DELAMINATION PREDICTION ON CFRP MATERIALS SUBJECTED TO A LIGHTNING STRIKE

Timothy M. Harrell[1], Ole Thybo Thomsen[1], Janice M. Dulieu-Barton1[1], and Lisa Carloni[2]

[1]University of Southampton, Faculty of Engineering and the Environment, University Road, Southampton, UK
Email: T.M.Harrell@soton.ac.uk, Web Page: http://www.sparcarb.com
[2]Global Lightning Protection Services A/S, Hededhusene, DK

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Abstract
This paper presents a coupled thermal-electric-mechanical model to predict the delamination damage of a Carbon Fiber Reinforced Polymer (CFRP) material when subjected to a lightning strike. A Finite Element Model (FEM) is used to predict the heat response of the CFRP material by solving the Joule heating governing equations. The results of the heat response are coupled with thermal stresses to predicte interlaminar stresses. A bilinear traction law is used to predict the delamination of the laminate. Solutions to the model are developed using a time dependent simulation with the 10/350μs standard waveform to mimic a typical lightning strike on a wind turbine blade in accordance to IEC61400 section 24 Ed 1.0. The time dependent model implements damage criteria and is able to identify damaged elements. The COMSOL software engine was used to derive the results from the thermal-electrical-mechanical model. The final result is a delamination map of the CFRP panel subjected to a lightning discharge.

1. Introduction

Carbon fiber composite materials are increasingly being used in the wind turbine, aerospace, and automotive industries to reduce the structural weight of components as a result of their high strength to weight and stiffness to weight ratios. However, the anisotropic material properties of Carbon Fiber Reinforced Polymers (CFRP), specifically their electrical and thermal conductivities, create challenges when protecting structures from lightning strike. Exposing CFRP to electric currents from lightning discharges can cause significant damage to CFRP structures. A coupled thermal-electric-mechanical model is developed, based on the Joule heating governing equations [1], which predicts the delamination damage in a CFRP materials when subjected to a lightning strike. The Joule heating model uses the Finite Element Method (FEM) to predict the temperature distribution through the CFRP material and the mechanical model calculates the thermal stresses which when used with cohesive zone elements predict delamination. Solutions for the model are obtained using a time dependent simulation with current inputs that mimic the 10/350 standard waveform used to test wind turbine blades according to the IEC61400 section 24 Ed 1.0 [2]. The cohesive zone elements are used to predict the extent of delamination.

2. Numerical Analysis Method

A thermal electrical mechanical model is employed to analysis the damage of CFRP materials due to a lightning strike. The damage simulation indicates the areas at the interlaminar surface which have become delaminated. The corresponding model does this by calculated a Joule heating (thermal-electrical effects) and combining those effects to calculate the stresses induced by thermal stresses. Both of these models were calculated through the use of the commercial finite element software COMSOL.

The phenomena of a lightning strike on a CFRP composite involves significant complexity that cannot be dealt with accurately by simplified analytical methods. Therefore, the governing equations and the associated boundary and initial conditions will be solved through the use of a finite element model. The finite element modelling has been completed using the commercial code COMSOL 5.3 [3]. The finite element formulation adopted is summarized from two COMSOL reports [4], [5].

2.1. Coupled Thermal Electrical Mechanical Model

The thermo-electric portion of the model is determined through the Joule heating equation. Joule heating is the phenomena where a resistive object is heated when subject to current. A Joule heating model is constructed by coupling of the Seebeck, Peltier, and the Thomson effects. The governing equations are listed below, according to [5]. The electric balance equations are:

$$-\nabla \cdot (\sigma \nabla V) = 0 \tag{1}$$

where σ is the electric conductivity and V is the electric potential.

The heat transfer equations are shown in equation (2):

$$\rho C_{CFRP} \frac{\partial T}{\partial t} + \nabla \cdot q = Q \tag{2}$$
$$q = -\kappa \nabla T + PJ$$

where ρ is the density, C_{CFRP} is the specific heat of the CFRP. T is the temperature, t is time, q is the heat flux, Q is the Joule heating equation ($Q = J \cdot (-\nabla V)$), κ is the thermal conductivity, P is the Peltier coefficient, and J is the current density. Since we will be investigating CFRP composite materials, the Peltier and Seebeck coefficients are have to be specified such that the anisotropic properties are represented. The constitutive relations are:

$$\begin{gathered} q = [P]J - [\kappa]\nabla T \\ J = [\sigma](E - [S]\nabla T) \\ D = [\varepsilon]E \end{gathered} \tag{3}$$

where $[P]$ is now the Peltier coefficient, $[\kappa]$ is now the thermal conductivity, $[\sigma]$ is now the electric conductivity, $[S]$ is now the Seebeck coefficient, D is the electric flux density, $[\varepsilon]$is the dielectric permittivity.

2.2. Thermal Stress Analysis

The temperature field from the Joule heating model are used to calculate the stresses induced by thermal expansion on the CFRP material. The equations governing the thermal stress are describe by

$$\nabla[c\nabla u + \alpha \Delta T] = 0 \tag{4}$$

where c is the stiffness matrix, u is the displacement field, α is the thermal expansion coefficient, and ΔT the change in temperature.

2.3. Cohesive Zone Elements

The interlaminar zones are modelled by cohesive zone elements. The separation of these regions are simulated by a bi-linear traction law. The traction law is presented in **Figure 1** where τ is the traction, τ_0 is initial traction strength, δ is the opening displacement between interfaces, δ_0 is the critical opening displacement, δ_f is the fracture displacement, K is the initial interface stiffness, and G_C is the critical energy release rate.

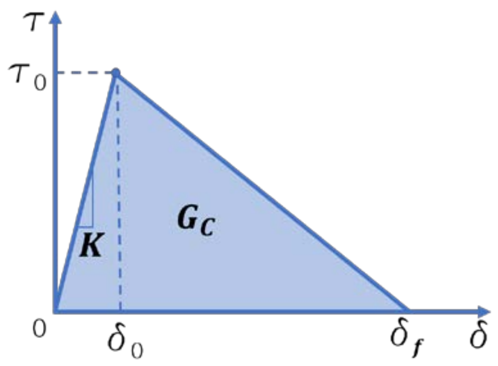

Figure 1. Bilinear traction separation law

The implementation of these cohesive zone elements will allow for the delamination prediction. The delamination will be predicted by stresses in the interface region which are larger than the initial traction strength. The elements which are greater than these values will then follow the bilinear traction law until the critical separation is reach and the element is considered to be completely delaminated or in other words does not contribute to the stiffness.

2.4. Numerical Model

The numerical model is a flat composite panel with a four unidirectional ply layup ($[0]_4$). The model is a quarter plate model measuring 20cm wide x 25cm long x 4mm thick. The outside edges are grounded, fixed and allowed thermal radiation. The inner edges are symmetric boundary conditions. On the top surface a circular surface is applied with normal current density set to the 10/350µs waveform divided by the area of the surface. The top and bottom surface are set to radiate heat. **Figure 2** shows the geometry and applied boundary conditions.

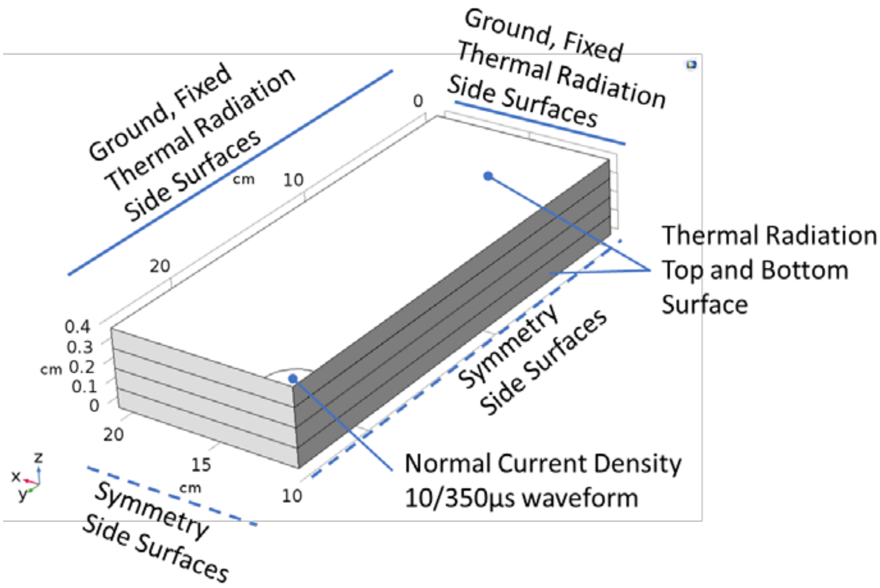

Figure 2. Thermal-electrical-mechanical quarter plate model with applied boundary conditions

The waveform is modelled by discrete points to mimic the 10/350µs waveform shown in **Figure 3**. The orange line indicates the lightning current discrete points used while the blue marks indicate a typical 10/350µs waveform.

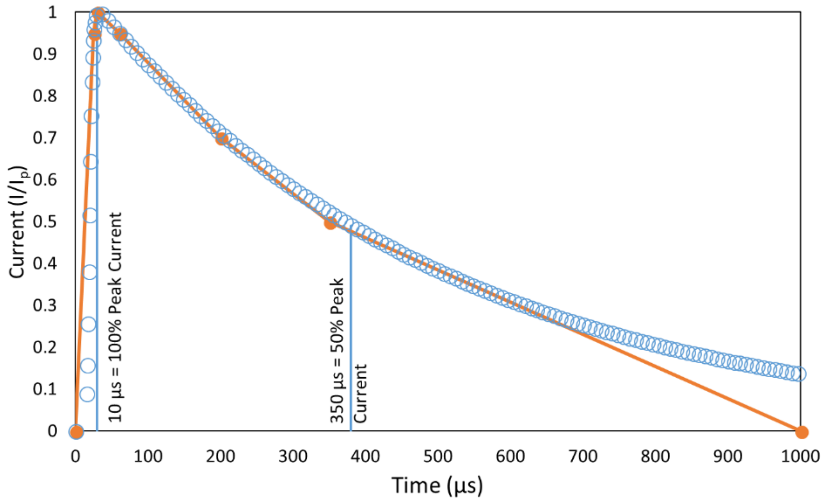

Figure 3. Normalized waveform used to model the lightning current into the structure

The model was run for two example lightning cases 20 kA and 60 kA.

2.5. Material Properties

The material properties were based on assumed properties for composite materials. **Table 1** indicates the thermal and electrical materials properties used.

Table 1. Thermal-electrical material properties for FEM model

Direction	Thermal Conductivity [W/(m K)]	Density [g/cm^3]	Heat Capacity [J/(g K)]	Electrical Conductivity [S/m]
Longitudinal	120			40000
Transverse	10.22	1.15	1.1	500
Through-thickness	10.22			500

Table 2 shows the mechanical properties used.

Table 2. Mechanical material properties for FEM model

Direction	Young's Modulus [Gpa]	Direction	Shear Modulus [Gpa]	Coefficient of Thermal Expansion [10^{-6} ε/K]
Longitudinal (1)	120	12	5.6	-0.76
Transverse (2)	13	13	1.93	36.34
Through-thickness (3)	13	23	1.93	35.96

Table 3 shows the traction properties used for the delamination modeling.

Table 3. Traction properties for FEM model

Characteristic Stiffness [Gpa]	Mode I Maximum Traction [Mpa]	Mode II Maximum Traction [Mpa]	Mode I Critical Energy Release Rate [Mpa]	Mode II/III Critical Energy Release Rate [Mpa]
9	80	110	400	1800

3. Results and Discussion

The results of the 20kA waveform delamination analysis are shown in **Figure 4**. The figure shows the interface damage indicated by the element which were larger than the critical energy release rate. These elements are shown with a value of 1 in the figure and the undamaged interface is shown with a zero. As can be seen in the plot, the with a 20kA strike for the average composite non-toughened, no protected CFRP the first layer is delaminated.

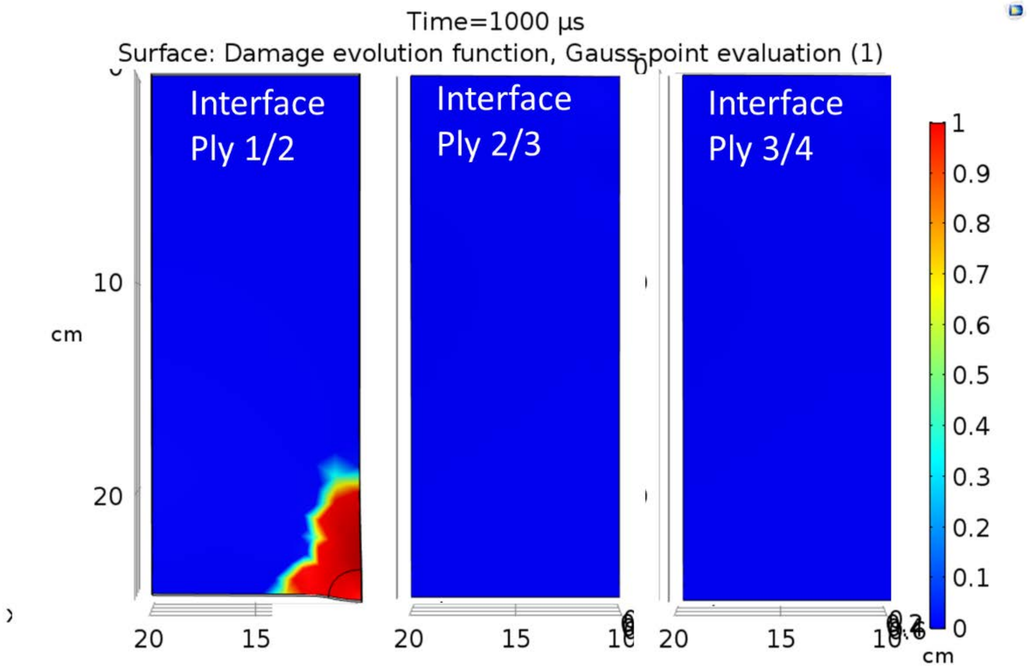

Figure 4. Delamination of different ply layers for a 20kA 10/350 waveform

The results of the 100kA waveform delamination analysis are shown in **Figure 5**. As can be seen in the figure, there is a significant increase in delaminated from a 100kA strike for the average composite non-toughened, no protected. All interfaces have indicated delamination and become progressively smaller the further into the panel thickness.

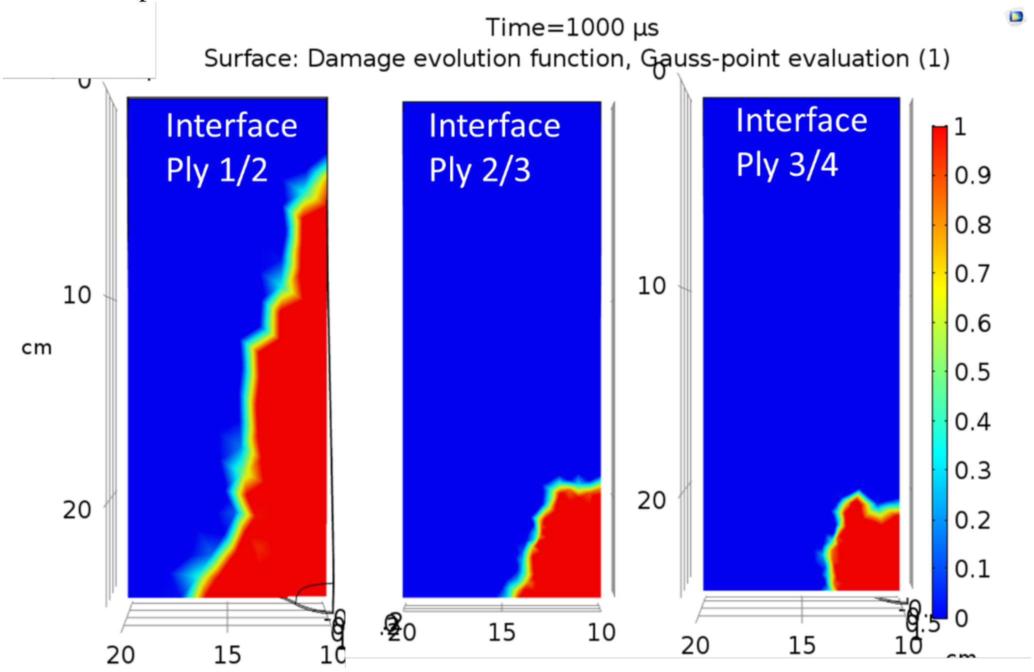

Figure 5. Delamination of different ply layers for a 100kA 10/350 waveform

4. Conclusions

The paper presents the results of a lightning strike delamination damage in CFRP panels. A coupled thermal-electrical-mechanical FE model implemented in the software tool COMSOL has been presented. The model is based on the assumption that the damage source of Joule heating (or resistive heating) can cause delamination in a CFRP material. The paper presents two different kilo-amperage results of delaminated interlaminar layers from a lightning strike.

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