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Ablation damage assessment of aircraft carbon fiber/epoxy composite and its protection structures suffered from lightning strike

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ABSTRACT

Aircraft carbon fiber/epoxy composite material is sensitive to lightning strike. Its damage assessment and protection design suffered from lightning strike is becoming increasingly important. Four different types of carbon fiber/epoxy composite laminates are selected, which are without protection, with full spraying aluminum coating, with local spraying aluminum coating and with spraying aluminum coating on glass cloth pasted to fastener head, respectively. Impulse electrical current tests were performed by implementing electrical current waveforms with different peak values with regard to different lightning zonings. Three-dimensional finite element models of composite laminate and its protection structures are accurately built to assess lightning ablation characteristics based on the coupled thermal/electrical/structural analysis and element deletion method, in which different electrical and thermal physical properties of the elements are defined depending on different temperature conditions. The results show that simulation results are good agreement with experimental results. Fiber damaged area, the damaged area and the maximum damaged thickness increases with the increase of electrical current peak. Aluminum coating has a good effect on anti-lightning strike. The thicker aluminum layer and the better to anti-lightning strike.

1. Introduction

Composite materials have offered many advantages compared with conventional materials especially at where high strength or stiffness to weight ratio is concerned, which are widely applied in various fields such as aerospace structures, pressure vessels and automotive parts [1], etc. Lightning strike is a recurring problem as aircraft may encounter one strike between certain flight hours. For example, a commercial aircraft may encounter one strike about once a year [2]. Lightning strike is also a common adversary for aircraft flight safety and usually occurs on aircraft taking off, landing or passing through storm cloud [3]. Unfortunately, carbon fiber reinforced polymer composites are unable to conduct the high lightning electrical current and cannot sufficiently prevent electromagnetic force from destroying. Lightning strikes maybe result in embrittlement, delamination and failure of composite materials [4]. It has a very important significance to study damage behavior of composite materials suffered from lightning strike and improve its safety by employing appropriate protection systems.

Effects of lightning strike on aircraft can be classified into two main categories, in which direct effects are associated with physical damage occurring at the attachment point and indirect effects concern the interference due to electromagnetic coupling with systems or cabling [5]. The coupling direct effects of composite materials suffered from lightning strike attribute to the very complex physical process and are difficulty to be completely simulated by the numerical calculation such as finite element (FE) method at present. Due to the high peak current and action integral, short duration and extreme requirement on experimental operating conditions and devices, there is little research on effects of composite materials suffered from lightning strike. In recent years, study on lightning damage of carbon fiber reinforced polymer composites through experimental and numerical methods has only an initial progress [1,6,7].

Feraboli and Miller [8] used a simulated generator to carry out lightning strike experiment, in which strike peaks up to 50,000 A and 28,000 V were inflicted on both pristine specimens and specimens containing a Hilok stainless steel fastener. Damage area was evaluated via ultrasonic scanning and further understanding of

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damage pattern was also gained via the advanced optical microscopy. Hirano et al. [9] examined damage evolution of graphite/epoxy composite laminates suffered from lightning strikes. In order to clarify the influence of lightning parameters and specimen size, artificial lightning testing was performed on a series of composite laminates. Damage state was assessed via visual inspection, ultrasonic scanning, micro X-ray inspection and sectional observation. At the same time, the coupled thermal/electrical analysis of carbon fiber reinforced polymer composites exposed to the simulated lightning current has been gradually conducted by several scholars. Ogasawara et al. [10] developed a coupled thermal/electrical model to analyze the angle-ply composite laminates, which takes into account laminate lay-up and anisotropic thermal/electrical behavior of unidirectional composite layers. However, their work ignored temperature dependency of electrical/thermal material properties and electrical arc load applied in numerical simulation may result in inaccurate results. Abdelal and Murphy [11] also presented a physics based modeling procedure to predict thermal damage of composite materials suffered from lightning strike, in which finite element method with non-linear material models was used to represent the extreme thermal behaviors of composite material and the embedded copper mesh protection system. Muñoz et al. [12] presented a finite element model to consider damage source observed in lightning strike such as thermal damage caused by Joule overheating and electromagnetic/acoustic pressure induced by electrical arc around the attachment point.

Experimental and numerical simulation results from previous literatures can be concluded that composite materials will appear severe thermal ablation damage under lightning strike effects. Several scholars [13,14] used theoretical and experimental methods to study thermal ablation microscopic mechanism and thermal shock effect on composite materials subjected to laser heat source. Griffis et al. [15,16] established a model with respect to temperature field and thermal ablation of carbon/epoxy composite laminate subjected to laser irradiation. Thermal decomposition of organic matrix material such as epoxy resin was approximated by bulk heat capacity elevation over an appropriate temperature range and the better results were achieved by this model. Then thermal stress was analyzed by finite element method. Negarestani et al. [17] and Zhou et al. [18] simulated ablation process of composite laminate and low carbon steel subjected to laser irradiation, respectively. The continuous variation of ablation boundary in analysis model was achieved and ablation size was described quantitatively.

A lot of problems are still worth studying although several scholars have also used finite element method to analyze damage mechanism of composite materials exposed to the simulated lightning electrical current. Based on previous work that have already been done, further study on ablation damage mechanism of composite material and its protection systems will be carried out when exposed to the simulated lightning current. Four different types of composite laminates are selected, which are without protection, with full spraying aluminum coating, with local spraying aluminum coating and with spraying aluminum coating on glass cloth pasted to fastener head, respectively. Three-dimensional finite element model is developed to predict transient temperature field together with the subsequent material removal when lightning electrical current inflicts the composite laminate specimens. The commercial finite element software ANSYS is applied for this purpose by utilizing its parametric design language. Firstly, temperature dependency of electrical/thermal material properties is defined. Then change conditions of boundary and load as well as the excited phase during lightning strike process are incorporated into the model combing with element birth and death technique. Taking into account fiber damage and resin deterioration, transient heat transfer and heat decomposition mechanism of composite material is demonstrated when suffered from lightning strike. Influence of the sprayed aluminum coating on composite protection structures is also evaluated in order to anti-lightning strike.

Impulse electrical current test is performed by implementing current waveforms with different peak values with regard to different lightning zonings. According to SAE ARP5414 standard about aircraft lightning zoning [19], three lightning zonings such as IA, IB and IIB are selected in accordance with three test specimens for above each type of specimens, respectively. The corresponding lightning current waveforms such as A, A + D and D wave are loaded to IA, IB and IIB zonings respectively. Taking into account that aircraft test waveforms in SAE ARP5412 standard [20] and lightning test methods in SAE ARP 5416 standard [21] are mainly applicable to lightning strike tests of aircraft metal structures and fuselage, the actual specific criteria have not really been formed to test direct effects of composite structures by artificial simulated lightning currents in a laboratory environment. Therefore, above standards can only be used as a reference for artificial lightning tests of composite structures, although these standards are not always suitable.

2. Experimental description and numerical analysis method

2.1. Experimental description

Composite specimens used for lightning strike test are carbon fiber/epoxy laminates T700/3234 with a 16-ply lay-up $[45/-45/0_2/45/90/-45/0]_S$, which size is 500 mm × 250 mm × 2 mm and thickness of each ply is 0.125 mm. For all the specimens with spraying aluminum coating, both kinds of aluminum layer thickness such as 0.1 and 0.2 mm is considered. For each type of the unprotected and protected specimens, 3 test specimens are prepared and so all 21 test specimens are used. Test specimen with local spraying aluminum coating is shown in Fig. 1. With regard to test specimens with spraying aluminum coating on glass cloth pasted to fastener head, metal fastener is inserted in geometrical center of composite laminate panel.

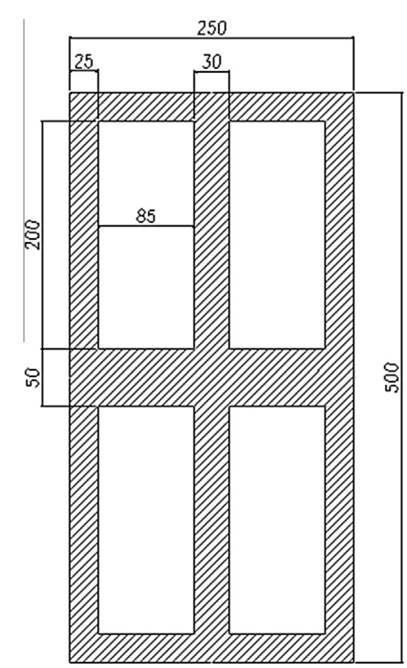

Fig. 1. Test specimen with local aluminum coating shown in the shaded area (Unit: mm).