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STUDY OF DAMAGE CHARACTERISTICS IN COMPOSITE STRUCTURES FROM SIMULATED LIGHTNING STRIKES

Gang Zhou*[1], James Golding[1], Xujin Bao[2] and Weiwei Sun[3]
[1] Department of Aeronautical and Automotive Engineering, Loughborough University, Loughborough, Leicestershire LE11 3TU, UK, * Corresponding author (**G.Zhou@Lboro.ac.uk**)
[2] Department of Materials, Loughborough University, Loughborough, Leicestershire LE11 3TU, UK
[3] C-Power (Technology) Ltd, No 8 Wu Hua Road, Hua Yuan Industrial Park, Tianjing, China

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ABSTRACT

This work investigated experimentally the direct effects of simulated lightning strikes in carbon/epoxy and E-glass/epoxy laminates. The direct effects were represented by Joule heating and kinetic shock waves. The experimental set-up was designed to maximize these direct effects by employing a solid electrode, pointed vertically to the surface of the specimens with a small electrode gap. The damage mechanisms were found to be in the form of resin sublimation, delamination and fibre tufting. The damage characteristics depended on type of composite materials, lightning current and action integral. In the carbon/epoxy laminates, resin sublimation and degradation were dominant at relatively low currents and with the further increase in current fibre tufting appeared due to kinetic shock waves. Penetration into the laminates was found to be limited to the only top two plies in the extreme case. The damage characteristics of the E-glass/epoxy laminates with a tiny hole were dominated by extensive delamination due entirely to shock waves with little sign of Joule heating. Analytical work will be desired to aid establishment of relationships between the damage characteristics and the lightning strike parameters via lightning channel radius and raised temperatures.

1 INTRODUCTION

Composite structures such as aircraft and wind energy turbine blades could be damaged by lightning strikes, even though the most of these modern composite structures have some lightning strike protection [1-2]. Damage inflicted in these structures, so-called the direct effects of the lightning strikes, can be attributed to one of or a combination of Joule heating and shock waves, dependent on composite materials and lightning strike parameters. To ultimately develop a lightweight and cost-effective protection for these structures, it is of paramount importance to develop a thorough understanding for the effects of the damage characteristics using both post-mortem microscopic examination and residual strength testing approaches. This highly complex multidisciplinary phenomenon is extremely challenging and crucial to the development of such effective protection schemes. This work investigated the direct effects of simulated lightning strikes on semi-conductive carbon/epoxy and non-conductive E-glass/epoxy, as they represent respectively the popular materials used in composite aircraft structural components and wind turbine blades. Some of the preliminary results were presented in [3].

2 DIRECT EFFECTS OF LIGHTNING STRIKES ON COMPOSITE STRUCTURES

The direct effects of lightning strikes describe the physical damage inflicted in composite structures and are manifested in resin damage driven primarily by Joule (or resistive) heating and fibre breakage (tufting) and delamination due largely to kinetic shock waves. These effects can systematically be investigated only under a controlled environment via so-called simulated lightning strikes. Natural lightning strikes on the composite structures are substantially different from the simulated lightning strikes. In the former, both aircraft and wind energy turbine blades are motional and are generally struck at an oblique angle so that not all the electrical energy under such circumstance could be channeled into the composite structures. On the contrary, the simulated lightning strikes are aimed at the ‘worst scenario’, i.e. to direct all the electrical energy vertically onto the selected composite structure targets in order to inflict damage. Therefore, once a range of regulated electrical energy input is provided, quantitative relationships between the damage characteristics and the lightning strike input can systematically be established.

In the simulated lightning strike for direct effects, electric current from a pulse generator was injected onto the surface of the composite specimen with an electric charge being transferred to its surface. A solid electrode was preferred (rather than a solid ball or a flexible wire) and hence could not only be positioned vertically to the specimen surface but also be controlled form a selected electrode gap between the tip of the electrode and the specimen surface. This was particularly desirable in considering that a wide range of the damage sizes was expected in a group of specimens so that the effects of the damage on their residual compressive performance could subsequently be evaluated. In this way, a lightning channel formed during a travelling of the electric charge to the specimen surface could be of cylindrical shape with a slight radially outward widening towards the surface of the specimen, as illustrated in Fig. 1. Consequently, the area of the lightning channel on the specimen surface covered by the electric arc could be approximated by the arc root radius of the lightning channel, though the arc root radius could expand outwardly during the lightning strike due not only to the mechanics of the lightning strike but also to carbon fibres being conductive. Unlike a ball tip, the solid conical rod also induced shock waves and ensured that the short discharged arc did not split or disperse at the root of attachment location so that the maximum deposition of the electric energy or current density on the specimen was achieved.

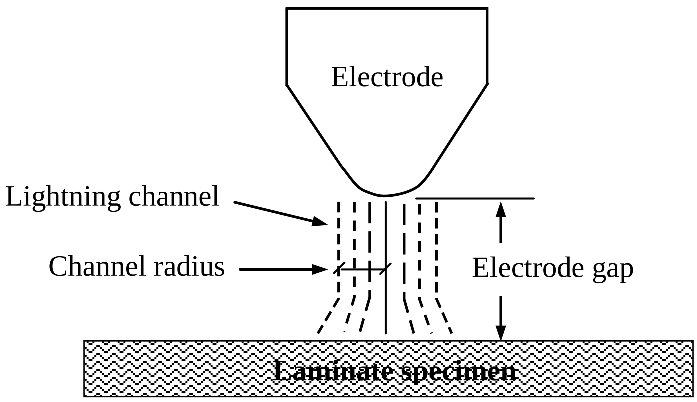

Fig. 1 Illustration of a lightning channel for direct effects on composite structure

A lightning current for direct effects is usually of transient nature and its waveform is commonly characterised by a double exponential current function I as given by

$$I = I_0\left(e^{-at} - e^{-bt}\right) \tag{1}$$

where I_o, a and b are constants and t the lightning strike duration. These constants can be determined with the availability of a measured waveform with front time t_1, half value tail time t_2 and peak current I_{max}, as illustrated in Fig. 2. Once available, current at any time of the lightning strike can be obtained. In particular, action integral (AI), the most important parameter of representing the strength of the lightning strike input for direct effects can be calculated by

$$\mathrm{AI} = \int_0^t I^2 \mathrm{d}t \tag{2}$$

Consequently, the total electric energy E_{in} deposited on the surface of the composite material with electric resistance during the lightning strike is given by

$$E_{in} = \int I^2 R \mathrm{d}t = \frac{\rho \cdot l}{A_1} \int_0^t I^2 \mathrm{d}t, \quad \rho = (1 + \lambda \Delta T) \rho_{\mathrm{m}} \tag{3}$$

in which l is a dimension in the thickness direction of composite material, ρ the resistivity of the material, λ the temperature coefficient of resistivity of the material and ρ_{rm} the resistivity at ambient or room temperature. This electrical energy E_{in} in Eq. (3) could be related to the thermal energy dissipated in the composite material to raise local temperature in the area. Since the thermal diffusion process in composite materials is slow when compared to the duration of the lightning strikes (less than 50 milliseconds), it could also be confined to the lightning channel and its immediate surrounding area. Sometimes, certain waveforms for direct effects such as 2.6/10 and 4/10 are recommended. The experimental results in [4] showed that the moderately different waveforms had little effect on the damage characteristics of the composite specimens.

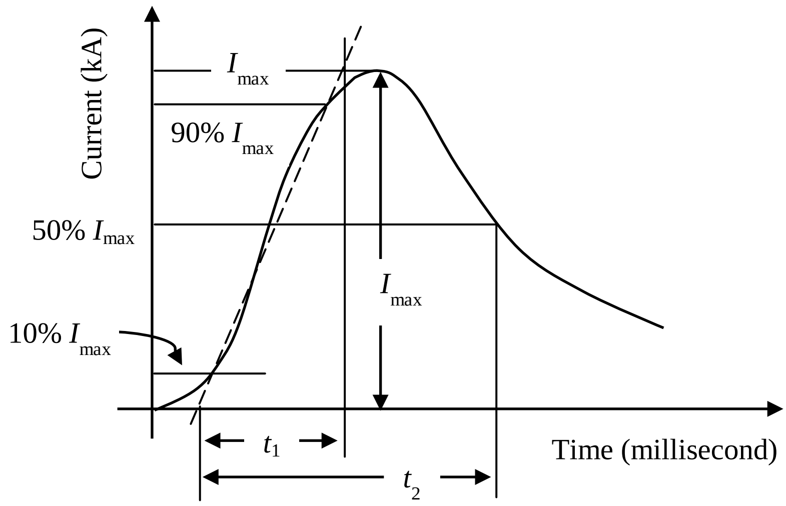

Fig. 2 Typical waveform of high current lightning strike with characteristic times

Kinetic over-pressure shock waves exhibited largely the mechanical effect and occurred simultaneously with the thermal effect. This mechanical effect could result in delaminations and fibre tufting in composite structures. However, a quantitative description of the mechanical effect for the investigation of direct effects on composite structures is not developed. A theoretical model for the strength of instantaneous shock waves normal to the surface of a structure used by Jones et al [5] is given in terms of pressure ratio by

$$\frac{P}{P_0} = \frac{\gamma}{2(\gamma + 1)} \cdot \left(\frac{r_0}{r}\right)^2, \quad r = \sqrt{c r_0 t} \quad \text{and} \quad r_0 = \sqrt{1.015 \frac{E_{in}}{\gamma P_0}} \tag{4}$$

in which γ is the specific heat ratio (1.4 for air), c is the speed of sound (343 m/s), t is the arrival time at the radius r and r_0 is the characteristic radius determined by the initial conditions.

3 EXPERIMENTAL SET-UP FOR LIGHTNING STRIKES

Plain weave 34-700/LTM45 carbon/epoxy laminate was 3.5 mm thick with 8 plies in a quasi-isotropic lay-up and UD tape-based PPG1062/LTM26 E-glass/epoxy laminate was 2 mm thick with 16 plies also in a quasi-isotropic lay-up. They were cured in an autoclave, following material manufacturer’s procedures. Both were of 150 mm by 100 mm. An experimental lightning strike set-up shown in Fig. 3 was intended to deliver electrical currents of short duration and relatively high magnitudes. In a test, a 10 mm diameter copper rod with a conical tip of 30^0 apex angle and with about 2 mm tip diameter was pointed vertically to the centre of a specimen with an electrode gap of no more than 24 mm. A lightning strike was a single current discharge accompanied always by an audible sound of explosion. For the carbon/epoxy specimens, burning flames of carbon fibres were always visible along with a smell of burned resin. Electrical currents of 3 to 91 kA were generated using an impulse generator configured with 8/20 waveform, with the lightning strike durations of no more than 30 milliseconds (ms). A varying degree of damage was induced in each of two groups of the unpainted unprotected composite specimens. A copper earth braid strip drew electrical current from the attachment location to ground, if the current did not attach to the laminate. All the lightning strike test results are summarised in Table 1.

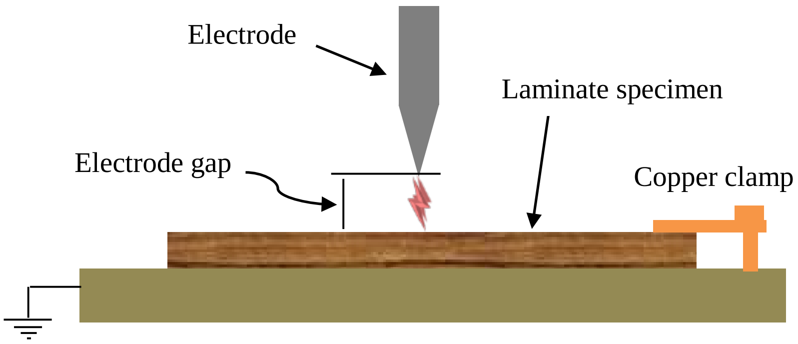

Fig. 3 A simulated lightning strike test set-up

Table 1 Lightning strike test results on unprotected composite laminates

Material	Panel ID	Peak current	Peak time	Charge transfer	Action integral	Damage area (radius)	Growth of fibre tufting	Area of fibre tufting
-	-	kA	μs	C	A^2s	mm^2 (mm)	-	mm×mm
Carbon/epoxy	C3-1	6.39	9.78	0.111	622	360 (10.7)	Exposed tow	-
	C3-2	11.87	9.78	0.197	2012	576 (13.5)	Exposed tow	-
	C3-3	21.38	9.78	0.360	6471	900 (16.9)	Resin hole	6×6
	C3-4	41.31	9.78	0.847	37242	1680 (23.1)	Resin hole	8×8
	C3-5	60.95	9.78	1.010	52985	2000 (25.2)	Yes	20×20
	C3-6	90.10	9.78	1.490	115925	2500 (28.2)	Yes	20×20
E-glass/epoxy	G2-1	29.82	9.91	0.521	14162	5693 (42.6)	Yes	25×25
	G2-2	10.03	9.50	0.148	1182	3877 (35.1)	Fibre splitting	-
	G2-3	2.54	9.99	0.039	81	7 (1.5)	-	-
	G2-4	4.69	9.66	0.074	293	1210 (19.6)	Fibre splitting	-
	G2-5	6.45	9.92	0.118	741	2349 (27.3)	Fibre splitting	-
	G2-6	3.60	9.72	0.0867	164	845 (16.4)	Fibre splitting	-

4 DAMAGE EXAMINATIONS AND EFFECT EVALUATION

4.1 Damage mechanisms and damage area estimations in the lightning struck specimens

Carbon fibres in the carbon/epoxy specimens are conductive, whereas E-glass/epoxy specimens are completely insulative. Thus, their damage characteristics under the lightning strikes are very different. The intense visual inspections of the struck carbon/epoxy specimens reveal that fibre tufting, resin sublimation and resin discolouring are three major damage mechanisms, irrespective of magnitude of lightning current. These damage characteristics appear in three concentric approximately rectangular regions, as an example shows in Fig. 4. The central region 1 is dominated by fibre tufting, as can be seen from a separate cut-up specimen in Fig. 5(a), except for the specimens being struck with the lower end of the lightning currents (C3-1 and C3-2). The fibre tows of the top ply in those two specimens were exposed due to resin sublimation but were bridging over a shallow cavity without tufting or breaking. The middle annular region is represented by the isolated exposed cross-over segments of fibre tows due to resin sublimation, as a spreading lightning arc swept through the immediate vicinity of the lightning channel at the very high temperature. The outer annular region includes just the area of discoloured resin, which could be scorched by the front of the out-sweeping lightning arc at the much lower temperature. The reason that these annular regions appear in the shape of squares is because the conductive carbon fibre tows in the top surface ply are in 45^0 angle directions so that they carried the thermal energy in those directions. A cut-up of a separate specimen (C3-3) shows a limited delamination and the penetration of the lighting strike reached only the third ply out of the total of eight, as resin is non-conductive. This seems plausible, as all the specimens were placed on a rigid table without a chance of bending during the lightning strikes and the limited delamination may very well be associated with fibre tufting. Therefore, the estimations of the damage areas in each of these specimens cover the entire area within the region 3. The surface damage obtained via visual inspections could be either close to or greater than C-scanned projected interior area [6]. Moreover, experiences in [1] suggested that the surface damage agreed well with AIs, as C-scanning is not able to pick up resin pyrolysis. Thus, the areas in the carbon/epoxy specimens as given Table 1 are based on the largest damaged surface areas.

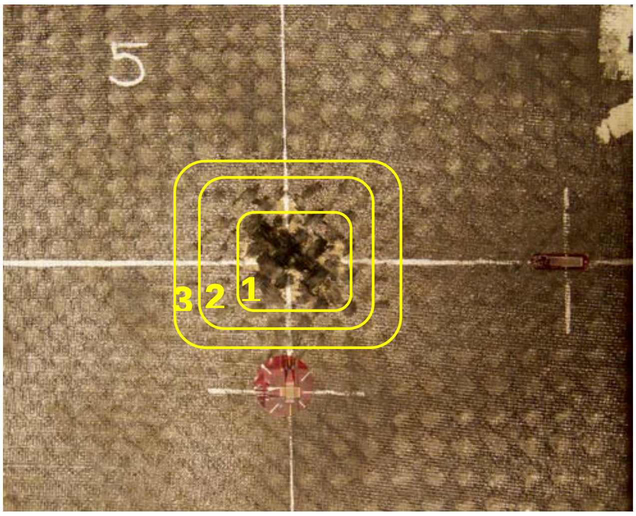

Fig. 4 Carbon/epoxy specimen struck by lightning current of 61kA

For the insulative E-glass/epoxy specimens, preliminary trials with the lighting current up to 70 kA did not inflict any damage, as that was because the levels of the transferred charges may not have been higher enough to overcome the dielectric breakdown strength of this material [1,7]. Thus a tiny pilot through hole of 0.5 mm diameter was drilled at the centre of all the specimens to overcome the dielectric barrier of the material. The major damage mechanism was found to be extensive delamination as an example in Fig. 5(b) shows. At the lower end of the lighting current range at 2.54 kA, there was almost no damage visible in specimen G2-3, whereas at the upper end of the lighting current range at 29.82 kA, there was some fibre tufting at the centre of the specimen. Soot is clearly visible through the delaminated interfaces but there was neither sign of resin discolouring nor smell of burned resin, interestingly. Although temperature in the lightning channel could rise up to 1000^0C, as reported [1], there is little visual evidence of Joule heating or resin pyrolysis in this E-glass/epoxy material. Since the E-glass/epoxy specimens were translucent, as could be seen in Fig. 5(b), this nature facilities significantly not only the examination of damage mechanisms but also the estimations of the delamination areas.

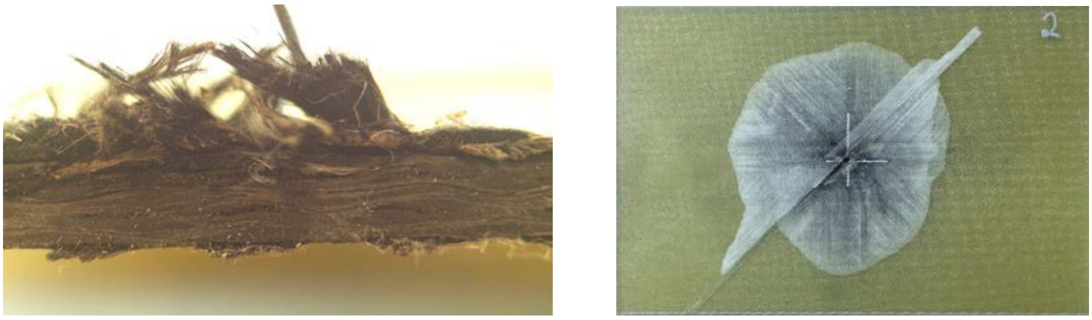

Fig. 5 (a) Carbon/epoxy struck by a 90kA current and (b) E-glass/epoxy struck by a 10kA current

4.2 Joule heating damage in composite materials

The thermal (Joule heating) and mechanical (shock wave) effects were very likely to be coupled throughout the lighting strike. Also, they may have done their damage at the different stages of the lighting strike duration. To gain a physical insight into the nature of such damage process, it is necessary to adopt an approach of separating the two. Moreover, the investigation of the Joule heating thermal damage process is largely limited to the carbon/epoxy specimens, as the E-glass/epoxy specimens showed little thermal effects because of their insulative nature. Nevertheless, ascertaining the resin's thermal decomposition process from sublimation to discolouring is still a daunting task.

When an electric energy of the lightning current was deposited on the surface of each carbon/epoxy specimen, local temperature within the lightning channel must have arisen to an extremely high level due to its finite conductivities in the in-plane directions. Since the direction of the lightning strike was in the insulative thickness direction, the attached lighting arc hence sublimated the surface resin in its path. Then the heat flow was obstructed by the exposed but firmly in-position carbon fibre tows. By this time, part of the heat flow or the thermal energy was diverted to the electrically-connected in-plane fibre directions where the resistance of the dissipations was significantly less, the remaining of the diffused heat flow for the given thermal energy had the significantly limited capacity to further sublimate the next resin layer between the top ply and the next ply down. Within a duration of less than 30 ms, a significantly higher level of lightning current or AI was needed for resin of the second ply to be sublimated. This understanding is in agreement not only with the qualitative surface inspection results in Table 1 but also with the trend of the damage area results in Fig. 6. The trends of the damage areas with the increase in AI were similar, as shown in [3].

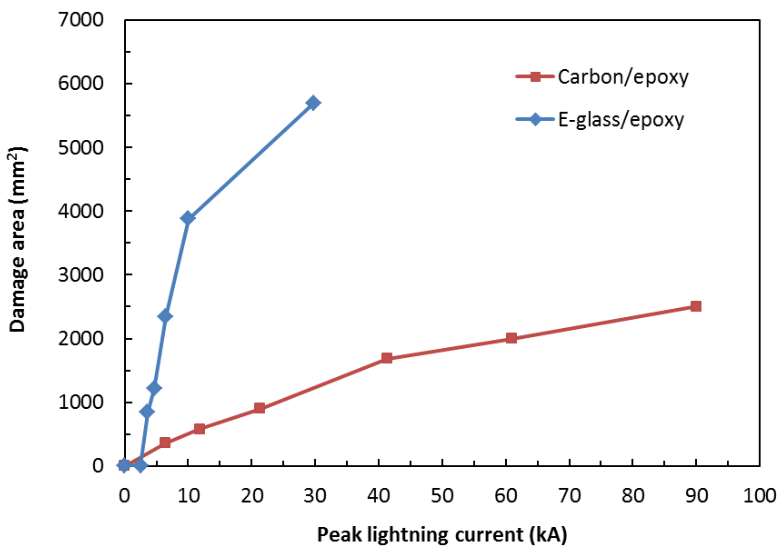

Fig. 6 Relationship between lightning current and damage area for laminates

Fig. 6 shows the parabolic variations of damage areas with the increase in peak current, which seems to decay towards the upper end of the lightning current range. Nevertheless, the very different trends from the different composite laminates had the different damage mechanisms. For the carbon/epoxy specimens, this trend seems to suggest that the thermal energies converted from the electrical energies had not been consumed just within the lightning channel. Instead, the areas covered by all three regions in Fig. 4 seem to be about three times of the lightning channel. Although the local temperatures in the lightning channel may well have been around 1000^0C, the duration of such high temperatures could be extremely short so that resin sublimation was largely confined within the lightning channel. For the E-glass/epoxy specimens, the decaying parabolic trend indicates that the most of the electrical energies had gone into a generation of delaminations and their enlargements.

4.3 Kinetic shock wave damage in composite materials

In the simulated lightning strikes for direct effects, there are two types of pressure present on the surface of the composite specimen, namely, kinetic pressure carried by current flow in the lightning channel and electromagnetic pressure. The latter is concerned only with the semi-conductive carbon/epoxy. On the hard solid surface, the extremely rapid increase in pressure at the front of the lightning arc led to a high concentration of the kinetic energy in the direction of wave propagation and radially outward expansion in a supersonic speed resulted in instantaneous over-pressurisation and hence caused cylindrical shock waves. On a basis of the experimental observations of both carbon/epoxy and E-glass/epoxy specimens, the kinetic shock waves seem to be the dominant one for both materials, with electromagnetic pressure being negligible in the carbon/epoxy. However, at present, there does not appear to have any established relationship that relates the strength of kinetic shock waves as predicted by Eq. (4) to the damage characteristics for the given electric energy or AI.

Nevertheless, in the case of the semi-conductive carbon/epoxy, while the very high temperatures within the lightning channel sublimated resin and left the fibre tows unsupported, the outward expanding shock waves were constrained in the in-plane directions, whereas they met the least resistance opposite to the current injection direction. Hence the reflected shock waves not only pulled the exposed fibre tows apart but also pulled them out. This is why the tufting of the broken carbon fibres and delaminations remained close to the specimen surface as in [8]. In the case of the non-conductive E-glass/epoxy, the reflected shock waves caused massive delaminations through the laminate thickness with some fibre tufting at the extreme lightning current.

4.4 Effect of lighting strike damage on the residual compressive strengths

To ultimately develop an in-depth understanding for the nature of the damage in the lightning struck composite specimens, the lightning strike damaged panels were further tested for their residual in-plane compressive strengths. The methodology follows that used for the residual in-plane compressive strengths of impact-damaged composite panels. The overall test results for compressive failure stresses are presented in Fig. 7 against damage areas. In the diagram, the term of compressive stress was used, rather than residual compressive strength, is because all the panels but one (G2-1) failed prematurely close to one of the loaded ends, as shown in Fig. 8. For the carbon/epoxy panels, this finding strongly suggests that the lightning damage was relatively shallow close to the surface of these panels and the respective extents of fibre tufting and delamination are relatively small. This is in agreement with the earlier examinations. If the depth of the damage were deeper than two plies, the panels could have failed in the mid-section region, when the extent of those two panels in the width direction is greater than 50%. This is because such damage with a presumed severity ought to be sufficient to instigate a further propagation in the width direction under in-plane compressive loads, thereby triggering a catastrophic failure of the panels. For the E-glass/epoxy panels, the panels with the delamination extent of 40 mm or greater were again expected to fail around the mid-section region, whereas the two least damaged panels were expected to fail close to the panel ends. However, the only one (G2-1) out of the three most damaged panels failed in the mid-section region and the other two (G2-4 and G2-5) did not, which is surprising.

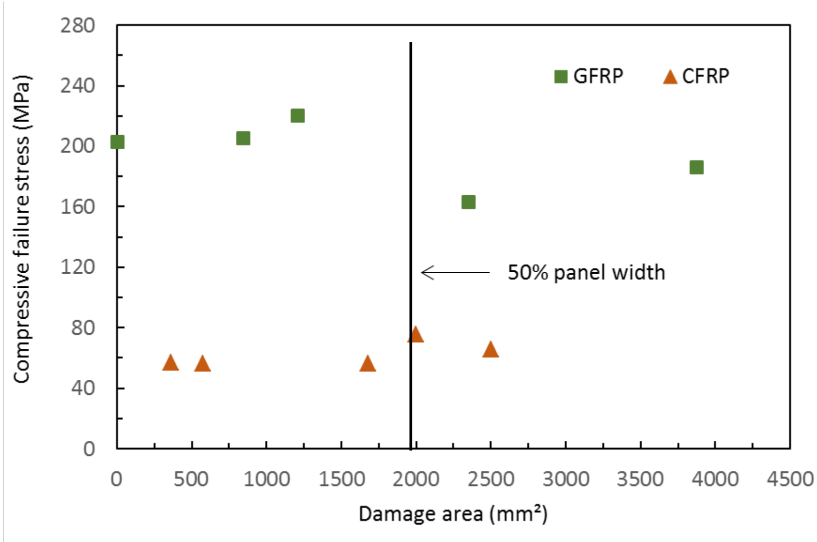

Fig. 7 In-plane compression test results of lightning struck carbon/epoxy and E-glass/epoxy panels

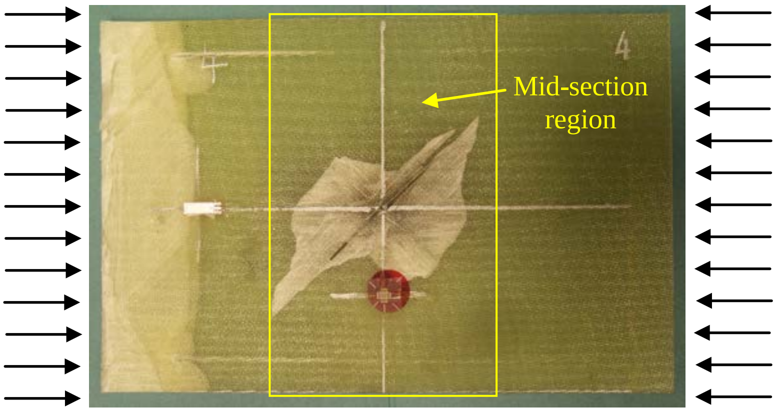

Fig. 8 An end failure of lightning struck E-glass/epoxy specimen G2-4 after in-plane compression test

5 CLOSING REMARKS

The present experimental investigation of simulated lightning strikes aimed at establishing the damage characteristics in both carbon/epoxy and E-glass/epoxy laminates which were associated with Joule heating and kinetic shock waves. The damage characteristics depended on type of composite materials in addition to lightning current, AI and charge transfer and they appeared in the form of resin sublimation, delamination and fibre tufting. The struck carbon/epoxy laminates were dominated by resin sublimation with relatively low currents due largely to Joule heating and by fibre tufting with moderate and high currents due largely to shock waves. Penetration into the laminate was limited to the only top two plies. The damage characteristics of the E-glass/epoxy laminates with a tiny hole were dominated by extensive delamination due entirely to shock waves. To gain a deeper understanding through quantitative relationships between the damage characteristics and key lightning strike parameters, a quantitative knowledge of lightning channel radius and raised temperature as well as temperature distribution will be very desirable and could be a significant challenging.

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