



Damage Characteristics of CFRP Laminates Subjected to Multiple Lightning Current Strike

Jinru Sun¹ · Xueling Yao¹  · Xiangyu Tian¹ · Jingliang Chen¹ · Yi Wu¹

Received: 13 July 2018 / Accepted: 8 November 2018 / Published online: 12 December 2018
© Springer Nature B.V. 2018

Abstract

The lightning damage depths and areas of carbon fiber reinforced polymer (CFRP) laminates subjected to multiple continuous sequential lightning current components with different timing combinations were experimentally evaluated. The experimental results indicated that the CFRP laminates suffered serious lightning damage, including fracture of the carbon fibers and layer delamination. After a multiple lightning strike composed of lightning components A, B and C, the surface temperature of the CFRP laminates, which was projected from the measured temperature with lower magnitude, can exceed 1600 °C. The damage area and depth were approximately 2790 mm² and 1.28 mm in the “ABCD” test mode. The damage depth was found to be closely related to lightning components A, B and D, which are accompanied by the shockwave and the overpressure effect, the dielectric breakdown effect and the local thermal effect. The increases in the surface temperature and damage area after lightning strike were mainly affected by the lightning component C with substantial thermal effect. The application sequence and material properties are important factors for evaluating the damage effect of the newly added lightning component on samples that have suffered from multiple continuous lightning components. The influencing factors and analysis method for CFRP laminate lightning damage subjected to multiple continuous sequential lightning components may provide both experimental support and a theoretical basis for studying the mechanism of the lightning effect and the refinement and improvement of a lightning direct effect test method for CFRP laminates in the future.

Keywords Carbon fiber reinforced polymer · Multiple continuous sequential lightning strike · Damage mechanism · Non-destructive testing

1 Introduction

Lightning strike seriously affects the safe operation of aircrafts. The aircrafts will suffer from burning, melting, structural distortion and explosion due to the acoustic shock,

✉ Xueling Yao
xlyao@xjtu.edu.cn

electromagnetic force and thermal effect caused by the attachment and infusion of lightning current [1, 2]. The likelihood for an aircraft of being struck is related to weather conditions, aircraft type, and flight height. Every strike incident takes an average of 3000 h in commercial transport time [3, 4].

The proportion of the carbon fiber reinforced polymer (CFRP) continues to grow in unmanned aircraft, stealth aircraft, military aircraft and commercial aircraft including Boeing 787 and Airbus A350XWA due to its mechanical advantages of low density, superior static strength, high durability and excellent workability [5, 6]. However, the electrical conductivity ($10^2 - 10^4$ S/m of in-plane direction, 10^{-4} S/m of in-thickness direction) and thermal conductivity ($10^{-1} \sim 10^0$ W/m $^\circ$ C) of CFRP laminates are very poor compared to those of metallic materials, such as aluminum, steel and titanium alloy (10^6-10^8 S/m and 10^2 W/m $^\circ$ C) [7–9]. Thus, the large amounts of charge and heat associated with a lightning strike cannot be transferred and dissipated effectively, causing a sharp increase in local temperature and serious damage, such as fiber sublimation, resin pyrolysis and deep delamination, in CFRP laminates.

Therefore, the experimental research and computational simulation into lightning damage properties and lightning protection methods in CFRPs has important scientific and practical value. Hirano et al. [10] examined the evolution of damage in CFRP laminates due to lightning strikes with the parameters of 2.6/10.5 μ s, 4/20 μ s and 7/150 μ s. They found that the damage modes can be categorized into fiber damage, resin deterioration, and internal delamination modes, and damage progression is governed by the strong electrical orthotropic properties of the laminates. Li et al. [11] used simulated lightning strike (6.8/24 μ s) with different current levels exerted on two stacking sequenced carbon woven fabric/epoxy laminates to study the damage behavior on the material experimentally. The experimental results showed that an enlarged resin pyrolyzed area appeared primarily along the weft orientation, while the delamination region extended equally in both the warp and the weft direction. The simulation model for lightning's direct effect on CFRPs has been established by many researchers to explore the lightning process and the lightning damage experienced by CFRP laminate [12–16]. Chemartin et al. [12] investigated the shapes and behaviors of lightning arc attachment on CFRP material subjected to lightning strike, and the thermal and mechanical constraints of the lightning damage effect were illustrated through numerical results. Liu et al. [13] used a comprehensive simulation procedure combining electrical-thermal analysis and BLOW-OFF impulse (BOI) analysis to investigate lightning direct effects on CFRPs. They proposed that the temperature distribution of the composite laminate was mainly affected by the electrical anisotropy because of Joule heating, and the strain fields determined from the analysis matched well with the damage pattern of lightning specimen. In addition, many researchers used the coupled electrical-thermal model and speculated that lightning damage was mainly related to the generation and conduction of the Joule heat, meaning that the distributions of resin deterioration, fiber fracture and delamination were dependent on the lightning energy and the anisotropy of the CFRP laminates [14–16].

The lightning strike process is a complex physical process which comprises of sequential current impulses and involves multiple physical fields such as the high-voltage shockwave, Joule heat and the electromagnetic force generated by strong current [17]. To simulate the lightning damage conditions in CFRP laminates for a real lightning process, the lightning current components should be applied in a combination within the given test shot, rather than as individual, distinct shots. As the lightning test method recommended in SAE ARP5412 and ARP5416 [1, 18], the stipulated lightning test on

CFRPs used in aircraft should be conducted with multiple continuous sequential lightning waveforms consisting of four components including initial stroke, intermediate current, continuing stroke and subsequent return stroke, as shown in Fig. 1. Although a lightning test method has been recommended in standards [1, 18], most researchers have conducted experimental and computational simulation studies using a single lightning current component (lightning component A or D) or a current impulse that differs from the lightning waveforms specified by ARP 5412 [10–16]. Few studies examined the lightning damage properties of CFRP materials subjected to multiple continuous sequential lightning components and aimed to explore at the lightning direct effect of different zones in aircraft [19]. With the development and extensive application of CFRP composites in the aerospace field, the lack of studies of the mechanism for the lightning direct effect and testing methods for lightning protection performance has become a bottleneck restricting the further development and application of advanced composite materials.

In this paper, the lightning damage of CFRP laminates under multiple continuous sequential lightning current components with different timing combinations was investigated experimentally via visual inspection, infrared temperature measurement, ultrasonic T-scan and C-scan. The contribution of lightning current components to the lightning damage of CFRP laminates was derived and the relationship between the properties of lightning current components and the lightning damage degree was obtained. The research improves the understanding of the electrical process and mechanism of lightning strike, and it can provide experimental support and a theoretical basis for the future refinement and improvement of the lightning test method and lightning protection characteristic assessment of CFRP laminates.

2 Experimental Method

2.1 Test Samples

Carbon fiber/epoxy (T300/3021) composite laminates, in which the volume fraction of carbon fibers is 60% approximately, were selected as the test specimens in experiment. The size of the samples is 300 mm × 45 mm × 3.6 mm with a 24-ply quasi-isotropic layup ($[-45/45/0/90_2/$

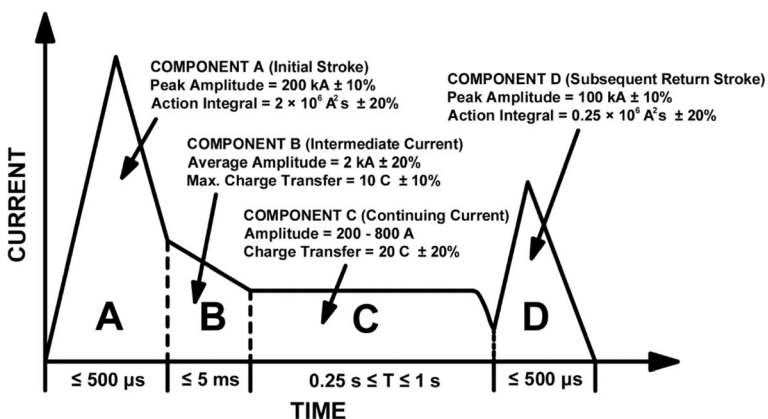


Fig. 1 Lightning current waveforms in the lightning direct effect test [1]

–45/0/45/0/90/45/–45]_s). The thickness of each layer is approximately 0.15 mm. The test samples used in this experiment are in the same batch as the samples in the literature [20], and the material properties, including anisotropy electrical conductivity, thermal conductivity and specific heat, can be referred to in the literature [20].

2.2 Experimental Setup

2.2.1 The Clamp Device

The clamp device used for fixing CFRP laminates is shown in Fig. 2.

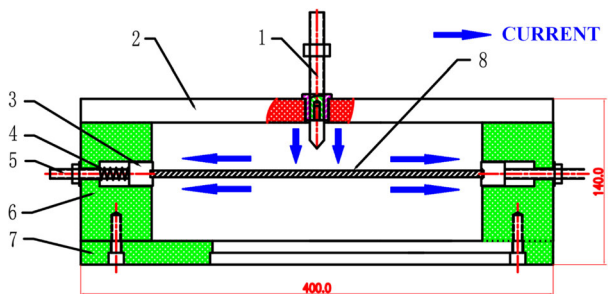
The positive electrode is a conical-head electrode made of copper lead screw with a diameter of 10 mm. The discharge gap between the electrode and the CFRP surface was adjusted to 2 mm. Under the compression force of spring in left, the CFRP laminate will be tightly embedded between the grooved copper bars. To simulate the spreading of lightning current and lightning damage in the CFRP laminates, the lightning injection point was positioned at the center of the tested laminate, and symmetrical copper bars were used as the negative electrodes. The current conduction path was indicated as the blue arrows shown in Fig. 2.

2.2.2 Lightning Direct Effect Test System

The multiple continuous sequential lightning direct effect test system (Fig. 3) developed by the High-voltage and High-current Measurement Technology and Equipment Engineering Laboratory (Xi'an Jiaotong University) was used in this study.

The test system can generate multiple continuous sequential lightning current components, including the lightning components A, B, C and D, as stipulated in SAE ARP 5412 [1]. Lightning current components A and D are unipolar current impulses generated by crowbar circuits. The lumped parameters chain consisting of capacitors and inductances is used to generate the lightning current component B. Lightning component C is the long-duration continuing current generated by a three-phase controllable rectifier circuit.

Notably, the lightning components shown in Fig. 1 are generally used in the lightning direct effect test for complete aircraft or its parts on a large scale. However, under the effect of



1 - Positive electrode; 2 - Cover plate; 3 - Copper bar; 4 - Spring;
5 - Negative electrode; 6 - Insulation support; 7 - Pedestal; 8 - CFRP Samples;

Fig. 2 The clamp device used to fix the CFRP laminates

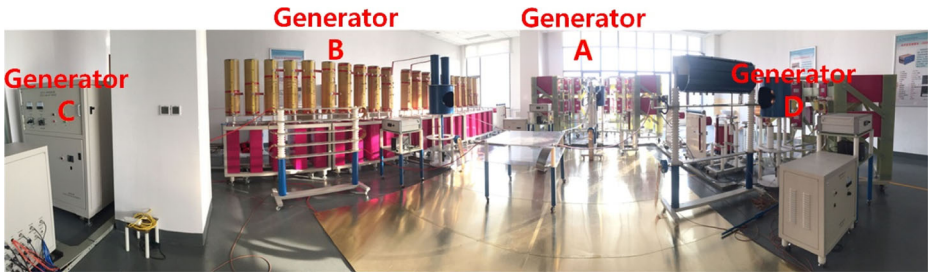


Fig. 3 Lightning direct effect test system

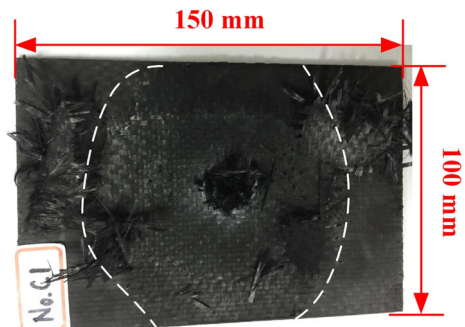
lightning component A with an amplitude of 100 kA, the CFRP laminate ($150 \times 100 \times 4$ mm) suffers severe lightning damage, as shown in Fig. 4.

The surface fiber was significantly fractured and warped, and the damage area on the test CFRP laminate extended to the edge of the sample laminate. If the subsequent lightning components are continuously applied under this damage condition, the damage area of the test CFRP laminate will not increase as expected due to the limited size of the test samples. To avoid an adverse effect on the validity and accuracy of the experimental results, the damage area should be contained within the specimen center and remote from any edges, which means that the lightning current components with rated intensity in lightning strikes test requires larger CFRP samples. Therefore, lightning impulse components with the same intensity reduction were used in this study. Specifically, the experimental lightning waveforms differ from the standardized lightning waveforms only in intensity, and their other parameters, including rise time and duration, meet the requirements of the standard, as shown in Fig. 5. Since the intensities of the test lightning current components are reduced by the same proportion, the research results obtained from this study are valuable for future studies into the contribution of higher intensities of each lightning component to the lightning damage effect of CFRP laminates.

2.3 Test Method

Because the intensity and frequency of lightning strikes on different parts and structures differ, the aircraft is divided into several zones with different combinations of test waveforms [19]. In this experiment, fifteen test samples of the same type were divided into five groups with different test modes, which were selected based on the stipulated test mode in SAE ARP 5414, as shown in Table 1. After the lightning strike test, the damage

Fig. 4 Lightning damage of a CFRP laminate under the effect of lightning component A with an amplitude of 100 kA



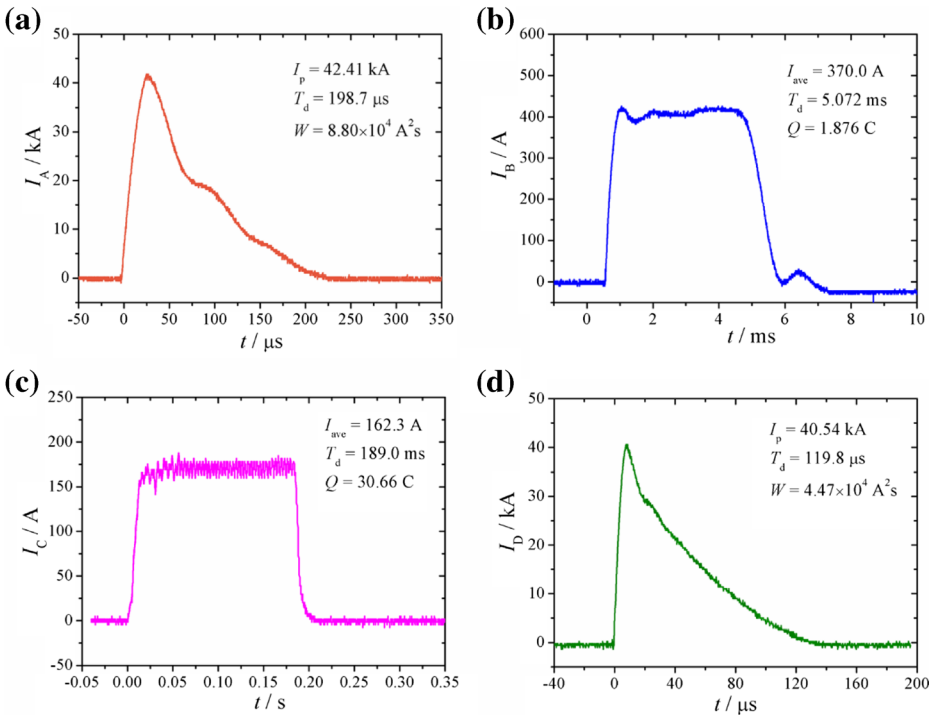


Fig. 5 The waveforms and parameters of the lightning current components: **a** lightning component A, **b** lightning component B, **c** lightning component C, and **d** lightning component D. I_p : amplitude; I_{ave} : average current; T_d : duration; W : electrical action integration; and Q : transfer charge

depths of these fifteen samples were measured, and typical samples (S1 to S5) were selected as the representative damage results in every test mode.

The lightning components in every test mode should be applied continuously in one shot, rather than as individual, distinct test shots. For example, in test mode “ABCD”, lightning component B is injected within 500 μ s after lightning component A; lightning component C is injected into the CFRP samples within 5–10 ms after lightning component B. Lightning component D is applied before the end of lightning component C, as shown in Fig. 6.

3 Results and Discussion

3.1 Visual Inspection of Lightning Damage

The lightning process is recorded by the high-speed camera. During the lightning strike, a dazzling white light was emitted by the arc, a red flame was generated from the burning

Table 1 The applied lightning components in different test modes and corresponding samples

Sample	S1	S2	S3	S4	S5
Test mode	“A”	“AB”	“DBC”	“ABC”	“ABCD”

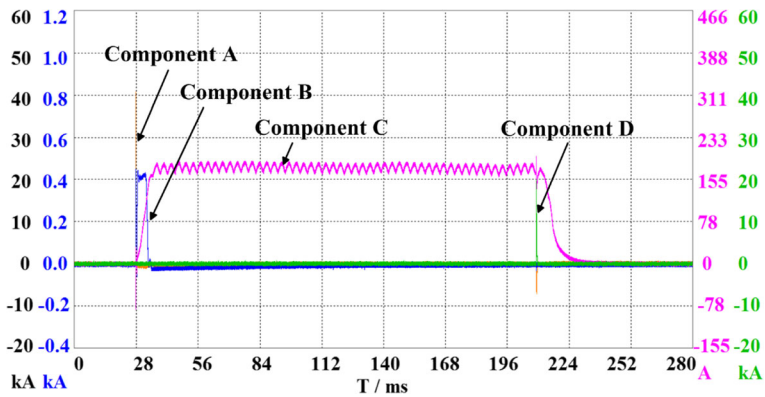


Fig. 6 Continuous test waveform for the “ABCD” test mode

laminate, and burst fibers were observed on the CFRP sample. After the lightning strike process, the black smoke and a pungent smell were generated after the lightning strike, as shown in Fig. 7.

The parameters of the applied lightning components in different combination and images of the CFRP samples after a lightning strike are shown in Table 2 and Fig. 8.

From the lightning damage shown in Fig. 8, the damage results are summarized as follows:

- (1) The tested sample S1 was subjected to lightning component A (peak current $I_p \approx 40\text{kA}$; transfer charge $Q \approx 3\text{C}$) suffered from an obvious bulge and fracture of carbon fibers along the surface fiber layer direction (-45° direction), especially at the lightning attachment point. At the same time, bundles of carbon fibers swelled up and were delaminated in the directions of -45° and 45° , which are the ply directions of the first and the second layers. The symmetrical delamination area expanded outward along the axis of the fracture fiber. Some local damage points caused by fiber fracture scattered on the surface of CFRP laminates, as shown in Fig. 8a. The damage in sample S2 is similar to the damage in sample S1, but the degree was more serious (Fig. 8b).
- (2) For samples S3, S4 and S5, the injection of the lightning component C led to an obvious near-circular erosion pit at the lightning attachment point. A large area of severe fiber fracture and delamination for several layers was observed around the lightning attachment point. Several piles of flaky carbon black powder were deposited on the sample surface, which could possibly result from sublimation of carbon fibers and pyrolytic carbonation due to the high temperature of the lightning arc. In sample S5, the damage area extended to the edge of the sample laminate. It is worth

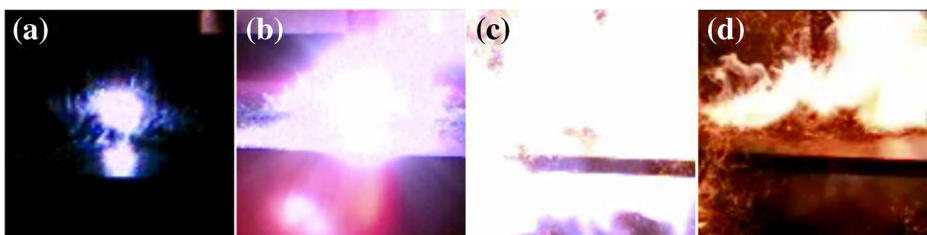


Fig. 7 The discharge process: **a** $t = 4.52 \mu\text{s}$; **b** $t = 9.04 \mu\text{s}$; **c** $t = 363.2 \mu\text{s}$; **d** $t = 726.4 \mu\text{s}$

Table 2 The parameters of lightning component waveforms in different test modes

	Component A			Component B			Component C			Component D		
	I_p/kA	$T_d/\mu s$	W/A^2s	I_{ave}/A	T_d/ms	Q/C	I_{ave}/A	T_d/ms	Q/C	I_p/kA	$T_d/\mu s$	W/A^2s
S1	41.67	26.76	79,225	—	—	—	—	—	—	—	—	—
S2	41.28	25.75	81,659	374.0	5.036	1.883	—	—	—	—	—	—
S3	—	—	—	362.9	5.070	1.840	163.0	187.8	30.61	35.21	14.00	47,968
S4	41.11	25.50	78,359	364.3	5.060	1.843	158.4	189.5	30.00	—	—	—
S5	40.81	25.50	76,353	375.4	5.054	1.897	170.3	191.3	32.57	19.89	14.50	18,804

noting that the size, shape and boundary conditions of the test sample will influence the lightning damage effect. The damage area in sample S5 would be greater if the size of sample S5 had been greater.

3.2 Temperature Properties of CFRP Laminates after Lightning Strike

When a CFRP laminate is struck by lightning current components, the temperature near the lightning attachment point will rise rapidly. The resin matrix will pyrolyze when the temperature exceeds 180 °C to 200 °C (aerobic conditions) and the carbon fibers will sublime at the temperature approaching 3000 °C [16, 21, 22]. The temperature distribution of sample S4 after the injection of lightning components in the “ABC” test mode was measured using a handheld infrared radiation thermometer (Fluke Ti125), as shown in Fig. 9.

As shown in Fig. 9, the high-temperature region is concentrated around the lightning attachment point and forms a near-circular erosion pit. After the lightning strike, for 13 s, which is the time required to enter the high-voltage test zone at the fastest speed and measure the surface temperature of the test sample, the maximum measured temperature of sample S4 is 142 °C. Considering the heat exchange with the outside environment, the CFRP laminate surface temperature drops exponentially after the lightning strike, as shown in Fig. 10.

Based on the temperature measured after the lightning strike test and considering both the temperature characteristics of arc ($10^3\sim 10^4$ K) [23, 24] and the duration of the lightning component combination (200 ms approximately), the curve fitting formula $T = A \times t^B$ and the certain value of $t = 1$ ms are selected to extrapolate the surface temperature of CFRPs. For sample S4, the curve fitting formula is $T = 277.183 \times t^{-0.25549}$. Therefore, the instantaneous temperature of the CFRP laminate surface after a lightning strike ($t = 1$ ms) can be

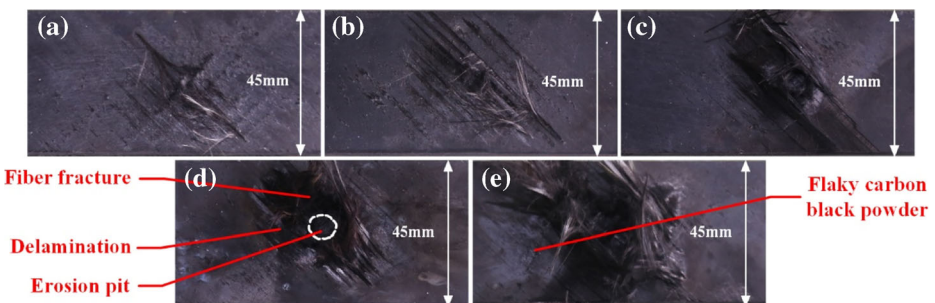


Fig. 8 The CFRP laminates after a lightning strike test: **a** S1, **b** S2, **c** S3, **d** S4, and **e** S5

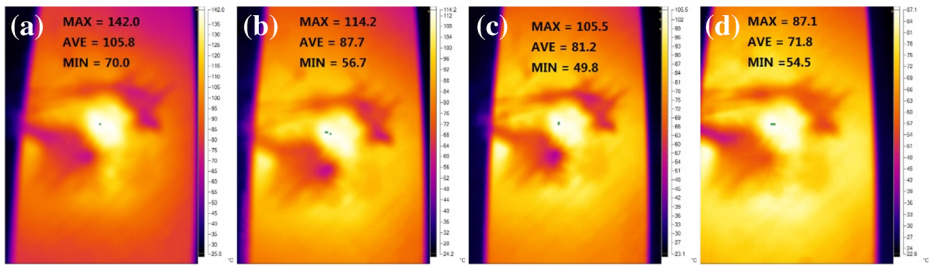


Fig. 9 Temperature distribution of sample S4 after lightning strike: **a** $t = 13$ s, $T_m = 142.0$ °C; **b** $t = 36$ s, $T_m = 114.2$ °C; **c** $t = 50$ s, $T_m = 105.5$ °C; **d** $t = 87$ s, $T_m = 87.1$ °C

estimated as 1614 °C. The same calculation method can be used to extrapolate the post-lightning surface temperature of other test samples (S1, S2 and S3) in the “A”, “AB” and “DBC” test modes, as shown in Fig. 11.

Although the extrapolated temperature does not indicate the precise value of CFRPs’ surface temperature, the extrapolated post-lightning temperatures of CFRP samples can represent the thermal effect of the applied lightning current components due to the same measurement and extrapolation method used for the temperature estimation of CFRP samples in different experimental modes. Comparing the post-lightning temperature ($t = 1$ ms) of the CFRP samples with different lightning test modes in Fig. 11, the surface temperature of the CFRP laminates increases with the number of applied lightning components. Correspondingly, the lightning damage of CFRP samples in Fig. 8 increases as the sample temperature increases. The post-lightning temperature of samples S3 and S4, which have endured the injection of the lightning component C, increases significantly, which indicate that the thermal effect of continuing current component C is more significant than that of the impulse current components A and B. In addition, considering the heat exchange between CFRP laminates and ambient environment during the loading process of lightning components, the maximum instantaneous temperature of CFRP

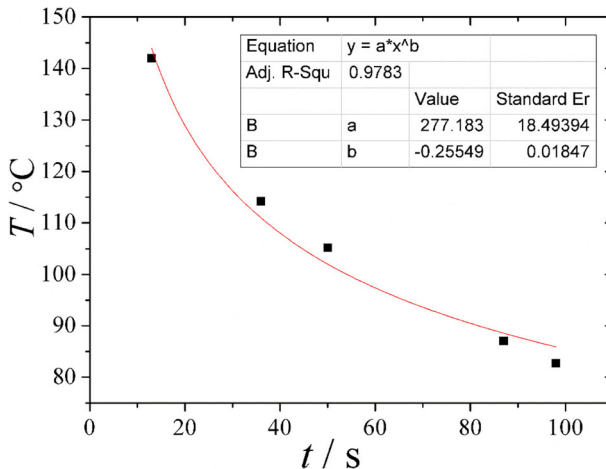


Fig. 10 Descending trend of the CFRP’s surface temperature (sample S4)

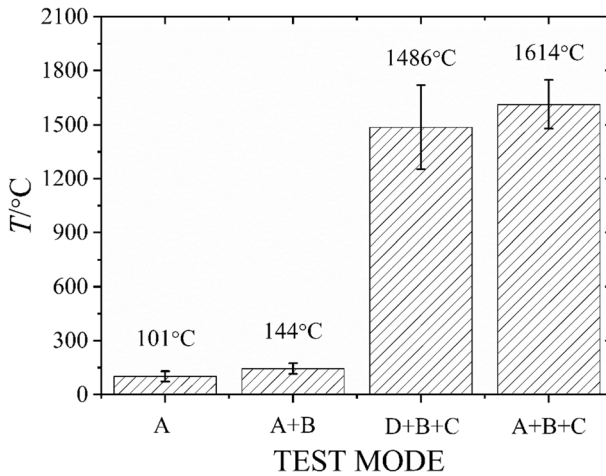


Fig. 11 Extrapolated post-lightning temperature of CFRP samples in different lightning test modes

laminates will be higher. The temperature rise in a large area of CFRP laminates may result in the sublimation of carbon fiber and the pyrolysis of the resin layer.

3.3 Damage Images of Ultrasonic Scan

Ultrasonic T-scan and C-scan were used to detect the lightning damage areas and damage depths of CFRP laminates. The ultrasonic test results for post-lightning test are shown in Figs. 12 and 13.

After the lightning strike, the smaller the thickness of the damage area was, the greater the damage depth. That is, the damage is more serious when the thickness is smaller in Fig. 13. From the scan results, the lightning damage areas are found to develop mainly in the directions of -45° and 45° . In particularly, the lightning damage area of sample S5 extended to the edge of sample S5 in the “ABCD” lightning test mode.

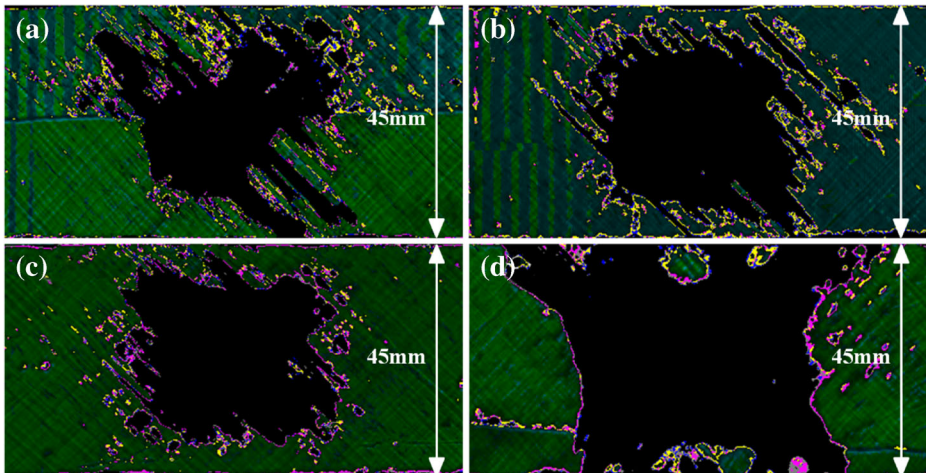


Fig. 12 Ultrasonic T-scan images of the lightning damage areas in CFRP samples: **a** S1, **b** S2, **c** S3, and **d** S5

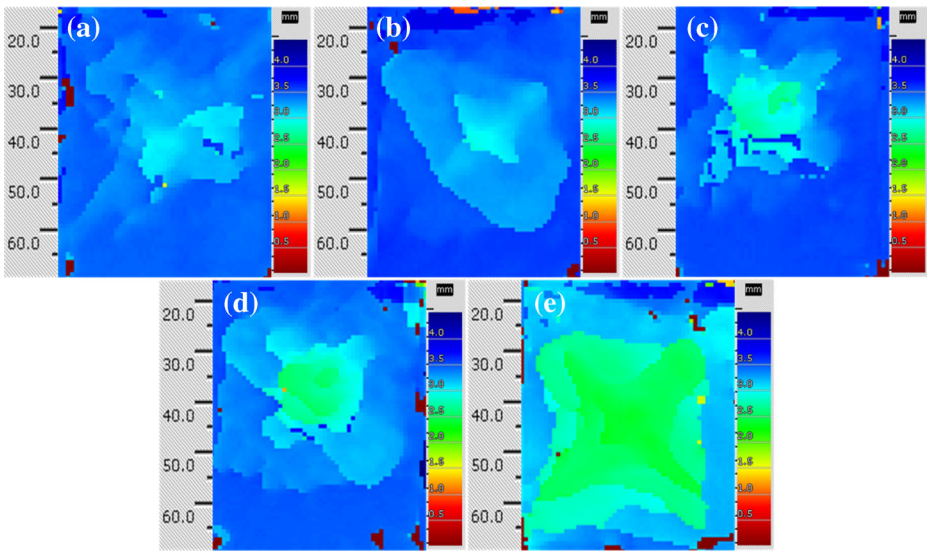


Fig. 13 Ultrasonic C-scan images of the lightning damage depth in the CFRP samples: **a** S1, **b** S2, **c** S3, **d** S4, and **e** S5 (The colors represent the thickness of the test CFRP laminate)

4 The Analysis for Lightning Damage of CFRP Laminates

4.1 Lightning Damage Areas and Depths of CFRP Laminates

The lightning damage types of CFRP laminates mainly include fiber breakage, delamination, resin pyrolysis and ablation [10], and the corresponding damage degrees are difficult to define and observe. Therefore, to quantitatively discuss the damage degree of the tested CFRP laminate, both the damage areas and the depths were calculated as a function of different test modes using the pixel statistics method from the scan images, as shown in Table 3. At the macroscopic level of the lightning effect, the damage area and damage depth represent different interaction processes of multiple continuous sequential lightning strikes. To be specific, the damage depth may be related to the shockwave and the overpressure effect, electromagnetic force effect and the local thermal effect caused by contact with the high temperature arcs; and the expansion of the damage area should result from the Joule heating effect generated when the current conducts in the CFRP laminates.

Since the lightning components contained in one test modes are applied sequentially, compared to the lightning damage effect in the test mode with fewer lightning components, the increase in the damage area and damage depth can be regarded as a contribution of the

Table 3 Lightning damage areas (S_d) and damage depths (D_d) of the CFRP samples in different test modes

Specimen	Test mode	Damage depth/mm	Damage area/mm ²
S1	A	0.513	1104
S2	AB	0.810	1323
S3	DBC	0.900	1453
S4	ABC	0.930	2400
S5	ABCD	1.280	2790

newly added lightning current component. The contributions of individual lightning components to damage depth and damage area are shown in Fig. 14.

The contribution of the lightning current component to the damage depth and damage area in Fig. 14 can be summarized as follows:

- (1) Both the damage areas and depths of CFRP samples increase with the increasing numbers of applied multiple lightning current components. The damage area was as large as 27.9 cm² and more than 8 fiber layers (1.28 mm) were destroyed when the lightning components A, B, C and D were applied continuously on sample S5 in a single shot.
- (2) The damage depth is affected significantly by lightning current components A, B and D, especially components A and D, rather than the low-amplitude, long-duration component C. The damage depth is 0.5 mm (sample S1) subjected to the single lightning current component A. The damage depth increases by 0.3 mm when lightning component B is applied continuously after lightning component A. However, when lightning component C is applied after lightning component A and B, the damage depth increases slightly, by only 0.12 mm (sample S4). Moreover, the final strike of lightning component D ($I_p = 20$ kA) results in the damage depth continuously increase by 0.35 mm in sample S5.
- (3) Lightning component C with a large transfer charge and a long duration seems to have a greater influence on the damage area than the other lightning current components. The damage areas of samples S2 and S5 increased by 219 mm² and 390 mm², respectively, due to the effects of lightning current components B (transfer charge of 1.88 C) and D (transfer charge of 2.07 C). Lightning component C led the damage area to significantly increase by 1077 mm² in sample S4, when it was applied continuously after lightning component A and B.
- (4) Although lightning current A contributes most to the damage depth and damage area (0.513 mm and 1104 mm², respectively), considering that lightning component A is applied on an intact CFRP sample S1, the damage is mainly distributed on the upper surface of the test sample. More than 80% of the damage area is concentrated within several upper layers, and the damage area with a damage depth greater than 0.5 mm does not exceed 150 mm².

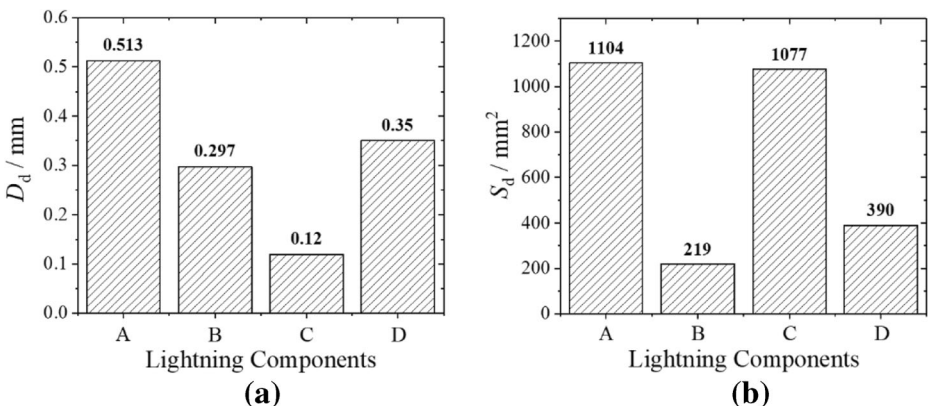


Fig. 14 The contributions of individual lightning current components to the **a** damage depth (D_d) and **b** damage area (S_d)

4.2 The Contribution of Lightning Components to Lightning Damage of CFRP Laminate

The characteristic parameters of each lightning current component contained in the multiple continuous lightning combinations are very different. For example, there is a difference of two orders of magnitude in the current amplitudes between lightning current C and lightning current A, and the difference in the current rising rate is close to four orders of magnitude. The transfer charge of lightning component C is approximately 20 times those of lightning components A and D. Therefore, the lightning strike process and damage effect of each lightning current component on CFRP laminate are also different. According to the analysis of the lightning damage results in Section 4.1, it can be seen that the damage depth is affected significantly by lightning components A and D. The extension of the damage area is closely related to lightning component C. We can speculate that the damage depth may be related to the shockwave and the overpressure effect, the electromagnetic force effect and contact with the high temperature arcs; the expansion of the damage area should result from the Joule heating generated when the current conducts in the CFRP laminates. Therefore, the generation process of lightning damage on CFRP laminates can be inferred as follows:

(1) Lightning damage depth

When lightning current components A and D, which have a high current rise rate and high amplitude, are applied to the CFRP laminates, and a huge amount of energy will be instantaneously released through the narrow discharge channel, leading to rapid compression and violent vibration in the surrounding air. The air shock will impose tremendous pressure on the CFRP laminates, and the intensity increases for higher-magnitude impulse currents and higher energy release rates. The impact effects and dielectric breakdown caused by the high-intensity electric field may result in instantaneous rupture and exposure at the lightning arc attachment point. In addition, the lightning damage depth of CFRP laminates may also increase due to the contact with the extremely high temperature of the impulse arc. Therefore, the carbon fibers at the lightning attachment point will melt and break, leading to exposure of the inner layer of the CFRP. Additionally, the current flowing through the inner carbon fiber layers further increases the damage depth. Based on the aforementioned analysis, we can speculate that the lightning damage depth of the CFRP laminates may be closely related to the amplitude and rise rate of the lightning impulse current.

(2) Lightning damage area

When a lightning strike is applied on the CFRP laminates, the lightning current will flow along the direction of carbon fibers inside the CFRP laminates. Joule heating is generated along the current conduction path, which is likely to result in pyrolysis of the resin and erosion or sublimation of the carbon fibers. The lightning damage expands outward along the axis of the fracture fiber and leads to a symmetrical fan-shaped delamination damage area in CFRP laminates. In addition, the relationship between the damage area and the surface temperature of the CFRP samples (Fig. 11) also indicated that the lightning damage area of a CFRP laminate is closely related to the thermal effect of the lightning components.

Notably, the lightning direct effect is a comprehensive effect that includes the shockwave and the overpressure effect, the thermal effect, the electromagnetic effect and the dielectric

breakdown effect, which means that the expansion of damage is not determined by a single lightning component but is affected by multiple factors.

4.3 The Lightning Damage of Multiple Continuous Sequential Lightning Strike

4.3.1 Comparison of the Lightning Damage Effect of a Single Lightning Component and Multiple Sequential Lightning Strikes

As shown in the multiple continuous sequential lightning strike experiments, since the application of pre-pulses will influence the thermal, electrical and mechanical properties of the test CFRP laminate, the lightning damage caused by the lightning component in a multiple continuous impulse sequence differs greatly from the damage effect of a single lightning component.

For example, when lightning component D, with an amplitude of 40 kA, whose action integral is approximately half of the action integral of the lightning current A component applied to sample S1, was applied to the CFRP laminate alone. The experimental results are shown in Fig. 15. Visual inspection of the test sample and ultrasonic scan results show that the lightning damage of the CFRP laminate is concentrated on the upper surface, with 1–2 layers, and the damage area is approximately 900 mm². It is worth noting that the type of lightning damage caused by lightning component D is similar to that of sample S1 due to the similarity between lightning components A and D.

However, the damage effect caused by lightning component D in “ABCD” test mode differs greatly from the test result in Fig. 15. From the experimental results shown in Fig. 13d and e, it can be seen that with the continuous injection of the lightning current A, B, and C components, the damage area at depths greater than 1.5 mm is less than 150 mm², and 60% of the damage area (approximately 1500 mm²) is distributed in the upper surface of the laminate at depths less than 0.5 mm. In comparison, with the additional application of lightning component D to sample S5, the newly generated damage area is only 390 mm², while the damage area at depths greater than 1.5 mm increases to more than 1000 mm², which means that in the “ABCD” test mode, the expansion effect of lightning component D on the damage area with deeper damage depth is quite significant. This can be explained by the inference that after the interaction of lightning components A, B and C, most of the damage area is in an extremely high-temperature state, which can cause melting and sublimation of the carbon fibers. Additionally, the ply delamination possibly occurs due to the internal pressure generated by pyrolysis of the resin, which can weaken the cohesive force and cause a significant decrease

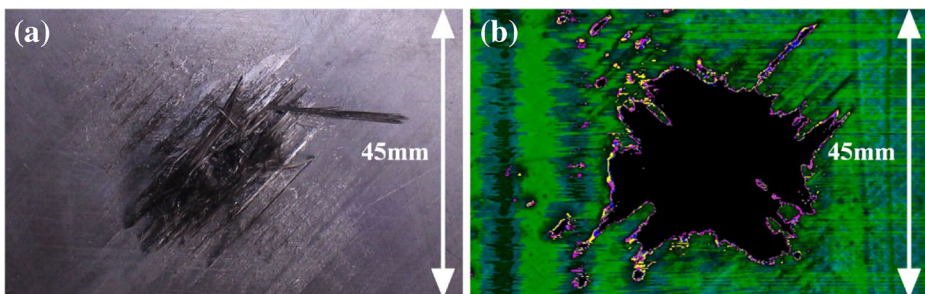


Fig. 15 The lightning damage of the CFRP laminate under lightning component D: **a** visual inspection, **b** ultrasonic scan

in the mechanical properties of the CFRP laminate. Thus, the subsequent application of lightning component D, which is accompanied by a large shockwave, overpressure effects and electromagnetic effects, is highly likely to result in an obvious expansion of the damage area at greater depths.

4.3.2 The Influence of Application Sequence on Lightning Damage in Multiple Sequential Lightning Strike

The application of pre-pulses influences the conducting process of the subsequent lightning current components on the test samples. Therefore, the application sequence of multiple continuous lightning components will greatly affect the lightning strike process and damage results of the CFRP laminates.

Despite the similarity of lightning components A and D, a large difference exists in the damage degree for the “ABC” and “DBC” test modes. Specifically, in test modes “DBC” and “ABC”, the damage distributions of samples S3 and S4 (Fig. 13c and d) show that, at greater depths, the damage is concentrated around the lightning current injection point in both the “DBC” and “ABC” test mode. The obvious difference is that the shallow damage zone of test sample S3 is mainly distributed in the -45° and 45° directions, while shallow damage in test sample S4 has no obvious directionality, which means that the damage develops in the -45° , 45° , 0° and 90° directions.

Considering the layout of the test CFRP laminate ($[-45/45/0/90_2/-45/0/45/0/90/45/-45]_S$), it can be found that the damage distributions of test CFRP samples in different test modes show significant differences between test samples S3 and S4, resulting from differences in the damage depths caused by lightning components A and D. As shown by the damage of sample S1 under lightning component A of 40 kA, the damage depth at the lightning injection point is close to the depth of the fourth carbon fiber layer with layout directions of -45° , 45° , 0° and 90° ($D_d=0.513$ mm, the thickness of each layer is approximately 0.15 mm). Therefore, although the subsequently applied lightning component C with a low voltage does not easily penetrate the resin layer in the thickness direction, lightning component C can conduct in the carbon fiber directions of -45° , 45° , 0° and 90° and results in a nearly circular distribution of the lightning damage area at the lightning attachment point. However, in the test mode of “DBC”, both the amplitude and the energy of the lightning component D are smaller than component A, which could result in a smaller damage depth under the effect of lightning component D. Thus, lightning components B and C can only conduct in the direction of the first and second plies of the test CFRP laminate, which leads the corresponding damage area to extend along the -45° and 45° directions.

4.3.3 The Influence of Material Properties on Lightning Damage in Multiple Sequential Lightning Strike

The lightning damage degree of test CFRP samples are affect by the electrical conductivity of CFRP laminates, which is the key parameter to determine the Joule heat (I^2R) generated during the current conducting process. For instance, the action integral of lightning component D with the amplitude of 20 kA is approximately 2×10^4 A²s, while the action integral of lightning component C with the average current of 200 A and duration of 200 ms is only 5×10^3 A²s. However, the thermal effect, which can be represented by the surface temperature, of lightning component C is significantly higher than that of the lightning component D. According to the

calculation, the contribution of lightning current component D to the lightning damage area of sample S5 is 13.9% with the action integral of lightning component D representing 18.55% of the total action integral of the four lightning components. Correspondingly, the contribution of the lightning current component C to the lightning damage area is approximately 39%, while the action integral of lightning component C merely accounts for 5.47% of the total amount.

The reason for the inconsistency between the action integral and damage effect of lightning components is the nonlinear characteristics of dynamic impedance of CFRP laminates [25]. When the high-amplitude lightning component A or D is applied, the equivalent impedance of CFRP sample is smaller, while the dynamic impedance will increase under the effect of the low-amplitude lightning component C. Therefore, the Joule heat (I^2R) generated by the lightning current component C is greater and the thermal effect is more remarkable, which lead to the significant increase in surface temperature and lightning damage area of CFRP laminate after lightning strike.

5 Conclusions

Based on an analysis of the lightning damage test results via visual inspection, infrared temperature measurement, ultrasonic T-scan and C-scan, the damage properties of CFRP laminates subjected to multiple continuous sequential lightning current components with different timing combinations were studied. The mechanisms of lightning direct effect and the dispersion performance of lightning components on CFRP laminates were preliminarily explored. The main conclusions are summarized as follows:

- (1) The CFRP laminates subjected to multiple continuous sequential lightning strikes suffered from fracture of fiber and plies separation. The surface temperature and lightning damage degree increased as the number of applied multiple continuous sequential lightning current components increased. The surface temperature of the CFRP laminates, which was projected from the measured temperature with lower magnitude, can exceed 1600 °C in the “ABC” test mode. When lightning components A, B, C and D were applied continuously in a single shot, the maximal damage area exceeded 2790 mm² and the structure of more than 30% fiber layers (1.28 mm, 8 layers) were destroyed.
- (2) The CFRP laminates suffered from the lightning strikes both in plane and in depth, while the different lightning current components affect damage areas and damage depths in different ways. The extension of lightning damage in depth direction accompanied with the fracture and burning of carbon fiber at the lightning attachment point is mainly caused by the high-amplitude and high-rising-rate lightning components A, B and D with local thermal effect, the mechanical impact effect and dielectric breakdown effect. The lightning damage area of CFRP laminate is mainly affected by the thermal effect of the lightning components C. The Joule heat generated during the lightning current flowing in the network of carbon fibers was inferred to be the reason for the pyrolysis of resin and erosion or the sublimation of carbon fibers, leading to the increases in the surface temperature and delamination damage area of the CFRP sample.
- (3) The mechanism for lightning damage effects caused by multiple continuous sequential lightning current components differs substantially from those of lightning components applied alone or separately. According to the lightning damage results of CFRP laminates subjected to multiple continuous lightning components with different combinations, it

can be deduced that the application of pre-pulses influences not only the thermal, electrical and mechanical properties of the test CFRP laminate but also the conducting process of the subsequent lightning current components on the test samples.

The combination of lightning current components and test conditions, including the lightning injection gap, the use of the ignition wire, the size and the clamping method of the test sample, will affect the flowing path and damage effect of the lightning current components on the CFRP laminate. Systematic and in-depth studies that comprehensively consider different lightning component combinations, the application sequence, the variability of material properties and test conditions need to be performed in the future to provide both experimental support and a theoretical basis for the refinement and improvement of a lightning direct effect test method for CFRP laminates.

Acknowledgements This work was supported by the National Natural Science Foundation of China [grant numbers 51477132, 51521065].

References

1. Society of Automotive Engineers.: ARP 5412, Aircraft lightning environment and related test waveforms. Warrendale, PA (2013)
2. Rupke, E.: Lightning direct effects handbook. Lightning Technologies Inc, Pittsfield (2002)
3. Fisher, F.A., Plumer, J.A., Perala, R.A.: Aircraft lightning protection handbook. Lightning Technologies Inc, Pittsfield (1989)
4. Mazur, V.: Lightning threat to aircraft: do we know all we need to know? *J. Aircr.* **30**, 156–159 (2015)
5. Roeseler, B., Sarh, B., Kismarton, M.: Composite Structures - the First 100 Years. 16th International Conference on Composite Materials, ICCM-16, Kyoto, Japan (2007)
6. Marsch, G.: Airbus A350 XWB update. *Reinf. Plast.* **54**, 20–24 (2010)
7. Yao, Y., Sun, J., Chen, J., Bai, D.: Direct current resistance testing methods of carbon fibre reinforced polymer. *Mater. Res. Innov.* **19**, 64–69 (2016)
8. Li, S., Yin, J., Yao, X., Chang, F., Shi, X.: Damage analysis for carbon fiber/epoxy composite exposed to simulated lightning current. *J. Reinf. Plast. Compos.* **35**, 1201–1213 (2016)
9. Cheng, J., Ji, H., Qiu, J., Takagi, T., Uchimoto, T., Hu, N.: Role of interlaminar interface on bulk conductivity and electrical anisotropy of CFRP laminates measured by eddy current method. *NDT&E Int.* **68**, 1–12 (2014)
10. Hirano, Y., Katsumata, Y., Iwahori, Y., Todoroki, A.: Artificial lightning testing on graphite/epoxy composite laminate. *Compos. Part A.* **41**, 1461–1470 (2010)
11. Li, Y., Li, R., Lu, L., Huang, X.: Experimental study of damage characteristics of carbon woven fabric/epoxy laminates subjected to lightning strike. *Compos. Part A.* **79**, 164–175 (2015)
12. Chemartin, L., Lalande, P., Peyrou, B., Chazottes, A., Elias, P.Q., Delalandre, C., Cheron, B., Lago, F.: Direct effects of lightning on aircraft structure: analysis of the thermal, electrical and mechanical constraints. *J. Aerospace Lab.* **5**, 1–15 (2012)
13. Liu, Z., Yue, Z., Wang, F., Ji, Y.: Combining analysis of coupled electrical-thermal and blow-off impulse effects on composite laminate induced by lightning strike. *Appl. Compos. Mater.* **22**, 189–207 (2015)
14. Yin, J., Li, S., Yao, X., Chang, F., Li, L., Zhang, X.: Lightning strike ablation damage characteristic analysis for carbon Fiber/epoxy composite laminate with fastener. *Appl. Compos. Mater.* **23**, 821–837 (2016)
15. Dong, Q., Guo, Y., Chen, J., Yao, X., Yi, X., Lu, P., Jia, Y.: Influencing factor analysis based on electrical-thermal-pyrolytic simulation of carbon Fiber composites lightning damage. *Compos. Struct.* **140**, 1–10 (2016)
16. 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)
17. Rakov, V.A.: The physics of lightning. *Surv. Geophys.* **34**, 701–729 (2013)
18. Society of Automotive Engineers.: ARP 5416, Aircraft lightning test methods. Warrendale, PA (2013)
19. Society of Automotive Engineers.: ARP 5414, Aircraft Lightning Zoning. Warrendale, PA (2013)

20. Yin, J.J., Chang, F., Li, S., Yao, X., Sun, J., Xiao, Y.: Lightning strike ablation damage influence factors analysis of carbon Fiber/epoxy composite based on coupled electrical-thermal simulation. *Appl. Compos. Mater.* **24**, 1089–1106 (2017)
21. Ogasawara, T., Hirano, Y., Yoshimura, A.: Coupled thermal-electrical analysis for carbon/epoxy composites exposed to simulated lightning current. *Compos. Part A.* **41**, 973–981 (2010)
22. Lowke, J.J., Voshall, R.E., Ludwig, H.C.: Decay of electrical conductance and temperature of arc plasmas. *J. Appl. Phys.* **44**, 3513–3523 (1973)
23. Munoz, R., Delgado, S., Gonzalez, C., Romano, B., Wang, Y., LLorca, J.: Modeling lightning impact Thermo-mechanical damage on composite materials. *Appl. Compos. Mater.* **21**, 149–164 (2014)
24. Semenov, S., Cetegen, B.: Spectroscopic temperature measurements in direct current arc plasma jets used in thermal spray processing of materials. *J. Therm. Spray Technol.* **10**, 326–336 (2001)
25. Sun, J., Yao, X., Xu, W., Chen, J.: Dynamic characteristics of carbon fiber reinforced polymer under nondestructive lightning current. *Polym. Compos.* **39**, 1514–1521 (2018)

Affiliations

Jinru Sun¹ · Xueling Yao¹ · Xiangyu Tian¹ · Jingliang Chen¹ · Yi Wu¹

Jinru Sun
jinru2014sun@163.com

Xiangyu Tian
t_xiangyu@163.com

Jingliang Chen
cjl@xjtu.edu.cn

Yi Wu
wuyic51@mail.xjtu.edu.cn

¹ State Key Laboratory of Electrical Insulation and Power Equipment, Xi'an Jiaotong University, No.28 Xianning West Road, Xi'an 710049, People's Republic of China