DAMAGE PREDICTION OF CFRP MATERIALS SUBJECTED TO LIGHTNING STRIKE

Timothy M Harrell[1], Ole Thybo Thomsen[1], Janice M Dulieu-Barton[1], Søren F Madsen[2] and Lisa Carloni[2]

[1] Faculty of Engineering and the Environment, University of Southampton, UK
[2] Global Lightning Protections Services A/S, Denmark

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ABSTRACT

This paper presents a coupled thermal-electric model to predict the thermal 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. Joule heating, also known as resistive heating, is the heating of the material when subjected to an electrical current. Solutions to the Joule heating model are developed using a time dependent simulation with the 10/350µs standard waveform used to test wind turbine blades in accordance to IEC61400 section 24 Ed 1.0. The time dependent model implements damage criteria and is able to identify damaged elements. The damage criteria are based on a combination of material decomposition by pyrolysis described by the Arrhenius equation. The COMSOL software engine was used to derive the results from the Joule heating model. An integrated MATLAB script was run during the simulation to determine the amount of damage that each element is subjected to during a lightning strike event. The final result is a damage map of the CFRP panel subjected to a lightning discharge. The damage model is validated through lightning discharge experiments. Two samples with unidirectional fibers were made by vacuum assisted liquid resin infusion to mimic the sparcaps of a wind turbine blade located near the wind blade tip region. The samples were tested using the arc entry test of IEC 61400-24 Ed 1.0 with simulated first return stroke electric current components (10/350µs) with magnitudes of 30 kA and 60 kA unipolar waveforms. The resulting damages were inspected by use of X-ray Computed Tomography (CT) to determine the total damaged volume. The CT scans used an imaging segmentation algorithm to systematically determine the location and type of the damage done to the CFRP. The resulting CT scans are compared to the damage model.

1 INTRODUCTION

Carbon fiber composite materials are increasingly being used in the wind turbine, aerospace, and automotive industries to reduce the mass of load carrying structures because of their high strength to weight and strength to stiffness ratios. However, Carbon Fiber Reinforced Polymers (CFRP) have a particular issue when dealing with lightning strikes. The anisotropic material properties, and in particular their highly directional electrical and thermal conductivities, create challenges when protecting structures exposed to electric currents from lightning discharges, which can cause significant damage to structures which contain CFRP material exposed to electric currents.

Lightning is a transient, high current electrical discharge which when attached to a structure can create high currents into the CFRP components. Lightning protection of wind turbine (WT) blades have received significant attention recently because most wind turbine blade manufacturers now feature blade designs that include conductive Carbon Fiber Reinforced Polymers (CFRP) composites for structural components. To properly protect these structures, it is important to understand the underlying fundamentals of the damage behavior during a lightning strike. Recent research has determined that Joule heating models are a good approach to studying the damage behavior [1]. Ogasawara et al. [2] introduced a coupled thermal-electric model which used damaged mechanics to determine an area of damage in CFRP panels. Abdelal [3] introduced temperature dependent properties to the models. Dong et al. [4] introduced a coupled thermal/electrical model which used pyrolysis to determine the damaged area.

This aim of this paper is to develop and validate a thermal-electric Finite Element Model (FEM), which is able to determine the thermally induced damage in the CFRP material. This paper presents a model which includes temperature dependent properties, and which distinguishes the difference between resin damage and fiber damage based on temperature.

2 EXPERIMENTAL METHOD

Two CFRP specimens were manufactured with Zoltek PX-35 plies. Five ply unidirectional laminate stacks were made using vacuum liquid resin infusion producing flat plates with the dimensions of 250 mm long x 250 mm wide x 4.5 mm thick. The waveform used to simulate a lightning strike was a 10/350µs waveform, which simulates the first return stroke during a direct strike according to IEC 61400-24 Ed1.0 [5]. Two different amperage magnitudes were used to determine have two different degrees of damage; 30kA and 60kA. Figure 1 shows the experimental setup and experimental waveforms performed with reference 10/350µs waveforms.

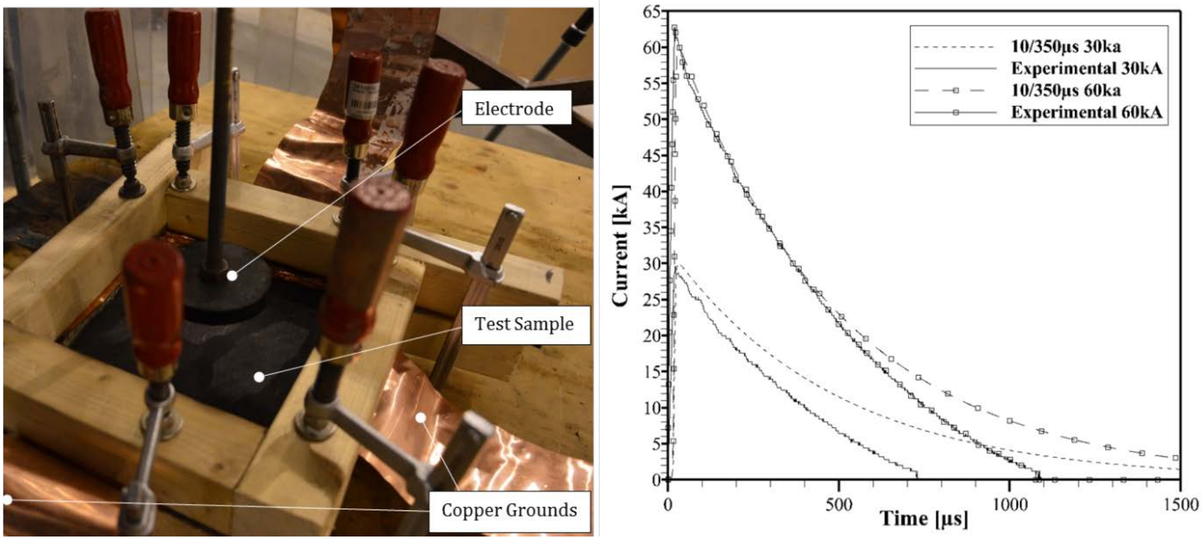

Figure 1: Simulated lightning strike experimental setup (left) and experimental waveform measurements (right).

The specimens that were subjected to electrical current were labeled as damaged and subsequently subjected to X-ray micro CT scanning for damage analysis.

3 NUMERICAL ANALYSIS METHOD

3.1 Joule Heating Finite Element Model (FEM) Formulation

A thermo-electric model has been implemented to determine the heating imposed on a wind turbine blade laminate due to a lightning strike. Thermo-electric models are able to show the effect of heating due to electrical current differences, also referred to as Joule heating. Joule heating occurs when a resistive object is 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 [6]. 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) with a change to the specific heat adding in details associated to the CFRP materials similar to [7]:

$$\rho\left(\phi_f C_f + \phi_M C_M + \phi_g C_g\right)\frac{\partial T}{\partial t} + \nabla \cdot q = Q \tag{2}$$
$$q = -\kappa \nabla T + PJ$$

where ρ is the density, ϕ_f, ϕ_M, ϕ_g and C_f, C_M, C_g are the volume fraction and specific heat of the fiber, matrix and pyrolysis gas, respectively. 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.

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 5.2a [8]. The finite element formulation adopted is summarized from two COMSOL reports [9], [10]. Since we will be investigating CFRP composite materials, the Peltier and Seebeck coefficients are have to be specified such that the anisotropic properties are respresented. The constitutive relations are:

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

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.

3.2 Numerical Model

The composite panel is a flat plate with a five ply unidirectional layup ($[0]_5$). The dimensions of the plate are 250mm wide x 250mm long x 4.5mm thick. The edges were grounded along the edge and a concentrated load was applied to the center of the top surface. Figure 2 shows the geometry and applied boundary conditions.

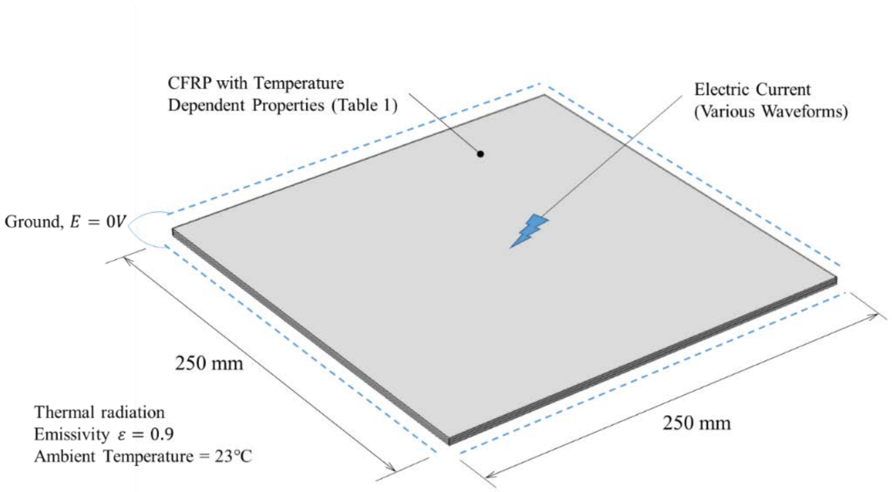

Figure 2: Thermal-electrical model with applied boundary conditions.

A lightning strike event, especially a direct strike, can induce large temperatures to be imparted on the CFRP material in excess of 3000°C. These temperature ranges are associated with material degradation, decomposition, and ablation. Due to this fact, it is necessary to include temperature dependent material properties in then modelling. For the purposes of this study, the material properties were separated into three temperature ranges. The “typical operating range” for a WT blade made of CFRP is a minimum of -50°C and a maximum of approx. 60°C which is less than a typical glass transition temperature (T_g). This temperature range is attributed with the typical material property values and does not change. Between the glass transition temperature and the boiling point (T_b) of carbon, the next temperature range is labelled “resin breakdown” in which resin decomposition occurs whilst the carbon fibers can still conduct the electric current. The properties for this temperature range are attributed with the electrical and thermal conductivity of the pure fibers. The last temperature range corresponds to the state where the boiling point of carbon is reached and ablation of the fibers start to take place. This section is called “Dielectric/carbon breakdown” and the associated electrical properties are given a value which is associated with a conductor so that electrical current can conduct as if it is in a plasma channel. Figure 3 shows the electrical conductivity.

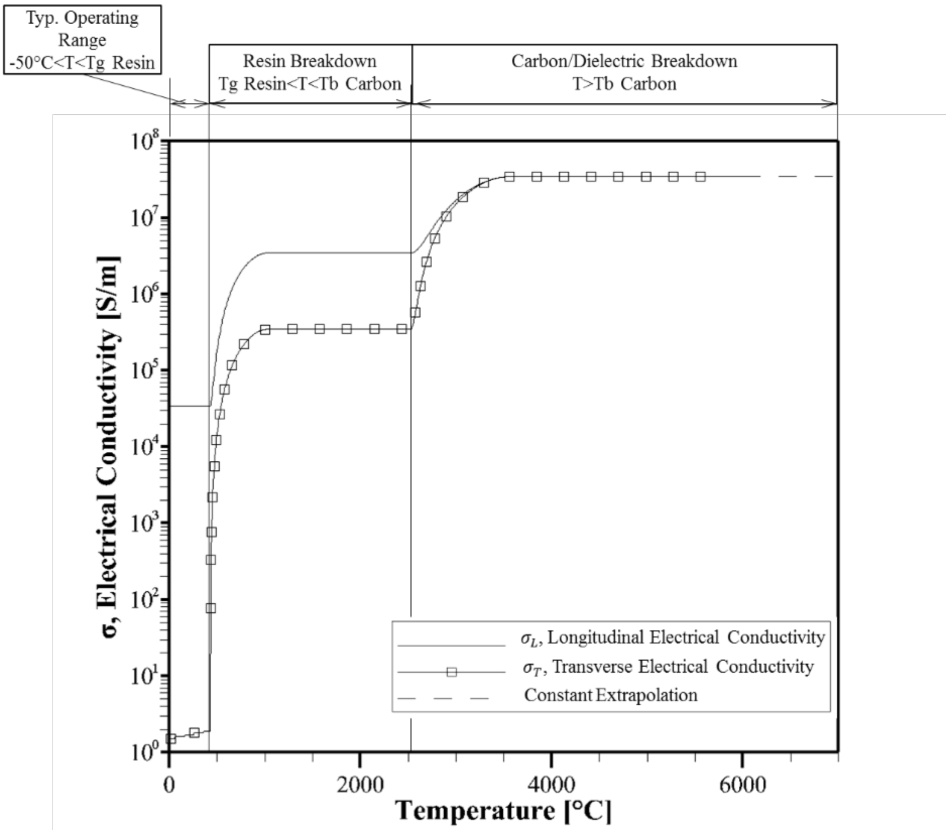

Figure 3: Temperature dependent properties of longitudinal and transverse electrical conductivity.

The associated temperature dependent material properties are presented in Table 1.

Temp. $[°C]$	Specific Heat $C_p\ \left[\frac{J}{kg\cdot K}\right]$	Density $\rho\ \left[\frac{g}{cm^3}\right]$	Longitudinal Electrical Conductivity $\sigma_L\ \left[\frac{S}{m}\right]$	Transverse Electrical Conductivity $\sigma_T\ \left[\frac{S}{m}\right]$	Thru-Thickness Electrical Conductivity $\sigma_{TT}\ \left[\frac{S}{m}\right]$	Longitudinal Thermal Conductivity $\kappa_L\left[\frac{W}{m\cdot K}\right]$	Transverse Thermal Conductivity $\kappa_T\left[\frac{W}{m\cdot K}\right]$
20	1350	1.5	18000	1.218	0.218	35.97	.0115
80	1350	1.5	18000	1.218	1.218	35.97	.0115
300	2100	1.1	3.4E6	3E5	3E5	35.97	2.12
3300	1900	1.1	4E7	4E7	4E7	35.97	2.12
>3300	6000	1.1	4E7	4E7	4E7	0.2	0.2

Table 1: Material properties for joule heating model

The time dependent FEM model was run for 5000μs with 1μs time intervals to solve the Multiphysics equations. Standard settings were used in COMSOL to arrive at a prediction.

3.3 Pyrolysis Modelling

The pyrolysis model uses the pyrolysis kinetic equation which utilizes thermogravimetric analysis (TGA) to develop a degree of pyrolysis or C. The pyrolysis behavior for the sample CFRP was evaluated using a thermogravimetric analyzer. The results are shown in Figure 4.

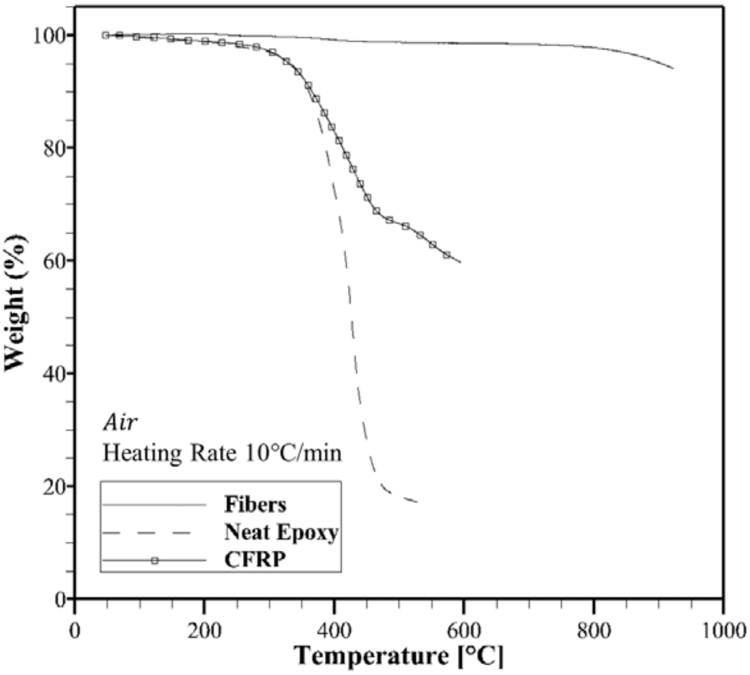

Figure 4: Thermogravimetric analysis results for carbon fiber/epoxy composites with heating rate of 10°C/min in nitrogen gas flow.

The degree of pyrolysis is typically defined as shown in equation (4) and is always between 0 and 1, where 1 is complete pyrolysis and 0 is no pyrolysis.

$$C = \frac{W_0 - W_i}{W_0 - W_t} \tag{4}$$

where W_i is the sample weight, W_0 is the initial weight, and W_t is the terminal weight during pyrolysis.

However, CFRP composites are made of two vastly different materials. Based on the TGA measurements, the carbon fibers and epoxy resin act completely independently. To account for this, the pyrolysis can be divided into an addition of fiber weights and matrix resin weights as follows:

$$C_{TOT} = \frac{W_{0f} - W_{if}}{W_{0f} - W_{tf}} + \frac{W_{0m} - W_{im}}{W_{0m} - W_{tm}} \tag{5}$$

where the additional f and m subscript are for fiber and matrix resin, respectively.

Taking the derivatives gives the rate of pyrolysis and can be expressed as a n-order chemical reaction kinetic equation as seen in Bai [11] but with separated pyrolysis equations for fiber and matrix:

$$\frac{dC_f}{dt} = K_f(T)(1-C)^n \, ; \, \frac{dC_M}{dt} = K_M(T)(1-C)^n \tag{6}$$

where n is the reaction and $K(t)$ is the reaction rate constant which is described by the Arrhenius equation

$$K(T) = Aexp\left(-\frac{E_a}{RT}\right) \tag{7}$$

where A is the pre-exponential factor, E_a is the activation energy, R is the gas constant equal to 8.314 J/mol/K. The activation energy for each the fiber and matrix resin were found to be 40 kJ/mol/K and 150 kJ/mol/K respectively.

The integrated form of the equation is generally expressed as [11]:

$$C_{TOT} = 1 - \left((n-1)Aexp\left(-\frac{Q}{RT}\right)t + 1\right)^{\frac{1}{1-n}} \tag{8}$$

The Scheil superposition principle [4] is commonly used to calculate pyrolysis during lightning strike events. The following equation is the Scheil superposition principle which was outlined in [4]

$$C_i = 1 - \left((n-1)Aexp\left(-\frac{Q}{R(T_{i-1}+T_i)/2}\right)t_i \ + 1\right)^{\frac{1}{1-n}} \text{ where } i = 1,2, \ldots j \tag{9}$$

where T_i is the temperature at time t_i, C_i is the pyrolysis at time t_i. The equation starts with T_0 being the initial temperature.

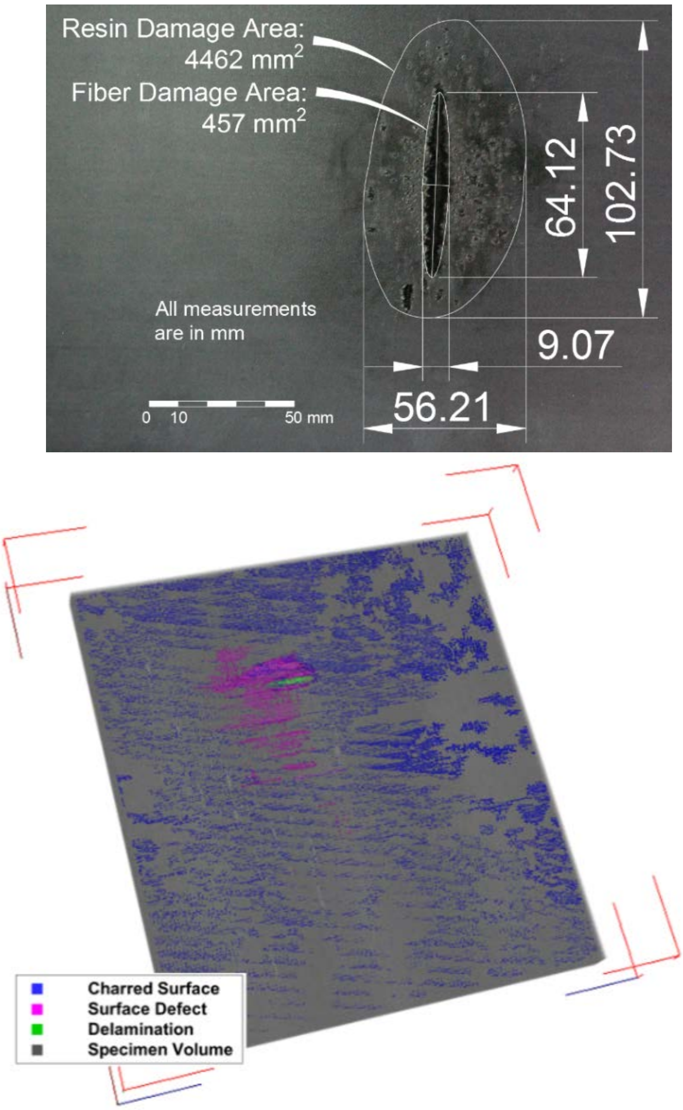

Figure 5: Visual indication (top) and X-ray CT (bottom) analysis of damage on CFRP panel after subjected to simulated lightning strike.

4 RESULTS

4.1 Experimental Validation

The CFRP samples that had been subjected to simulated lightning strikes displayed two distinct areas seen visually; a zone with fiber damage in which the fibers were exposed and a zone with resin damage in which the resin was evaporated. The zones were analyzed with visual and X-ray CT scanning . The visual analysis showed the surface area which which had visual damage. The X-ray CT was used to scan sections which had less dense material (i.e. air) to determine where the damage existed. An example of the analyses are shown in Figure 5.

4.2 Numerical Results

The numerical simulation results displays a similar shape to the experimentally determined damage. The degree of pyrolysis was calculated and the damaged zones for the fibers and the resin are shown in Figure 6, where the red indicates the area of damage picked up by a 1 in degree of pyrolysis.

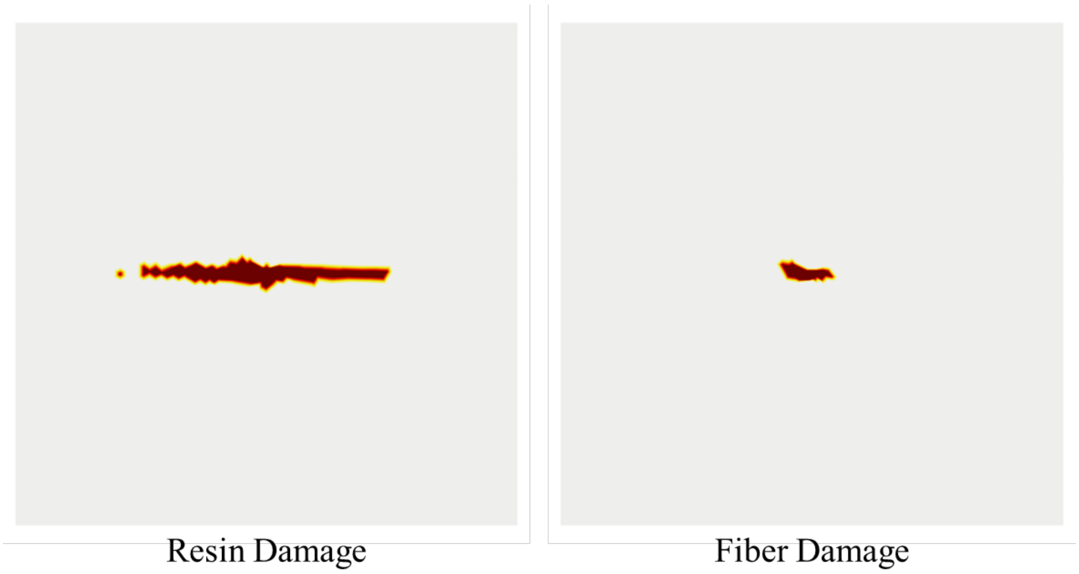

Figure 6: Numerical prediction of fiber damage and resin damage based on degree of pyrolysis.

Overall, there is a good match between the predicted and experimentally observed damage in the tested CFRP samples. The depth of damage predicted by the coupled thermal-electrical model was about 15% less than the depth of damage found from the experimentally tested CFRP plate samples. Also, the predicted volume of damage is less than that in the experiment with difference of about 26%. Moreover, the experimentally investigated CFRP plates displayed significant ply lifts and this behavior cannot be reproduced in the developed model. The developed numerical thermal-electrical model includes significant differences between the transverse and longitudinal electrical conductivities which is the cause of the narrow damage area seen in Figure 6. A complete overview of the experimentally obtained and predicted damage depths and damages resin and fiber volumes are given in Table 2.

Sample	Damage Depth			Resin Damage Volume			Fiber Damage Volume		
	Exp.	Num.	% Error	Exp.	Num.	% Error	Exp.	Num.	% Error
30 kA	0.834	0.741	11.2%	3721	3044	18.2%	381.1	324.3	14.9%
60 kA	0.978	0.836	14.6%	6372	4741	25.6%	817.7	634.5	22.4%

Table 2: Damage depth, resin volume and fiber damage volume comparison of model and numerical simulation results.

5 CONCLUSION

The paper presents the results of comparative study of lightning strike induced damage in CFRP panels. A coupled thermal-electrical FE model implemented in the software tool COMSOL has been presented. The model is based on the assumption that the principal source of damage is Joule heating (or resistive heating), and the model includes damage due to material decomposition by pyrolysis described by the Arrhenius equation. Thus, the predicted damage can be separated into resin and fiber damage to indicate the area of maximum structural loss. Comparison of the experimental observations and the model predictions shows that all significant damage features are predicted by the model, moreover, that the predicted damages in terms of damage depth and damage to both resin and fibers are reasonably accurate.

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