EVALUATION OF LIGHTNING RESISTANCE OF CHOPPED CARBON FIBER TAPE REINFORCED THERMOPLASTICS

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Abstract

Damage behavior of ultra-thin chopped carbon fiber tape reinforced thermoplastics (UT-CTT), which is a kind of randomly oriented strands (ROS) made by water dispersed thin tape, due to lightnig strike is investigated in this study. Thin-ply prepreg is applied for CTT and quasi-isotropic laminate, and the influence of prepreg thickness and fiber discontinuity on the damage behavior is examined. Simulated lightning strike test was performed on these specimens with capturing the damage generation behavior by high-speed camera and the post-lightning specimes were observed by 3D measuring macroscope. The damage of quasi-isotropic laminate with thin-ply prepreg showed an in-plane isotropic behaivior with a hemisphere shape of vaporized resin. In UT-CTT, the damage behavior showed in-plane isotropy regardless of the prepreg thickness, but the thinner prepreg made the damage depth slightly shallow and the principal damage was fluffing of carbon fiber, in stead. Thus, the lightning resistance is assumed to be higher in the case of thin-ply prepreg based CFRTP, but the residual mechanical properties should be evaluated in the future.

1. Introduction

Lightning strike has been one of the serious problems for carbon fiber reinforced plastics (CFRP) and a lot of studies investigated about continuous fiber reinforced laminate for airplane structure [1-8]. Hirano et al. [1] clarified a fundamental damage behavior of CF/Epoxy laminate. Another studies conducted an simulated lightning strike test to CFRP plate with fasteners or lightning strike protection (LSP) such as metal mesh or foil [2-5]. Based on the experimental studies, computational analysis was also conducted to predict damage behavior [7,8]. As a result, the effective LSP, that is, metal mesh or foils has been

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widely used for commercial aircrafts. Recently, Yokozeki et al. [9] developed a CF/PANI, which is an electrically conductive matrix resin, and Hirano et al. [6] obtained a superior improvement about lightning damage supresssion by this material. The improvement of lightning resistance has been well done in continuous CFRP laminate with thermoset resin, but there are no studies about the lightning resistance of continuous and discontinuous carbon fiber reinforced thermoplastics (CFRTP) although ROS is a promising material and some commercial products already exist such as Hexcel HexMC® and Quantum Lytex® 4149. When applying ROS widely to airplane and automotive structure, lightning resistance is one of the important factors to be investigated in order to secure the safety and reliability of the product.

Hence the objective of the present study is to reveal the fundamental damage behavior of CFRTP under lightning strike, especially about quasi-isotropic laminate and ultra-thin chopped carbon fiber tape reinforced thermoplastics (UT-CTT). Simulated lightning strike test is applied to these CFRTP with impulse current generator (ICG) and the damage behavior is observed by high-speed camera. In addition, post-lightning specimens are observed by 3D measuring macroscope.

2. Material fabrication and test setup

2.1. Specimens

An ultra-thin prepreg sheet was produced by tow spreading technology at Industrial Technology Center of Fukui Prefecture, the detail of which can be referred to in a previous study [10]. The thickness of the sheet was 44 µm sheet and the fiber volume fraction (V_f) is 55 %. CF is a polyacrylonitrile (PAN) based one (TR50S, Mitsubishi Rayon Co. Ltd.) and matrix resin is a PA6 (Diamiron C®, Mitsubishi Plastics Co. Ltd.). A prepreg sheet was prepared from three ultra-thin sheets, which were laminated and heated to produce 132 µm-thick sheets. From the two different prepreg sheet thicknesses, four kinds of material were fabricated. An ultra-thin quasi-isotropic laminate (UT-QI(1t)) and UT-CTT(1t) were made from the ultra-thin prepreg, while UT-QI(3t) and UT-CTT(3t) were made from the three-times thicker prepreg sheets. All the specimens were made by press molding. The stacking sequence of UT-QI was $[45/0/-45/90]_{6s}$. In UT-CTT, the tape length and width were 18 mm and 5 mm, respectively. Details of a manufacturing process of UT-CTT can be viewed in our previous studies [11,12]. The specimens were cut to 120 mm × 120 mm and these were dried in a vacuum dryer with 90°C for more than 24 hours.

2.2. Testing conditions

A simulated lightning strike test was conducted with an ICG (SSGA 200-360, Haefely Test AG, see the left figure of Figure 1). A simulated impulse current of Component A, which is defined in SAE ARP-5412 [13], was applied to the specimens. Although a peak current is 200 kA in the original waveform of Component A, the peak current was set to 20, 30 and 40 kA in the present study. The aim of this lower current was a suppression of the damage area to use a smaller specimen with various lightning parameters. The current waveform was also defined by the time-to-peak current (T_1) and the time to decay to fifty percent of its maximum amplitude (T_2). The applied impulse current was measured with a current transducer (Model 1330, Pearson Electronics, Inc.) and a digityal oscilloscope (DPO4054, Tektronix, Inc.). A typical measured waveform was shown in Figure 2 and the lightning parameter in all the measured current could be viewed in Table 1. The right figure of Figure 1 shows the specimen setup which is composed of a copper jig and discharge probe with conical tip. Specimens were fixed with the frame-type jig which was connected with the ground of the impulse current generator. The inside dimensions of the frame was 110 mm × 110 mm. The gap between the tip of the discharged probe and the specimen was 2 mm. These testing setup was decided based on a previous study by Hirano et al. [3]. The behavior during the simulated lightning strike test was observed by a high-speed camera (HPV-2, Shimadsu Corporation) with a frame rate of 500 kfps.

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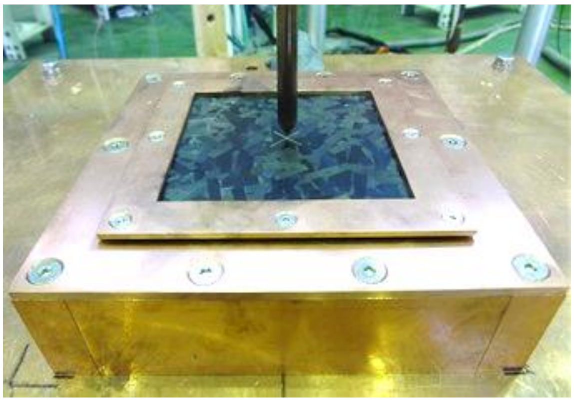

Figure 1. Impulse current generator (left) and specimen setup (right).

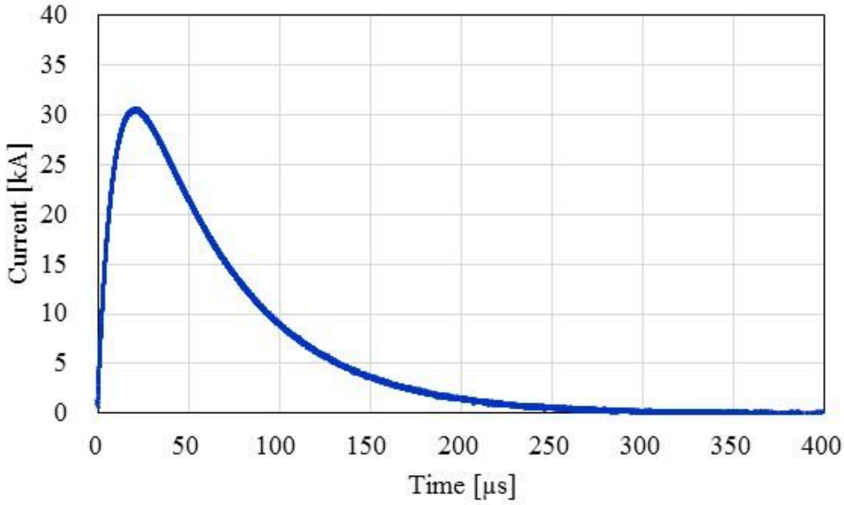

Figure 2. Typical measured impulse current waveform (30.55 [kA], T_1/T_2 = 14.09/71.46).

Table 1. Testing conditions for simulated lightning strike test.

S/N	Peak current [kA]	T_1 [μs]	T_2 [μs]	Action integral [kJ/Ohm]
UT-QI(1t)_1	19.87	14.05	71.60	19.93
UT-QI(1t)_2	30.59	14.08	71.20	46.99
UT-QI(1t)_3	39.97	14.05	71.28	80.23
UT-QI(3t)_1	19.83	14.16	71.62	19.85
UT-QI(3t)_2	30.50	14.09	71.53	46.91
UT-QI(3t)_3	39.89	14.07	71.53	80.24
UT-CTT(1t)_1	19.81	14.06	71.73	19.87
UT-CTT(1t)_2	30.55	14.09	71.46	46.98
UT-CTT(1t)_3	39.97	14.06	71.43	80.47
UT-CTT(3t)_1	19.76	14.09	71.92	19.81
UT-CTT(3t)_2	30.44	14.08	71.72	46.85
UT-CTT(3t)_3	39.83	14.08	71.65	80.11

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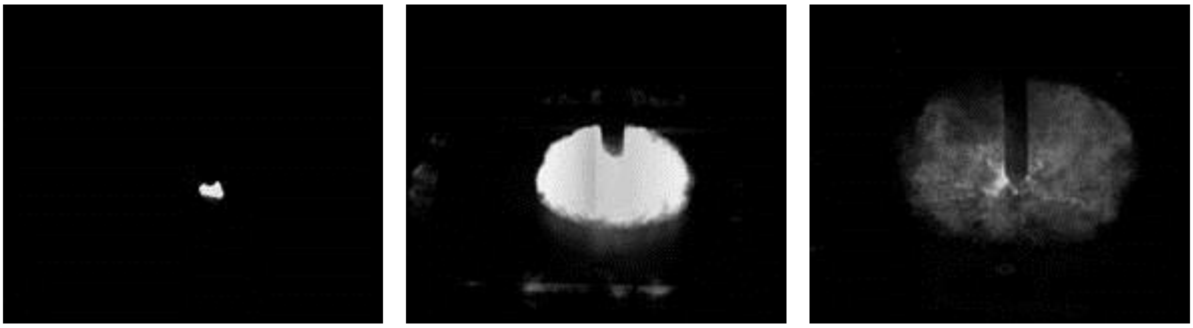
3. Experimental results

3.1. Quasi-isotropic laminate

Light emission caused by sublimation of carbon fibers and vaporization of resin could be viewed just after the origin of the lightning current (see Figure 3 (a) and Figure 4 (a)). The orientation angle of the surface ply was 45°, so the perpendicular direction, that is, -45° direction had the highest resistance and generation of joule heat was also the highest. Figure 3 (a) and Figure 4 (a) reflected the anisotropy and the light emission expanded to -45° direction. Comparing these two figures, the light emission of UT-QI(3t) had the higher anisotropy. Additionally, although the degree of anisotropy became lower in the case of UT-QI(1t) (see Figure 3 (b)), the anisotropy remained in UT-QI(3t) (see Figure 4 (b)). Figure 3 (c) and Figure 4 (c) clearly captured the vaporized resin which was spread to all directions in UT-QI(1t) and to mainly -45° direction in UT-QI(3t). High temperature due to the vaporized resin may cause a surface damage, so the shape of surface damage was different in the two material. Figure 5 and Figure 6 were overhead view of the post-lightning speicimens, 2D and 3D contour images taken by 3D Measuring Macroscope (VR-3200, KEYENCE Corporation). They showed that the surface damage was spread in UT-QI(1t) in all directions and that it was a biased shape to -45° direction in UT-QI(3t).



(a) t = 2 μs (b) t = 24 μs (c) t = 64 μs

Figure 3. Typical results of damage generation behavior taken by high speed camera (UT-QI(1t)_3, applied impulse current is 39.97 kA, T_1/T_2 = 14.05/71.28).

(a) t = 2 μs (b) t = 24 μs (c) t = 64 μs

Figure 4. Typical results of damage generation behavior taken by high speed camera (UT-QI(3t)_3, applied impulse current is 39.89 kA, T_1/T_2 = 14.07/71.53).

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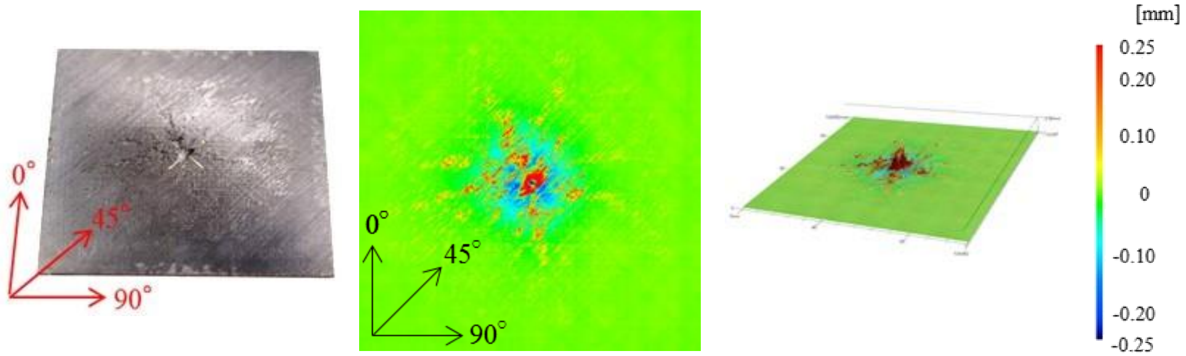
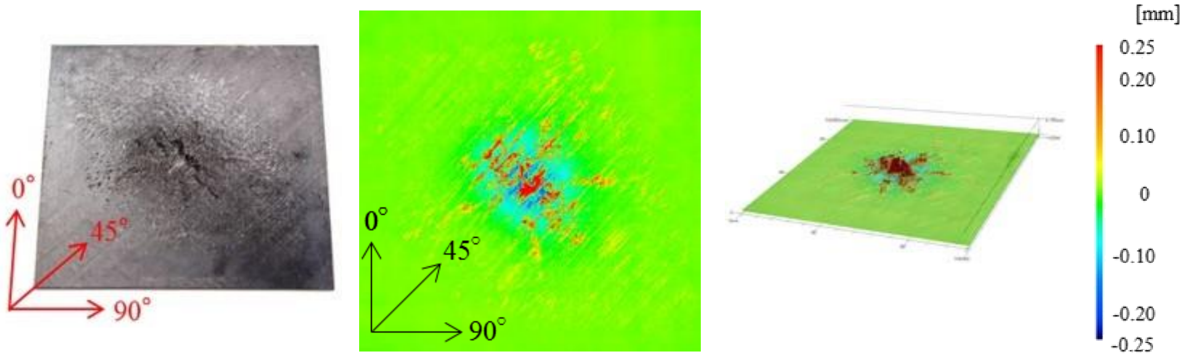


(a) overhead view (b) 2D contour image (c) 3D contour image

Figure 5. Typical experimental result of simulated lightning strike test; overhead view of post-lightning specimen, 2D and 3D contour images taken by One-shot 3D Measuring Macroscope (UT-QI(1t)_3, applied impulse current is 39.97 kA, T_1/T_2 = 14.05/71.28).



(a) overhead view (b) 2D contour image (c) 3D contour image

Figure 6. Typical experimental result of simulated lightning strike test; overhead view of post-lightning specimen, 2D and 3D contour images taken by One-shot 3D Measuring Macroscope (UT-QI(3t)_3, applied impulse current is 39.89 kA, T_1/T_2 = 14.07/71.53).

3.2. UT-CTT

The observation with a high-speed camera revealed that the shape of light emission was a hemisphere shape in both UT-CTT(1t) and UT-CTT(3t) as shown in Figure 7 and Figure 8, although the shape was slightly anisotropic one especially in the case of UT-CTT(3t) at the initial stage of the damage generation behavior (see Figure 8 (a)). The vaporized resin of hemisphere shape obviously reflected in-plane isotropy of the electrical property of UT-CTT. The damages of UT-CTT(1t) and UT-CTT(3t) had both in-plane isotropic characteristics, but the area with red color which indicates fluffing of carbon fiber was wider in the case of UT-CTT(1t) compared to UT-CTT(3t) (see Figure 9 (b)(c) and Figure 10 (b)(c)). On the other hand, the resin vaporized area which corresponds to the blue part in these figures was slightly deeper in the case of UT-CTT(3t) although the red area was smaller.

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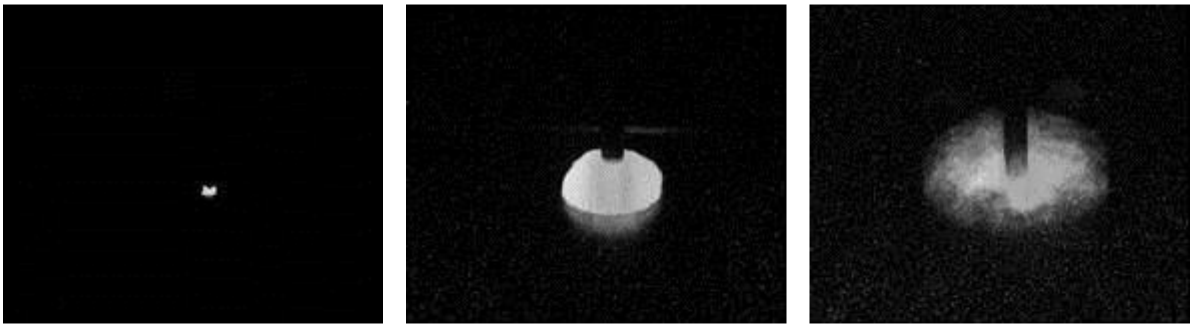
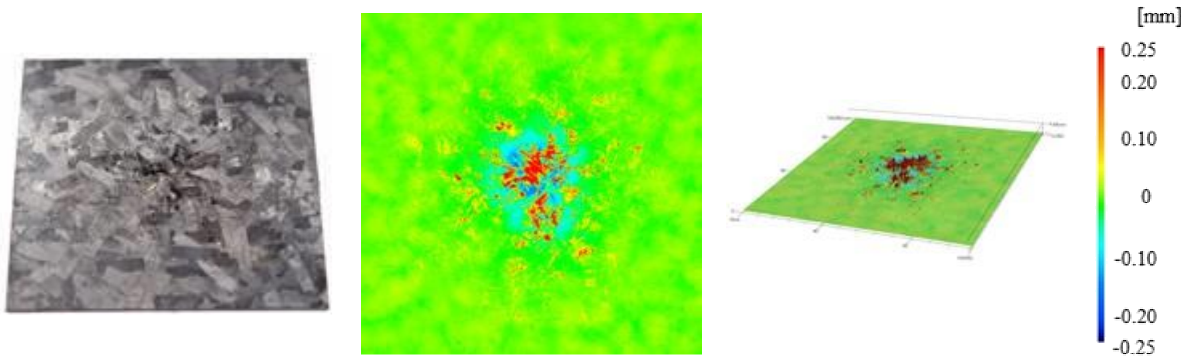


(a) t = 2 μs (b) t = 24 μs (c) t = 64 μs

Figure 7. Typical results of damage generation behavior taken by high speed camera (UT-CTT(1t)_3, applied impulse current is 39.97 kA, T_1/T_2 = 14.06/71.43).

(a) t = 2 μs (b) t = 24 μs (c) t = 64 μs

Figure 8. Typical results of damage generation behavior taken by high speed camera (UT-CTT(3t)_3, applied impulse current is 39.83 kA, T_1/T_2 = 14.08/71.65).



(a) overhead view (b) 2D contour image (c) 3D contour image

Figure 9. Typical experimental result of simulated lightning strike test; overhead view of post-lightning specimen, 2D and 3D contour images taken by One-shot 3D Measuring Macroscope (UT-CTT(1t)_3, applied impulse current is 39.97 kA, T_1/T_2 = 14.06/71.43).

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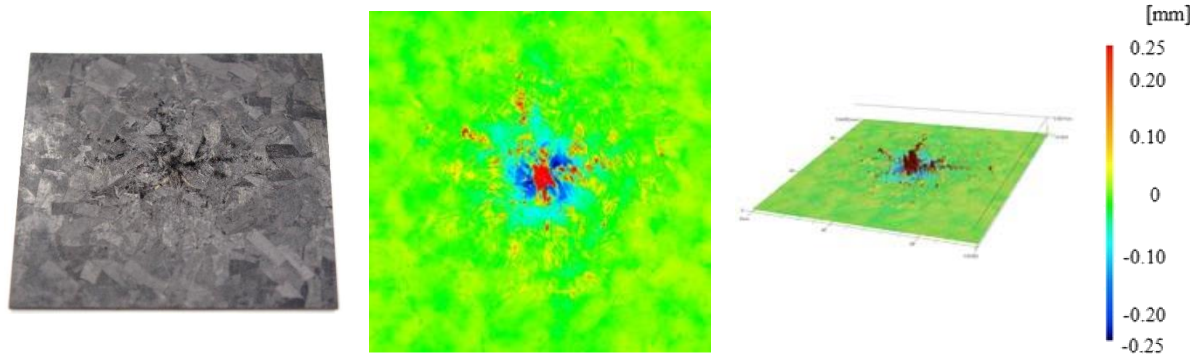

(a) overhead view (b) 2D contour image (c) 3D contour image

Figure 10. Typical experimental result of simulated lightning strike test; overhead view of post-lightning specimen, 2D and 3D contour images taken by One-shot 3D Measuring Macroscope (UT-CTT(3t)_3, applied impulse current is 39.83 kA, T_1/T_2 = 14.08/71.65).

4. Discussion

A difference of damage shape was clearly observed in the case of quasi-isotropic laminates as mentioned in Section 3.1. A previous study also showed that a damage due to lightning strike occurs in the shallow area of a plate in the case of CFRP laminate [1], but the only one layer of 44 µm-thickness can't flow the all lightning current, so the layers under the surface, which has the layup of 0/-45/90/45/0/..., flows the current because of the melting and vaporization of matrix resin between each ply. In the case of UT-CTT(3t), the surface layer of 45° continues until the depth of 132 µm, so the most part of lightning damage spread to -45° direction. The deeper resin vaporized area is assumed to be caused by the higher volume resistivity of UT-CTT(3t) (see Table 2). The higher volume resistivity generates the larger joule heat, and the resin aroud the lightning strike point was melted and vaporized by high temperature.

Table 2. Volume resistivity of UT-QI(1t), UT-CTT(1t) and UT-CTT(3t).

S/N	In-plane resistivitry		Out-of-plane resistivity	
	[ohm・cm]	CoV [%]	[ohm・cm]	CoV [%]
UT-QI(1t)	0.0068	2.0	34	17
UT-CTT(1t)	0.0090	3.1	29	4.6
UT-CTT(3t)	0.024	7.2	24	9.9

5. Conclusions

The present study investigates the lightning resistance of UT-CTT which is a kind of ROS made by water dispersed thin tape. Damage generation behavior of CFRTP was successfully captured by high-speed camera. The influence of prepreg thickness on the behavior was investigated. Though quasi-isotropic laminate composed of thicker prepreg showed anisotropic behavior, in-plane isotropic behavior with of a hemisphere shape was observed in quasi-isotropic laminate with thinner prepreg. In UT-CTT, damage depth slightly decreased in that composed of thinner prepreg and the main damage was fluffing of carbon fiber on the UT-CTT plate, in stead.

Although the results of the present study implies that the lightning resistance of CFRTP which is composed of thinner prepreg is higher than that composed of thick prepreg, it is important to evaluate the residual mechanical properties after lightning strike.

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