Applied Mathematical Modelling 53 (2018) 118–131

Contents lists available at ScienceDirect

Applied Mathematical Modelling

journal homepage: www.elsevier.com/locate/apm

Modeling of thermal response and ablation in laminated glass fiber reinforced polymer matrix composites due to lightning strike

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ARTICLE INFO

Article history:
Received 18 January 2017
Revised 14 July 2017
Accepted 23 August 2017
Available online 8 September 2017

Keywords:
Lightning strike
Polymer matrix composite
Thermal ablation
Moving boundaries
Finite element analysis
Element deletion method

ABSTRACT

Thermal response and ablation of laminated glass fiber reinforced polymer matrix composites subjected to lightning strike are studied. The associated nonlinear time-dependent heat transfer model includes specific features of lightning arcs observed in physical measurements such as lightning channel radius expansion, non-uniform lightning current density, and associated heat flux. Moving spatially and temporally non-uniform lightning-current-induced heat flux boundary and moving boundary due to material phase transition caused by rapid surface ablation are also included. To predict moving phase boundary in the laminated anisotropic composites, an element deletion method is developed and embedded into finite element analysis (FEA), which is performed using ABAQUS. The Umeshmotion + ALE method based on the user subroutine Umeshmotion and arbitrary Lagrangian–Eulerian (ALE) adaptive mesh technique is also used, when applicable (i.e., moving phase boundary is confined within a top layer of the composite laminate). Heat transfer analysis is performed for a non-conductive laminated glass fiber reinforced polymer matrix composite panel representing the SNL 100-00 wind turbine tip. Thermal response of the panel subjected to pulsed and continuing lightning currents at three different lightning protection levels, LPL I, LPL II, and LPL III, is studied. Temperature-dependent anisotropic thermal properties of the composite panel are included in the analysis. The FEA results include temperature distributions and ablation zone profiles. The results show the Umeshmotion + ALE method is sufficient for the pulsed lightning current at all three LPL levels since the moving phase boundary, i.e. the ablation front, is found to be confined within the top layer of the laminate. For the continuing lightning currents at all three LPL levels, the Umeshmotion + ALE method is not applicable since the moving phase boundary comes to rest at depths exceeding the thickness of the top layer of the composite laminate.

1. Introduction

Fiber reinforced polymer matrix composites are known to be susceptible to the lightning strike damage, which represents a serious design concern for the composite structures as compared to the metal structures. Polymer matrix composites are

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http://dx.doi.org/10.1016/j.apm.2017.08.019

adversely affected by heat. Above glass transition, a rapid degradation of the polymer matrix occurs. Further increase in temperature leads to the matrix decomposition followed by delamination, fiber breakage, vaporization, and sublimation. Heat discharged by the lightning arc channel into a structure comes from the direct contact of the lightning channel and the structure and from the electric current passing through the structure, if the structure is electrically conductive. If the structure is electrically non-conductive, Joule heating is produced once the lightning discharge voltage reaches the breakdown strength. In both cases of electrically non-conductive and conductive structures, rapid temperature increase often leads to the severe surface damage and even catastrophic structural failure [1,2].

Most of the early lightning strike studies were focused on the physics of the lightning return stroke and prediction of the electric and magnetic fields observed at the remote distances [3–5]. Gas dynamics models [6–15] were developed to determine evolution of the lightning arc channel, its temperature and pressure, and associated shock wave. Recently, a number of studies examining direct effects of the lightning on the lightning-struck composite structures have been published [16–28]. Most of these papers are focused on examination of lightning-induced damage in carbon fiber reinforced polymer matrix (CFRP) composites that are widely used in aerospace structures [16–26]. Glass fiber reinforced polymer matrix (GFRP) composites received less attention despite of their use in various structural applications including wind turbine blades [27–32]. Lightning strikes are among the top two most frequently reported causes of loss in wind energy insurance claims in the United States [28,33]. A better understanding of the response of non-conductive GFRP composites to a lightning strike is essential for the development of the lightning strike protection systems.

The models describing interaction between the lightning arc channel and a structure [16–20] are based on many simplifying assumptions that include constant radius of the lightning channel, uniform surface heat flux, and are deficient in description of material phase transitions. Expansion of the lightning channel radius during the initial pulsed current of the return stroke, which is described in all gas dynamic models [6–15] is ignored, and instead a fixed lightning channel radius is assumed based on some input from the experiments. This significantly simplifies a mathematical treatment of the problem as it fixes the lightning channel boundary and reduces the problem complexity to dealing with temperature-dependent material properties and material phase transitions. At the same time, such simplification affects predictive capabilities of the models.

In the present paper, we study heat transfer with moving boundaries in fiber reinforced laminated composites subjected to the lightning strike. The focus is on the mathematical formulation of the problem and numerical analysis. The mathematical formulation includes moving boundary of the lightning channel, spatially and temporally non-uniform lightning-induced heat flux, and temperature-dependent material properties. Moving boundary associated with material phase transition is also taken into account. Computational procedures enabling handling material phase transition and ablation front propagation in a layered structure subjected to rapid heating due to interaction with a lightning arc channel are developed. Nonlinear transient heat transfer finite element analysis of a GFRP composite laminated panel subjected to lightning current is performed in ABAQUS. The obtained results include temperature distributions and ablation zone profiles.

2. Mathematical model

2.1. Problem formulation

In this section, we present a mathematical formulation of the heat transfer problem with moving boundary for an electrically non-conductive anisotropic structure subjected to the lightning current. Lightning-induced heating in an electrically non-conductive anisotropic structure prior to the dielectric breakdown is described by the following nonlinear transient heat transfer equation:

$$\nabla \cdot (\mathbf{k}(T)\nabla T) = C(T)\rho \frac{\partial T}{\partial t}. \tag{1}$$

Here T denotes the temperature, $\mathbf{k}(T)$ is the temperature-dependent thermal conductivity tensor, $C(T)$ is the temperature-dependent specific heat, ρ is the density, and t is time.

Lightning current flows in a narrow straight cylindrical arc channel whose size depends on the current waveform, pressure, density, etc. [6–13,34,35]. Lightning arc channel injects heat into the structure with a non-uniform heat flux, $Q(r, t)$, that is a function of electric current waveform $I(t)$ as well as electric current density distribution within the channel, $J(r, t)$, and lightning channel radius $R(t)$ (see Fig. 1).

Lightning channel radius $R(t)$ expands over time, thus leading to a heat transfer problem with a moving boundary. The corresponding boundary condition at the top surface of the structure, $z = 0$, is

$$-k_z(T)\frac{\partial T}{\partial z}\bigg|_{z=0} = Q(r,t), \qquad r \le R(t), \tag{2}$$

where k_z is the thermal conductivity in the through-the-thickness direction. Explicit expressions for the non-uniform heat flux $Q(r, t)$, electric current density $J(r, t)$, and lightning channel radius $R(t)$ will be discussed in Sections 2.2 and 2.3. At the