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Ablation damage characteristic and residual strength prediction of carbon fiber/epoxy composite suffered from lightning strike

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ABSTRACT

Ablation damage characteristic of carbon fiber/epoxy composite laminate suffered from lightning strike was studied by the coupled thermal–electrical–structural analysis and element deletion. Residual strength of composite laminate after lightning strike ablation was globally predicted by Hashin criterion. Results show that lightning ablation effects decrease with the increasing electrical conductivity or specific heat, while thermal conductivity has little influence on them. Residual strength of composite laminate is generally greater than 80% and decreases with the increasing peak current or ratio of time to the maximum current and that to 50% of the maximum current under static tensile load. The work can provide detailed technical support for lightning damage evaluation and residual strength prediction of aircraft carbon fiber/epoxy composite laminates in theory, which is seldom reported compared with lightning test researches available up to now.

1. Introduction

It is estimated that aircrafts will suffer from one lightning strike in flight of 1000–1500 h, and almost once every year especially in the regions with much more lightning storms. In general, the probability of lightning strike for short-distance aircrafts is higher than that for long-distance aircrafts. There are three kinds of lightning strike phenomenon including inter-cloud discharge, intra-cloud discharge and cloud to ground discharge. Researches show that the last one influences on aircraft safety greatly. Lightning discharge will bring higher energy, larger voltage and current, faster current change and shorter discharge time [1]. Lightning strike is related to local climate, flight envelope and aircraft layout, which will be produced due to intercepting and triggering with aircraft during discharge. Murooka surveyed and analyzed the lightning strike accidents of Japanese commercial aircrafts. Relationship between lightning strike accident and flight altitude in summer and autumn was presented. And that between lightning strike accident and atmosphere temperature in a year was also presented [2]. Uman studied the lightning strike reports of F-100F, F-106B, CV-580 and C-160 aircrafts systematically. Action mechanism between aircraft and lightning strike was described elaborately. Relationship between lightning strike accident for different engines and flight altitude as well as distribution of space charge was presented [3]. Up to now, over 2500 aircrafts have been damaged due to lightning strike. Because of the attachment of lightning strike arc produced by the supersonic shock wave of plasma with extraordinarily high temperature and pressure, direct effect of lightning strike can result in aircraft ablation, erosion, explosion, structural distortion and strength degradation, etc. [4].

Composite laminates have been widely applied in designing aircraft structures because of their excellent mechanical performance, weight loss and corrosion prevention, etc. But electroconductivity of composite laminates is worse compared with that of metal materials such as aluminum and titanium alloys. Composites are sensitive to lightning storms and have a higher possibility to suffer from lightning strike. Lightning strike can damage and degrade the strength and rigidity of composite laminates. Though carbon fiber is a good electrical conductor and resin matrix is a good electrolyte for some kinds of composite laminates such as carbon fiber/epoxy composites, the whole composite laminates are insulated materials and have bad electroconductivity [5–7].

At present, studies on lightning damage evaluation of composite laminates are mainly based on long gap discharge tests [8–10]. Results show that lightning strike can induce fiber breakage, matrix cracking and delamination accompanied with ablation and thermal decomposition under the thermal shock of supersonic plasma. The mechanical characteristics of composite laminates suffered from lightning strike are different from those under a

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common low velocity shock. The burning and detonation characteristics of composite laminates can be independently observed by adjusting the test parameters of lightning discharge, which makes it possible to study the complex lightning damage mechanics of composite laminates in theory, for example by means of numerical simulation. At the same time, test results under static tensile and compression loads show that residual strength of composite laminates after lightning strike decreases obviously. Residual strength of composite laminates after lightning strike is greater than that after low velocity shock [8,9].

Few researchers analyzed the lightning responses of composite laminates or predicted its residual strength in theory nowadays. Ogasawara, et al., studied the temperature distribution of carbon fiber/epoxy composite suffered from lightning strike by coupled thermal–electrical analysis [11]. Featherston et al., developed a method to assess the shock effect suffered from lightning strike [12]. But both works cannot take into account the damage resulting from lightning strike through numerical simulation. As a pilot study, Abdelal et al., used the numerical simulation to predict the thermal damage of carbon fiber/epoxy composite and its copper mesh protection system suffered from lightning strike by the coupled thermal–electromagnetic analysis, in which the material properties are temperature dependent [13]. In this paper, ablation damage characteristic of a carbon fiber/epoxy composite laminate suffered from lightning strike will be studied by the coupled thermal–electrical–structural analysis and element deletion. At the same time, residual strength of the composite laminate after lightning ablation will also be globally predicted by Hashin criterion. Damage mechanism and pattern of the composite laminate was simulated. Transient heat transfer and decomposition of the composite laminate was also demonstrated. In our previous research, lightning parameters of impulse current waveform such as peak current, electrical charge and action integral were studied how to influence on the ablation effects such as ablation size and inner damage of the composite laminate [14]. In this paper, material properties of the carbon fiber/epoxy composite laminate influencing on ablation effects will be further studied. Nowadays, studies on lightning damage evaluation and residual strength prediction of composite laminates in theory have seldom been reported in available literatures.

2. Ablation damage simulation of composite laminate suffered from lightning strike

2.1. Model description and analysis method

A carbon fiber/epoxy composite laminate IM600/133 is used for ablation analysis suffered from lightning strike. Its ply number is 8 and stacking sequence is $[45/90/-45/0]_s$. Initial material properties of the carbon fiber/epoxy composite laminate are given in Table 1. Three-dimensional finite element (FE) model of carbon fiber/epoxy composite suffered from lightning strike is built by ANSYS software as shown in Fig. 1. The coupled thermal–electrical solid element SOLID69 is selected to simulate composite laminate. SOLID69 has eight nodes and can be used to solve a three-dimensional thermal and electrical conduction question, in which Joule heat generated by current flow is included in heat balance. At each node of this element, there are two degrees of freedom such as temperature and voltage. This solid element is applicable to a three-dimensional, steady-state or transient thermal analysis and requires an iterative solution to include Joule heating effect in thermal solution. For electrical conductivity matrix, thermal conductivity matrix, heat generation load vector and specific heat matrix, integration points are all $2 \times 2 \times 2$ [15]. Impulse electrical current is set to the top surface center of composite laminate. The following thermal and electrical boundary conditions are defined. The third kind of thermal conduction boundary condition is applied to top and side surfaces of composite laminate, which specifies the air temperature around composite laminate and the heat conversion coefficient between composite laminate and air. The second kind of thermal conduction boundary condition is applied to bottom surface of thermal insulated composite laminate, which specifies that thermal flow density is 0 W/m^2, thermal emission ratio is 0.9 and air temperature is 25 °C. Electrical potential of bottom and side surfaces of composite laminate is 0 V.

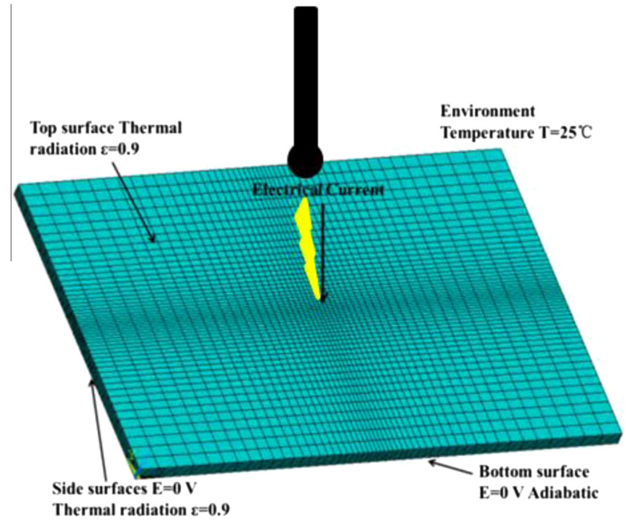

Fig. 1. FE model of carbon fiber/epoxy composite laminate suffered from lightning strike.

Aircraft surfaces can be divided into several regions called lightning strike zones described in Society of Automotive Engineers (SAE) standard and are given in Table 2 [16], which represent the areas likely to experience types of lightning voltages and currents. An example of lightning strike zone division for a transport aircraft is shown in Fig. 2, in which Zone 1A is the first return stroke zone, Zone 1B is the first return stroke zone with long hang on, Zone 1C is the transition zone for the first return stroke, Zone 2A is the swept

Table 1
Initial material properties of carbon fiber/epoxy composite laminate.

Direction	Thermal conductivity (W/m °C)	Electrical resistivity (Ω m)	Coefficient of thermal expansion	Specific heat (J/kg °C)
Longitudinal	11.8	2.89×10^{-5}	5×10^{-6}	1065
Transverse	0.609	0.82	4×10^{-6}	
Through-thickness	0.609	308.77	4×10^{-6}	
Direction	Elastic ratio (Gpa)	Poisson ratio	Shear modulus (Gpa)	Density (kg/m^3)
Longitudinal	137	0.34	$G_{31} = 4.36$	1520
Transverse	8.2	0.34	$G_{12} = 4.36$	
Through-thickness	8.2	0.34	$G_{23} = 3$	