

Lightning Strike Ablation Damage Influence Factors Analysis of Carbon Fiber/Epoxy Composite Based on Coupled Electrical-Thermal Simulation

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Abstract According to the mathematical analysis model constructed on the basis of energy-balance relationship in lightning strike, and accompany with the simplified calculation strategy of composite resin pyrolysis degree dependent electrical conductivity, an effective three dimensional thermal-electrical coupling analysis finite element model of composite laminate suffered from lightning current was established based on ABAQUS, to elucidate the effects of lightning current waveform parameters and thermal/electrical properties of composite laminate on the extent of ablation damage. Simulated predictions agree well with the composite lightning strike directed effect experimental data, illustrating the potential accuracy of the constructed model. The analytical results revealed that extent of composite lightning strike ablation damage can be characterized by action integral validly, there exist remarkable power function relationships between action integral and visual damage area, projected damage area, maximum damage depth and damage volume of ablation damage, and enhancing the electrical conductivity and specific heat of composite, ablation damage will be descended obviously, power function relationships also exist between electrical conductivity, specific heat and ablation damage, however, the impact of thermal conductivity on the extent of ablation damage is not notable. The conclusions obtained provide some guidance for composite anti-lightning strike structure-function integration design.

Keywords Carbon fiber/epoxy composite · Lightning strike ablation damage · Influence factors · Coupled electrical-thermal simulation

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1 Introduction

Compared with conventional metal materials, carbon fiber/epoxy composite owns many advantages, such as high modulus, high specific strength, good corrosion resistance and outstanding design ability characteristics, which has already become a competitive alternative material to aluminum and titanium alloys and is being increasingly used in the territory of aerospace, automotive, and other transportation industry segments. For instance, the F-22 military fighter plane uses about 25% composite materials by weight and Boeing 787 Dreamliner uses composite materials as approximately 50% by weight, the previous applied range of composite limited to non-load bearing structures as stabilizers, while now developed into main load bearing structures as wing and fuselages [1, 2]. However, because of the inferior electrical and thermal conductivity of composite as compared with conventional metal materials, their lower lightning damage resistance becomes a major issue.

Lightning is a natural phenomenon with high-voltage and high-current, an aircraft may suffer from one lightning strike between each 1000 and 3000 h of flight based on the statistics on airliner, even once a year especially in regions with much more lightning storms, and usually occurs on aircraft taking off, landing or passing through storm cloud [3–5]. When lightning hits metallic structure, lightning current injected into the structure from the lightning attachment point will be conducted away soon and will not cause serious damage. While for composite structures, lightning current could generate vast resistive heating at the lightning attachment point due to its poor electrical conductivity, accompany with the supersonic shockwave with high temperature and magnetic force effects produced by lightning strike arc, the composite structure will be serious damaged as fiber fracture, resin pyrolysis and delamination at the lightning attachment point and nearby region, eventually decrease the mechanical properties of structure and lead to catastrophic consequence [6]. Hence, lightning strike is a common adversary for aircraft flight safety and need pay more attention, and clarifying the ablation damage of composite subjected to lightning strike show important scientific significance and value to promote the application of carbon fiber/epoxy composite on aircraft.

Hirano et al. [7] conducted a series of experimental researches to examine the evolution of damage in graphite/epoxy composite laminates due to lightning strikes by means of visual inspection, ultrasonic testing, micro X-ray inspection and sectional observation, meanwhile, the influence of lightning parameters and specimen size to damage extent were also clarified. Feraboli and Miller [8, 9] did some artificial lightning strike tests to understand the fundamental damage response of both pristine specimens and specimens containing a Hilok stainless steel fastener, damage extent and mechanisms were evaluated via ultrasonic scanning and advanced optical micro-scope, subsequent mechanical testing to assess the residual tensile and compressive strength and modulus of the materials was performed according to ASTM standards. Furthermore, lightning strike damage was compared with the low velocity impact damage also. At the same time, the coupled thermal/electrical analysis of carbon fiber/epoxy composite exposed to the simulated lightning current has been gradually conducted by several scholars [10–15]. According to the simulation work done before, the critical influence factor to affect the accuracy of simulation results is constructing a reliable electrical conductivity model. For carbon fiber/epoxy composite laminate, its electrical conductivity is anisotropy, and will be changed accompany with temperature arise, however, experimental data on the electrical conductivity of carbon fiber/epoxy composites above 330 °C has already rarely been reported. Ogasawara et al.

[10] assumed that the electrical conductivity in the thickness direction changed linearly from $7.64 \times 10^{-7}(\Omega\text{m})^{-1}$ to $0.1(\Omega\text{m})^{-1}$ between 600 °C to 3000 °C, however, they ignored the correlation between electrical properties and thermal decomposition, which might lead to inaccurate results. Abdelal and Murphy [11] followed the work done by Ogasawara et al. [10], presented an improved method to model the composite panel subjected to lightning strike, in which temperature-dependent electrical conductivity model referred to literature [16, 17], but it was difficult to convergence during calculation, especially for high lightning current. Dong et al. [12, 13] presented pyrolysis degree-dependent electrical conductivity, and excellent agreement between experimental and numerical results were observed. Wang YQ et al. [14] found that the temperature-dependency of the electrical conductivity for carbon fiber is similar to that of semiconductors, based on the Arrhenius equation, expression of temperature-dependency electrical conductivity for carbon fiber was got, however, the model ignored the influences of resin pyrolysis and ablation scallops to the electrical conductivity in the thickness direction.

In this paper, we adopt the similar calculation strategy of electrical conductivity as literature [12, 13], in which electrical conductivity is dependent on the resin pyrolysis degree during temperature arise, however, we have done some simplification to electrical conductivity calculation method. Based on the simplified calculation strategy of electrical conductivity and mathematical analysis model constructed on the basis of energy-balance relationship in lightning strike, an effective three dimensional thermal-electrical coupling analysis finite element model of composite laminate suffered from lightning current was established based on ABAQUS, simulated predictions of the established model agree well with the composite lightning strike directed effect experimental data, and then analyzed the effects of lighting current waveform parameters and thermal/electrical properties of composite laminate on the damage extent with regards to lightning strike ablation damage.

2 Lightning Strike Direct Effects Experiment for Composite

2.1 Experimental Setup

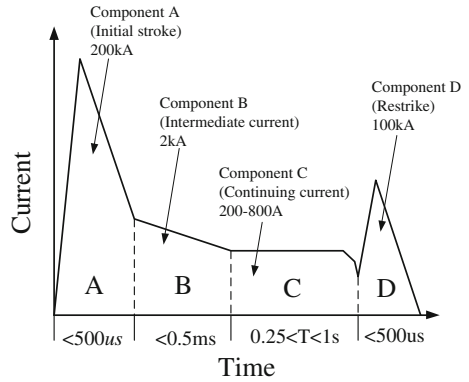
Carbon fiber/epoxy (T300/3021) composite laminate was selected as the test specimens, in which the volume fraction of carbon fibers is 60% approximately. The specimen was designed with reference to ASTM D7137 [18], which dimensions are $150 \times 100 \times 3.6$ mm and contain 24 layers with a stacking sequence of [45/−45/0/90/90/−45/0/0/45/0/90/−45/45]_s.

In order to simulate the lightning current, the high impulse current generator developed by Xi'an Jiao-tong University was selected. During the test, fixed the test specimens in the test jig completely, in order to reduce the contact resistance between specimen and test jig, meanwhile, ensure all side surfaces of the specimen with the same electric potential, conductive silver sol was selected to coat on all side surfaces and then covered with copper foil. The location of the copper probe locates upon the center of the specimen and the distance of the specimen from copper probe was set to 1 mm.

2.2 Artificial Lightning Waveform and Test Conditions

According to SAE ARP 5412A [19], lightning strike current waveforms to evaluate direct effects are comprised four components (A–D), as shown in Fig. 1. Current components A and

Fig. 1 Simulated normative lightning current waveforms



D usually are used to do lightning strike tests due to their higher peak current compared with other current components. The double exponential equation mathematical expression of the current components formulated by SAE ARP5412 as following:

$$i(t) = I_0(e^{-\alpha t} - e^{-\beta t}) \tag{1}$$

Where I_0 is current constant, α is reciprocal value of wave tail time constant, β is reciprocal value of wave front time constant and t is the time.

During the test, lightning current waveform was set to component D, which is the restrike of the lightning infliction according to SAE ARP 5412A [19]. One of the measured electrical current applied on the panel is plotted in Fig. 2. Correspondingly, parameters T_1 and T_2 in Fig. 2 represent the time from origin to maximum current and time to 50% of the maximum current respectively.

Based on the purpose of the study, lightning strikes at three different peak currents were used to inflict lightning strike damage to the specimens, test conditions and lightning strike parameters for the current experiment are shown in Table 1.

Fig. 2 Component D waveform

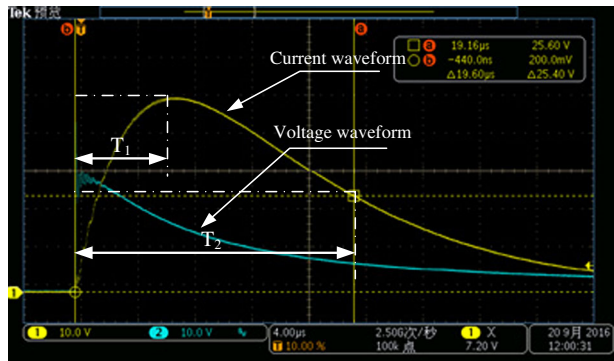


Table 1 The conditions and lightning strike parameters for the current experiment

Test conditions	T ₁ / T ₂ (μs)	Peak current /kA	Action integral /(A ² s)	Numbering
1	4.85/19.60	31.4	13572	D1
2	4.82/19.60	51.2	35738	D3
3	4.90/19.80	79.2	86786	D4

3 Coupled Thermal/Electrical Analysis Model

3.1 Mathematical Analysis Model Description

When lightning hit composite structure, lightning current will inject into the structure from lightning attachment point, and generate vast resistive heating due to the poor electrical conductivity of composite, then ablation damage will occur accompany with temperature rises, simultaneously, heat transfer between high-temperature zone and low-temperature zone in composite will appear also. So that, if just take lightning strike ablation damage into account, the essence of composite lightning strike ablation damage analysis process can be simplified into a problem of nonlinear heat transfer which include inner heat source.

The coupled thermal-electrical analysis model for composite subjected to lightning current comprises the governing equations of heat transfer, energy transition between electrical and thermal and resin pyrolysis kinetics. The former two governing equations are specified in ABAQUS theory manual [20], and these equations were also adopted in some works [10–15].

Mathematical analysis model of ablation damage of carbon fiber/epoxy composite subjected to lightning current constructed based on the energy-balance relationship was described in our previous works [21, 22], and do not restate here.

In this paper, we adopt the similar calculation strategy of electrical conductivity as literature [12, 13], in which electrical conductivity is dependent on the resin pyrolysis degree during temperature arise, to do our coupled thermal/electrical analysis, simplified calculation method of electrical conductivity will be specified in next chapter.

3.2 Simplified Calculation Method of Resin Pyrolysis Degree Dependent Electrical Conductivity

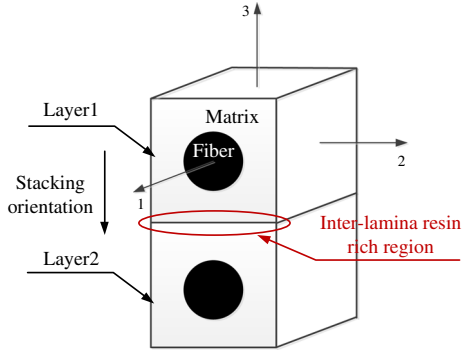
First, electrical conductivity of carbon fiber/epoxy composite in the longitudinal direction at room temperature is determined using the rule of mixtures [14]:

$$\sigma_1 = \sigma_f V_f + \sigma_m (1 - V_f) \quad (2)$$

Where σ_1 is the overall electrical conductivity of the composite lamina in the longitudinal direction (in S/m); σ_f is the electrical conductivity of carbon fiber (in S/m); V_f is the fiber volume fraction; σ_m is the electrical conductivity of the polymer-matrix (resin) (S/m).

For single layer of composite, electrical conductivity in the transverse direction σ_2 is equal to that in the thickness direction σ_3 theoretically, and both are much lower than that in the longitudinal direction. However, for composite laminate with multiple layers, due to the existence of the resin rich regions between layers in the through the thickness direction, as shown in Fig. 3, electrical conductivity in the through-the-thickness direction is even lower

Fig. 3 Schematic of the inter-lamina resin-rich region



than that in the transverse direction actually. Base on literature [14] we can get that electrical conductivity in the transverse direction is around 5×10^{-5} times that in the longitudinal direction, while electrical conductivity in the through the thickness direction is around 8×10^{-6} times that in the longitudinal direction for unidirectional composite lamina. According to the relationships above, we can calculate the overall anisotropic electrical conductivities for composite laminate at room temperature, if the carbon fiber and resin electrical conductivity and their corresponding volume fraction are known.

In literatures [12, 13], it is assumed that electrical conductivity in the transverse direction and thickness direction were resin pyrolysis degree dependent and the electrical conductivity in the longitudinal direction kept a constant. In this study, we adopt the similar change strategy of electrical conductivity, accompany with temperature rises, electrical conductivity in the longitudinal direction keep a constant, that in the transverse and thickness direction change linearly with the resin pyrolysis degree.

Assuming that initial value of the electrical conductivity in the transverse and thickness direction are $\sigma_2(T_0)$ and $\sigma_3(T_0)$, and electrical conductivity when resin pyrolysis completely are $\sigma_2(T_f)$ and $\sigma_3(T_f)$ respectively, during the temperature rises, resin pyrolysis degree is $\alpha(T)$, expression of electrical conductivity in the transverse and thickness direction with temperature can be expressed as:

$$\sigma_i(T) = \sigma_i(T_0) + \alpha(T)(\sigma_i(T_f) - \sigma_i(T_0)) \quad (i = 2, 3) \tag{3}$$

Where T is the changed temperature, T_0 is the room temperature (25 °C), T_f is sublimation temperature of carbon fiber (3316 °C [11]).

The following empirical equation is often applied for estimating the decomposition kinetics for a thermosetting resin [23].

$$\frac{d\alpha}{dT} = \frac{A}{\beta} \exp\left(-\frac{E_a}{RT}\right) (1-\alpha)^n \tag{4}$$

Where A is the pre-exponential factor, E_a is the activation energy, R is the universal gas constant ($R = 8.314 \text{ J/mol/K}$), β is a constant heating rate, n is the reaction order.

Eq. (4) can be integrated by the separation of variables method such that [24]:

$$g(\alpha) = \int_0^\alpha \frac{d\alpha}{(1-\alpha)^n} = \frac{A}{\beta} \int_{t_0}^{t_1} \exp\left(-\frac{E_a}{RT}\right) dT \tag{5}$$

Solve Eq. (5) to get the expression of α .

$$\alpha(T) = 1 - \exp \left[\frac{1}{1-n} \ln \left\{ 1 - (1-n) \int_{t_0}^t \frac{A}{\beta} \exp \left(-\frac{E_a}{RT} \right) dT \right\} \right] \tag{6}$$

Material used in this study is T300/3021, fiber volume fraction $V_f=60\%$, electrical conductivity for carbon fiber $\sigma_f=58,823$ S/m and electrical conductivity for resin $\sigma_m=6 \times 10^{-8}$ S/m.

Based on Eq. (2) and the relationships among electrical conductivity in three directions, T300/3021 electrical conductivity of composite laminate at room temperature can be calculated, as is shown in Table 2.

Value of composite resin decomposition kinetic parameter in Eq. (4) presented as followed: $n = 3.03, A = 3.07 \times 10^{12} (1/\text{min}), E_a = 160 (kJ/mol/K)$ [24]. Based on Eq. (6), we can get the decomposition degree curves of resin under different temperature rising rate (5 °C/min., 10 °C/min., 20 °C/min., 50 °C/min. And 100 °C/min), which is shown in Fig. 4. From Fig. 4, it can be seen that temperature range of resin decomposition is about 290 °C ~ 800 °C. Resin initial decomposition behavior can be regarded as damage criteria, that is to say, temperature profile greater than 290 °C of simulation result can be regarded as ablation damage.

According to literature [11], it is assumed that electrical conductivity in the transverse and thickness direction $\sigma_i(T)=200$ S/m ($i = 2, 3$), and combined Eq.(3), Fig. 4 and Table 2, we can get the electrical conductivity in the transverse and thickness direction accompany with temperature rises, as is shown in Fig. 5.

3.3 Finite Element Model

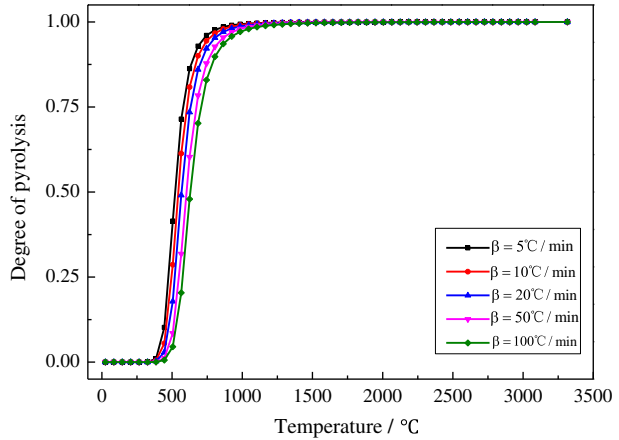
According to the experimental test setups, an effective three dimensional thermal-electrical coupling analysis finite element model for carbon fiber/epoxy laminate subjected to lightning current is established based on ABAQUS. The model contains 24-plyes, and each ply is 0.15 mm, the length of the model is 150 mm and the width is 100 mm, stacking sequence of all the plyes are [45/-45/0/90/90/-45/0/0/45/0/90/-45/45]_s. Refine the mesh at the center of the model, each layer of the laminate is explicitly discretized by using 3D element DC3D8E, total number of simulation elements of specimen is 57,600. Material properties, such as thermal conductivity, specific heat and density are given in Table 3.

The simulated lightning current is located on the top surface center of the specimen. In order to simulate the true test environment, boundary conditions of the simulation model are as follows: electrical potential of the side surfaces are assumed to be zero due to electrically grounded; thermal radiation will occur because of transient heat transmit of the specimen, assuming the upper and side surfaces radiate heat and the bottom surface is adiabatic, the emissivity is 0.9 and the environment temperature is 25 °C. Figure 6 shows the simulation model of a specimen subjected to lightning strike.

Table 2 T300/3021 electrical conductivity of carbon fiber/epoxy laminate at room temperature

Longitudinal(S/m)	Transverse(S/m)	Through-the-thickness(S/m)
$\sigma_1 = 35293$	$\sigma_2 = 1.764$	$\sigma_3 = 0.2822$

Fig. 4 Pyrolysis degree curves of resin under different temperature rising rates



For the sake of validating the accuracy of the numerical method, electrical currents injected into the simulation model are in accordance with Table 1 strictly. For the purpose of analyzing the effects of lighting current waveform parameters on damage extent with regards to lightning strike ablation damage, lightning current waveform parameters of lightning current applied in the numerical model are listed in Table 4.

4 Results and Discussion

4.1 Numerical Method Validity

For the sake of validating the accuracy of the numerical method, simulated predictions compared with the experimental data from visual damage appearance, projected damage area and maximum damage depth.

The visual damage appearance comparing results between simulation and experiment under different peak current are shown in Fig. 7. Observing the post-lightning specimens in Fig. 7,

Fig. 5 Electrical conductivity in transverse and thickness direction accompany with temperature rises

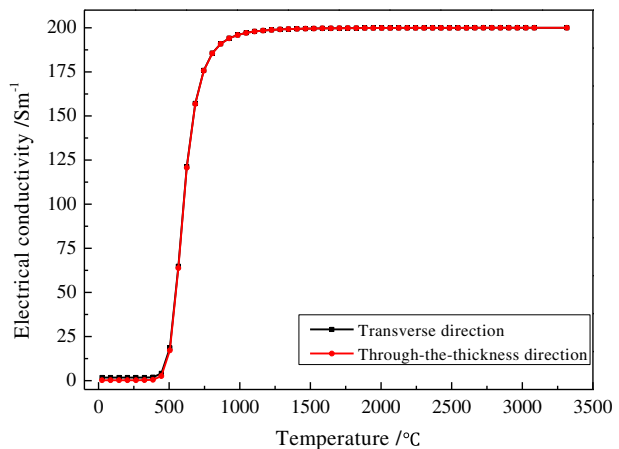


Table 3 Composite thermal material properties vs. temperature [11]

Temperature (°C)	Density (kg/mm ³)	Specific heat (J/kg°C)	Longitudinal thermal conductivity (W/mm°C)	Transverse thermal conductivity (W/mm°C)
25	1.52e-6	1065	0.008	0.00067
343	1.52e-6	2100	0.02608	0.00018
500	1.1e-6	2100	0.001736	0.0001
510	1.1e-6	1700	0.001736	0.0001
1000	1.1e-6	1900	0.001736	0.0001
3316	1.1e-6	2509	0.001736	0.0001
>3316	1.1e-6	5875	0.001050	0.001015

there exist obvious fiber breakage, delamination and resin ablation damage on the surface, and all the directions of superficial damage are in accordance with the fiber direction of the surface layer. Under the same lightning current parameters, the simulated predictions of visual damage appearance agree well with that of experiment. By means of manually estimated, visual damage sizes of simulation and experiment are shown in Table 5. Compared the results in Table 5, we can see that the visual damage area of experiment is slightly larger than that of simulation, and with the enhancement of peak current, the area difference between experiment and simulation increases. Based on the damage mechanism analyzed before, under the act of lightning current, conclusive factors of composite lightning damage including resistive heating, internal expand pressure, acoustic shock effects and magnetic force. However, coupled thermal/electrical analysis model constructed just take the resistive heating into account, so, visual damage area is relatively small. Simultaneously, the comparing results also indicate that lightning strike damage due to resistive heating occupied the dominant component than other factors for this kind of composite laminate.

The internal damage morphologies of the post-lightning specimens were measured by Acoustic Micro Imaging System, accompany with simulated projected damage distribution are shown in Fig. 8. Images in Fig. 8 (a), (b) and (c) indicate that simulation ablation damage in each layer presents obvious directions, and the internal damage territory is much larger than the visual damage. Compared with the simulation projected damage distribution, internal damage morphologies got by Acoustic Micro Imaging System also presents directionally, which are marked in Fig. 8 (d), (e) and (f) roughly, it is obviously that the damage direction of experiment is less remarkable than simulation. Table 6 shows the simulated projected damage

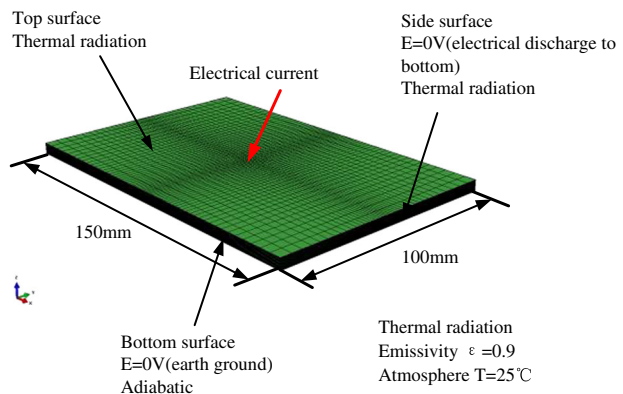
Fig. 6 Simulation model of composite exposed to simulated lightning current

Table 4 Waveform parameters of lightning current

T1/T2 (μs)	Peak current (kA)	Charge Transfer (C)	Action integral (A ² s)	Time (μs)
2.6/10.5	10	0.121	867.5	30
	30	0.363	7807.5	
	50	0.605	21687.5	
	80	0.968	55520.0	
4/20	10	0.240	1700.0	60
	30	0.720	15300.0	
	50	1.200	42500.0	
	80	1.920	108800.0	
5/28	10	0.377	2587.5	100
	30	1.132	23287.5	
	50	1.887	64687.5	
	80	3.020	165600.0	
6/69	10	0.830	5875.0	200
	30	2.490	52875.0	
	50	4.150	146875.0	
	80	6.640	376000.0	

sizes and experimental internal damage sizes, from which we can see that the former area is smaller than the later, and the area difference is larger than that of visual damage area under the same lightning current parameters. As is mentioned before, simulation results just take the resistive heating into account, while the experimental internal damage area results from all the damage factors, on the other hand, because of the different layup orientations for each layer in the laminate, damage projected area for different layers exist dislocations, damage from factors except resistive heating will more obvious, therefore, area difference between experimental internal damage and simulation projected area is more larger. Visual damage mainly including ablation damage in first layer and delamination damage between first and second layer, according to Table 5, visual damage area difference between experiment and simulation of specimen D4 is 10.6%, but due to the ablation damage in each layer and delamination damage between layers, damage area difference between experimental internal damage and simulation projected area is 22.05%.

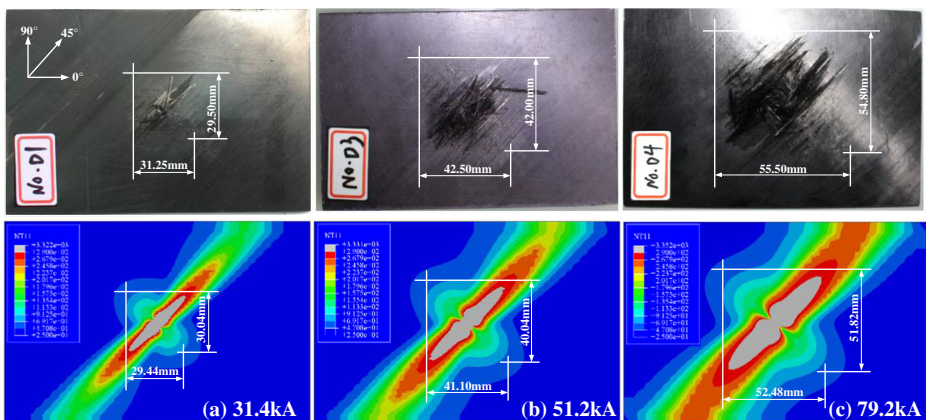


Fig. 7 Comparison of visual damage between experiment and simulation

Table 5 Visual damage sizes compared between experiment and simulation

Numbering	Peak current /kA	Visual damage sizes/mm				Visual damage area/mm ²		Error
		Experiment		Simulation		Experiment	Simulation	
		Length	Width	Length	Width			
D1	31.4	31.25	29.50	29.44	30.04	921.88	884.38	-4.06%
D3	51.2	42.50	42.00	41.10	40.04	1785.00	1646.00	-7.78%
D4	79.2	55.50	54.80	52.48	51.82	3041.00	2718.00	-10.60%

By means of Acoustic Micro Imaging System, experimental maximum damage depth is also quantified, as shown in Table 7, when compared to the simulated maximum damage depth, we can see that both the experimental and simulated maximum damage depth increase with the rise of peak current, under the same lightning current parameters, all errors of maximum damage depth between experiment and simulation are less than 10%, which indicate that the simulation results have a good corresponding to the experimental data.

According to the above compared results from the aspect of visual damage appearance, projected damage area and maximum damage depth, the model constructed in the paper is capable to simulate the ablation damage of carbon fiber/epoxy composite laminate inflicted from lightning current.

4.2 Effects of Lightning Current Parameters on Ablation Damage

Based on the coupled thermal/electrical analysis model constructed, effects of lightning current parameters as peak current, waveform parameters, charge transfer and action integral, on the extent of composite lightning strike ablation damage are analyzed, to confirm the characterization parameter of ablation damage.

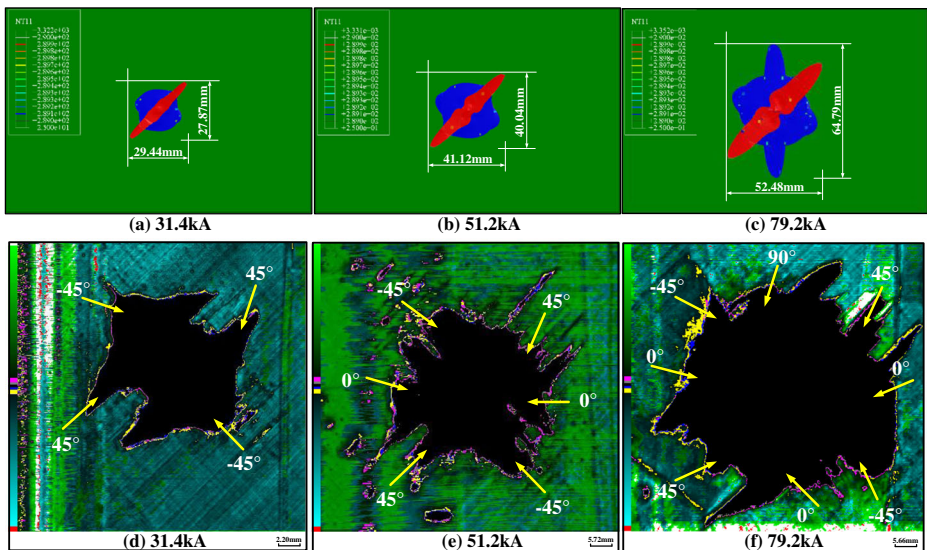


Fig. 8 Comparison of Internal damage distribution between experiment and simulation

Table 6 Internal damage sizes compared between experiment and simulation

Numbering	Peak current/kA	Internal damage sizes/mm				Internal damage area/mm ²		Error
		Experiment		Simulation		Experiment	Simulation	
		Length	Width	Length	Width			
D1	31.4	34.36	33.58	29.44	30.04	1153	884	-23.33%
D3	51.2	47.69	46.52	41.12	40.04	2218	1646	-25.78%
D4	79.2	67.23	64.98	52.48	64.79	4362	3400	-22.05%

The scatter points of visual damage area, projected damage area, maximum damage depth and damage volume with peak current for different current waveforms are plotted in Fig. 9, from the fitting curves in Fig. 9 we can see that under the same current waveform, visual damage area, projected damage area, maximum damage depth and damage volume change linearly with the peak current rise approximately. Furthermore, under the same peak current, extent of these above damage form also increases with the current waveforms rise. However, compared the damage extent under lightning current A (current waveforms 2.6/10.6 μ s, peak current 80kA) with lightning current B (current waveforms 6/69 μ s, peak current 50kA) in the single scatter plot in Fig. 9, damage extent of all the mentioned damage forms of the former is less than that of the later, it indicates that just the peak current or the current waveform are unable to characterize the extent of ablation damage completely.

Effects of charge transfer on visual damage area, projected damage area, maximum damage depth and damage volume are plotted in Fig. 10. From the single scatter in Fig. 10 that accompany with the enhancement of charge transfer, change trend of the extent of these above damage form displays increased trend, however, there exist several scatter points which decrease with the enhancement of charge transfer. For the sake of investigating the correlation between charge transfer and ablation damage extent, regression analysis with respect to extent of ablation damage and charge transfer were analyzed by Matlab software, and regression analysis functions are set as linear and power function respectively. Under the two different kinds of regression analysis functions, the related indexes R^2 are shown in Table 8. According to the values of related indexes R^2 , all the damage forms above show power function relationship with charge transfer, that is to say, charge transfer could characterize the extent of ablation damage to some degree.

The effects of action integral on visual damage area, projected damage area, maximum damage depth and damage volume are plotted in Fig. 11, single points in Fig. 11 present the ablation damage extent under different action integral. It can be easily known that the extent of

Table 7 Maximum damage depth compared between experiment and simulation

Numbering	Peak current/kA	Maximum damage depth/mm		Error
		Experiment	Simulation	
D1	31.4	0.45	0.475	5.56%
D3	51.2	0.63	0.656	7.50%
D4	79.2	0.96	0.890	-7.29%

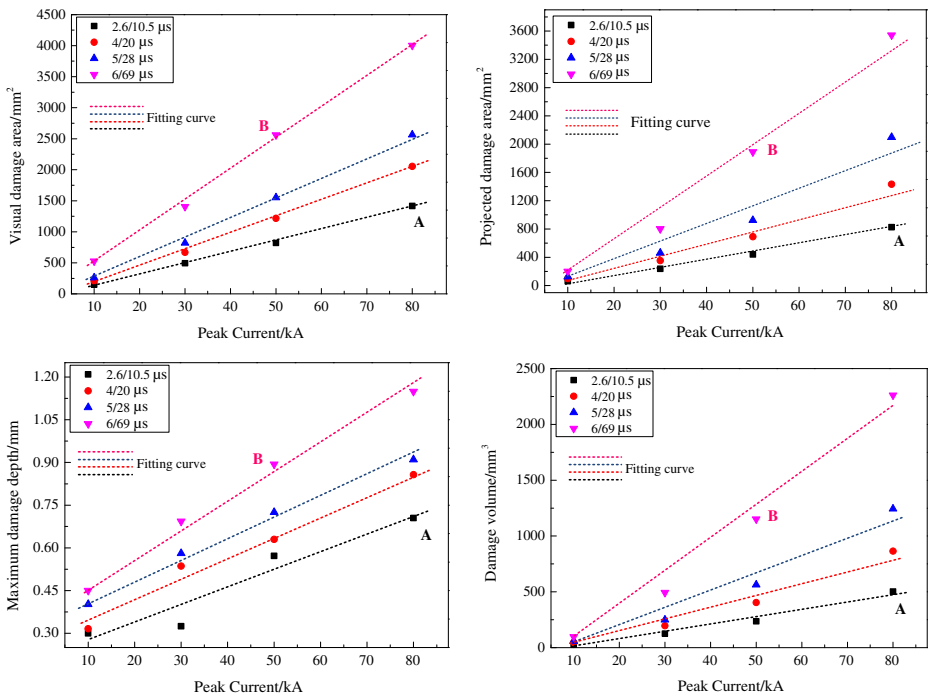


Fig. 9 Effects of peak current on the extent of ablation damage

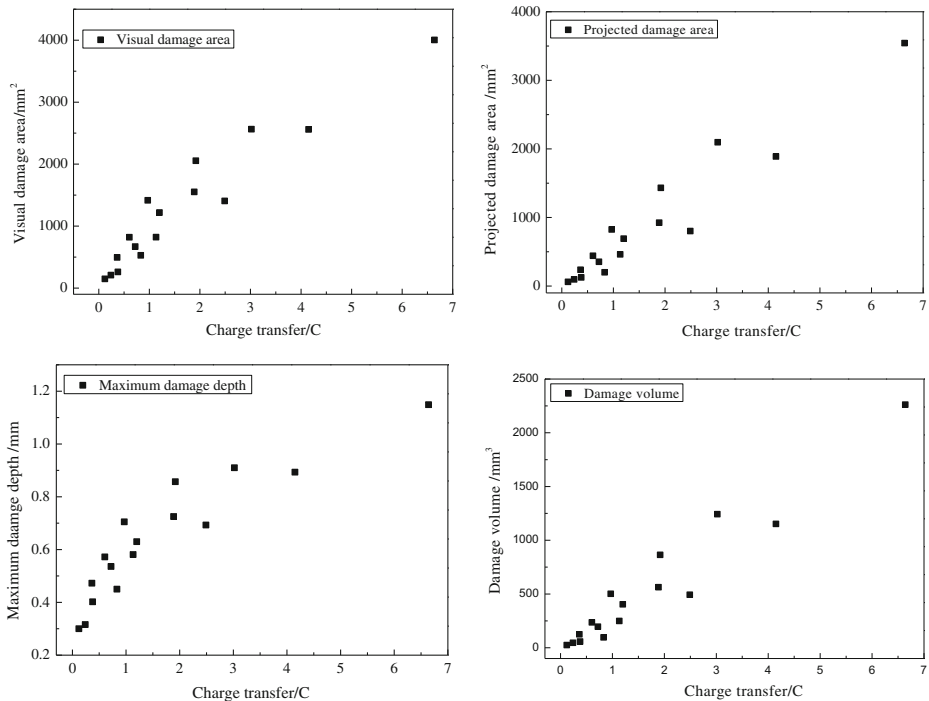


Fig. 10 Effects of charge transfer on the extent of ablation damage

Table 8 Related indexes- R^2 of regression analysis

Damage type Regression functions	Visual damage area	Projected damage area	Maximum damage depth	Damage volume
Linear	0.9120	0.9259	0.8014	0.9326
Power	0.9315	0.9260	0.9121	0.9328

ablation damage increases with the rise of action integral, and the following behaviors between them present well. Similarly, for the sake of investigating the correlation between action integral and ablation damage extent, regression analysis with respect to extent of ablation damage and action integral were analyzed by Matlab software, and regression analysis function is set as power function, under which, the related indexes R^2 between action integral and visual damage area, projected damage area, maximum damage depth and damage volume are 0.9976、0.9969、0.99、0.9989 respectively. According to the values of related indexes R^2 , all the damage forms above show strong power function relationship with action integral, that is to say, action integral could characterize the extent of ablation damage perfectly.

Action integral as the critical parameter to measure the intensity of lightning current, which multiplied by resistance can be used to calculate the resistance heating generated during lightning strike, and the simulated ablation damage fully caused by resistance heating. This is why the action integral can be used to characterize the extent of ablation damage.

4.3 Effects of Thermal/Electrical Properties on Ablation Damage

The effects of composite thermal and electrical properties, as electrical conductivity, thermal electrical conductivity and specific heat, on the extent of composite lightning strike ablation damage are analyzed in this chapter, to provide some guidance for composite anti-lightning

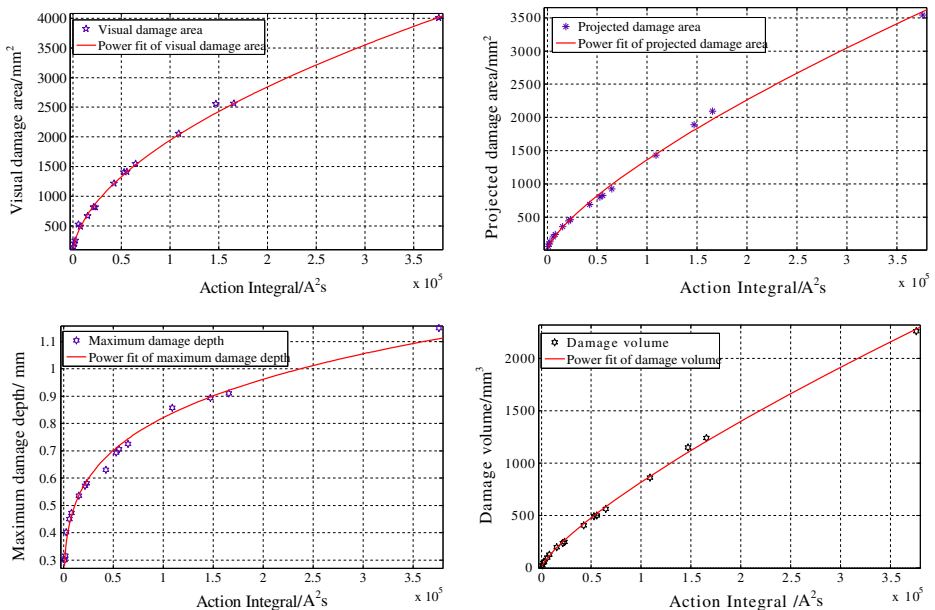


Fig. 11 Effects of action integral on the extent of ablation damage

strike design. During the simulation, the simulated lightning current waveform remains 4/20 μ s and the peak current reaches 30kA. And extent of lightning strike ablation damage is represented by visual damage area. Figure 12 shows the visual damage distribution and size under original material properties.

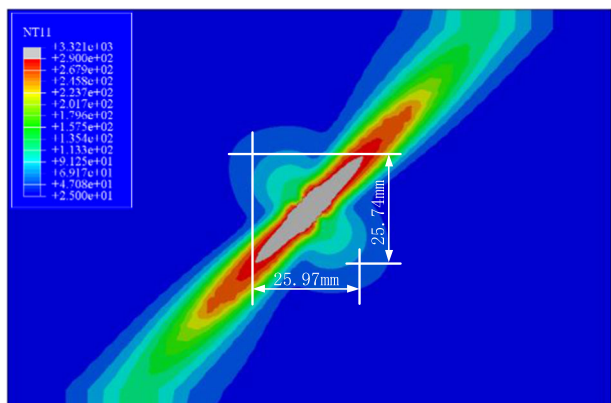
When the electrical conductivity increases from 3.5293×10^4 S/m to 3.5293×10^7 S/m, visual damage distributions under different electrical conductivity are shown in Fig. 13(a)–(c). Compared Fig. 13(a)–(c) with Fig. 12, accompany with the enhancement of electrical conductivity, visual damage extent decreased promptly. When the electrical conductivity enhances three orders of magnitude than the original, the visual damage territory is hardly to be observed. The simulated ablation damage is fully caused by resistance heating, and accompany with the increase of electrical conductivity, resistance heating generated during current conduct will decrease a lot, so, the ablation damage extent decrease promptly. Currently, improving the composite anti-lightning strike ability through enhance its own electrical conductivity becomes a major research issue.

When the thermal conductivity increases from 8.0 W/(m·K) to 8000 W/(m·K), visual damage distributions under different electrical conductivity are shown in Fig. 13(d)–(f). Compared Fig. 13(d)–(f) with Fig. 12, visual damage extent of composite laminate has no obvious change accompany with the enhancement of thermal conductivity. Lightning strike occurs in an extreme short time, and during which vast resistance heating generated, through its magnitude of thermal conductivity increases three orders, resistance heating generated by current conduct cannot be conducted away instantaneously. Therefore, thermal conductivity of composite has little effects on the extent of ablation damage.

When the specific heat increases from 1065 J/kg $^{\circ}$ C to 10,650 J/kg $^{\circ}$ C, visual damage distributions under different specific heat are shown in Fig. 13(g)–(i). Compared Fig. 13(g)–(i) with Fig. 12, it can be seen that visual damage area decreases with the increasing specific heat. With higher specific heat, more energy will be needed for unit volume rising the same temperature, and under the same resistance heating, the higher specific is, the slower temperature arise rate and fewer temperature rising volume present, so, the corresponding ablation damage extent of composite tends to decrease.

The visual damage areas under different thermal/electrical conductivities of composite are simulated, and then by means of regression analysis, the fitting curve of visual damage area with regards to electrical conductivity is shown in Fig. 14 (a), from which we can clearly see

Fig. 12 Ablation damage under origin material properties



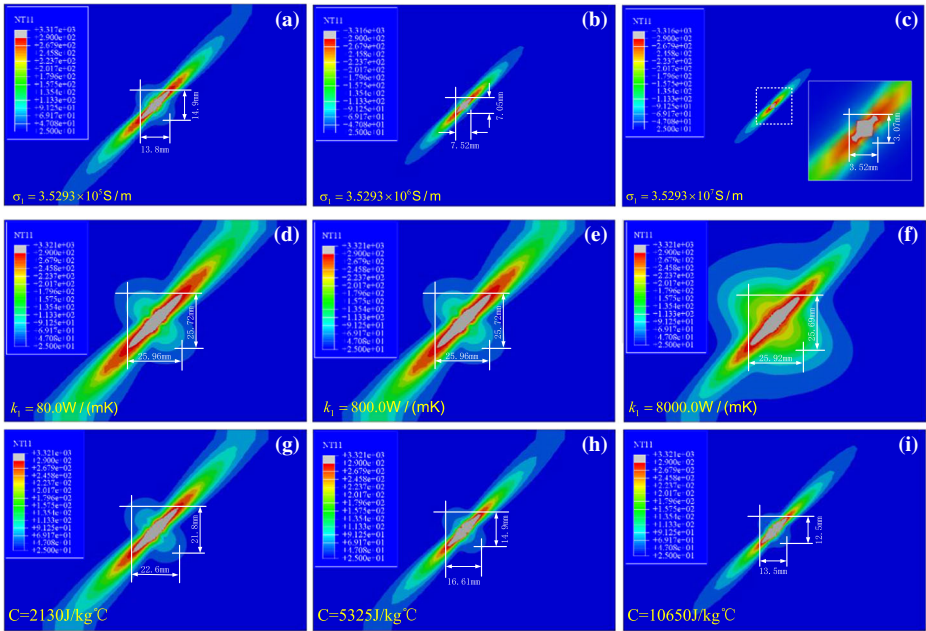


Fig. 13 Ablation damage distribution under different thermal/electrical material properties

the strong power function relationships between ablation damage and electrical conductivity, and related indexes R^2 between action integral and visual damage area is 0.9995. The fitting curve between visual damage area and thermal conductivity is shown in Fig. 14 (b), it can be seen that with the increase of the thermal conductivity, ablation damage is hardly changed. The

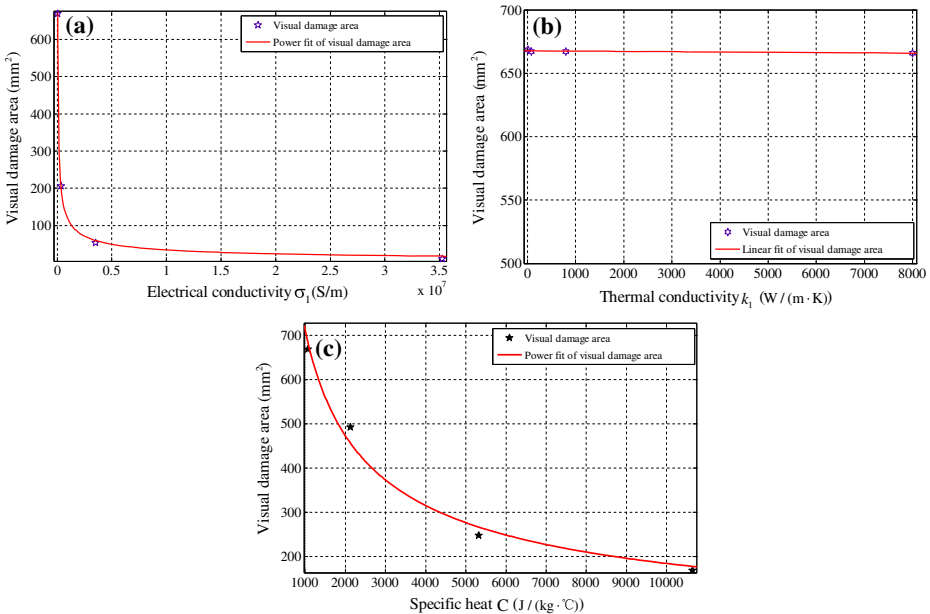


Fig. 14 Effects of thermal/electrical material properties on visual damage area

fitting curve between visual damage area and specific heat is shown in Fig. 14 (c), from which we can see that visual damage area also has a strong power function relationship with the specific heat, related indexes R^2 between specific heat and visual damage area is 0.9870.

According to the analysis above, we can draw the conclusion that composite anti-lightning ability can be improved obviously by enhancing the composite own electrical conductivity or specific heat, among them, effect of enhancing electrical conductivity on reducing ablation damage is most remarkable. There exist no obvious affection between thermal conductivity and ablation damage.

5 Conclusions

According to the mathematical analysis model constructed on the basis of energy-balance relationship in lightning strike, and accompany with the simplified calculation strategy of composite resin pyrolysis degree dependent electrical conductivity, an effective three dimensional thermal-electrical coupling analysis finite element model of composite laminate suffered from lightning current was established based on ABAQUS. The accuracy of numerical method was validated by comparing with composite lightning strike directed effect experimental data from visual damage appearance, projected damage area and maximum damage depth, and well consistency was obtained.

Effects of lighting current waveform parameters and thermal/electrical properties of composite laminate on the damage extent with regards to lightning strike ablation damage were analyzed by simulation. Results indicate that extent of composite lightning strike ablation damage is obviously affected by lighting current waveform parameters and action integral could characterize the extent of ablation damage perfectly. Visual damage area, projected damage area, maximum damage depth and damage volume show strong power function relationship with action integral. Composite own thermal/electrical material properties could affect the ablation damage extent, with the same lightning current parameters, ablation damage extent can be decreased by enhancing the composite own electrical conductivity or specific heat, and visual damage area has a strong power function relationship with the thermal conductivity and specific heat. There exist no obvious affection between thermal conductivity and ablation damage. The conclusions obtained provide some guidance for composite anti-lightning strike structure-function integration design.

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References

1. Miller, A.: The Boeing 787 dreamliner. Keynote address. In: 22nd American society for composites technical conference, Seattle, WA; September. (2007)
2. Mall, S., Ouper, B.L., Fielding, J.C.: Compression strength degradation of nanocomposites after lightning strike. *J. Compos. Mater.* **00**, 1–15 (2009)
3. Larsson, A., Delannoy, A., Lalande, P.: Voltage drop along a lightning channel during strikes to aircraft. *Atmos. Res.* **76**, 377–385 (2005)
4. Gagne, M., Therriault, D.: Lightning strike protection of composites. *Prog. Aerosp. Sci.* **64**, 1–16 (2014)
5. Wang, F.S., Ji, Y.Y., Yu, X.S.: Ablation damage assessment of aircraft carbon fiber/epoxy composite and its protection structures suffered from lightning strike. *Compos. Struct.* **145**, 226–241 (2016)

6. Lightning Direct Effects Handbook, AGATE-WP3.1–031027-043-design guideline, (2002)
7. Hirano, Y., Katsumata, S., Iwahori, Y.: Artificial lightning on graphite/epoxy composite laminate. *Compos. Part A*. **41**, 1461–1470 (2010)
8. Feraboli, P., Kawakami, H.: Damage of carbon/epoxy composite plates subjected to mechanical impact and simulated lightning. *J. Aircr.* **47**, 999–1012 (2010)
9. Feraboli, P., Miller, M.: Damage resistance and tolerance of carbon/epoxy composite coupons subjected to simulated lightning strike. *Compos. Part A*. **40**, 954–967 (2009)
10. Ogasawara, T., Hirano, Y., Yoshimura, A.: Coupled thermal–electrical analysis for carbon fiber/epoxy composites exposed to simulated lightning current. *Compos. Part A*. **41**, 973–983 (2010)
11. Abdelal, G., Murphy, A.: Nonlinear numerical modeling of lightning strike effect on composite panels with temperature dependent material properties. *Compos. Struct.* **109**, 268–278 (2014)
12. Dong, Q., Guo, Y.L., Sun, X.C.: Coupled electrical-thermal-pyrolytic analysis of carbon fiber/epoxy composites subjected to lightning strike. *Polymer*. **56**, 385–394 (2015)
13. Dong, Q., Guo, Y.L., Chen, J.L.: Influencing factor analysis based on electrical–thermal-pyrolytic simulation of carbon fiber composites lightning damage. *Compos. Struct.* **140**, 1–10 (2016)
14. Wang, Y.Q., Zhupanska, O.I.: Thermal Ablation in Fiber-Reinforced Composite Laminates Subjected to Continuing Lightning Current. 57th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, San Diego, California, USA. (2016)
15. Wang, F.S., Ding, N., Liu, Z.Q.: Ablation damage characteristic and residual strength prediction of carbon fiber/epoxy composite suffered from lightning strike. *Compos. Struct.* **117**, 222–233 (2014)
16. Fanucci, J.: Thermal response of radiantly heated Kevlar and graphite/epoxy composites. *J. Compos. Mater.* **21**, 129–139 (1987)
17. Griffis, C.A., Nemes, J.A., Stronesifer, F.R., Chang, A.I.: Degradation in strength of laminated composites subjected to intense heating and mechanical loading. *J. Compos. Mater.* **20**, 216–235 (1986)
18. Standard test method for measuring the damage resistance of a fiber reinforced polymer matrix composite to a drop-weight impact event. ASTM D7136M-07, American Society for Testing and Materials (ASTM), West Conshohocken, PA, USA. (2007)
19. SAE-ARP-5412A, Aircraft lightning environment and related test waveforms. (2005)
20. Abaqus: Users’ Manual, version 6.14. ABAQUS, Inc. (2014)
21. Yin, J.J., Li, S.L., Chang, F.: Ablation damage characteristic analysis of composite laminate with fastener subjected to lightning strike. *Appl. Compos. Mater.* **23**, 821–837 (2016)
22. Li, S.L., Yin, J.J., Yao, X.L.: Damage analysis for carbon fiber/epoxy composite exposed to simulated lightning current. *J. Reinf. Plast. Compos.* **35**, 1201–1213 (2016)
23. Bai, Y., Keller, T., Vallee, T.: Modeling of thermo-physical properties and thermal responses for FRP composites in fire. Asia-Pacific Conference on FRP in Structures. APFIS. (2007)
24. Lee, J.H., Kim, K.S., Kim, H.: Determination of kinetic parameters during the thermal decomposition of epoxy/carbon fiber composite material. *Korean J. Chem. Eng.* **30**, 955–962 (2013)