

High Current and Multi-Physics Modeling of Carbon Fiber Reinforced Polymers (CFRP) plates and Joints under Lightning Strike Conditions

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Abstract

This paper presents multiphysics modeling of coupled thermal-electrical behavior across the composite joints formed by highly anisotropic conductivity materials such as carbon-carbon, but separated by intentional dielectric barriers including adhesive, and demonstrate the driving physics behind the high current conduction across the joints under lightning strike conditions. The joint configuration can be formed in any direction of the carbon fiber composite panel. The multiphysics model combines the quasi-static electromagnetic properties with the transient heat transfer properties using COMSOLTM multiphysics numerical solver. To demonstrate the non-linear effects impacting the high current conduction across the carbon-fiber joint, lightning current waveforms were incorporated away from the joint. The model was evaluated under a number of different configurations to study the high current conduction across the composite joints.

Introduction

Modern military and commercial aircrafts are heavily dependent on the composite structures such as carbon fiber reinforced polymers (CFRP) due to their light weight, high mechanical stiffness and fuel efficiency. When using these CFRP materials in aircraft construction, however, there are a lot of challenges from lightning strikes causing damages to the aircraft structure due to the resistive heating [1,2]. The impact of the lightning strike is significant across the composite joints formed by composite layers but separated by intentional dielectric barriers. To minimize the effect of lightning strike conditions on the aircraft joints, it is important to understand the current conduction behavior across the joints.

This paper presents the mathematical and finite element based multiphysics modeling of the coupled thermal-electrical behavior across the composite joints. The joints can be formed in any direction of the carbon fiber composite panel and were formed by carbon fiber composite polymer (CFRP) materials but separated by intentional dielectric barriers. To demonstrate the physics behind the high current transfer across the joints under lightning strike

conditions, high current waveform was included away from the joints.

Multiphysics Modeling

The multiphysics model couples the electrical and thermal behavior of carbon fiber material as shown in figure 1.

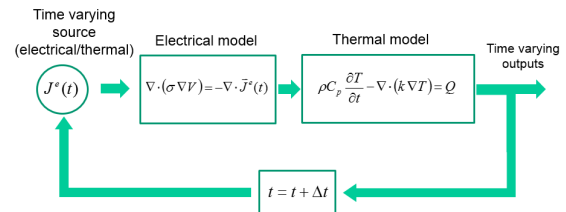


Figure 1: Illustration of the electro-thermal multi-physics model

The electrical model is a quasi-static model that computes the distribution of electrical potential as a function of space and time. Secondary quantities such as current density, electric fields and power dissipation are then calculated from the potential distribution.

The governing partial differential equation is given by

$$\nabla \cdot (\sigma \nabla V) = -\nabla \cdot \vec{j}^e(t)$$

Where V denotes the electrical potential distribution (function of space and time), J^e denotes the external current source (e.g. lightning strike) and is time varying, σ denotes the conductivity tensor which is a function of space (x, y and z), temperature (T), electric field strength (E) and polarization (i.e. anisotropic). The conductivity tensor can be explicitly written as in tensorial form

$$\vec{\sigma}(x, y, z, t, T) = \begin{bmatrix} \sigma_{xx}(T) & \sigma_{xy}(T) & \sigma_{xz}(T) \\ \sigma_{yx}(T) & \sigma_{yy}(T) & \sigma_{yz}(T) \\ \sigma_{zx}(T) & \sigma_{zy}(T) & \sigma_{zz}(T) \end{bmatrix}$$

The thermal model is a fully time-varying heat conduction model that computes the distribution of temperature as a function of space and time. Secondary quantities such as heat-flux are then calculated from the time varying temperature distribution.

The governing partial differential equation is given by

$$\rho C_p \frac{\partial T}{\partial t} - \nabla \cdot (k \nabla T) = Q$$

Where T denotes the temperature distribution (function of space and time), ρ and C_p denotes the material density and specific heat respectively, k denotes the heat conduction coefficient and is assumed to be dependent on the direction of heat flow (i.e. tensor quantity) and Q denotes the heat generation term due to dissipation of electrical currents. Q is given explicitly in terms of the electrical variable as

$$Q = -\vec{j} \cdot \nabla V$$

Composite Joints formed by CFRP plates with connecting adhesive layer:

The goal of these numerical study was to evaluate the ability of the finite element model to predict current distributions and heating patterns for two CFRP plates connected by an adhesive layer. To show the effect of high current conduction across the joints, we studied a number of variations of the modeling setup. Figure 2 shows the geometry for these simulations. For this example, the two CFRP plates were assumed to be 75mm x 150mm x 4mm in size with the carbon fibers running along the y-axis. The plates were joined by a thin adhesive layer (0.5mm). Current is ejected between the two ends of the structure and the resulted current density, potential distribution, and heating patterns were calculated using COMSOL multiphysics solver.

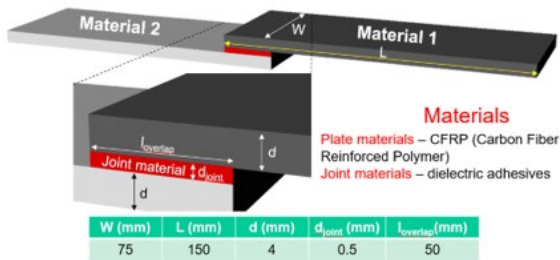


Figure 2: Two CFRP plates are joined by a thin adhesive layer

To show and predict the high current conduction across the carbon-fiber joints, we simulated the geometry under several cases.

Case I: Current is injected from the edge

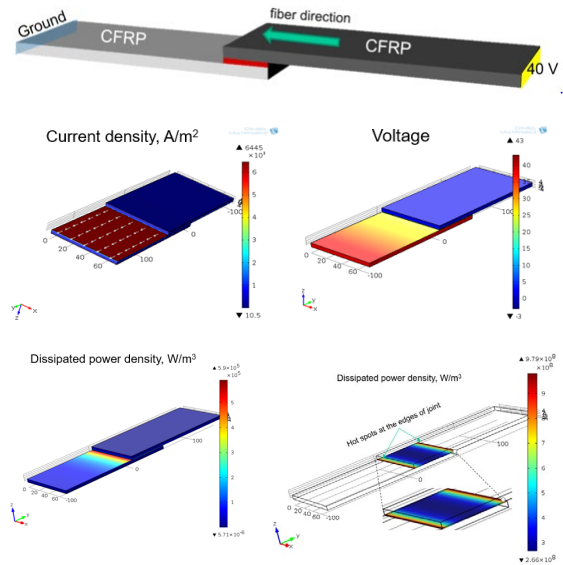
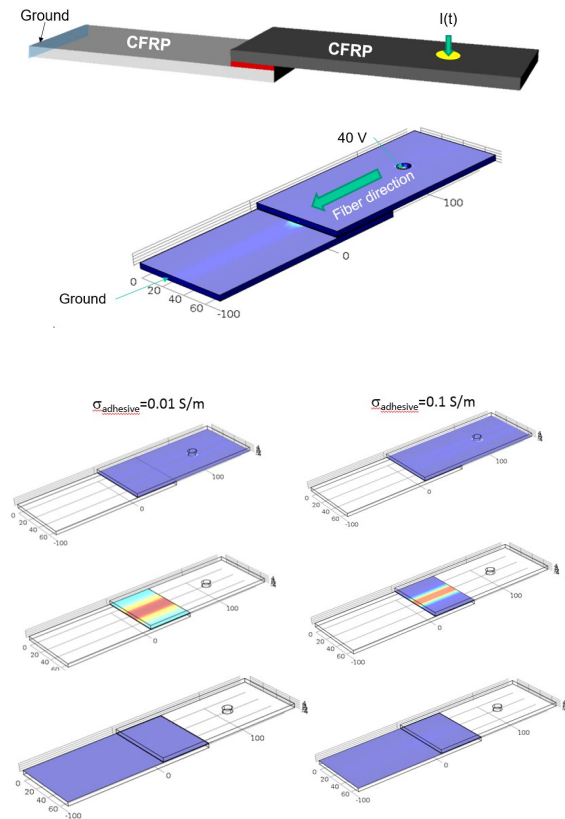


Figure 3: Joint study for excitation at the edges

Case II: In this case, current was injected uniformly on top of the CFRP surface in a hole



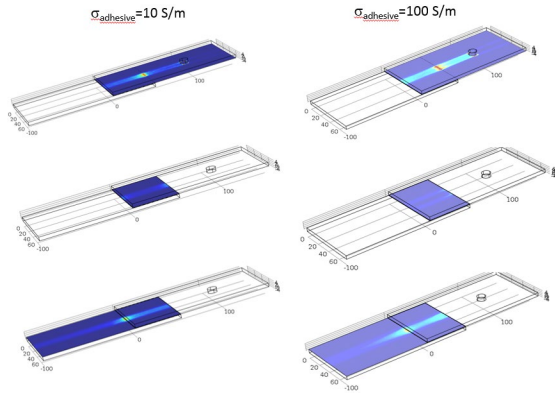


Figure 4: Joint study for current excitation through hole

Case III: In this case, metallic fastener and edge conductors were attached in the joint area and power dissipation were calculated. Fiber contact with fasteners likely have a large impact on the current distribution and heating characteristics of the joint.

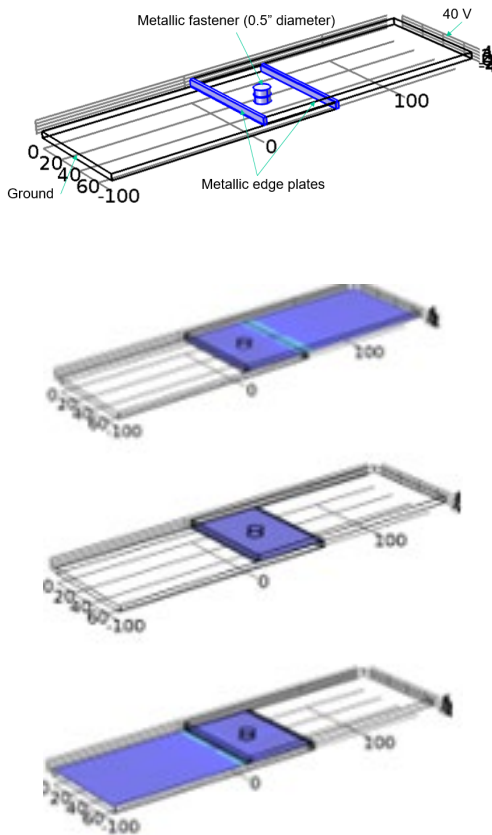


Figure 5: Joint study with metallic fastener and edge conductors

Conclusions

In this study, we conducted a finite element based multi-physics modeling of coupled thermal-electrical behavior of carbon-fiber joints under different configurations. From the study, it was observed that the presence of a fastener and edge conductor will likely to have a large impact on current conduction across the joints.

References

1. G. Abdelal, A. Murphy, "Nonlinear numerical modelling of lightning strike effect on composite panels with temperature dependent material properties," *Composite Structures* 109(2014) 268-278
2. T. Ogasawara, Y. Hirano, A. Yoshimura, "Coupled thermal-electrical analysis for carbon fiber/epoxy composites exposed to simulated lightning current," *composites: Part A* 41 (2010) 973-981