of delamination and matrix cracks are shows on representative volume model. The results are normalized as damage parameter vs changes in resistance or resistivity for comparison.

The experimental and simulation results of fiber breaks are shown in figure 4 and 5. For fiber breaks simulation in COMSOL, anisotropic electrical conductivity of unidirectional CFRP composite measured or predicted from micromechanics is used. Figure 4 shows the electrical potential distribution as a function of percentage of fiber breaks. Top and bottom figure shows electrical distribution for zero and 80% fiber breaks, respectively. Fiber breaks were simulated experimentally by cutting the sample across the width at the center of the sample length using a hack saw. Fiber breaks are mostly sensitive when the current flows along the fiber direction. Hence, the electrodes were attached at the ends of the sample. A 270 mm length and 25 mm width and a 2 mm thickness unidirectional CFRP samples was used. The change in resistivity was measured as function of percentage of fiber breaks. The resistivity of the sample was also extracted from the parametric COMSOL simulation as function of % of fiber breaks. Figure 5 shows the experimental and simulation results comparison.

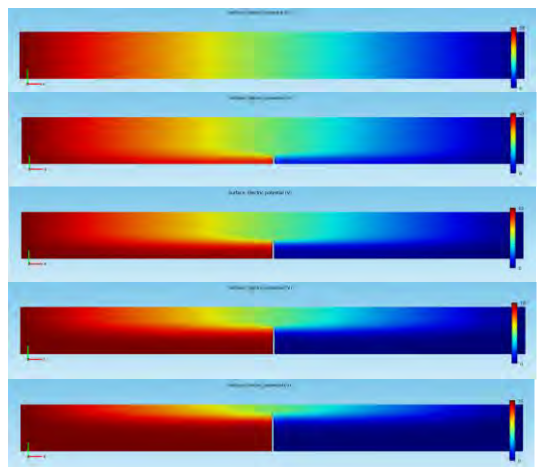

Figure 4 Electrical potential distribution contour plots as a function of % of fiber breaks.

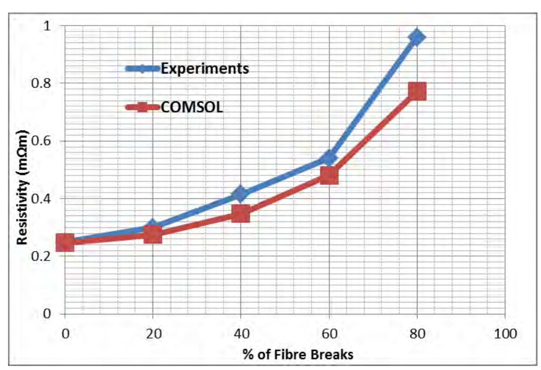

Figure 5 Experimental and COMSOL fiber breaks simulation comparison.

The matrix cracks and delamination was investigated on a representative unidirectional CFRP sample. The electrode configuration as shown in figure 3 was used. Figure 6 shows typical electrical potential distribution, zero and 60% of delamination length, at the top and bottom respectively. Figure 7 shows the change in resistance as function of delamination depth.. Matrix cracks are also expected to provide similar performance. The homogenized model for the fiber breaks and the micromechanical model for the delamination show significant changes in resistance with damage. Thus, the resistivity measurement of carbon fiber composites can provide good indication about the health of composite structures.

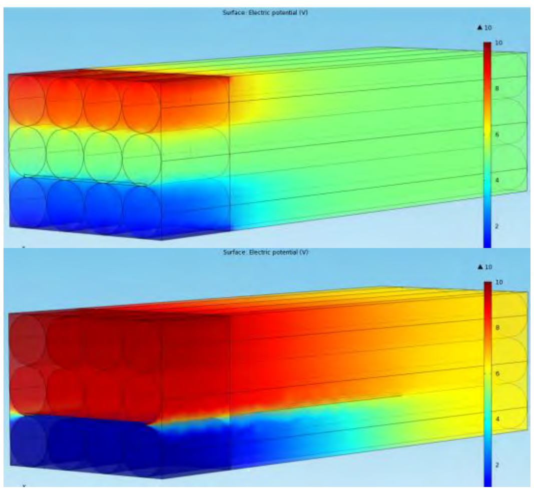

Figure 6. Electrical potential distribution as function of delamination depth.

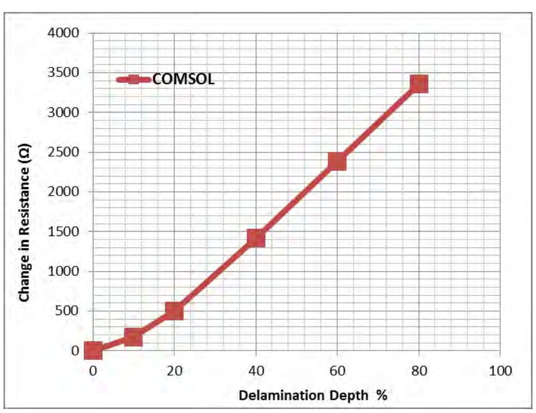

Figure 7 Changes in electrical resistance as function of delamination depth.

5. Conclusion

A brief review of damage modes and damage detection in carbon fiber composites are given. The COMSOL model results show that the electrical resistance change is sensitive to fiber breaks and delamination. The homogenized and micromechanical model demonstrated the changes in resistance as function of damage. The methodology developed can be used to study and optimize the electrical resistivity measurement technique for improving the damage detection capability and reliability of composite structures.

6. References

1. C Thiagarajan et.al, "Electrical Potential Techniques for Damage Sensing in Composite Structures" , in Smart Structures and Materials, pp 128-131, SPIE proceedings, vol 2361, pub SPIE, 1994

2. P E Irving, C Thiagarajan, "Fatigue Damage Characterization in Carbon Fiber Composite Materials using an Electrical Potential Technique", Journal of Smart Materials, (1998), pp 456-466.

3. COSMOL ACDC user manual, Theory for the Electric Currents Interface, 2011.

7. Acknowledgements

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