SIMULATION OF LIGTHNING STRIKE ON COMPOSITE LAMINATES : INFLUENCE OF THE MATRIX PYROLYSIS ON THE TEMPERATURE FIELD

C. Huchette*[1], J. Rannou[1], P. Beauchêne[1], L. Chemartin[1]

[1] *Onera – The French Aerospace Lab F-92322 Châtillon, France*
* *Corresponding Author: Cedric.Huchette@onera.fr*

Keywords: Lighting, Pyrolysis, Electrical breakdown, Thermal analysis, Electrical analysis, Multiphysics analysis

Abstract
The aim of this study is to propose a comprehension model of the thermo-electric phenomena taking place and focusing on the resulting damaging pyrolysis. Recent studies at Onera led to the development of a magneto-hydrodynamic model in order to simulate the lightning channel. The output of this model (direct heating and electric current) can used as boundary conditions in the present finite element (FE) simulations of lightning strike on composite material. Pyrolysis is a very important damaging mechanism that affects thermal and electric conductivities as well as mechanical properties. Pyrolysis is driven by (i) dielectric breakdown due to high electric fields and conductivity anisotropy and (ii) volumic severe heating. A simple breakdown law is introduced within non-linear electrostatic and heat transfert FE models. Qualitative results are presented to illustrate the importance of taking into account the pyrolysis in this kind of simulation.

1. Introduction

The use of composite laminates for primary aircraft structures like fuselage implies to take into account the lightning strike hazard. Lightning strike is a threat to both metallic or composite structures, and requires careful considerations from a certification standpoint. The main difference between metallic and composite materials lies in the poor conductivity properties of the latter. However only few public research activity has been devoted to the study of lightning direct effects on the integrity of carbon fibre reinforced polymers (CFRP) structures [1, 2, 3, 4, 5].

Hiranno *et al*. [1] demonstrate by an experimental approach the similarity between the impact damage and the lightning strike damage. The authors also investigate the influence of the impulse waveform and conclude that the fiber damaged area and damage thickness is dominated by the peak current of the lightning strike, while the resin deterioration area and the delamination projection area are dominated by the electrical charge and the action integral of waveform, respectively. Feraboli *et al*. [2] also analyse the influence of the peak current of the lightning strike on the damage area of CFRPs for plane coupon or bolted joined coupons.

Ogasawara *et al*. [3] used a fully coupled electrical and thermal finite element analysis software in order to estimate the matrix damage area due to the impulse waveform. In their analyse they only applied as boundary conditions the experimental waveform of the impulse current. For the thermal behavior of the composite, they identify the pyrolysis behavior using a thermogravimetric analyzer and classical empirical equations for estimating the pyrolysis kinetics of the resin. In order to take into account the dielectric breakdown, the authors assume that the electrical conductivity of the material depend linearly from the temperature of resin degradation (600°C) to the temperature of sublimation of the fiber. This is the reason why a fully coupled electrical and thermal analysis is needed.

Abdelal and Murphy [5] also used a fully coupled electrical and thermal finite element analysis. They analyse the effect of the copper mesh protection system on the degradation of the composite. As Ogasawara *et al*. [3], the authors take into account the evolution of the pyrolysis behavior of the composite laminate but also take into account the thermal behavior of the protection system (melting, evaporation, and ablation). Nevertheless they don't take into account the influence of the electrical breakdown in their simulation. Nevertheless, they adopted a more rigorous modelling approach than Ogasawara *et al*. [3].

The aim of the present work is to demonstrate the influence of the electric breakdown on the estimation of the thermal behavior of composite laminate subjected to lightning strike. The first section deals with the physics involved in the lightning strike on composite structure, the second part describes the numerical model adopted and the electrical breakdown models proposed. The third section focuses on the first results obtained with this first numerical approach.

2. The multiphysics problem

The work of Chemartin *al* [4] permits to strengthen how the loading due to a lightning strike is complex. As shown on Figure 1, the structure is submitted to:

- strong electric currents resulting in resistive heating due to Joule effect ;
- severe direct heating due to the plasma channel ;
- hydrodynamic pressure also due to the plasma.

This figure illustrated the different physics needed to be taken into account in order to simulate the damage due to lightning strike on composite laminated structures. Structural dynamics is not treated in this early work. On the opposite to metallic material due to the poor electrical conductivity of the matrix, the Joule effect has a major role in the evolution of the temperature inside the material. This is the reason why the estimation of the current density field is essential. Moreover, the anisotropic electric behavior of the composite ply (the electrical conductivity of the fiber is 10^3 times higher that the resin one) implies a high gradient of electric potential in the thickness of the composite laminate which leads to electrical breakdown. This electrical breakdown induces an instantaneous pyrolysis of the matrix but improves not only the electrical conductivity but also thermal one of the material due to the char formed.

As mentioned previously, the influence of the heating due to the plasma channel (more than 30000 K in the plasma channel) and the Joule effect need to be taken into account in a transient thermal problem in order to estimate the pyrolysis of the material and the damage inside the composite material. In this preliminary work, we only focus on the effect of the electrical breakdown on the thermal behavior of the material. Nevertheless and as mentioned previously the physical material parameters (electric, thermal or mechanical) depend on the temperature of the material and imply to have a coupling between these different physics. Hence a partitioned coupling algorithm is set up to account for *(i)* the influence of Joule effect and breakdown on the heat transfer problem and *(ii)* temperature and pyrolysis on the electrostatic model. Direct heating and electric current due to the plasma channel are taken as boundary conditions from the magneto-hydrodynamic model developed in [4].

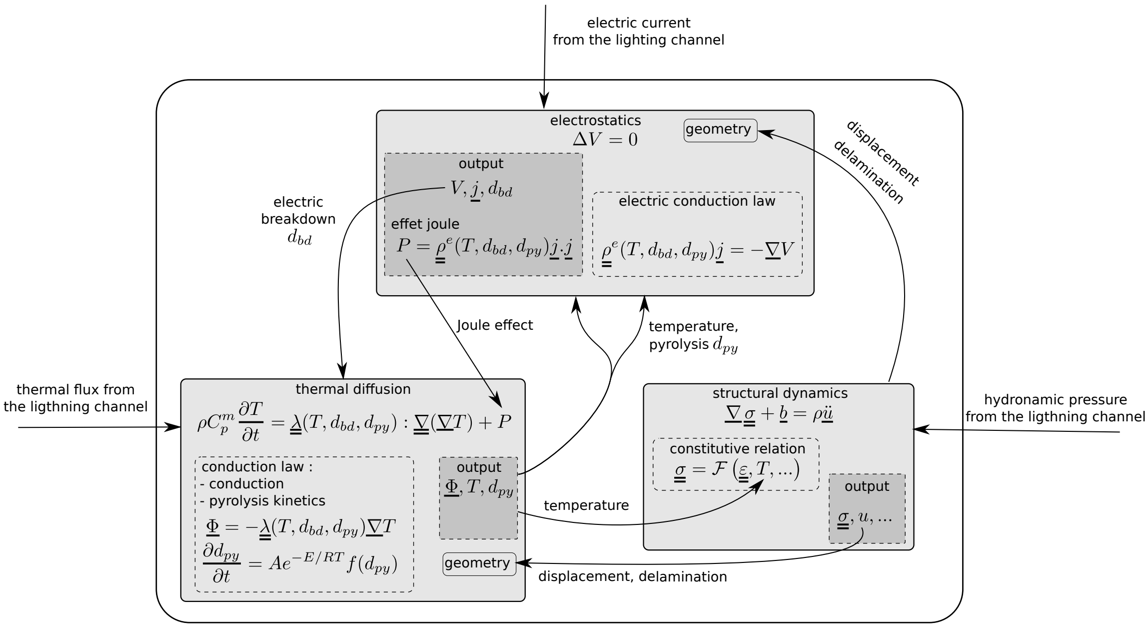

Figure 1. Scheme of the physics involved during a lightning strike within the material.

3. The numerical model

3.1. The electrical model

An electrostatic conduction model is used to determine the current distribution within the laminate. The conductivity law writes :

$$\underline{j} = -\underline{\underline{\sigma}}\nabla U \tag{1}$$

where $\underline{j}$ and U are the current density vector and the electric potential respectively. $\underline{\underline{\sigma}}$ is the electrical conductivity second order tensor. For a sane material (exponent o), the matrix form in the material frame of the anisotropic conductivity writes :

$$\underline{\underline{\sigma}}^o = \begin{pmatrix} \sigma_f^o & 0 & 0 \\ 0 & \sigma_m^o & 0 \\ 0 & 0 & \sigma_m^o \end{pmatrix} \tag{2}$$

where σ_f and σ_m are the electrical conductivities in the fiber and the matrix directions respectively. As can be seen in Figure 2.a, fiber and transverse conductivities differ in three orders of magnitude, the current thus tends to flow in the fiber direction within the top ply where it is injected. This generates electric fields that have a high component in the out-of-plane direction thus leading to electric breakdown.

The following criterion is used to detect breakdown :

$$\|\underline{\nabla} U\| > E_m^{bd} \tag{3}$$

where E_m^{bd} is a material parameter (see table 1). Since this phenomenom is sudden, it is treated in an explicit way : when criterion (3) is met at the end of a time increment, breakdown is only taken into account in the next one by changing conductivity following :

$$\underline{\underline{\sigma}} = \underline{\underline{\sigma}}^o + I_{bd}(\underline{\underline{\sigma}}^{py} - \underline{\underline{\sigma}}^o) \tag{4}$$

I_{bd} is an internal binary parameter which equals 0 for sane material and 1 for breakdowned material which is considered to pyrolyzed. σ^{py} is the conductivity of the pyrolyzed material (parameters σ_f^{py} and σ_m^{py} in table 1).

parameter	value
$\sigma^o_{e_f}$	*c.f.* Figure 2
$\sigma^o_{e_m}$	*c.f.* Figure 2
$\sigma^{py}_{e_f}$	$1.6 \times 10^{10} S.m^{-1}$
$\sigma^{py}_{e_m}$	$1.6 \times 10^{10} S.m^{-1}$
E^{bd}_m	$19.6 \times 10^6 V.m^{-1}$

Table 1. Electrical material parameters for a carbon/epoxy laminate[6].

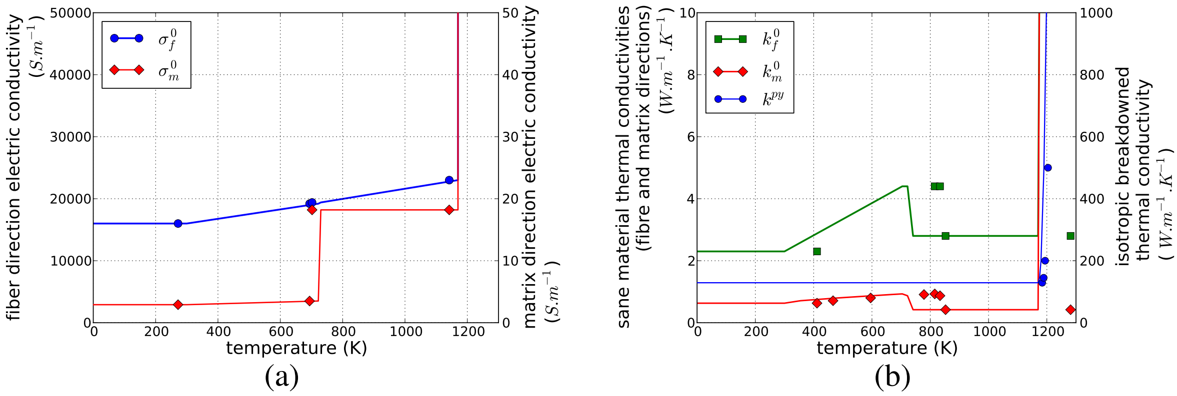

Figure 2. Electric (a) and thermal (b) conductivities dependence on temperature for a carbon/epoxy laminate [6].

3.2. The thermal model

A simple thermal anisotropic conduction law is used to model the heat transfer. Two conduction coefficients k_f^o and k_m^o are used for the sane material in the fiber and the matrix directions respectively (Figure 2.b). The material that has been pyrolyzed due to electric breakdown has an isotropic conductivity k^{py} (Figure 2.b). The effective thermal conductivity thus writes :

$$\underline{\underline{k}} = \underline{\underline{k}}^o + I_{bd}(\underline{\underline{k}}^{py} - \underline{\underline{k}}^o) \tag{5}$$

Thermally activated pyrolysis is currently not taken into account and thermal conductivities are artificially increased at 1170K to represent thermal degradation (Figure 2.b) An improvement would consist in taking into account the thermal pyrolysis through an autocatalytic kinetics like in [3, 5].

3.3. Thermo-electric partitioned coupling

Electrostatic and transient thermal models are solved with different instances of the finite element solver Z-set [7]. Both models need to be coupled since breakdown and temperature have an influence on electric and thermal conductivities. Moreover, one of the major source of heating is the Joule effect whose volume specific power is expressed as :

$$P_{Joule} = -\underline{j}.\underline{\nabla}U \tag{6}$$

The partitioned coupling algorithm aims at linking the two instances of Z-set and is illustrated in Figure 3 :

1. a first electrostatic increment is performed. I_{bd} and Joule heating volume specific power (P_{Joule}) fields are transferred to the heat transfer model;
2. the temperature field is transferred to the electrostatics computation.

Electrostatic increments are still solved in an explicit way thus resulting in successive resolutions of linear problems. However thermal analysis is highly non-linear and may require subcycling with adaptive time steps Δt_h.

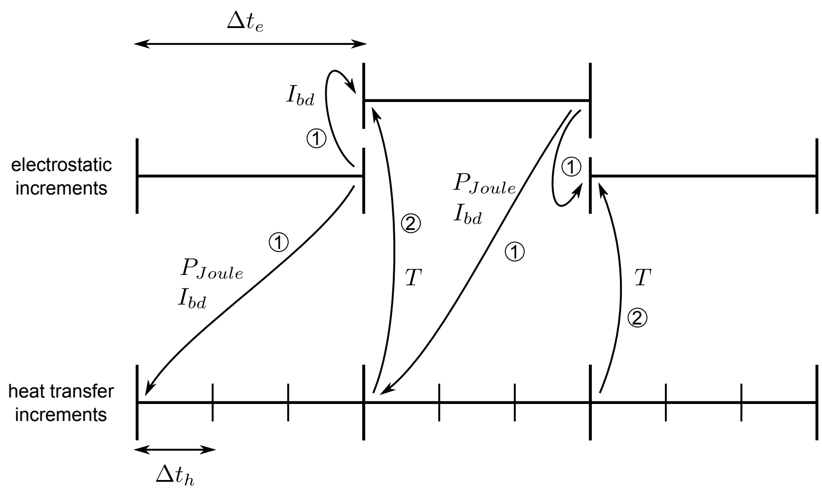

Figure 3. Weak coupling scheme of electrostatics and thermal models.

4. Application

A 8 plies laminated plate is considered (Figure 5). In addition to boundary conditions on the plate sides, electric current density (j_n) and heat flux (q_n) are imposed on a circular surface of variable radius $R_c(t)$ on the top of the plate. The following expressions are approximations of the output of the magneto-hydrodynamic model [4] :

$$\begin{aligned} j_n(t) &= \frac{218810\left(e^{-11354t} - e^{-647265t}\right)}{\pi R_c^2(t)} && \text{in } A.m^{-2} \\ q_n(t) &= 10\, j_n && \text{in } J.m^{-2} \\ R_c(t) &= 9\sqrt{t} && \text{in } m \end{aligned} \tag{7}$$

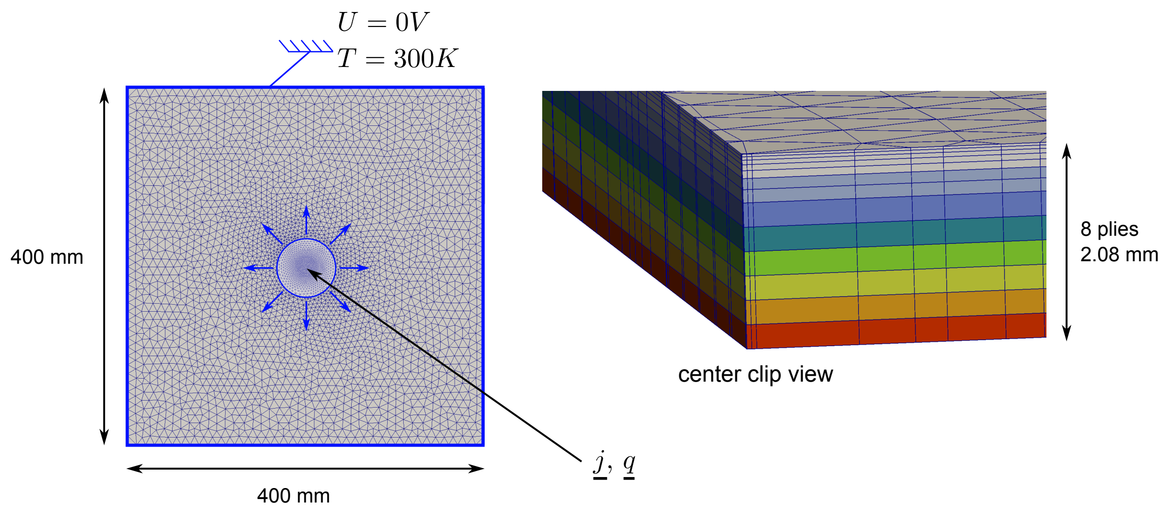

Figure 4. Geometry, boundary conditions and mesh of the model.

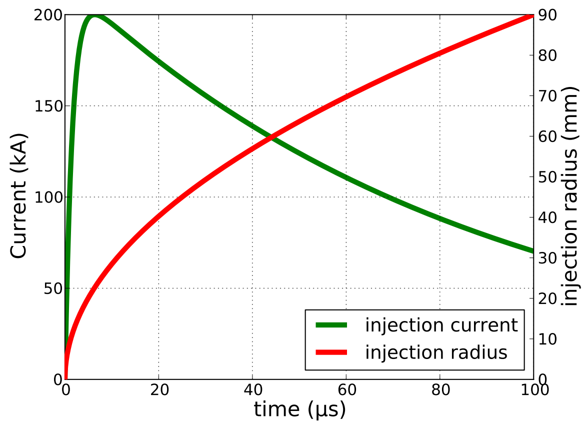

Figure 5. Time evolution of the injected current and the injection radius.

Electric potential and temperature fields are shown at $10\mu s$ in Figure 6 just after the peak current injection. It can be seen that temperature remains very high in the top ply but since breakdown is taken into account, current and heat can flow in the thickness direction thus leading to high temperature "pockets" in the bottom plies. Tacking into account the thermal degradation as mentioned in section 3.2 would improve the physical representation of this kind of model.

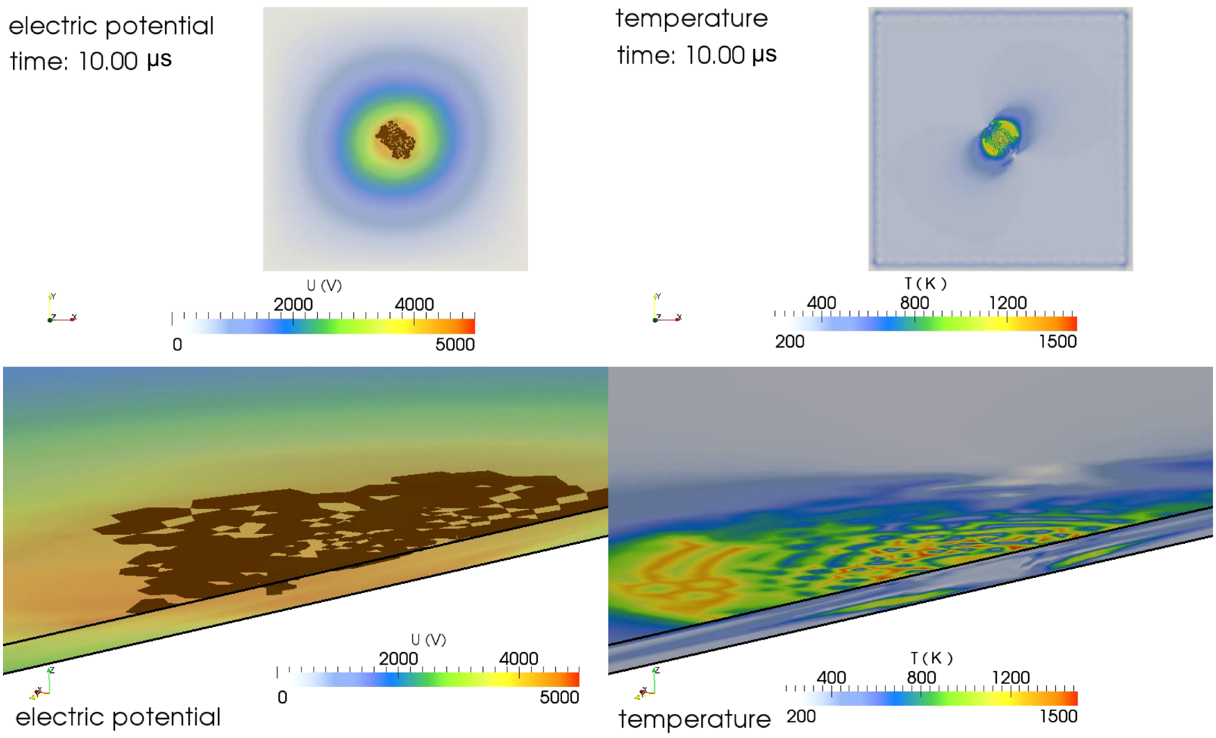

Figure 6. Electric potential (left) and temperature (right) fields at 10μs. Pyrolyzed material due to breakdown is represented in black (left).

5. Concluding remarks

In this work, a specific care has been focused on the estimation of a realistic thermal behavior of a composite structure subjected to lightning strike impact. This is a reason why we developed an efficient numerical strategy that permits to take into account all the different physics involved in this multiphysics problem, *i.e.* the electrical and thermal problem. The numerical strategy is based on a partitioned coupling problem that considered in a first hand an electrostatic problem and in a other hand a transient thermal problem.

The electrostatic problem permits to compute the current density in the material and takes into account the apparition of instantaneous pyrolysis of the matrix due to electrical breakdown. A very simple criterion is used in order to modelling this matrix damage that implies a very sudden improvement of the electrical and thermal conductivities. Independent from the breakdown phenomenon, the electrical conductivity is dependent of the temperature.

In the transient thermal problem, Joule effect field and the state of the material estimated by the electrostatic problem are taken into account in order to estimate the temperature inside the material. Thermally activated pyrolysis is taken into only by an artificial increased of the thermal conductivities. Further works will take into account an autocatalytic reaction kinetics in order to improve the estimation of the temperature field but also to have a description of the damage state of the matrix and of the fiber in in the composite material. Thanks to the electrical breakdown phenomenon, the electrical density and the heat flux can flow in the thickness of the composite, limits the temperature gradient in the composite and implies hot spot in the opposite face of the lighting strike.

This work is a first step in order the simulate the damage effect of the lightning strike on composite laminate and strengthens the influence of the breakdown in the analysis. Further works will take into account the mechanical loading due to the lightning and permit to estimate the damage due to this complex loading, the damage tolerance of the structure and to propose numerical design tool for composite laminate.

References

[1] Yoshiyasu Hirano, Singo Katsumata, Yutaka Iwahori, Hirooshi Hatta, and Akira Todoroki. Fracture behavior of CFRP laminate under artificial lightning strike. In *ECCM13*, page , Sweden, Stockholm, 2008.

[2] Paolo Feraboli and Mark Miller. Damage resistance and tolerance of carbon/epoxy composite coupons subjected to simulated lightning strike. *Composites Part A: Applied Science and Manufacturing*, 40(6-7):954967, July 2009.

[3] Toshio Ogasawara, Yoshiyasu Hirano, and Akinori Yoshimura. Coupled thermal–electrical analysis for carbon fiber/epoxy composites exposed to simulated lightning current. *Composites Part A: Applied Science and Manufacturing*, 41(8):973–981, 2010.

[4] L Chemartin, P Lalande, B Peyrou, A Chazottes, PQ Elias, C Delalondre, BG Cheron, and F Lago. Direct effects of lightning on aircraft structure: analysis of the thermal, electrical and mechanical constraints. *J. Aeros. Lab*, 5, 2012.

[5] G. Abdelal and A. Murphy. Nonlinear numerical modelling of lightning strike effect on composite panels with temperature dependent material properties. *Composite Structures*, 109:268–278, March 2014.

[6] Frédéric Lago. *Modélisation de l'interaction entre un arc électrique et une surface : application au foudroiement d'un aéronef.* PhD thesis, Université Paul Sabatier, 2004.

[7] Z-set, material and structure analysis suite.