Evaluation of the Lightning Strikes on Carbon Fibers Panels for Aircraft Structural Parts

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Abstract: Airliners are often subjected to dangerous atmospheric and weather hazards among which lightning strikes represent a threat for flight safety. Lightning strikes are essentially a random transient high-voltage and high-current phenomenon which may occur in order to restore charge equilibrium by means of an electrical discharge. Recently, the use of Carbon Fibers Reinforced Composites as structural parts in aircrafts as an alternative to traditional metallic materials, such aluminum, steel, titanium and derived alloys, has been growing, driven by the requirements in terms of weight reduction, pollution impact, reliability, passenger comfort, etc. Unfortunately, most composites, due to the limited electrical conductivity are not able to dissipate lightning currents as the traditional metals. Therefore, in new generation aircraft fuselages or wings, such ability must be reached by improving the overall conductivity of the composites. Experimental studies on different test samples may be carried out, but such an approach is costly and time consuming. Therefore numerical studies can assist aircraft designer in evaluating the direct and indirect effects due to lightning strikes In this paper the multiphysics features of COMSOL ® are used to simulate the physical processes involved in lightning strikes hitting a panel of carbon fiber reinfroced composites. The considered structure is made with 7 plies of CFRC (overall thickness 150µm) impregnated with epoxy resin (thickness layer of about 55 µm) loaded with 0.5% (by weigth) MWCNTs. The simulation results achieved with CRFCs are compared with those obtained for aluminum sheets of similar thickness.

Keywords: lightning effect, CFRC, nanocomposite.

1. Introduction

Lightning strikes represent a serious concern for flight safety of airliners [1]. The strong electric fields present in the atmosphere lead to the electrical discharges which may restore the charge equilibrium. In an aircraft made with traditional materials the high conductivity of the fuselage and wings provides a highly conductive path to the lightning currents. However, in some cases direct and indirect effects may be observed consisting in small holes on the fuselage and damages on the radome and antennas [2] due. In recent years many academic and industrial research efforts have been focused on new materials for the replacement of the traditionally employed aluminum, steel and titanium, in order to achieve lighter and hence more energy efficient aircrafts. Such innovative materials have to withstand significant mechanical stresses, strong humidity, large temperature variations and very high lightning strike currents [3-5]. In particular, in order to reduce the threat of lightning strike damage, several requirements in terms of electrical, chimical and mechanical properties, must be guaranteed by such materials.

Recently, the application of polymer composites for the realization of aeronautic structural parts has been growing, driven by the increase in performance and most of all by weight reduction issue [6]. In particular, Carbon Fibre Reinforced Composites (CFRCs) based on epoxy resins are the object of growing interest since they provide excellent mechanical properties. However, the components manufactured with CFRCs must be loaded with metal wires or Multi Walled Carbon NanoTube for ensuring the ability to withstand the very high currents associated to the ligthning strikes and avoid the risk that a puncture of the structure could lead to a catastrophic failure of the aircraft.

In fact, in lightning strikes large amount of energy are fastly released, inducing the ionized channel to evolve with high speed. As a result, the shockwave on the impact surface converts its kinetic energy into a pressure rise and at the same time, Joule heating takes places. These two combined effects require that the new CFRCs materials were characterized by excellent mechanical strenght in order to withstand the pressure rise and high electrical and thermal conductivity in order to avoid that the temperature rise may exceed the glass transition temperature leading to the composite failure [7,8]. In the aviation industry, the electrical conductivity equivalent of 10 S/m for the composite is taken as the target conductivity able to dissipate the lightning currents without the use of metal fibers or conductive metallic screens that are harmful in terms of the total weight [8-9]. Several research efforts have been undertaken to approach such a goal by improving the overall conductivity of the CFRCs through the production of nanofilled impregnation resin with enhanced properties. In particular, in the EU IASS project [10] very high conductivity values have been obtained for CFRCs panels by loading a typical aeronautic epoxy resin with different types of carbon nanostructures, i.e. Multi Wall Carbon Nanotubes (MWCNTs) or Carbon NanoFibers (CNFs)][11-14].

In the pursue of more reliable and efficient aircrafts employing larger amounts of CFRCs, numerical simulations can assist the aircraft designers to devise structural parts potentially subject to lightning strikes. In fact, by a proper choice of the considered model, the very costly and time consuming experimental tests can be sensibly limited. Therefore, this work is aimed at investigating numerically by using the multiphysics features of COMSOL ® the physical processes involved in lightning strikes on an aircraft panel manufactured with 7 plies (thickness of about 150µm) of carbon fiber impregnated with epoxy resin (thickness layer of about 55 µm) loaded with MWCNTs (0.5 wt%).

Numerical tests are presented in which equivalent high intensity currents hit the composite structure model. The results obtained for CRFCs are compared to those obtained for aluminum sheets traditionally adopted in aircraft structural parts.

2. Use of COMSOL Multiphysics

Simulated lightning strikes tests are carried out on an equivalent multilayer isotropic panel representative of the CRFC modelled with COMSOL Multiphysics (R). The main assumptions in the considered model are that the influence of the temperature on the electrical conductivity is neglected while the local temperature rise in a material due to Joule heat generation depends on electrical current. Therefore, a combined model is adopted in order to analyse the coupling between thermal and electrical fields whose governing equation is: $Q_r = E \cdot J$ where Q_r is the resistive heating, E is the electric field strenght and J is the current density.

The electrical problem is described by charge conservation and the Electro Quasi Static formulation of the Maxwell equations. An irrotational electric field is considered since the characteristic wavelength of the electromagnetic field is much larger than the geometrical dimensions of the system under analysis and the energy is mainly associated to the electric field E [15]. The thermal field is described by the energy balance relation. In particular:

$$\frac{\partial \rho}{\partial t} + \nabla J = 0; \quad J = \sigma E + J_e; \qquad (1)$$
$$E = -\nabla V$$

where ρ is the charge density, □ is the electrical conductivity of the panel, Je is the externally generated current density associated to the ligthning strike and V is the electric potential.

For the heat transfer in solids the classical heat diffusion equation is adopted [16]:

$$rC_p \frac{\partial T}{\partial t} - \nabla \cdot (k \nabla T) = Q \qquad (2)$$

where r is the material density, T is the temperature, C_p is the heat capacity, k is the thermal conductivity and Q the heat source.

Of course, for steady-state problems, the charge density ρ and the temperature T do not change with time and the related terms disappear in the above equations. Finally, the surface-to-ambient radiation boundary conditions are take into account, in terms of surface-to ambient radiation flux (i.e. q) in agreement with the following relation:

$$q = \varepsilon \sigma_{S-B} (T_{amb}^4 - T^4) \qquad (3)$$

where ε is the surface emissivity, σ_{S-B} is the Stefan-Boltzmann constant and T_{amb} is the ambient temperature.

Simulation predictions of the lightning strike effect on composite materials are compared with the results carried out for aluminum sheet of equal thickness, representative of actual aircraft structural part. In the case of the CRFCs panels a thin coating obtained by means of aluminum paint representative of an aircraft skin is considered on the surface to form a low resistivity film without affecting the overall weight [7]. Figure 1 shows a schematic set up of the simulated structures, while the main thermal/electrical properties of the employed materials are summarized in Table I.

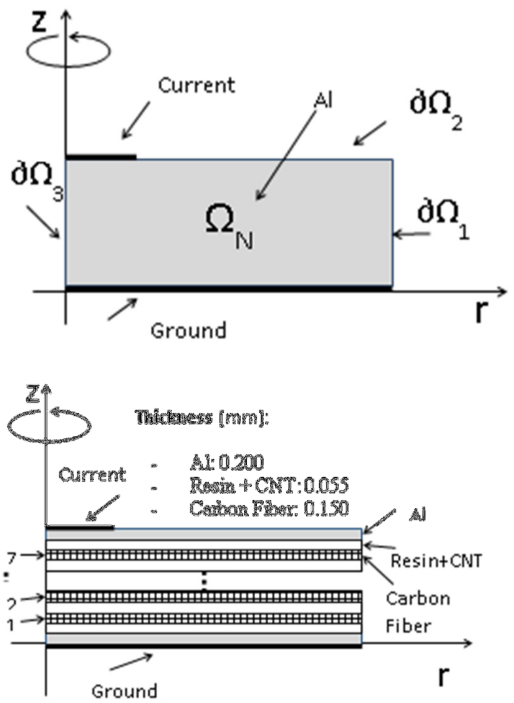

Figure 1. Schematic set up of the simulated panels: aluminium structural part (up) and CFRC laminate composed by 7 plies of carbon fiber cloths impregnated with resin (down).

Table 1: Material properties of aluminium and CFRC/elements

	Aluminium	Resin + CNTs
Electrical conductivity [S/m]	$20\times10^{+6}$	10
Heat capacity [J/kg•K]	900	1500
Thermal conductivity [W/m•K]	238	0.26
Material density [kg/m^3]	2700	1580

For the simulations considered herein, a current generator able to inject a rectangular time-dependent current waveform with an average amplitude of 100kA is adopted to simulate the impulse current of ideal lightning strike. The diameter of lightning bolt ranges from 1 to 10 mm and it may affect the predicted results [9]. In the present study an average value of 5mm is adopted while its influence will be investigated in a future paper.

4. Result

In Figures 2 the simulated temperature distribution in 3D and 2D for aluminium panel and in Figure 3 the simulated temperature distribution in 3D and 2D for CFRCs characterized by an electrical conductivity of 10 S/m are reported.

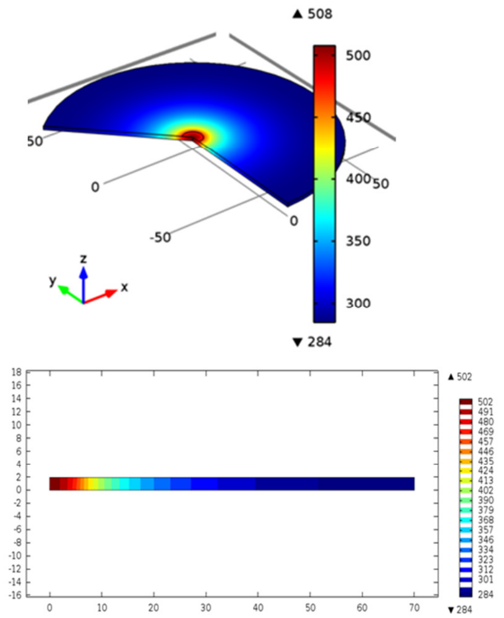

Figure 2 Simulated temperature distribution in 3D and 2D view for aluminum panel

For the aluminium panel a temperature of about 540K is observed in the most stressed area, it remains below the melting temperature of the material thus ensuring and adequate tolerance damage. On the contrary, a much higher (about 10 times) temperature is reached by the CFRC panel.

Therefore, higher conductivity is required in order to avoid overheating and to ensure structural thermal resistance to confine the damage.

In particular, by observing the results in 3D-view, it is interesting to note as for the aluminum panel the thermal damage areas are mainly localized in close vicinity of the striking point of the lightning since the low resistivity of the materials reduces the surface current density which in turn limits the Joule heating in the surrounding areas.

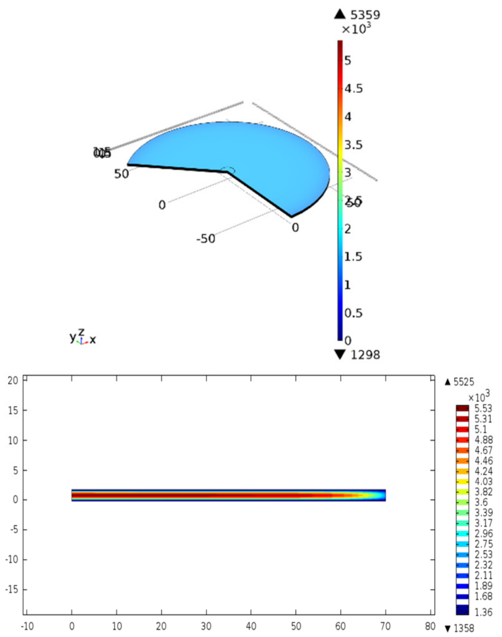

Figure 3 Simulated temperature distribution in 3D and 2D view CFRCs characterized by an electrical conductivity of 10 S/m

Instead in the case of the CFRCs panels (see Figure 3) almost the total simulated area is interested by a quasi-uniform heating. This is also visible from the 2D-view which also allows to understand the thermal diffusion in both the radial direction and through the thickness of the material, as previously discussed. The maximum value for the temperature is reached in central parts of the structures due to the lack in heat dissipation with the surrounding environment.

Moreover, some visible sections of constant temperature correspond to the carbon fiber layers that, due their high conductivity, hinder the temperature increase in the underlying layers

5. Conclusions

A models of carbon fibre reinforced composites in a multi-physics environment carried out in order to assist the aircraft design when subjected to lightning strikes. The effect of lightning strikes has been simulated by using a coupled thermal-electrical analysis. The results have been compared with those obtained for aluminum sheets with equal thickness. A very high temperature rise is observed up to the sublimation temperature for the composites This means that Joule heating significantly affects the thermal behaviour of CFRCs due to their low conductivity compared to that of metals and thus compromising the structural integrity needed for ensure flight safety. Further simulations on CFRCs with different thickness and numbers of carbon fiber plies and impregnated with an electrically improved resin are currently in progress. The results will be presented in a future work.

6. References

[1]Larsson A The interaction between a lightning flash and an aircraft in flight. C.R. Phys., **3**, 1423-1444 (2002).

[2]Petrov N I, Haddad A, Griffiths H, Waters R T Lightning strikes to aircraft radome: electric field shielding simulation, 17th International Conference on Gas Discharges and Their Applications, 513-516, ISBN: 978-0-9558052-0-2 (2008).

[3]Huda Z, Edi P. Materials selection in design of structures and engines of supersonic aircrafts: A review. Mater. Des., 46, 552–560.

[4]Lopes J C O (2008). Materials selection for aeronautical structural application. Cienc. Tecnol. Mater., **20 (3/4)**, 78–82 (2013)

[5]Williams J C, Starke A Jr. Progress in structural materials for aerospace systems, Acta Mater., **51**, 5775–5799 (2003)

[6]Guadagno L, Raimondo M, Vittoria V, Vertuccio L, Naddeo C, Russo S, De Vivo B, Lamberti P, Spinelli G, Tucci V. Development of epoxy mixtures for application in aeronautics and aerospace, RSC Adv., **4**, 15474–15488 (2014)

[7]Kawakami H, Feraboli P. Lighting strike damage resistance and tolerance of scarf-repaired mesh-protected carbon fiber composites. Compos. Part A-Appl. S., **42**,1247-1262 (2011)

[8]Feraboli P, Kawakami H. Damage of carbon/epoxy composite plates subjected to mechanical impact and simulated lightning. J. Aircraft, **74**, 999-1012 (2010)

[9]B. De Vivo, L. Guadagno, P. Lamberti, A. Sorrentino, V, Tucci, L. Vertuccio, V. Vittoria: “Comparison of the Physical Properties of Epoxy-Based Composites Filled with Different Types of Carbon Nanotubes for Aeronautic Applications”, Advances in Polymer Technology, **31**, 205–218 (2012)
[10] http://www.iass-project.eu
[11] L. Guadagno, U. Vietri, M. Raimondo, L. Vertuccio, G. Barra, B. De Vivo, P. Lamberti, G. Spinelli, V. Tucci, F. De Nicola, R. Volponi, S. Russo, “Correlation between electrical conductivity and manufacturing processes of nanofilled carbon fiber reinforced composites”, Composites Part B, **80**, pp. 7-14 (2015)
[12] L. Guadagno, M. Raimondo, L. Vertuccio, U. Vietri, G. Barra, B. De Vivo, P. Lamberti, G. Spinelli, V. Tucci, R. Volponi, G. Cosentino, F. De Nicola “Effective formulation and processing of nanofilled carbon fiber reinforced composites”, RSC Adv., **5**, pp. 6033-6042 (2015)
[13] L. Guadagno, M. Raimondo, L. Vertuccio, M. Mauro, G. Guerra, K. Lafdi, B. De Vivo, P. Lamberti, G. Spinelli, V. Tucci, “Optimization of graphene-based materials outperforming host matrices”, RSC Adv., **5**, 36969–36978 (2015)
[14] L. Guadagno, M. Raimondo, V. Vittoria, L. Vertuccio, K. Lafdi, B. De Vivo, P. Lamberti, G. Spinelli and V. Tucci, “The role of carbon nanofiber defects on the electrical and mechanical properties of CNF-based resins”, Nanotechnology, **24**, 305704 (2013)
[15] C. Petrarca, V. Tucci, M. Vitelli: Temperature distribution on a outdoor insulator subjected to different pollution levels, IEEE Trans. on Dielectrics and Electrical Insulation, **7**, 416-423 (2000)
[16] Abdelal G, Murphy A Non linear numerical modelling of lightning strike effect on composite panels with temperature dependent material properties. Compos. Struct., **109**, 268-278 (2014).

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