On Mechanisms of Damage Propagation in Carbon Fibre Composites under Lightning Strikes for Aerospace Applications

Rabia Abid
Cardiff School of Engineering
Cardiff University
CF24 3AA

Summary-To characterize material behaviour of lightweight aerospace structures under lighting strikes that use carbon fibre composites, experimental campaign was undertaken, in Cardiff High Voltage Lab and Morgan-Botti Lightning Laboratory. The experimental campaign was divided in two main testing types, Non-destructive Testing and High Current Testing causing damage**.** Non-destructive Testing was done under increased lightning impulse currents, with higher levels of lightning currents up to the level where damage did not evolve in the material. The current in this range was 10A-80A. Samples used had metal electrodes with a fastener at the centre for current injection and a metal ring for current return. High Current Testing was done in the Cardiff High Voltage Lab, in the Amperes range about 350A and in Morgan-Botti Lightning Lab, in the Waveform D kilo-amperes current range. For the current up to 350A tests, 150 mm x 150 mm square carbon composite material samples with a thickness of 2 mm and having a fastener and metal ring were used, similar to those used for Non-destructive testing. For the high current tests using the D Waveform with magnitudes up to 70kA, two square samples of 550 mm x 550 mm were used with a thickness of 5 mm. The dent depth and ply level damage due to the waveform D lightning impulse current was estimated using scanning electron microscopy. It was found that the mechanical strength for samples impacted with 350 A current did not show any significant change in mechanical parameters whereas mechanical strength was considerably reduced for samples subjected to lightning current of more than 11kA magnitude. The outcomes from these investigations are useful in designing aerospace composites better protected against lightning strikes.

Keywords- Carbon Fiber Reinforced Polymers (CFRP), Lightning Strikes, Waveform D

CONTENTS

1. STATEMENT- THE INDUSTRIAL CHALLENGE-DEFINING THE PROBLEM

With the on-going quest towards more lightweight aircraft and better fuel efficiency, the demand is greater from the aerospace industry to replace conventional materials with composite equivalents. Owing to their high strength to weight ratio, carbon-fibre-reinforced plastics (CFRPs) are already well established and the 20% increase in fuel efficiency that they offer has resulted in substantial fuel savings. The anisotropic electrical conductivity of CFRPs, which is high along the fibres but minimal across them, stems from the arrangement of the different components, with conducting carbon fibres in different orientations reinforced with epoxy to fulfil mechanical strength requirements. This leads to complex electrical phenomena under different external conditions. Anisotropic electrical conductivity also accounts for the unpredictable behaviour of CFRPs under lightning strikes and the inevitable damage that arises. Figure 1 shows a damaged carbon composite aircraft wing part showing the erosion of carbon fibre layers.

The resistivity of CFRP materials is 1000 times higher than that of aluminium, such that a CRFP sample will dissipate 1000 times more energy than an equivalent one made of aluminium for the same lighting current magnitude. The risk of lightning-induced damage is, therefore, much greater for CFRPs as the electrical charge is less readily dissipated. This damage may involve thermal decomposition of the epoxy layers, melting and burning, de-lamination, and vaporisation of the resin. A thin protective metal layer (typically 20-µm thick) is commonly coated on CFRPs to dissipate lightning current and to prevent its penetration into the material. However, this layer also makes the material and, hence, the aircraft heavier. A key objective is, therefore, to design CFRP components and structures with effective lightning protection without compromising their other attractive properties for the aerospace industry, principal among which is their lightweight nature. Understanding the electrical behaviour of these materials is indispensable in this context and involves characterising their electrical properties (primarily their electrical resistance) under different modes of energisation. Ultimately, a detailed study of effect of lightning currents is required. This work investigated the damage effect of lightning current by measuring the residual mechanical strength in carbon fibre composites post lightning current under different levels. Important observations were that low-level lightning currents up to 350A do not cause any significant damage. However, lightning currents in the kA range can do where mechanical strength got adversely effected. These outcomes aid the mechanical design requirements for future composite aircraft for development of composite structures and components better protected against lightning strikes.

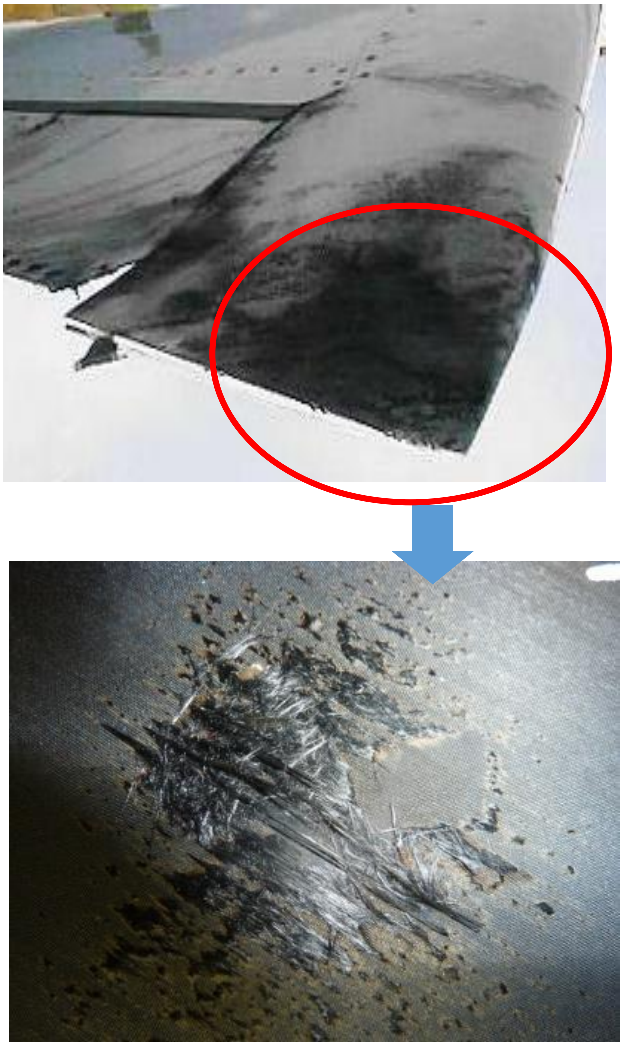


Figure 1: Damage due to Lighting Strike (bottom) on a wing part (top) of a composite aircraft

2. AIM OF THIS PAPER

The purpose of this work was to understand the effects of lightning strikes by performing non-destructive testing of carbon composites in the first stage and then subsequently testing these composites in the lighting strike current range causing eminent damage to the material. The primary objectives in these investigations were:

(i) To visualize damage in carbon composites under variable current range from 10 A to 70kA.
(ii) To measure voltage trends for the material at the same current range as in (i)
(iii) To analyse the mechanical strength degradation of carbon fibre composites under lightning impulses of Amperes range and Lightning strikes in the kA range. These affect both the mechanical and electrical performance of the composite components and structures.

3. BACKGROUND

The different types of damage caused by lightning strikes to aircraft have been recalled/summarized by Uman and Rakov [1]; they are generally due to the flow of the discharge current that induces or aggravates structural deformation through burning, eroding, and/or blasting. To predict the type and extent of this damage, carbon fibre reinforced composite (CFRP) parts can be modelled and simulated using appropriate software, e.g. as in [1]. Carbon fibre composites are good electrical conductors in the direction parallel to the orientation of the fibres, but poor conductors in directions orthogonal to this. Indeed, the epoxy used as a filler between the fibres has a high resistivity such that the conductivity between and across layers is much lower than along them [1]. Earl has modelled the behaviour of CFRP structures and skin under both direct and indirect lightning effects [2]. His study reveals that the properties of CFCs depend on the characteristics of the underlying material and that numerical modelling is an effective tool to understand their electromagnetic properties.

To evaluate the direct effects of lightning strikes, Earl [2] presents a model that represents a test T-joint with an aluminium spar and CFC skin with additional foil for lightning protection. In the original study [2], the model was meshed with different layers of cells, with the tested CFC panel aligned with the mesh to reflect its anisotropic conductivity. For the sake of simplicity, only flat panels were modelled. However, a study of curved panels would have been more interesting. The goal of the aforementioned study was an estimate of lightning-induced damage in T-joints. The results obtained demonstrate that changes in the measured waveforms can be predicted from the sum of resistances between the return conductor and the spar. Furthermore, Earl [2] also outlines how these models can be used to predict the electromagnetic properties of CRFP panels with arbitrary structures.

Feraboli and Miller [3] studied un-notched and filled-hole CFRP samples under different lightning current magnitudes (viz. 10 kA, 30 kA, and 50 kA). The mechanical properties of these samples were then tested to estimate the extent of the damage. The authors concluded that the damage in the filled-hole sample was greater at high currents than that in the un-notched samples, for the un-notched sample, the damage was only a few plies deep. However, for the filled-hole sample, the damage spread either throughout the fastener or to the entire lamina lay-up. The types of damage reported included vaporisation of the resin and inter- and intra-ply arcing. However, the authors did not investigate damage types and mechanisms, which is a primary concern in this field. The main objective of the tests performed by Feraboli and Miller [3] was an improved understanding of the effects of a metal fastener on CFRPs during lightning strikes. Indeed, two of the most important factors in estimating the damage to a CFRP panel are the position of the metallic fastener and the conductivity of the constituent materials. The standard samples used by Feraboli and Miller [3] (as defined by Boeing) to measure residual strength were very small (304 mm × 38 mm), which introduces complex finite-width effects in the calculations of damage and of the residual strength. This is a limitation of their work. Indeed, the results obtained in their study cannot be extrapolated to larger panels because of the finite width of the samples, which constrains the formation of damage and its propagation.

Hirano et al. [4] investigated the damage in CFRP samples subjected to artificial lightning strikes. The types of damage they recorded included fibre damage, resin deterioration, and delamination. The authors [5] concluded that the anisotropic electrical properties of the graphite/epoxy laminate affected damage propagation in the in-plane direction in each layer. These results, therefore, indicate that the behaviour under lightning strikes of CFRPs is strongly related to their electrical properties. However, they in their study [5] neglected the influence of the stacking sequence of the constituent materials, the testing samples all being composed of the same materials arranged in the same stacking sequence. Therefore, more work is needed to understand the effects of different materials and stacking orientations on the damage caused to CFRP panels by lightning strikes.

The damage was inspected using ultrasonic techniques, which revealed that the sliders, track lines, and impact zones all experienced superficial burns. The damaged area covered approximately 160 mm × 210 mm in the vicinity of the impact site. The delamination zone was 68 mm × 45 mm across and 1.4 mm deep. Prominent burns were also found in the bronze mesh surface [5].

In view of the above review of published outcomes in the field an experimental campaign was designed to study the progressive damage mechanisms at different levels of lightning current impulses with minimum current of 10A and maximum of 70kA. The sample sizes and layups were varied dependent on the current levels, for current levels in kilo-amperes flat panels without metal electrodes were used since these samples had to be fitted onto a metallic plate in Morgan-Botti Lightning Laboratory, whereas for the remaining samples below the kilo-amperes range the design used comprised a central fastener (current injection) and metal ring (current return electrode). The next section describes the Non-destructive testing performed in the current range of 10A-80A.

4. NON-DESTRUCTIVE ELECTRICAL CHARACTERIZATION UNDER LIGHTNING IMPULSE CURRENTS OF LESS 100A

Tests were conducted using aluminium metal electrodes. The middle electrode was aerospace fastener EN6115V4-5, which has a nominal diameter of 6.3 mm. The rivet electrodes (6.3 mm in diameter) on the edge of the sample were placed at 22.5° intervals and a crown ring was fitted through the rivets. The dimensions of samples were 150 mm × 150 mm × 2 mm (see Fig. 2). A third set of samples was prepared with an embedded electrode design but without the metal ring and with smaller (3.2 mm) rivets. These samples were 100 mm × 100 mm in size. A total of 41 samples were tested under both low and high current intensities. A subset was also characterised under high-DC intensity. All samples were tested under direct and impulse currents up to 100 A in the lower voltage test range, then tested at current magnitude up to 350 A. All samples in this category had ply lay-ups of (45, 135, 0, 0, 90, 0, 135, 0) and were HTS/977 type carbon fibre composites.

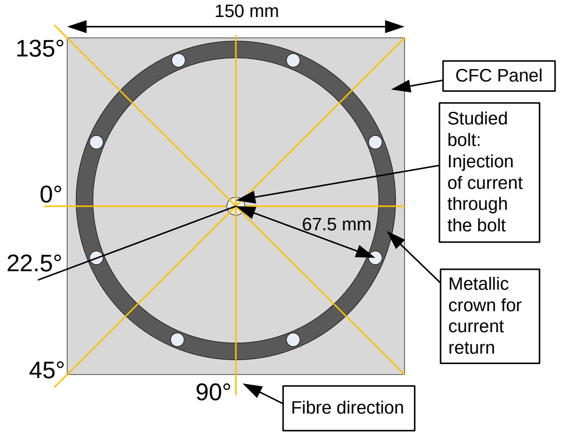


Fig. 2 Schematic of the embedded electrode setup with a metal ring used in this study to measure potential and current distribution in carbon composites.

Fig. 3 shows that energy dissipated in these samples increases non-linearly with the peak intensity of the current impulse. The non-linear increase in the energy dissipation explains how high-intensity lightning strikes could inflict substantial damage to aircraft components. However the energy dissipation up to 80A is in µJ which is quite low therefore currents up to 80 A may not result in significant damage to carbon composite aircraft.

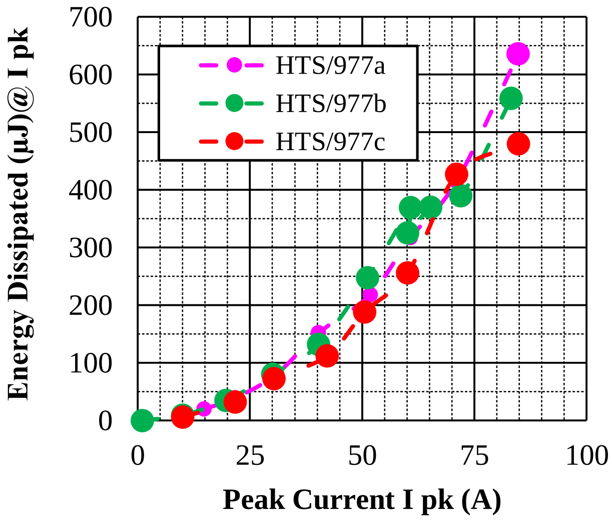


Fig. 3 Energy dissipated at peak intensity vs. current magnitude in different metal-ring carbon fibre composite samples with an embedded electrode.

5. EXPERIMENTAL TESTING IN MORGAN BOTTI LIGHTNING LABORATORY

5.1 Program of Work: Current Injection Tests

Low-current measurements provide useful information regarding the material resistance, which is independent of current magnitude. However, it is also important to characterize the material under high currents to induce extreme conditions and cause changes to resistance and impedance parameters. The tests performed in this work are divided into two current ranges as summarized in Table 1. For all tests, M21/T700s material type samples were used.

Table 1: Tests and samples description used for testing

Range	Test Current	Material Type	Dimensions (mm)	Electrical samples	Mech. samples
A	50A-350A	M21/T700s	150 x 150 x 2	5	1
B	17kA-70kA	M21/T700s	550x 550 x 5	2	1

5.1.1 Electrical Testing In Range A

These tests were conducted in the High Voltage Laboratory at Cardiff University. All test samples had square dimensions of 150 mm x 150 mm and a thickness of 2 mm. The samples were made of 8 plies with quasi isotropic layup of (0, 45, 90, 45)s. In this category samples had a central fastener and a metal ring with 8 rivets on the perimeter to allow current return, as shown in Figure 2.

5.1.2 Electrical Testing In Range B: Waveform D Tests Kilo-amperes Range

These tests were conducted at the Cardiff University's Morgan-Botti Lightning Laboratory (MBLL). The two samples were square panels measuring 550 mm x 550 mm x 5 mm and had unidirectional ply lay-up (all 20 layers oriented at 0^{o}). For these two samples, Sample 1 was injected with three different current levels of 11kA, 13kA and 17kA respectively at three different locations on its surface. Sample 2, on the other hand, was subjected to impulse currents of 30kA (twice), 50kA and 70kA injected at four different locations respectively. Sample 1 was also used for mechanical strength tests whereas Sample 2 was used only for microscopy analysis.

Mechanical and physical examination of the tested samples was performed to quantify the damage caused by these injected currents.

5.2 Mechanical Strength Measurements on Samples Subjected To Current Ranges A and B

Mechanical tests were conducted post electrical testing in both ranges: one sample from Range A was tested using the 4-point bend test and one sample from Range B tested using the 3-point bend test.

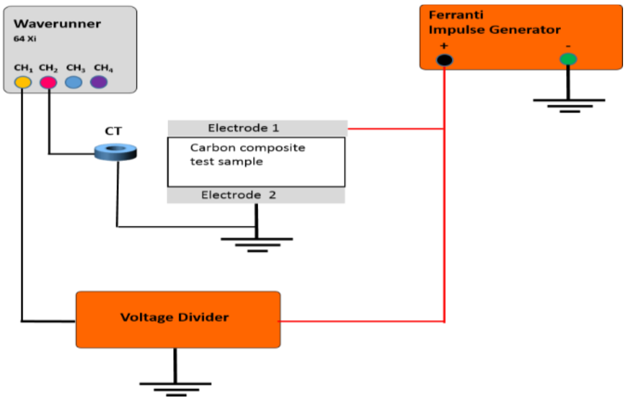
6. TEST CONFIGURATION FOR ELECTRICAL TESTS

6.1 Range A- 350 A current testing

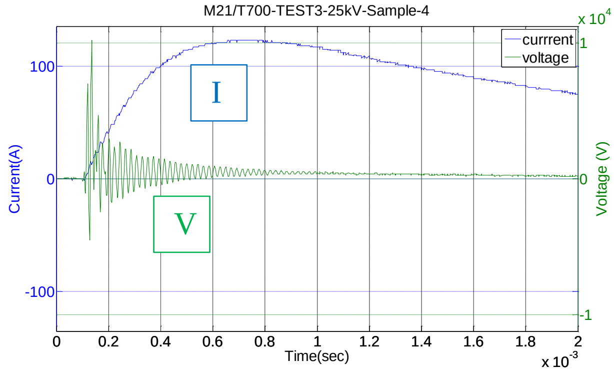
Fig. 4 (a) shows the circuit configuration used for these current tests. A Ferranti impulse generator was used for injecting current into the central fastener. The voltage was measured using a capacitive voltage divider. The current was measured using a current transducer with a current sensitivity of 0.1 V/A. The metal ring electrode was grounded. A Lecroy digital oscilloscope was used to record the data. Testing was conducted with one current injection for varying charging voltage of the generator. At 48 kV charging voltage, the measured current was 350 A for the tests on carbon composite samples.

6.2 Range B- Waveform D Characterization

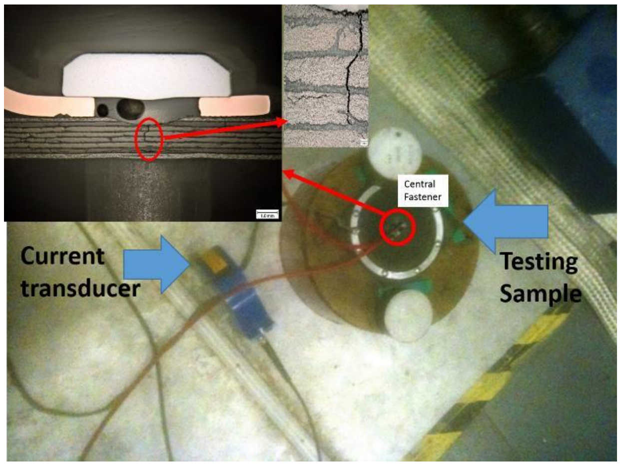
The configuration of the high current lightning test with damaged area is shown in Fig. 5 together with a typical waveform D shape as generated by the MBLL D-Bank in the inset. A current transducer with a sensitivity of 0.001 V/A was used to measure the high-magnitude impulse current. The sample was clamped to the rig with small G-clamps. For the first sample, the strikes ranged from 11 kA to17kA and for the second sample from 30kA to 70 kA. Following these latter tests, ply damage was then studied through microscopy. For samples subjected to current from 30kA to 70kA, which were injected at different locations on the sample surface, the size of the delamination on the surface was measured using a scanning electron microscope. The dent depth of the fibre-scale damage was also measured.



(a) Schematics of the experimental set up in Cardiff High Voltage



(b) V-I graph of the carbon composite sample at 25kv charging voltage in Cardiff High Voltage



(c) Photograph of the carbon composite sample under test in High Voltage Lab with scanned electron image of the damage at the fastener site (inset)

Fig. 4 (a) Schematics of the experimental set up in Cardiff High Voltage Lab (b) V-I graph of the carbon composite sample at 25kV charging voltage (c) Photograph of the carbon composite sample under test in High Voltage Lab with scanned electron image of the damage at the fastener site (inset)

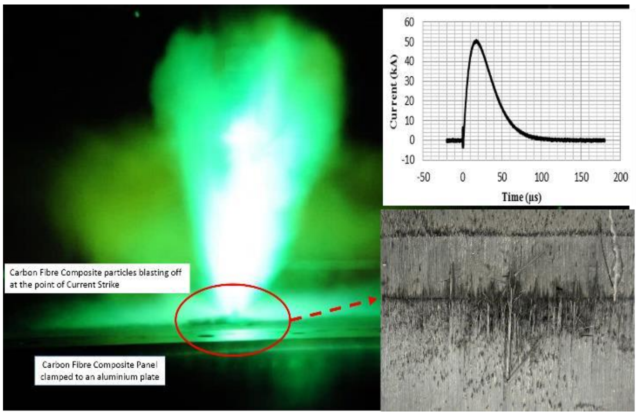


Fig. 5: High current MBLL test photograph and generated impulse shape (inset) with damage at the current injection site.

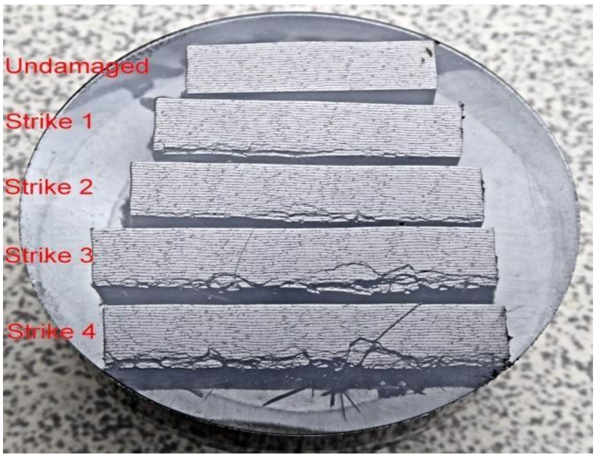
7. RESULTS AND DISCUSSION

7.1 Range A: Tests with Current Impulses up to 350 A

To characterize the material in this range, it was observed that, with a charging voltage set up of 48 kV, the peak current that could be injected into a carbon composite samples did not exceed 350 A. It was observed that the thickness of the samples made no significant difference on the maximum current that could be injected. All quasi-isotropic samples in Range A exhibited similar responses as can be seen in Figure 4(b). The voltage magnitude across the sample is expected to be very small. Therefore, electromagnetic interference dominates and is clearly visible through the measured high frequency oscillations. The tests revealed that the damage was limited to the fastener region and did not propagate into the material as can be seen in Figure 4(c) inset.

7.2 Range B: Waveform D Test Results

In this study, based on a single test conducted on a unidirectional panel causing irreversible damage, a microscopic analysis was performed to examine the damage penetration for strikes ranging from undamaged to 70 kA. Figure 6 shows details of ply damage obtained for the four impulse tests with the samples in the mounting resin shown in Fig 6(a). It can be seen that the number of damaged plies increased with the lightning strike current magnitude (see Fig.6 (b)). For the first test at 30 kA, damage occurred up to ply 4, while for second test 2 (at the 30 kA), damage penetrated as far as ply 5. The damage then penetrates to ply 6 for 50 kA and to ply 20 for 70 kA. From the back surface of the panel, no penetration was visible.

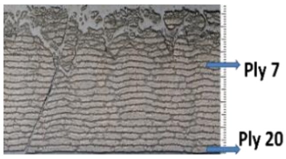


(a) Lightning current struck samples mounted in a resin for scanned electron microscopy study

(i)30 kA Impulse 1

(ii) 30 kA Impulse 2

(iii) 50 kA Impulse



(iv) 70 kA Impulse

(b) Ply level damage in the sample studied corresponding to Strike 1(i), Strike 2(ii), Strike 3(iii) and Strike 4 (iv) in (a) above.

Fig. 6. Ply damage as viewed by scanning electron microscopy for a unidirectional M21/T800s sample after waveform D testing.

It is a common practice to correlate the damage depth with the action integral of the waveforms. This was implemented here, using a Microsoft Excel template. The net electrical charge Q delivered by a lightning impulse is given by

$$Q = \int_0^t i dt \quad (1)$$

The action integral, which is proportional to the total electrical energy, is given by

$$I = \int_0^t i^2 dt \quad (2)$$

For Sample 2, the area of surface delamination for a 30 kA impulse is 6×10^{-3} m^2, increasing to 8×10^{-3} m^2, and 16×10^{-3} m^2 for 50 kA and 70 kA impulses respectively. The action integrals calculated for the 50 kA and 70 kA waveforms are 0.309 A^{2}s and 0.810 A^{2}s respectively, with the waveform T1/T2 defined as 5.24/7.96 and 7.21/18.1, respectively (T1 being the front time and T2 the time to half the maximum value). For action integrals of 0.31 A^{2}s and 0.81 A^{2}s, the delamination size on the surface reaches respectively 0.008 m^2 and nearly 0.016 m^2. Larger action integrals appear to be correlated and indicative of greater surface delamination and greater ply penetration; up to the 5th and 20th plies for action integrals of 0.31 A^{2}s and 0.81 A^{2}s respectively.

In the waveform D test performed in this work, a notable feature is observed which is characterised by the spread of the damage over the sample surface. This is attributed to lack of lightning protection, which is usually in the form of a very thin metal layer, for the unidirectional sample. Thus, the current attempts to follow the path of least resistance that is, in the direction of the fibres instead of the transverse direction which, in turn, causes damage to the surface. Because there is no lightning protection layer for the panel, the current penetrates into the panel layers in addition to spreading across the surface. The mechanism leading to this damage is complex, with the fibres acting as current carriers, but the current does not easily traverse the highly resistive resin matrix which prevents the flow of the current in some directions. However, since the longitudinal resistance in this study was determined to be roughly 40 mΩ, it is clear that the current would flow in the longitudinal direction, although there is no means of determining which portions of the current would flow longitudinally and transversely. Moreover, the current penetration or spread over the surface of any carbon composite panel would essentially be dependent on the ply layup.

8. MECHANICAL STRENGTH TESTS

8.1 Mechanical Strength Test In Range A

In this test, one sample which was subjected to repeated lightning current impulses of 350A at the Cardiff High Voltage Laboratory was subsequently examined using mechanical 4point bending test. The flexural strength map is shown in Figure 7. This sample was divided into several smaller samples to study its mechanical strength in terms of the flexural modulus of various parts of the sample.

No visible differences were found in the ranges of the mechanical strengths measured in this way for samples extracted with a 90° top layer because the flexural strengths are mirror images of each other on both sides of the panel. However, the samples extracted with a 0° top layer were found to have different flexural strengths.

The fastener area of the same sample was studied for microscopic damage, and cracking was found below the fastener but diminished by the end of the eighth ply. The damage did not propagate throughout the sample as shown above in Figure 4(c) inset.

The total elongation/deflection at failure was also recorded for the samples. Samples having a 90° top layer were found to have a lower flexural modulus and higher elongation at failure compared with the samples having a 0° top layer. There is no reported literature on the flexural strengths of those samples subjected to currents of 50 A to 350 A, especially for samples with fasteners. The experiments conducted in this work provided sound information on the degradation of the mechanical strength in the lightning current range up to 350A. To the authors' knowledge, there is no reported literature on the material characterisation in this current range. Therefore, the work described in this paper, especially that related to panels with fasteners provides new information regarding damage induced by low current impulses.

8.2 Mechanical Strength Test in Range B

One of the samples, which was tested with waveform D at MBLL, was subjected to a 3-point bending test. For comparison, an undamaged region was also tested. Figure 8 shows the three-point bending test results.

These results indicate that the flexural strength is highest in the undamaged area but decreases as the lightning current increases. Specifically, the sample subjected to a maximum lightning strike current of 17 kA was found to have a flexural strength of 976 MPa, as can be seen in Figure 8. The flexural strength decreased as the lightning strike current increased, whereas the flexural strengths from the undamaged samples were mostly between 1200 MPa and 1250 MPa. The above findings verify that the mechanical strength of carbon composites is only affected in the high current kA range, and not in the low current Amperes range.

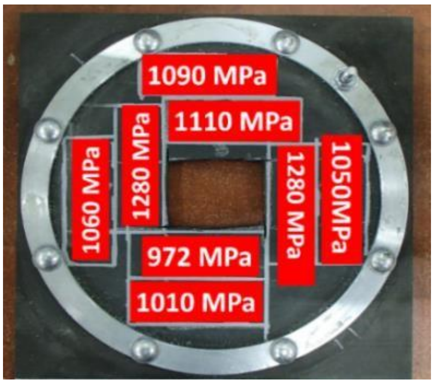


Fig. 7. Flexural strength map for metal ring electrode sample subjected to 350A lightning current impulse

The findings presented herein enable us to determine the effects of high currents on the mechanical strength of the samples, which is more useful than observing the thermal effects in carbon fibre composites. The analysis of high current (kA range) test results obtained in this study revealed that the bending strength/flexural strengths are reduced by 21% whereas in the low current range (Amperes), the measured change in the mechanical strength is negligible.

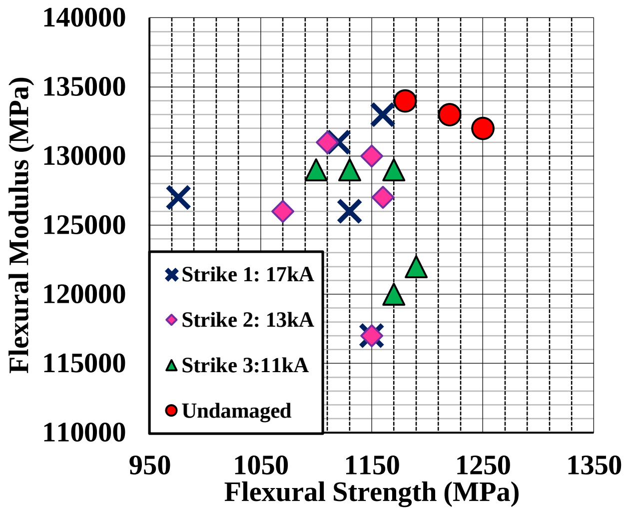


Fig. 8. Flexural strength parameters for a unidirectional sample after lightning current test with waveform D at the MBLL

9. CONCLUSION

The mechanical strength is important to an aircraft structure as it dominates the mechanical design in conventional aircraft construction. Therefore, it is important to investigate the effect of lightning strikes on the properties on carbon composite materials.

Impulse current characterization was performed to evaluate the damage mechanisms affecting carbon fibre composites. Two current ranges were used, in the ampere and kilo-ampere ranges. The applied current impulses in the ampere range did not produce any measurable changes to mechanical strength of carbon fibre composites test panels.

Two samples without lightning protection foil were subjected to lightning currents of magnitude between 11 kA to 70 kA. The damage in one of these samples that was subjected to 30kA (twice), 50kA and 70kA was compared on the micro scale with that caused by currents ranging from 50 A to 350 A. In this work, it was found that, in the kilo-amperes range, the mechanical strength fell as the applied peak current magnitude increased from 11kA to 17kA. This reduction in the mechanical strength indicates that a lightning strike in the kA range may adversely affect the mechanical integrity of a structure made of carbon composites.

These parameters allow the aircraft mechanical designers to understand the ranges of current that would damage a carbon composite structure, and to design carbon composite structures for future composite aircrafts with better lightning protection.

10. REFERENCES

[1] M.A. Uman, V.A. Rakov, *Lightning: Physics and Effects*, Cambridge University Press, UK, 2003.

[2] Earl, Simeon J., "Some Methods for Modelling CFC for the Effects of Lightning," Seminar on Challenges in the Modelling and Measurement of Electromagnetic Materials, 2006. The Institution of Engineering and Technology, pp.33,38, Oct.2006

[3] P. Feraboli and M. Miller, "Damage resistance and tolerance of carbon/epoxy composite coupons subjected to simulated lightning strike", *Compos. Part A: Appl. Sci. Manuf.*, vol.40, pp.954-967, 2009.

[4] S. K. Yoshiyasu Hirano, Yutaka Iwahori, Akira Todoroki, "Artificial Lightning Testing on Graphite/Epoxy Composite Laminate," Composites Part A: Applied Science and Manufacturing, vol. 41, pp. 1461-1470, 2010

[5] T. Ogasawara, Y. Hirano, A. Yoshimura, "Coupled thermal–electrical analysis for carbon fiber/epoxy composites exposed to simulated lightning current", *Compos. Part A: Appl. Sci. Manuf.*, vol.41, pp.973-981, 2010.