THERMAL DAMAGE CHARACTERISTICS OF CFRP LAMINATES SUBJECTED TO LIGHTNING STRIKE

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ABSTRACT

In this paper, the dynamic temperature field was simulated by fully coupled thermal-electrical model and temperature dependent nonlinear material properties. Meanwhile, the pyrolysis degree field was calculated by combining the dynamic temperature field and n-order chemical reaction kinetic equation. The dynamic temperature field and pyrolysis degree field reveal the thermal damage characteristics of CFRP laminates subjected to lightning strike. The resin pyrolysis and fiber ablation caused by Joule heat of lightning current are the principal patterns that will seriously degrade the usability of CFRP. The work is helpful for the research of lightning damage behaviors, mechanisms and anti-lightning optimizations of CFRP laminates.

INTRODUCTION

Carbon fiber reinforced polymer (CFRP) composites have been widely used in present aircraft structures because of their excellent mechanical performance, anti-aging/fatigue/corrosion ability and energy saving advantage. However, compared with metals, the relatively poor electrical conductivity of CFRP laminate makes CFRP based aircrafts quite vulnerable to lightning strikes[1]. CFRP will suffer from serious damage of resistive heating, shock waves, dielectric breakdown, gas blow-off and magnetic force when subjected to lightning strikes[2]. Among all, the thermal damage may be the especially remarkable one as the resistive heating can induce resin pyrolysis, carbonization, fiber ablation, and sublimation. Especially, the resin pyrolysis will seriously degrade the strength and rigidity of composite laminates on account of adhesive ability loss of reinforced fibers. The lifetime of polymers or composites to failure is generally defined when 5% mass loss is reached[3].

In this paper, the dynamic temperature field was simulated by fully coupled thermal-electrical model and temperature dependent nonlinear material properties. Meanwhile, taking advantage of the subroutine HETVAL in software ABAQUS, the pyrolysis degree field was calculated by combining the dynamic temperature field and *n*-order chemical reaction kinetic equation. The kinetic equation parameters of CFRP pyrolysis were obtained by analyzing TG data using Friedman method. Scheil additivity rule[4] was introduced into the

subroutine to tackle kinetic equation and deduce pyrolysis degree during the dynamic process of lightning strike.

MODEL AND METHOD

The composite laminate model was the quasi-isotropic stack of $[45^o/0^o/-45^o/90^o]_{4S}$ with dimension of 150 mm×100 mm which was referred to ASTM D7173. The lightning current was injected into the model at the center node of top surface, and the voltage was presumed to be zero at the bottom and side surfaces. The thermal boundary consisted of heat radiation and convection on the model surfaces.

The temperature dependent material properties of IM600/133, referred to previous researches[2,4,5,6], were adopted to characterize the material nonlinearity of CFRP during a lightning strike. The resin pyrolysis (300 ºC - 3000 ºC) and carbon fibers sublimation (3316 ºC[5]) were taken into account. Besides, it was assumed that CFRP would turn into sublimed virtual conductive state with superconductor-like property if its temperature exceeded 3316 ºC, signifying lightning attachment points moving inward after the surface material was ablated. The simulation was divided into two time stages, in-lightning stage (30 μs) and post-lightning stage (30 s). The lightning current waveform of t_1/t_2 = 4 μs / 20 μs, I_{peak} = 40 kA was used in the finite element simulation, where t_1 is the nominal time to lightning current peak, t_2 is the nominal time of current decaying to its half peak, and I_{peak} is current peak[2].

RESULTS AND DISCUSSION

The temperature and pyrolysis degree distributions along thickness direction, namely the path from the top surface center (where the depth is zero) to bottom surface center, are shown in Fig. 1 and Fig. 2, respectively.

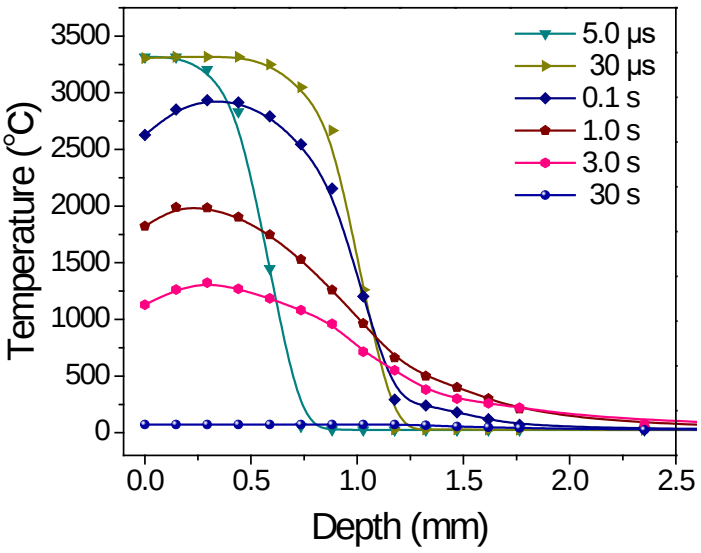

Fig. 1 Temperature distribution along thickness direction under 40 kA.

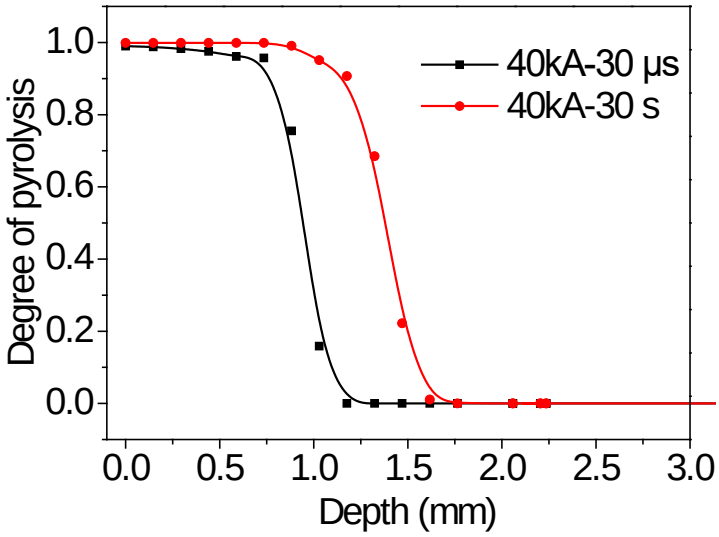

Fig. 2 Pyrolysis degree distribution along thickness direction under 40 kA.

The temperature distribution in Fig. 1 shows that the laminate will suffer from an extremely rapid heating-cooling process when subjected to a lightning strike as its temperature will increase to 3000 ºC in 5 microseconds and cool down in 30 seconds. The temperature of 3000 ºC can reach 0.8 mm in depth in 30 μs, and the carbon fibers can be ablated under such a high temperature. In addition, the Joule heat will induce serious damage to the resin because the pyrolysis temperature range of epoxy resin is generally between 300 ºC and 600 ºC[2]. As it exceeds 3000 ºC in the thin laminate, the temperature gradient in depth is so larger that the thermal stress will accelerate CFRP failure by means of stress concentration or delamination.

Unlike temperature, the pyrolysis degree is irreversible and unable to decrease in post-lightning period. The pyrolysis degree along thickness direction in both in-lightning (30 μs) and post-lightning (30 s) periods under 40 kA is shown in Fig.2. The pyrolysis curve approximately moves inward 0.4 mm from 30 μs to 30 s, which means that the resin pyrolysis still continues even no extra Joule heat generation. Therefore, CFRP will suffer from thermal damage (at least resin pyrolysis) not only during the striking moment but also in post-lightning period as the Joule heat cannot be immediately conducted out after a strike.

CONCLUSION

The dynamic temperature field and pyrolysis degree field reveal the thermal damage characteristics of CFRP laminates subjected to lightning strike. The resin pyrolysis and fiber ablation caused by Joule heat of lightning current are the principal patterns that will seriously degrade the usability of CFRP. To get a better understanding of CFRP lightning damage mechanism, the post-lightning thermal damage should be taken into consideration.

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