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Lightning strike damage behavior of carbon fiber reinforced epoxy, bismaleimide, and polyetheretherketone composites

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ABSTRACT

This study examined lightning strike damage to cross-ply carbon fiber reinforced epoxy (CF/epoxy), bismaleimide (CF/BMI), and polyetheretherketone (CF/PEEK) composite laminates to clarify the effects of the resin properties on lightning strike damage to CFRP laminates. Simulated lightning current (Component A) in accordance with SAE ARP 5412B was applied to each specimen. The maximum current was defined as 40 kA and 100 kA. The duration of impulse current T_1/T_2 was approximately 30/80 μs. Results show that CF/BMI and CF/PEEK sustained remarkably minor damage such as carbon fiber breakage, changes in color of matrix resin, and delamination on the front surface compared to CF/epoxy. Moreover, no remarkable delamination was observed inside CF/BMI or CF/PEEK. These experimentally obtained results indicate that the electrical conductivity and onset temperature of thermal decomposition, the char yield, the interlaminar fracture toughness and other material properties strongly affect lightning strike damage to CFRP laminates.

1. Introduction

Carbon fiber reinforced plastic (CFRP) composites have been applied to primary aircraft structures because of their high specific stiffness and strength. Aircraft are sometimes struck by lightning, which damages structures. Metal mesh has been applied to protect CFRP surfaces from lightning strikes [1]. Nevertheless, it is difficult to protect them completely from lightning strikes. Inspection and repair must be done. To improve the damage resistance of CFRP structures against lightning strikes, it is important to elucidate the mechanisms of damage to CFRP laminates exposed to lightning strikes.

Damage to CFRP caused by lightning strikes is a complicated phenomenon because physical and chemical phenomena are associated with such strikes, such as Joule heat, thermal decomposition of the CFRP resin, combustion, acoustic force, and Lorentz force. Simulated lightning current tests were conducted in earlier studies to clarify the related damage mechanisms [2–6]. These works reported damage of many kinds such as delamination, carbon fiber breakage, thermal decomposition of matrix resin, and transverse cracks. However, damage simulations conducted by solving electrical and thermal equations were done with direct comparison to experimentally obtained results [7–14]. The area which is higher than the matrix resin decomposition temperature, as calculated using numerical simulation, roughly agreed with the actual lightning strike damage area.

It is widely understood that the electrical conductivity of CFRP strongly affects lightning strike damage [15–17]. Many researchers have therefore attempted to increase the electrical conductivity of CFRP to reduce lightning strike damage. For example, Gou et al., Han et al., and Li et al. applied nanomaterials such as carbon black and carbon nanotubes to the matrix resin (CFRP resin) to increase the electrical conductivity [18–20]. Yokozeki et al. and Kumar et al. developed a novel conductive thermosetting resin by application of polyaniline (PANI) [21,22]. Hirano et al. reported that lightning strike damage to CF/PANI was remarkably minor compared to that of CF/epoxy [23]. In addition, Rehbin et al. increased the electrical conductivity of CFRP by application of silver-coated knitting yarns to non-crimp fabrics. The lightning strike damage was reduced [24]. Nevertheless, aside from studies examining electrical conductivity, no report of the relevant literature describes a detailed study of how lightning strike damage to CFRP is affected by resin properties.

The objective of this study is to clarify how matrix resin properties affect the lightning strike damage behavior shown by CFRP laminates. Simulated lightning current tests were conducted with the same carbon fiber in reinforced CFRP laminates produced with resins of three kinds: CF/epoxy, CF/bismaleimide (BMI), and CF/polyetheretherketone (PEEK). BMI is a thermosetting resin with higher heat resistance than epoxy resin, whereas PEEK is a crystalline thermoplastic resin with high fracture toughness. Regarding CF/BMI and CF/PEEK, their mechanical

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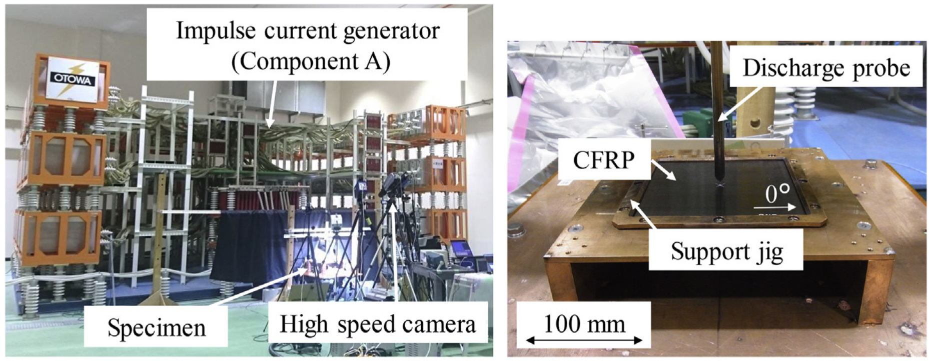
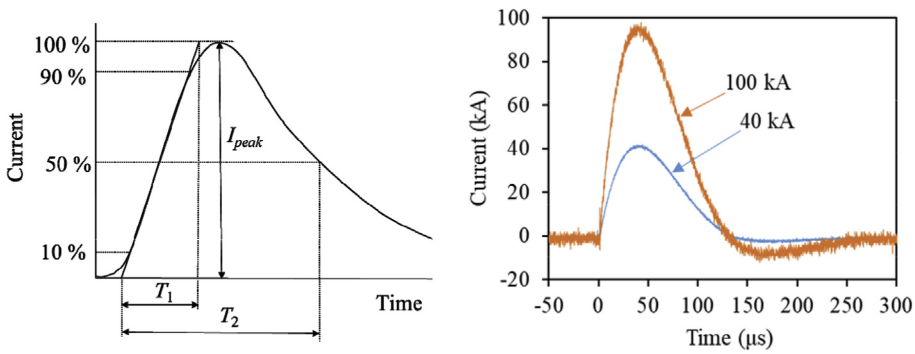


(a) Impulse current generator (Component A). (b) Support jig and discharge probe.

Fig. 1. Experimental setup for simulated lightning current tests.



(a) Lightning waveform parameters. (b) Typical results of measured simulated lightning current waveforms 40 kA and 100 kA.

Fig. 2. Lightning waveform.

properties as CFRP composites have been investigated in detail [25]. However, the damage caused by lightning strikes has not been reported in the relevant literature. Investigations of the relation between the lightning damage characteristics and material properties such as electrical conductivity and thermal decomposition were discussed along with details of the effects of matrix resin properties of CFRP laminates related to lightning strike damage.

2. Experimental

2.1. Material and specimen

Cross-ply laminates of CF/epoxy (IMS60/#133), CF/BMI (IMS60/#304), and CF/PEEK (IMS60/Victrex PEEK 150G), to which the same PAN type carbon fiber (IMS60) were applied, were prepared for simulated lightning strike tests. Unidirectional prepreg tapes obtained from Toho Tenax Co. Ltd., Japan were laminated to $[0/90]_{4s}$ and were molded using an autoclave or a hot press. Each specimen had 150 mm width and 150 mm length. The CFRP laminates, CF/epoxy, CF/BMI, and CF/PEEK, respectively had 2.2, 1.9, and 2.2 mm thicknesses in spite of the same fiber areal weight (45 g/m^2). The fiber volume fraction, which was calculated using fiber areal weight, fiber density, and thickness of laminates, were respectively 59, 67 and 59% for CF/epoxy, CF/BMI and CF/PEEK. As described herein, the longitudinal and transverse direction are defined, respectively, as 0° and 90°.

2.2. Test conditions and lightning current waveform

Simulated lightning current tests were conducted using an impulse current generator (Otowa Electric Co., Ltd., Japan) at the National Composite Center, Nagoya University, Japan (Fig. 1(a)). The specimen and experimental setup for the impulse current testing are presented in Fig. 1(b). A specimen was fixed to a copper jig connected to the ground. A positive impulse current was applied to the center of each specimen from the discharge probe (7 mm diameter) fixed above the specimen. The gap separating the tip of the discharge probe and the specimen was 2 mm.

The component A waveform, which simulated the initial stroke in accordance with SAE ARP 5412B, was applied to the center of each specimen. The component A waveform is expressed with the current peak value (I_{peak}), the front time from nominal origin to I_{peak} (T_1) and the duration from the nominal origin to 50% I_{peak} through I_{peak} (T_2) as parameters (Fig. 2(a)) [26]. In addition, action integral I is defined as $I = \int_0^t i^2 dt$. Therein, i signifies the electrical current during impulse current testing. I denotes a value proportional to the electrical energy. The current peak values were defined as 40 kA and 100 kA for this study (Fig. 2(b)). Lightning waveform conditions for each specimen are presented in Table 1.

Table 1
Testing conditions for applied simulated lightning currents.

Material	Peak current I_{peak} (kA)	Waveform T_1/T_2 (μs)	Action integral I (kA^{2}s)
CF/epoxy-40 kA	42.0	27.7/84.6	92.0
CF/BMI-40 kA	43.2	27.9/84.0	94.3
CF/PEEK-40 kA	42.8	27.2/83.8	92.6
CF/epoxy-100 kA	98.0	28.2/83.3	477
CF/BMI-100 kA	100	30.9/86.0	497
CF/PEEK-100 kA	100	29.4/82.9	486