VISUALIZATION AND NDT EVALUATION OF LIGHTNING DAMAGE BEHAVIOR OF CFRP LAMINATE

Y. Hirano[a*], H. Kusano[b], T. Sonehara[a]

[a]*Advanced Composite Research Center, Japan Aerospace Exploration Agency, 6-13-1 Ohsawa, Mitaka, Tokyo 181-0015, JAPAN*
[b,] *Analytical & Measuring Instruments Division, Shimadzu corporation, 1-3, Kanda Nishiki-cho, Chiyoda-ku, Tokyo 101-8448, JAPAN*
[c]*,Shoden Corporation, 365, Sanno-cho, Inage, Chiba,263-0002, JAPAN*
**hirano.yoshiyasu@jaxa.jp*

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Abstract

This paper examines the effect of acoustic shock wave associated with lightning current on damage behavior of CFRP laminate. Schliren photography technique is adopted to visualize the acoustic shock wave propagation from tip of discharge prove when lightning arc is attached to the CFRP laminate. The influence of applying an insulation sphere to a discharge prove and surface LSP mesh on damage behavior is examine by performing artificial lightning tests. After the lightning test, NDTs are performed to understand the damage behavior inside the specimens.

1. Introduction

The superior mechanical properties of carbon fiber reinforced plastics (CFRP) to conventional metallic materials enable us to reduce the structural weight of large-scale weight critical structures such as airframe, wind turbine blade, and automobiles. However, CFRP usually have inferior thermal and electrical conductivity to aluminum alloy, lightning strike makes internal damage, which reduces the residual strength [1, 2]. Therefore, CFRP structures require special attention in design regarding lightning damage. In previous paper, the direct effect of lightning strikes on laminated composite structures and their fracture behavior have been investigated [3, 4]. For an effect of fastener installation, results have shown that the presence of a fastener increases both the damage and the reduction in residual compressive stress due to a lightning test [5]. A numerical simulation with coupled thermal and electrical analysis has been proposed to estimate damage behavior due to lightning strike. Considering the Joule heat effect, the analysis result shows good agreement with experimentally obtained lightning damage. On the other, different damage mechanism in between in-plane direction and thickness direction has been suggested. It is considered that the acoustic shock waves associated with generated lightning arc is one of the occasions of the difference of damage behavior [3].

In this study, therefore, understanding the detail mechanisms of CFRP laminate when impulse lightning current is attached, artificial lightning test with simulated lightning current is conducted. The damage behavior of CFRP laminate is observed with high-speed camera.

Schliren photography technique is also adopted here to avoid the effect of intense flush light and visualize the acoustic shock wave propagation from tip of discharge prove when lightning arc is attached to the CFRP laminate. After the lightning test, NDTs are performed to understand the damage behavior inside the specimens.

2. Experiments

2.1. Experimental setup

An impulse high-current generator (ICG) produced by Haefely Test AG (Figure 1) was applied here to simulate natural lightning current. The specimens are simply placed on a grounded copper plate, so the top surface of the specimen is not covered with any material. The discharge probe is connected to the ICG. In this study, two different types of electrode were applied to examine the effect of acoustic shock waves on damage behavior: a metal electrode with conical tip (Figure 2 (a)), and a jet diverting electrode with insulating sphere (Figure 2 (b)) which can avoid confining acoustic shock waves between the electrode and specimen surface. The gap spacing between electrode and specimen surface is 2-3mm and 10mm for the conical tip electrode and the jet diverting electrode, respectively. In case of jet diverting electrode, aluminum wire of 0.05mm in diameter is connected from rod of discharge probe to specimen surface as initiation wire to ensure an arc entry of impulse current.

Figure 3 schematically shows the layout of optical devices for schliren photography. The system used in this study is composed of a flush light (PE-60SG produced by Panasonic), a pair of schlieren mirror, a high-speed camera (HPV-X produce d by Shimadzu Corporation),

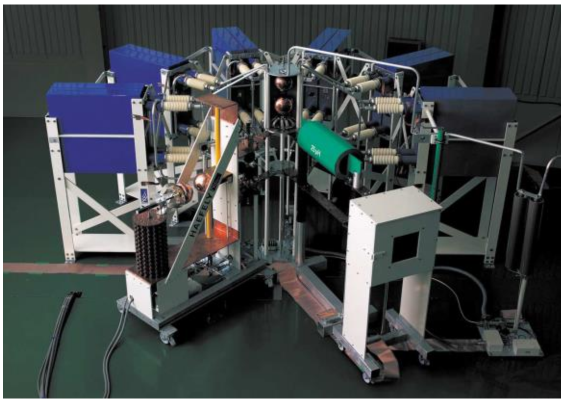
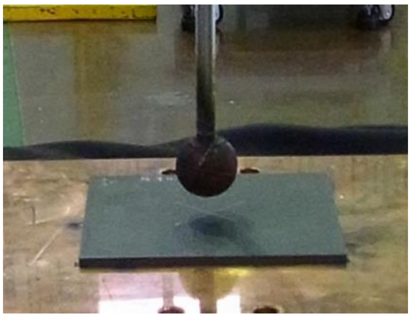


Figure 1. Impulse Current Generator (ICG)

a) Discharge probe with conical tip



b) Discharge probe with insulating sphere

Figure 2. Specimen setup and discharge probes

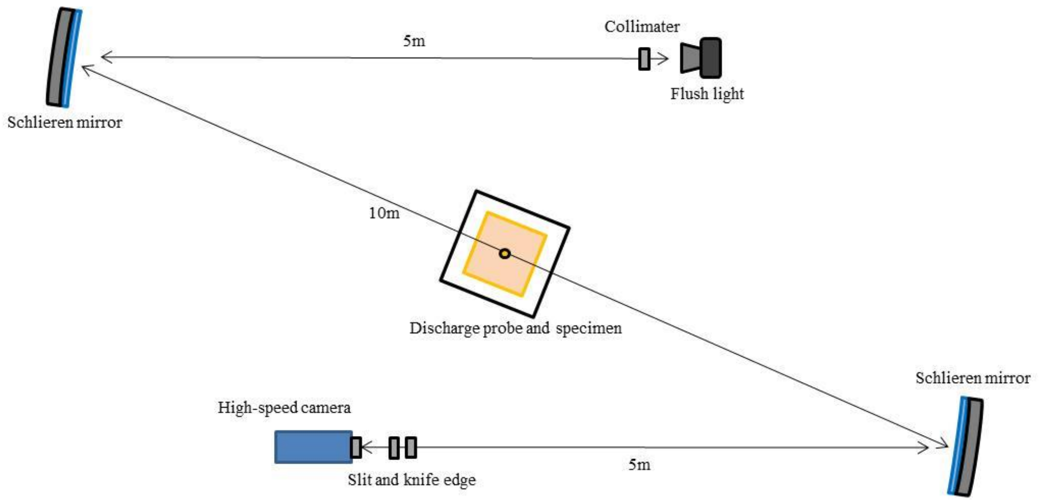


Figure 3. Experimental setup for schliren photography

and optical devices such as collimater and knife edge. The guide number of the flush light is 60m. The diameter and focal length of the schlieren mirror is 0.3m and 10m, respectively. Maximum frame rate and maximum frame number of the high-speed camera is 10Mfps and 128frames, respectively. The image size of each frame is 400pix × 250pix. The trigger signal for discharge of impulse current, high-speed imaging, and flush lighting is controlled with a delay pulse generator (DG-535 produced by Stanford Research Systems).

2.2. Specimen and materials

The material used in this study is CFRP laminate made of T700 #2500 prepreg sheet produced by Toray. Prepreg molding in an autoclave was followed by a recommended cure cycle. The layup of the laminates is [45/0/-45/90]4s. The size of specimen is 150×150mm. In order to examine an effect of LSP (Lightning Strike Protection) mesh, two different specimen of surface finish with lightning protection mesh and without any protection are prepared. For the lightning protection mesh, expand metal 2CU4-100FA (produced by Dexmet Co.) was applied.

2.3. Testing condition

The applied artificial lightning waveform is exponential, which can be characterized by the time to peak current (t_1) and the time required for the wave to decay to one-half of its maximum amplitude (t_2). Figure 4 represents the measured lightning current applied in this study. The figure shows the wave form of applied current is t1/t2 = 17.8/55.16 [μs]. The peak currents applied are 20.42 kA, which are not as high as components A or D in the SAE report [6], but high enough to damage these small size specimens. The peak current was selected so as to avoid the excessive damage of specimen and light emission associated with lightning current discharge. The experimental condition tested in this study is listed in Table 1.

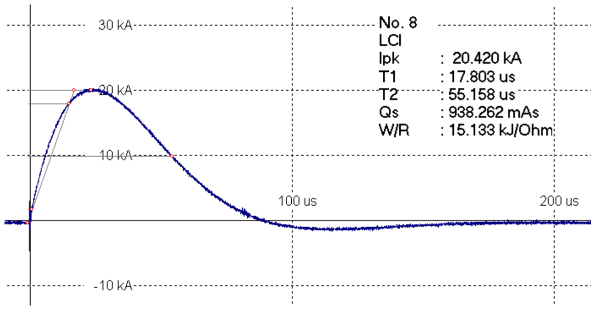


Figure 4. Typical measured impulse current waveform (20.42[kA], 17.8/55.16)

S/N	Peak current [kA]	t1	t2	LSP	Discharge probe
A-1	19.76	17.86	55.70	N/A	Conical
A-2	40.82	17.83	55.56		
A-3	19.37	18.72	56.83		Insulatin sphere
A-4	40.36	18.18	55.89		
B-1	19.96	18.20	55.80	With LSP	Conical
B-2	41.25	17.88	55.37		
B-3	19.86	18.78	56.40		Insulatin sphere
B-4	40.85	18.00	55.59		

Table 1. List of testing condition for artificial lightning test and schliren photography.

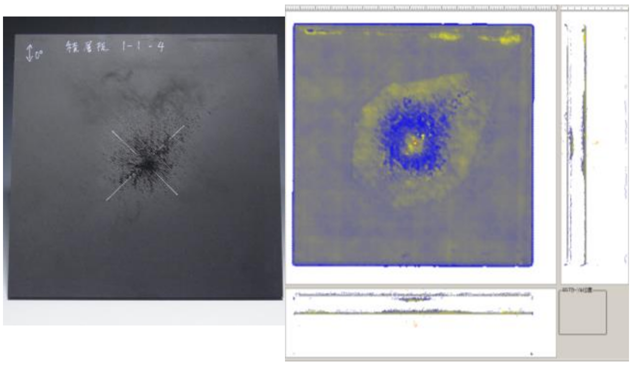
3. Results and discussion

3.1. Lightning damage behavior of CFRP laminate

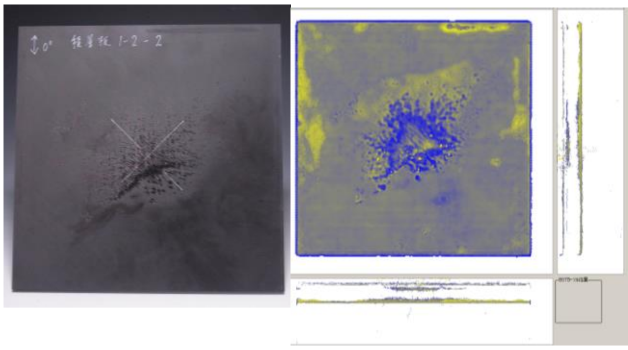
Figure 5 represent the typical damaged CFRP laminate after lightning test. Top view and ultrasonic C-scan images are schematically shown. The ultrasonic testing machine applied in this study is a high frequency ultrasonic parser/receiver HIS-3 produced by Krautkramer Co. LTD. Ultrasonic testing was scanned from lightning current attached surface with 1.0MHz transducer.

Specimen without LSP mesh (A-2 and A-4) shows damage modes of fiber breakage, resin vaporized area, and resin deterioration area. Each damage modes are indicated in the UT testing result as the center yellow region, surrounding blue region, and outer most yellow region, respectively. From the B-scope result, it can be observed that the damage is limited in vicinity of specimen surface. In both case, small delamination can be observed just under the fiber breakage area in few layers from specimen surface. Compared with the case with insulation sphere (A-4), smaller fiber damage area and resin vaporized area, and larger resin deterioration area can be observed in case of conical tip discharge probe (A-2).

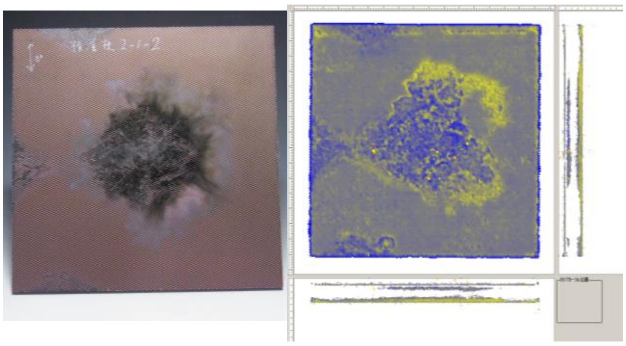
On the other, specimen with LSP mesh (B-2 and B-4) shows damage modes of LSP mesh vaporized area and surface resin deterioration area. In case of conical tip discharge probe, LSP mesh vaporized area propagate in concentrically, though that of the case with insulation sphere propagate irregularly. From the UT B-scope results, it is considered that damage is limited in the surface LSP mesh and first layer of CFRP laminate in both cases. There is no fiber breakage and delamination can be observed. It is showed that applying the LSP mesh to CFRP laminate is effective to reduce the lightning damage.



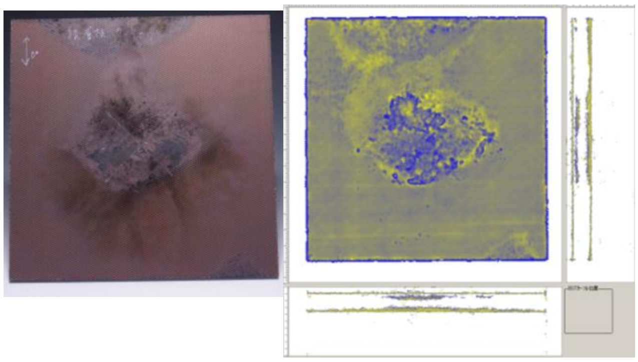
a) A-2, Specimen without LSP, applied impulse current is 40.82kA, 17.83/55.56, with conical tip discharge probe



b) A-4, Specimen without LSP, applied impulse current is 40.36kA, 18.18/55.89, with insulation sphere



c) B-2, Specimen with LSP, applied impulse current is 41.25kA, 17.88/55.37, with conical tip discharge probe



d) B-4, Specimen with LSP, applied impulse current is 40.85kA, 18.0/55.59, with insulation sphere

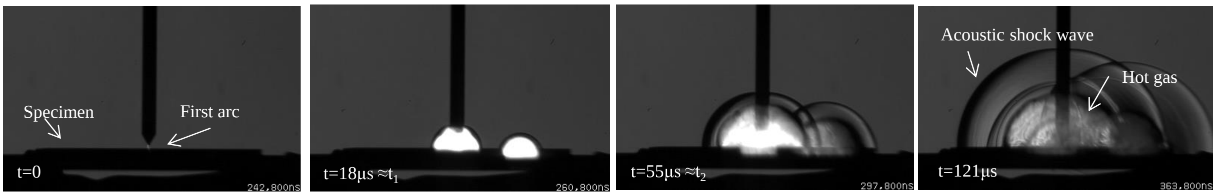
Figure 5. Typical experimental result of artificial lightning test; overhead view of post-lightning specimen and ultrasonic C-scan result

3.2. Results of schliren photography

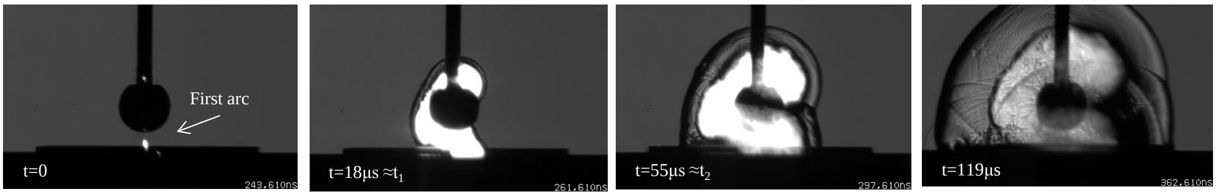
Typical obtained schliren photography is shown in Figure 6. In the figure, (a), (b), (c), and (d) represent the result of specimen A-1, A-3, B-1, and B-3, respectively. The frame rate of high-speed imaging is 1Mfps for each testing condition. The first left figure shows the frame in which first arching is observed. The second left figure shows the frame when maximum current is applied (t_1). The third left figure shows the frame when the applied current is decay to the half of peak current (t_2). The rightmost figure shows the very last frame of high-speed imaging (about 120μs after from the first arc).

In case of conical tip discharge probe, specimen A1 and B-1, first arc is observed between the tip of discharge probe and the specimen surface whether or not the specimen has surface LSP mesh. At the maximum current (t_1), extremely bright hemispherical flush can be observed between electrode and specimen surface. It is considered that this hemispherical flush consists of arc associated with insulation breakdown and hot gas of vaporized epoxy resin due to Joule heat effect. The excessive luminance makes difficult to observe inside of the hemispherical flush in detail. Without LPS mesh (A-1), the shape of light emitting part is almost hemisphere; the maximum diameter of the part is observed at specimen surface. On the other, with LPS mesh (C-1), the shape of light emitting part is elliptically distributed; the maximum diameter is in the middle of the light emitting part. It can be considered that high temperature area of without LSP specimen due to Joule heat effect is larger than with LSP specimen. Since LSP mesh well conduct the applied impulse current and generated heat in-plane direction, the surface temperature domain having temperature high enough to vaporize epoxy resin is limited to small area of underneath the discharge probe. This different distribution of surface high temperature results in the difference of the shape of light emitting part between with LPS and without LSP mesh protection.

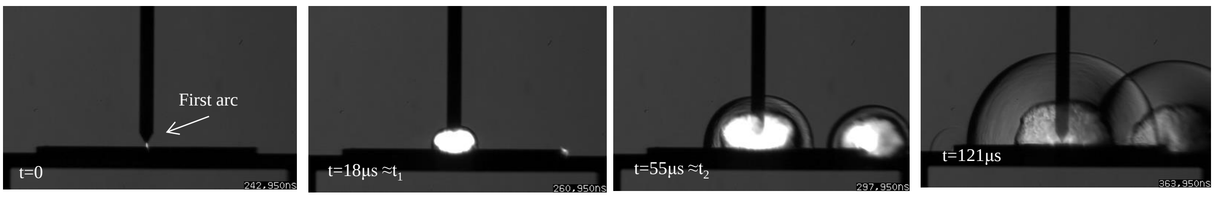
When applied current is decay to the half of maximum current (t_2), arc flash and high temperature area of hot gas can be observed separately. The outer most shadow line represents the acoustic shock wave. Though the shape of hot gas region is difference between the specimen with LSP and without LSP as same as the t_1 stage, outer shape of acoustic shock is hemisphere in both specimens. This indicate that acoustic shock wave is generated by the arc discharged at gap between the tip of discharge probe and specimen surface and propagation of the shock wave is hardly affected by the emitted hot gas. At stage of t = 120µs, since discharge of impulse current is almost finished (See Figure 2), the schliren photography shows the propagated acoustic shock wave and high temperature region of hot gas. Though the hemisphere of acoustic shock wave is developed from the t_2 stage, the region of hot gas seems mostly unchanged. This is because epoxy gas is no longer generated after finishing the applying impulse current. Comparing the diameter of acoustic shock wave hemisphere between t=120µs and t=55µs (t2), propagation speed of shock wave can be calculated as 475.36 m/s on average. In case of specimen with LSP (B-1), only the outermost strong acoustic shock wave can be observed. However, in case of without LSP (A-1), several strong shock waves subsequent to the first outermost shock wave can be observed. It is considered that the cause of these several subsequent acoustic shock waves is the fiber breakage and internal damage associated with the impulse current (See Figure 5 (a)).



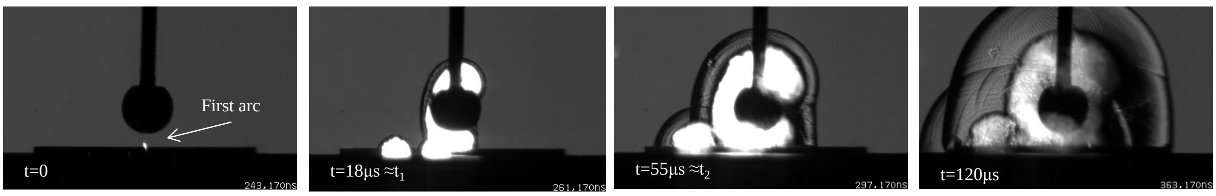
a) Specimen A-1: conical tip discharge probe, without LSP mesh



b) Specimen A-3: discharge probe with insulation sphere, without LSP mesh



c) Specimen B-1: conical tip discharge probe, with LSP mesh



d) Specimen B-3: discharge probe with insulation sphere, with LSP mesh

Figure 6. Typical results of schliren photography

In case of discharge probe with insulation sphere, specimen A-3 and B-3, the first arc is observed between the tip of initiation wire connected to the rod of discharge probe and specimen surface (See Figure 6 b), d)). At the maximum current (t_1), extremely bright region of arc associated with insulation breakdown can be observed along the initiation wire from the rod of discharge prove to specimen surface. Brightness of the arc is higher than that of conical tip discharge probe; the larger part of applied energy of impulse current is used for ionization of air associated with insulation break down. Focusing on the near specimen surface, with of bright region of the specimen A-3 without LSP is larger than that of B-3 with LSP. The reason of this is the same as the case of conical tip discharge probe; the difference of electrical and thermal conductivity of specimen surface affects the high temperature distribution and resin vaporization behavior. When applied current is decreased to the half of maximum current (t_2), outermost acoustic shock wave can be observed. However, the acoustic shock wave has irregular shapes compared with the case of conical tip. It seems that there is many source of acoustic shock wave in case of with insulation sphere. In fact, many interfered small acoustic shock waves can be observed inside the outermost shock wave at stage of t=120μs. The calculated speed of shock wave from the difference between the stage of t=120μs and t=55μs (t_2) is 549.52m/s.

As shown in the result of schliren photography, propagation of acoustic shock wave associate with the insulation break down of atmosphere and the development of hot gas region is heavily affected by the difference of discharge probe and with or without LSP on the specimen surface. However, the observation result of post lightning specimen and the NDT results (Figure 5) indicate that the difference of acoustic shock wave propagation and development of hot gas region have an insignificant effect on CFRP damage behavior. Especially, they have little influence on damage behavior in thickness direction and fiber breakage which have large effect on residual strength of damaged CFRP. Damage behavior of CFRP laminate suggest that applying insulation sphere and initiation wire makes difficult to control the location of lightning current attached. Because the leader channel easily shifts with using initiation wire, lightning attached point is also moved and result in expanding of fiber breakage region (Figure 5 (b)).

It is known that an acoustic shock wave could be partially confined between tip of discharge prove and specimen and cause excessive damage when the tip of discharge prove is not covered with insulation sphere [7]. In this study, confine of acoustic shock wave and resulting excessive damage of specimen is not observed. It can be considered that shock waves are not reflected at tip of electrode since the discharge probe applied in this study has conical tip.

Under the testing condition examined in this study, it can be concluded that the acoustic shock waves originated in lightning impulse current is little influence on the damage behavior of CFRP laminate. From the aspect of controlling the lightning attached location of small size specimen, applying a discharge probe with conical tip is more preferable than applying an insulation sphere with an initiation wire.

4. Conclusions

In this study understanding the detail mechanisms of CFRP laminate when impulse lightning current is attached, schliren photography technique is adopted to visualize the acoustic shock wave propagation. Obtained conclusions are follows:

· Propagation of acoustic shock wave associated with lightning impulse current successfully visualized with schliren photography technique. The hot gas region inside the outermost shock wave consists of arc and vaporized epoxy resin emitted from the CFRP laminate.

· Behavior of acoustic shock wave propagation and the development of hot gas region is heavily affected by the difference of discharge probe and with or without LSP on the specimen surface. However, under the testing condition examined in this study, it can be concluded that the acoustic shock waves originated in lightning impulse current is little influence on the damage behavior of CFRP laminate.

· Controlling the lightning attached location of small size specimen, applying a discharge probe with conical tip is more preferable than applying an insulation sphere with an initiation wire.

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