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Nonlinear numerical modelling of lightning strike effect on composite panels with temperature dependent material properties

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ABSTRACT

This paper presents a physics based modelling procedure to predict the thermal damage of composite material when struck by lightning. The procedure uses the Finite Element Method with non-linear material models to represent the extreme thermal material behaviour of the composite material (carbon/epoxy) and an embedded copper mesh protection system. Simulation predictions are compared against published experimental data, illustrating the potential accuracy and computational cost of virtual lightning strike tests and the requirement for temperature dependent material modelling. The modelling procedure is then used to examine and explain a number of practical solutions to minimize thermal material damage.

1. Introduction

Damage from lightning strike is a major challenge when using continuous Fibre-Reinforced Plastic (FRP) in the construction of aircraft. Lightning strike damage is due to high orthotropic electric resistivity of the FRP material, which leads to high thermal loads that cause decomposition of the plastic matrix and delamination of the plies. Experimental testing of lightning strike on aircraft materials and structures is expensive. Moreover, the large number of design parameters involved in FRP material, plus the design variables associated with an embedded lightning strike protection systems result in a vast design space, in which purely empirical design and development is very time consuming. Thus, protection systems are typically restricted to the most feasible design of a few considered, or are limited to a known, previously used design space. Unfortunately this can result in non-optimum designs being selected which can in turn cause problems at a later design stage.

The aim of this paper is to formulate a coupled thermal-electrical Finite Element analysis procedure to enable the investigation of the design variables that control lightning strike damage in epoxy/graphite FRP material. The major contribution of this is the formulation and verification of temperature dependent material properties, a key attribute not considered within previous literature. The proposed modelling procedure is applied to model a test specimen plate and the results verified against published experimental data, illustrating the potential accuracy and computational cost of virtual lightning strike tests and the requirement for temperature dependent material modelling. The modelling procedure is then applied to a number of practical lightning strike protection systems and the simulation results used to further understand, and for the first time to quantify, the physical behaviour which minimizes the level of thermal material damage.

Lightning strike is made of plasma at 30,000 K degrees temperature, and electrons that progress at speeds of higher than 5000 m/s, to conduct 39.55×10^3 Joule/Ohm of energy (40 kA strike) within micro-seconds. Lightning strikes have significant effects on structures; resistive heating, magnetic forces, and overpressure. Previous researchers investigated these direct effects, assuming for example that damage in composite laminates is due to overpressure only without considering the effect of resistive heating [1–3]. Others investigated the effect due to resistive heating [4] as the main source of damage to the composite material, but applied highly idealized electric loading in numerical simulations, and used temperature independent material properties. Yet their general approach is unique, using coupled electrical/thermal FE analysis. This work built on this approach, introducing temperature dependent material properties, char material properties to simulate material status after decomposition, gas material properties to simulate material ablation status, and modelling the complex physics of protection systems using UMATH material subroutine (available in ABAQUS). Thus this paper is the first to capture many aspects of the Multiphysics that interact within lightning strikes. Simulation of the protection system included modelling melting, evaporation, and ablation, while interacting with the composite panel through temperature dependent thermal conductance properties.

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2. Background

2.1. Lightning strike physics

The physical consequences of a lightning strike on an aircraft can be summarized as;

- Resistive heating at the lightning arc contact point which decomposes the FRP resin.
- An overpressure due to the explosion of the lightning channel, which leads to the propagation of a strong shock wave in a radial direction away from the arc. The explosion is due to the fast increase in the arc temperature in the conducting channel, up to 30,000 K within a time interval of a few microseconds.
- A magnetic force due to fast conduction in any metallic component, including for example a metallic element used as part of a lightning protection system.

In order to minimize the damage of a lightning strike on current FRP aircraft components a metallic mesh located at the surface of the component or special types of conducting paints are used to shield and protect the underlying load bearing FRP material. If we consider for example a copper mesh based protection system, the copper will have a melting temperature of the order of 1083 C (T_m), a boiling temperature of 2800 C (T_b) and a critical temperature of 8000 C (T_c). Additionally the vaporization temperature of the copper will be a function of the local pressure P and thus given the presence of the shock wave it is possible that vaporization could occur below the boiling temperature. Consequently when a copper mesh embedded at the surface of a FRP component is subjected to a high energy electric load complicated coupled physical processes ensue. The copper surface heats up, melts, vaporizes and once the surface temperature reaches approximately 90% of the critical temperature explosive boiling occurs, which results in ejection of a mixture of vapour and liquid droplets. Considering the behaviour of typical thermosetting plastics, when subjected to increasing temperature the material will decompose (between 300 and 500 C). Above 500 the material will be a char, and ablation will begin above 3000 C. Between and throughout these phases the material's thermal and electrical properties will change with temperature. Finally, carbon fibre tows subjected to increasing temperature will also char and ultimately ablate (3316 °C); again thermal and electrical properties will change with phase and temperature.

2.2. Preceding literature

Haigh Taylor [1] focused on the mechanical effects of lightning strike on test panels, using mechanical and optical instruments to measure the force imparted by an electric arc on a panel over time. The extracted force measurements were then compared to equivalent tests in which only mechanical impulse loading was applied. Gineste et al. [2] followed the work done by Haigh Taylor [1] and used visual interferometric optical methods to measure deflections at multiple locations over time. A model was developed to extract from the measured deflection the mechanical impulse induced by the strike. Lepetit et al. [3] presented further progress in the same research direction, considering the impact of explosive boiling of protection system paint and its influence on the induced FRP damage.

The methodologies of Haigh Taylor, Gineste and Lepetit [1–3] ignore the electric properties of the material and the coupling between the electromagnetic and the thermal behaviours. This is significant as deformation and high thermal strains will result at the arc contact point due to the impact of the plasma of electrons at extreme temperature (>30,000 °K), and joule heating due to the electric resistivity of the material. The preceding models also ignored the decomposition of the epoxy material due to high thermal load and its effect on orthotropic electric/thermal conductivity of the material. Thus only magnetic and overpressure forces due to the electric arc strike are included and the influence of a major cause of damage, plasma and resistive heating has been neglected. Lepetit et al. [3] captures the effect of explosive boiling experimentally, but the applied numerical modelling, based on explicit dynamic analysis, again ignores the impact of coupling between the electromagnetic and the thermal behaviours.

Ogasawara et al. [4], using coupled electromagnetic/thermal Finite Element (FE) simulations modelled lightning strikes numerically, including coupling between electromagnetic and thermal behaviour. The simulations considered specimens without lightning protection systems (i.e. a protective mesh or paint) and the associated complexity of modelling their electrical/thermal performance. However, Ogasawara et al. [4] simulations ignored the temperature dependency of the electrical/thermal material properties and used a technique for the application of the electric arc load which may produce inaccurate results. An explanation of a more accurate method to apply electric current is discussed later in this paper.

Chemartin et al. [5] presents a comprehensive survey of the thermal and mechanical direct effects of lightning strike on aircraft skin panels. They developed both numerical and experimental models to simulate the plasma between the cathode and the panel, capturing its temperature and conduction profile. They simulated the lightning strike in flight conditions to characterize the sweeping stroke process and to evaluate dwell time, which is an important parameter for the waveform definition to be applied on the swept zones of aircraft. Their experimental approach was very comprehensive, not only modelling the damage and electric spark generation in aircraft panels, but also modelling the electric arc physics. Using basic mathematical expressions they modelled the thermal and mechanical forces applied on aircraft panels, but did not model the panel structure, its interaction with the force applied or resulting panel damage.

Using experimental tests to study the impact of lightning strike is expensive and limited to studying the effect of a few parameters at a time, such as decomposition and delamination in the vicinity of the lightning strike. Using a purely empirical approach to optimize the performance of a lightning protection system is inevitably time consuming and expensive. Thus in this paper we build on the preceding work by proposing an improved technique to model the lightning strike effects on composite panel with and without a protection system. We address the resistive heating force and its interaction with the composite structure, and the protection system thermal performance. A coupled electromagnetic/thermal FE analysis is proposed with material properties modelled as functions of temperature. A user material subroutine is used to model the complex physical behaviour of the protection system. Magnetic forces and overpressure participation are addressed in the following work, where a coupled mechanical simulation is used and laminate delamination is modelled. Developing a numerical tool that models the complex physical process of lightning strike on composite panels with protection systems is essential for the efficient optimization of current lightning strike protection systems and developing new protection system concepts.

3. Experimental setup

There are generally two configurations of lightning strike test setup. The simplest configuration is for the specimen to be located on top of a copper plate. In the second configuration the specimen