EXPERIMENTAL STUDY OF LIGHTNING DIRECT EFFECTS ON CARBON FIBER REINFORCED EPOXY, BISMALEIMIDE AND PEEK 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 was applied to each specimen. The maximum current was defined as 40 kA. Results show that CF/BMI and CF/PEEK exhibit remarkably minor damage such as carbon fiber breakage, changes in color of matrix resin, and delamination on the front surface compared to CF/epoxy. In addition, no remarkable delamination was observed inside CF/BMI and CF/PEEK. These experimentally obtained results indicate that not only the electrical conductivity but also onset temperature of thermal decomposition, the char yield and other material properties strongly affect lightning strike damage to CFRP laminates.

1. Introduction

Carbon fiber reinforced plastics (CFRP) have been widely applied to aircrafts because of their high specific strength and stiffness. Lighting occasionally strikes flying aircraft and produces structural damage. Once the CFRP structures are damaged, inspection and repair are required. To improve the damage resistance of CFRP structures against lightning strikes, it is important to clarify the damage mechanisms of CFRP laminates exposed to lightning strikes.

Lightning strike damage to CFRP laminates were investigated experimentally in earlier works [1-2]. These works reported damage of many kinds such as delamination, carbon fiber breakage. It is widely understood that the electrical conductivity of CFRP strongly affects lightning strike damage. Therefore, many researchers have attempted to increase the electrical conductivity of CFRP by applying nanomaterials [3-5], by developing a novel conductive thermosetting resin [6] or by applying silver-coated knitting yarns to non-crimp fabrics [7]. However, the effect of other material properties except electrical conductivity on lightning strike damage have not been investigated in detail.

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 properties as CFRP composites have been investigated in detail. 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. Simulated lightning current test

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 used for simulated lightning current tests. Unidirectional prepreg tapes obtained from Toho Tenax Co. Ltd., Japan were laminated to cross-ply ($[0/90]_{4s}$) and were molded by 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 thickness. 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 lighting current tests were carried out using an impulse current generator (Otowa Electric Co., Ltd., Japan) at the National Composite Center, Nagoya University, Japan. 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 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 front time from nominal origin to I_{peak} (T_1) and duration from the nominal origin to 50% I_{peak} through I_{peak} (T_2) as parameters [8]. 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 value was defined as 40 kA for this study (Fig. 1). Lightning waveform conditions for each specimen are presented in Table 1.

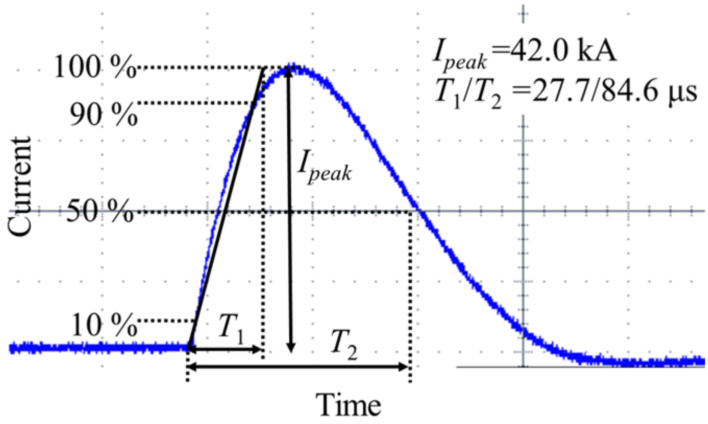


Figure 1. Typical lightning waveform.

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^2s)
CF/epoxy	42.0	27.7/84.6	92.0
CF/BMI	43.2	27.9/84.0	94.3
CF/PEEK	42.8	27.2/83.8	92.6

3. Results

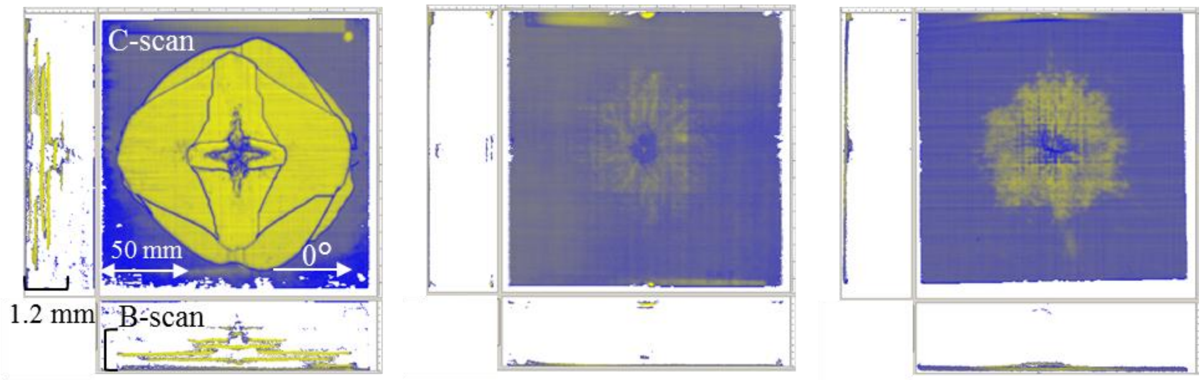
Surfaces of the test specimen after impulse current testing are presented in Fig. 2. In the CF/epoxy, carbon fiber breakage was observed around the impulse current attachment point. The inner layers were exposed to the surface. Ply lift from the arc attachment point was observed along the fiber direction of the top layer (0°). In addition, carbon fiber breakage was observed along the transverse direction (90°). Changes in color were observed in a rhombus shape of 60 mm on one side. However, damage such as thermal decomposition of matrix resin and carbon fiber breakage was not observed on the back surface of the specimen.

In the CF/BMI and CF/PEEK, radial carbon fiber breakage was observed around the arc attachment point. The diameter of carbon fiber breakage was approximately 45 mm in the CF/BMI and CF/PEEK. Circular changes in color of the resin were observed from the arc attachment point in a wider range than the fiber breakage. The diameters were approximately 65 mm in CF/BMI and CF/PEEK. No damage was observed on the back surface in either test condition.

Non-destructive inspection was performed from the back surface using ultrasonic equipment (HIS-3; Krautkraner Japan Co. Ltd., Japan) to evaluate internal damage (delamination). The scanning pitch was 0.50 mm × 0.50 mm. The scanning probe had 3.5 MHz of frequency. The non-destructive inspection results are depicted in Fig. 3. For convenience of direct comparison with Fig. 2, right and left were reversed in Fig. 3. Delamination was detected within approximately 1.2 mm from the front surface in the CF/epoxy. The thickness corresponds to 10 plies. B-scan results indicated the CF/BMI and CF/PEEK had no remarkable delamination.

(a) CF/epoxy (b) CF/BMI (c) CF/PEEK

Figure 2. Arc attachment surface.



(a) CF/epoxy (b) CF/BMI (c) CF/PEEK

Figure 3. Non-destructive inspection results using ultrasonic technique.

4. Discussions

Lightning strike damage of the CF/BMI and CF/PEEK was remarkably slight compared to that of the CF/epoxy under these test conditions. Because the same carbon fiber (IMS60; Toho Tenax Co. Ltd.) was applied to all CFRP specimens, results suggest that the difference in the matrix resin characteristics strongly affects the lightning strike damage to CFRP laminates. In addition to this, the fiber volume fraction of the CF/BMI was higher compared with other composites, therefore the direct comparison should be carefully made, because the fiber volume fraction (thickness) affects the material properties.

First, the effect of electrical conductivity of CFRP, which has been studied in many earlier studies, is discussed. The electrical conductivity of the unidirectional CFRP laminates ($[0]_{16}$) used for the impulse current testing was measured. Electrical conductivities of the longitudinal, transverse and through-thickness directions were measured using four-probe method with an LCR meter (HiTESTER 32522-50; Hioki E. E. Corp.). The experimentally obtained results are summarized in Table 2. The electrical conductivities of the CF/BMI and the CF/PEEK in thorough-thickness direction were found to be 7.42 S/m and 1.51 S/m, respectively, which are considerably higher than that of the CF/epoxy (0.0839 S/m). The higher through-thickness electrical conductivity of CF/BMI is probably due to the higher fiber volume fraction. The CF/epoxy used for this study was developed for application to aircraft primary structures. It possesses high impact resistance. The electrical conductivity of

CF/epoxy in the through-thickness direction is low because of the resin-rich layers. Therefore, the electrical conductivity of CF/BMI and CF/PEEK is high, which might affect the suppression of lightning strike damage. However, Hirano et al. reported that the lightning strike damage of CF/epoxy is remarkably greater than that of CF/PANI [6]. The respective electrical conductivities of the through-thickness direction of their CF/epoxy and CF/PANI were 2.7 S/m and 74 S/m. This result indicates that the effect of electrical conductivity on the lightning strike is not remarkable in this range of electrical conductivity (<10 S/m). Therefore, other material properties might affect lightning strike damage.

Table 2. Fiber volume fraction (V_f) and electrical conductivity (S/m) of CF/epoxy, CF/BMI and CF/PEEK composites.

Material	Fiber volume fraction, V_f (%)	Electrical conductivity (S/m)		
		Longitudinal direction	Transverse direction	Through-thickness direction
CF/epoxy	59	8100	6.67	0.0839
CF/BMI	67	7610	19.8	7.42
CF/PEEK	59	3120	48.5	1.51

Next, the effect of heat resistant of matrix resin is discussed. Thermogravimetric analysis was conducted to evaluate the CFRP pyrolysis behavior. Weight change was measured in argon gas flow under a constant heating rate of 20°C/min from 50°C to 1000°C using a thermogravimetric analyzer (STA-449C; Netzsch-Geratebau GmbH). The specimen had 5 mm width and 5 mm length. The TGA results are presented in Fig. 4. The result of the CF/epoxy is cited from the literature [9]. The onset temperature of thermal decomposition is 280°C for the CF/epoxy; the char yield is 75%. By contrast, in the CF/BMI and the CF/PEEK laminates, the respective onset temperatures of thermal decomposition are 370°C and 530°C, with char yield of 85% and 82%. The higher char yield of the CF/BMI may also be derived from the higher fiber volume fraction. The heating rate during an actual lightning strike is much higher than 20°C/min around the arc attachment point. The onset temperature of thermal decomposition depends strongly on the temperature elevation rate [9]. Therefore, no quantitative discussion can be made using TGA results. However, comparison of the CF/epoxy with the CF/BMI suggests that the difference in the char yield might influence the lightning strike damage more strongly than the difference of the onset temperature of thermal decomposition. In addition, comparison of the CF/epoxy and the CF/PEEK demonstrates the possibility that both the difference between the onset temperature of thermal decomposition and the char yield affect lightning strike damage. Therefore, the TGA results suggest that heat resistance of the matrix resin affect lightning strike damage.

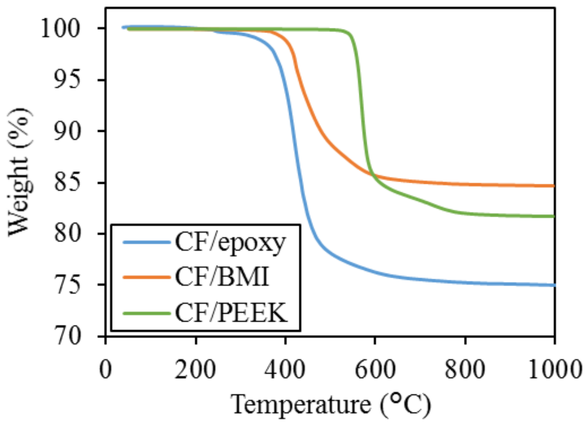


Figure 4. Thermogravimetric analysis results for CF/epoxy [9], CF/BMI and CF/PEEK in argon gas flow. The heating rate was 20°C/min.

Conclusions

This work examined the effects of matrix resin properties on the lightning strike damage behavior experimentally. Lightning strike damage was investigated for CF/epoxy, CF/BMI and CF/PEEK. The CF/BMI and CF/PEEK composites showed slight lightning strike damage such as carbon fiber breakage, changes in color and delamination on the front surface compared to CF/epoxy. Moreover, no remarkably delamination was observed in CF/BMI and CF/PEEK. This result indicates that not only the electrical conductivity but also the onset temperature of the thermal decomposition, char yield and other material properties strongly affect lightning strike damage.

Acknowledgments

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