Investigation of Damage in Composite structures Caused by Simulated Lightning Strikes

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Abstract

The direct effects of simulated lightning strikes on both carbon/epoxy and E-glass/epoxy laminates have been investigated with high currents. Unprotected specimens were struck with a single impulse for a range of lightning currents. The key effects found to damage the laminates are Joule heating and shock waves. The two laminates reacted to the effects differently due to the fact that carbon fibres are conductive, whereas E-glass fibres are not. In carbon/epoxy laminates, the effect of Joule heating covered the whole lightning channel due to fibres acting as current paths. Some fly-over carbon fibre tows appeared to be bare due likely to resin vaporisation during the strike. At high lightning currents, carbon fibres in the channel were pulled out and apart in the form of tufting due to shock waves. The damage in translucent E-glass/epoxy laminates was characterised by extensive delamination throughout the thickness and fibre tufting. With visible soot infiltrating the delaminated interfaces and little evidence of resin pyrolysis on the laminate surface, the primary element of the direct effects that contributed to this damage was reflected shock waves. The introduction of a 0.5 mm hole made this possible as the dielectric breakdown strength of the material was not overcome under the present lightning set-up.

1 Introduction

Composite structures have widely been used in load-bearing structures in aircraft and wind energy turbine blades. However, they could still be damaged by the direct effects of lightning strikes, even though the most of these composite structures have some protection against lightning strikes [1-2]. Damage inflicted in these structures can be attributed to one of or a combination of two main aspects of the direct effects, i.e. Joule heating and shock waves. To ultimately develop a lightweight and cost-effective protection scheme for these load-bearing composite structures against lightning damage, it is of paramount importance to develop a thorough understanding of damage characteristics before the residual performance of the lightning damaged composite structures could accurately be evaluated. This highly complex multidisciplinary phenomenon is extremely challenging and crucial to the development of effective protection schemes. While Joule heating is the thermal effect, overpressure shock waves reflect largely the mechanical effect. Two polymeric composite materials chosen for this investigation are semi-conductive carbon/epoxy and non-conductive E-glass/epoxy, as they represent the most popular material systems used respectively in composite aircraft structures and wind turbine blades.

2 Direct effects of lightning strikes on composite structures

2.1 Lightning strike physics for composite materials

In a simulated lightning strike for direct effects, electric current from a pulse generator is injected onto the surface of a composite specimen with an electric charge being transferred to its surface. Since the tip of a solid electrode is positioned vertically at a small distance (electrode gap) away from the specimen surface, a travelling of the electric charge to the specimen surface forms a lightning channel and could be of cylindrical shape with a slight radially outward widening towards the specimen, as illustrated in Figure 1. The surface area (A_1) of the lightning channel covered by the electric arc could be approximated by

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$$A_1 = \pi r(t)^2 \qquad (1)$$

in which $r(t)$ is the arc root radius of the lightning channel from the arc axis. This arc root radius could expand outwardly during the lightning strike.

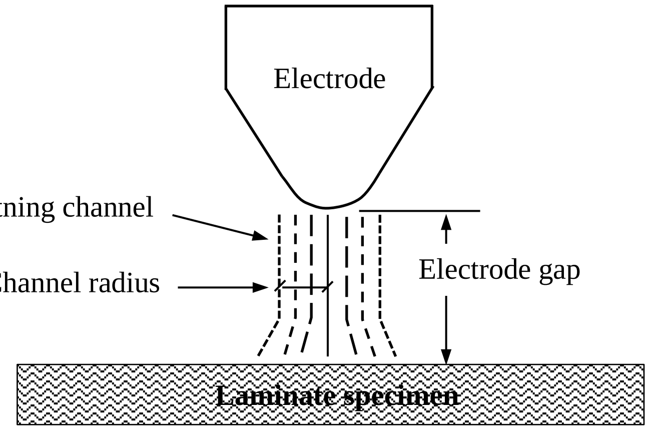

Figure 1 Illustration of a lightning channel for direct effects on composite structure (not to scale)

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

$$I = I_o \left(e^{-at} - e^{-bt}\right) \qquad (2)$$

in which I_o, a and b are constants and t the lightning strike duration. The measured front time t_1, half value tail time t_2 and peak current I_{max} of the waveform, as illustrated in Figure 2, are needed to determine these constants. Once available, current at any time of the lightning strike can be obtained. In a standardised lightning strike testing, certain waveforms for direct effects such as 2.6/10 and 4/10 are recommended. Experimental results in [3] showed that the moderately different waveforms had little effect on the damage characteristics of the composite specimens. The simulated lightning strike events for direct effects typically last no more than 30 milliseconds.

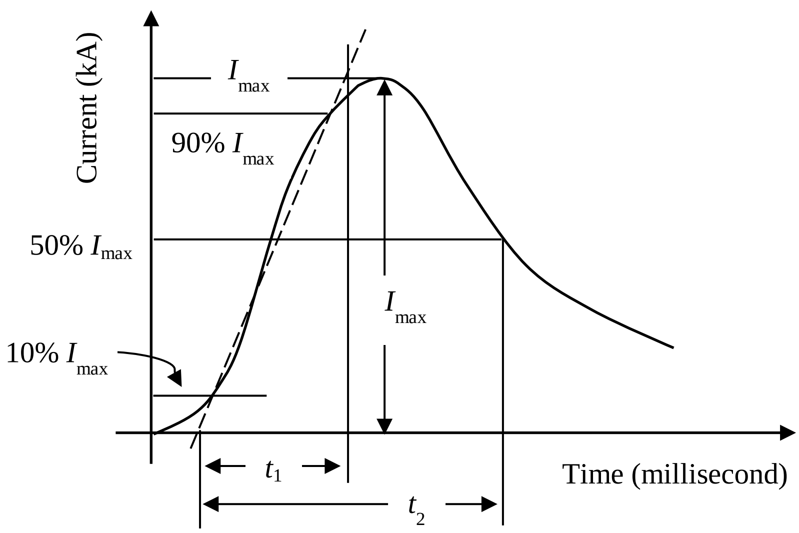

Figure 2 Typical waveform of high current lightning strike with characteristic times

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The most important parameter of representing the direct effects of such lightning strike is action integral (AI), as defined by

$$\mathrm{AI} = \int_0^t I^2 dt \tag{3}$$

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

$$E_{in} = \int I^2 R \mathrm{d}t = \frac{\rho \cdot l}{A_1} \int_0^t I^2 \mathrm{d}t \qquad \rho = (1 + \lambda \Delta T)\rho_{\mathrm{rm}} \tag{4}$$

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 energy is positive when the current is injected into the composite material.

2.2 Joule or resistive heating in lightning struck composite materials

Joule heating describes a raise of local temperature in the composite material with finite conductivities when the electric energy of the lightning current is converted to heat through resistance losses. When such losses that start within the lightning channel reach a critical level, they result in damage in the struck composite materials. The damage not only penetrates into the thickness direction but also spreads across the lightning channel of the composite material. To evaluate the effect of the damage on the residual compressive behaviour, it is particularly important to develop an understanding of the lightning channel radius on the surface of the composite material in addition to a historical distribution of the local temperature and heat flux. While there have been numerical endeavours [1,4-5], the most well-known theoretical model for predicting the lightning channel radius $r(t)$ (in meters) for instant current I was developed by Braginskii [6] as given by

$$r(t) = \frac{\alpha}{\rho_0^{1/6}} I^{1/3} t^{1/2} = \begin{array}{ll} 0.282 I^{1/3} t^{1/2} \text{ with } \alpha \text{ of } 0.294 & \text{Braginski} \\ 0.0978 I^{1/3} t^{1/2} \text{ with } \alpha \text{ of } 0.102 & \text{Vooray} \\ 0.1917 I^{1/3} t^{1/2} \text{ with } \alpha \text{ of } 0.2 & \text{Author} \end{array} \tag{5}$$

in which ρ_o is the air density of 1.29 kg/m^3 at atmospheric pressure and α is a constant of 0.294. Although this model was developed for natural lightning strikes, it could be adapted to predict the lightning channel radius of the simulated lightning strikes, as it depends only on the magnitude of peak current and time. The value of 0.102 for α was also suggested by Cooray [7] for the better agreement with experimental data. A fitting constant of 0.2 is used here for α in Eq. (5) to yield the overall coefficient of 0.1917 for better agreement with the present experimental data. All radius values calculated using Eq. (5) with the original and present fitting constants are presented in the last two columns in Table 1.

Although obtaining accurate temperature distributions in the lightning struck composite material is much more challenging, some crude estimation of raised temperatures in the axis direction of the lightning channel could be obtained by considering one-dimensional energy balance. Since the thermal diffusion process in composite materials is slow when compared to the duration of the lightning strike (within 30 milliseconds), the electrical energy E_{in} is assumed to be very much confined to the lightning channel so that it is dissipated in the area almost in the 'adiabatic' conditions (i.e. no heat or energy crosses the radial boundary of the lightning channel). As a result, the deposited electrical energy in Eq. (4) could be equated to the thermal energy dissipated completely in the composite material to raise the temperature ΔT at time t as

$$E_{in} = \frac{(1 + \lambda \Delta T)\rho_{\mathrm{rm}} \cdot \Delta z}{A_1} \int_0^t I^2 \mathrm{d}t = \Psi A_1 \Delta z c_p \Delta T \tag{6}$$

Then the temperature rise in the area is given by

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$$\Delta T = \frac{f\rho_{\mathrm{rm}}\int I^2 \mathrm{d}t}{c_{\mathrm{p}}\Psi A_1^2 - \lambda\rho_{\mathrm{rm}}\int I^2 \mathrm{d}t} \tag{7}$$

in which ψ is a density of the material, c_{p} is the specific heat of the material and constant f is inserted to reflect that a value of 0.2389 was used in [1] for metallic aircraft skins [1] and unity was used in [8] for metals and composites. The raised temperature ΔT must be added to ambient or room temperature for final temperature. Moreover, in the larger part of the lightning channel area, a substantial rise of resistivity ρ could be small due to the relatively low values of temperature coefficients of resistivity of the materials. For example, the values of λ for aluminium and copper in [1] are 0.00429 and $0.00393^0\mathrm{C}^{-1}$, respectively. The variations of σ in composite materials appear to be small [9] and thus Eq. (7) can further be simplified to be

$$\Delta T = \frac{f\rho_{\mathrm{rm}}\int I^2 \mathrm{d}t}{c_{\mathrm{p}}\Psi A_1^2} = \frac{fE}{c_{\mathrm{p}}\Psi A_1\, l} = \frac{fE}{mc_{\mathrm{p}}} \tag{8}$$

in which m is the mass of heat dissipated volume of A_1 by l in the material. It can be seen that this temperature rise is linearly proportional to AI or proportional to the deposited energy and is a result of Joule heating in the thickness direction of the composite material. Its values could be calculated, if the resistivities and specific heats of the two composite materials are available. In addition, Eq. (8) suggests that the temperature rise ΔT would follow a normal distribution for a given lightning channel area.

2.3 Acoustic shock waves in lightning struck composite materials

In the simulated lightning strike for direct effects, there are two types of pressure present on the surface of a composite material, namely, acoustic kinetic pressure carried by current flow in the lightning channel and electromagnetic pressure. On a hard solid surface, radially outward expansion in a supersonic speed results in over-pressurisation and hence causes shock waves. Which pressure is present and/or dominant on the surface of a composite specimen depends on whether or not composite materials are conductive. For semi-conductive carbon/epoxy, both pressures could be present, whereas for non-conductive E-glass/epoxy, there is only kinetic pressure. On the basis of experimental observations of both carbon/epoxy and E-glass/epoxy tests, the kinetic shock waves seem to be the dominant one for both materials, with electromagnetic pressure being negligible in carbon/epoxy. However, at present, there does not appear to have any established relationship relating AI or electric energy to lightning-induced kinetic shock waves.

3 Experimental set-up and testing procedure for simulated lightning strikes

An experimental set-up shown in Figure 3 aims at investigating the direct effects of simulated lightning strikes with short-duration high currents, rather than a certification testing of full-scale composite structures at 200 kA current with the AI of 2×10^6 $\mathrm{A}^2\mathrm{s}$ [1]. Under this set-up, a 10 mm diameter solid copper rod electrode with a conical tip of 30^0 apex angle and with about 2 mm tip diameter was pointed vertically to the centre of a composite specimen with an electrode gap of no more than 24 mm. A lightning strike test was just a single current discharge with a typical waveform shown in Figure 4 and was always accompanied by an audible sound of explosion. Unlike a ball tip, it was intended to induce shock waves and also to ensure that the discharged arc was short so that it did not split or disperse at the root of attachment location. In this way, it was expected to maximise the deposition of electric energy or current density on the specimen and enhance possibility of causing physical damages. High currents from 3 to 91 kA were generated using an impulse generator configured with 8/20 waveform. A varying degree of damage was induced in each of two groups of clamped unpainted and unprotected composite specimens. A copper earth braid strip of about 45 mm away from the specimen centre drew electrical current from the attachment location to ground, if the current did not attach to the laminate. Both plain weave 34-700/LTM45 carbon/epoxy and UD tape-based PPG1062/LTM26 E-glass/epoxy laminates of 150 mm by 100 mm were cured in an autoclave, following material manufacturer's procedures. Their lightning strike test results are summarised in Table 1 along with

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current function constants. Figure 5 shows exponentially increasing trends of AI with measured peak current, which agree with what is predicted theoretically in Eq. (3).

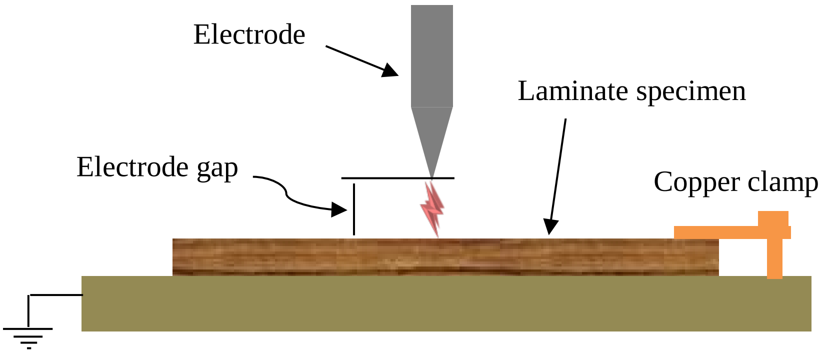

Figure 3 An experimental set-up of a simulated lightning strike test

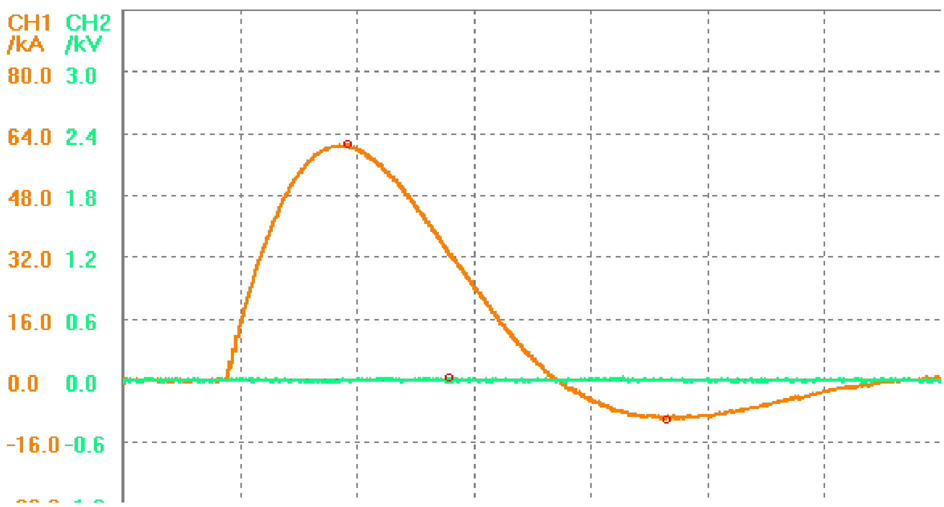

Figure 4 A typical waveform of a simulated lightning strike test (10 microseconds per major horizontal tick)

Table 1 Lightning strike test results on unprotected composite laminates

Mat.	Panel ID	Tail/front time	Peak current	*a*	*b*	Const. current	Peak time	Charge transfer	Action integral	Damage area (*r* in mm)	r_1	r_3
-	-	t_2/t_1	I_{max}	-	-	I_o	t_{max}	*Q*	AI	-	*r*	*r*
-	-	μs/μs	kA	μs^{-1}	μs^{-1}	kA	μs	C	A^2s	mm^2	mm	mm
Carbon/epoxy	C3-1	21.54/8.03	6.39	0.0978	0.1594	38.26	9.78	0.111	622	360 (10.7)	16.4	11.1
	C3-2	20.80/7.85	11.87	0.0987	0.1580	71.94	9.78	0.197	2012	576 (13.5)	20.1	13.7
	C3-3	21.10/8.00	21.38	0.0969	0.1550	129.58	9.78	0.360	6471	900 (16.9)	24.5	16.6
	C3-4	20.78/7.95	41.31	0.1057	0.1532	393.43	9.78	0.847	37242	1680 (23.1)	30.5	20.7
	C3-5	20.74/7.85	60.95	0.0987	0.1580	369.39	9.78	1.010	52985	2000 (25.2)	34.7	23.6
	C3-6	20.66/7.78	90.10	0.1001	0.1612	542.77	9.78	1.490	115925	2500 (28.2)	39.5	26.9
E-glass/epoxy	G2-1	20.68/7.71	29.82	0.0947	0.1657	161.2	9.91	0.521	14162	5693 (42.6)	27.5	18.7
	G2-2	20.00/6.80	10.03	0.0882	0.2294	29.1	9.50	0.148	1182	3877 (35.1)	18.7	12.7
	G2-3	20.34/7.12	2.54	0.0861	0.2152	7.82	9.99	0.039	81	7 (1.5)	12.2	8.3
	G2-4	20.34/7.63	4.69	0.1166	0.1983	26.1	9.66	0.074	293	1210 (19.6)	14.7	10.0
	G2-5	20.34/7.76	6.45	0.1082	0.1624	51.6	9.92	0.118	741	2349 (27.3)	16.5	11.2
	G2-6	20.34/7.07	3.60	0.0867	0.2168	11.1	9.72	0.0867	164	845 (16.4)	13.5	9.2

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4 Lightning strike test results and damage characteristics of composite panels

Eight ply carbon/epoxy laminates in a quasi-isotropic lay-up have a nominal thickness of about 3.5 mm and are electrically semi-conductive. They were lightning-tested with an electrode gap of about 1 mm. The surface damage was obtained via visual inspections, as it was suggested that the surface damage could be either close to or greater than C-scanned projected interior area [10]. Moreover, experiences in [1] suggested that the surface damage agreed well with AIs, as C-scanning is not able to pick up resin pyrolysis.

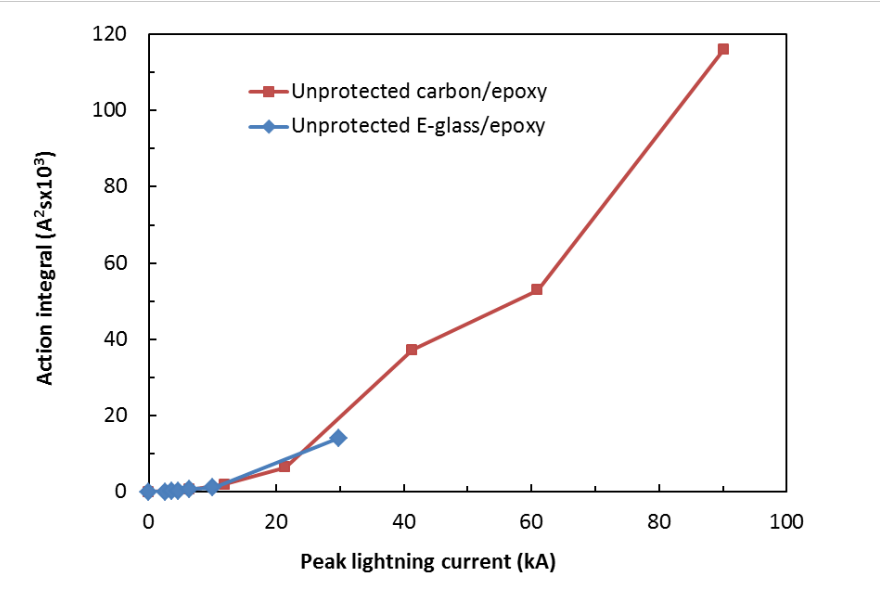

Figure 5 Relationship between lightning current and AI for composite laminates

Lightning damage to these carbon/epoxy laminates includes resin pyrolysis and/or vapourisation, delamination and tufting of carbon fibres, as shown in Figure 6(a). The flames of burning carbon fibres were visible in the majority of the tests, all with a loud bang, which was associated with kinetic shock waves or over-pressurisation in a short time. The surface observations of the struck specimens show three features. (1) There is always an approximately circular or diamond surface area, which could be interpreted as a lightning channel (see Figure 6(a)). This area increased with the increased level of lightning current or AI, as shown in Table 1 and Figure 7. (2) Each of the surface areas could be divided into a much smaller central area surrounded by two annual ring areas. While the inner annual area has regular exposed fly-over fibre tows with no resin, the outer annual area shows only extensive discolouring. (3) At the lower end of the lightning current range, the central area exhibits extensive exposed fibre tows in both directions. However, once the lightning currents became moderate and high, fibre tufting occurred, as shown in Figure 6(a). In the thickness direction, the damage penetrated no more than a couple of plies into the surface. In all the lightning struck specimens, their back (distal) surfaces did not appear to be affected at all. As conductive carbon fibres carried current and resin is non-conductive, a temperature rise on the surface was much fast so that resin over the fly-over fibre tows got vapourised. Moreover, the reflected shock waves not only pulled the exposed carbon fibres apart but also pulled them out opposite to the current injection direction against the least resistance. This is why the tufting of the broken carbon fibres and delaminations remained close to the strike surface [11].

As both E-glass fibres and epoxy are non-conductive, pristine 2 mm thick E-glass/epoxy laminates were not damaged at all in initial lightning strike test trials with current levels going up to as much as 69 kA. This was because the level of voltage drop or transferred charge from the impulse generator may not have been higher enough to overcome the dielectric breakdown strength of the material [1,12]. It was then decided to introduce a tiny through hole of 0.5 mm diameter. As a result, with the much lower current and AI levels, the massive delamination was generated in all specimens but one, in addition to fibre tufting from top few plies and fibre splitting from the top ply, as clearly shown in Figure 6(b) due to its translucency. When the deposited kinetic energy reached the conductive support underneath with some being reflected, the outward expansion of the reflected caused massive delaminations through the laminate thickness with some fibre

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tufting. Although temperature in the lightning channel could rise up to 1000^0C, as often reported [1], there is little visual evidence of Joule heating or resin pyrolysis in this E-glass/epoxy material, apart from some soot. Moreover, there was no smell of burned resin, unlike in the case of carbon/epoxy. This seems to suggest that for non-conductive E-glass/epoxy the extensive damage was attributed more to shock waves than to Joule heating and that the electric conductivity of E-glass/epoxy could be coupled to Joule heating in such a way that the very low value of the electric conductivity for E-glass/epoxy correlated to having close to none of Joule heating.

Figure 6 (a) Carbon/epoxy struck by a 90kA current and (b) E-glass/epoxy struck by a 10kA current

Figure 7 shows the variation of damage areas visually estimated with the aid of an optical microscope with peak currents, along with the lightning channel areas calculated using the radius predictions of the Braginskii's model with the assumption that the shape of the lightning channels was circular. A common non-linear decaying trend of damage areas with increasing current is easily observed. Since temperature in the lightning channel increased linearly with the increase in AI, it could thus be deduced that the greater amount of AIs could have been consumed right in the lightning channel. Since both dominant damage characteristics of resin vapourisation and fibre tufting in carbon/epoxy remained localised and are close to the strike surface within the lightning channel, the degree of delamination is very limited and hence the size of damaged areas is moderate. Moreover, it might be fortuitous that the predictions of the Braginskii's model agree well with the measured data. However, for E-glass/epoxy whose most dominant damage characteristic being delamination, its size of damaged areas is much greater than those of carbon/epoxy laminates. It was not surprising that the area predictions of lightning channel using the Braginskii's model don't agree with the measured damage area data.

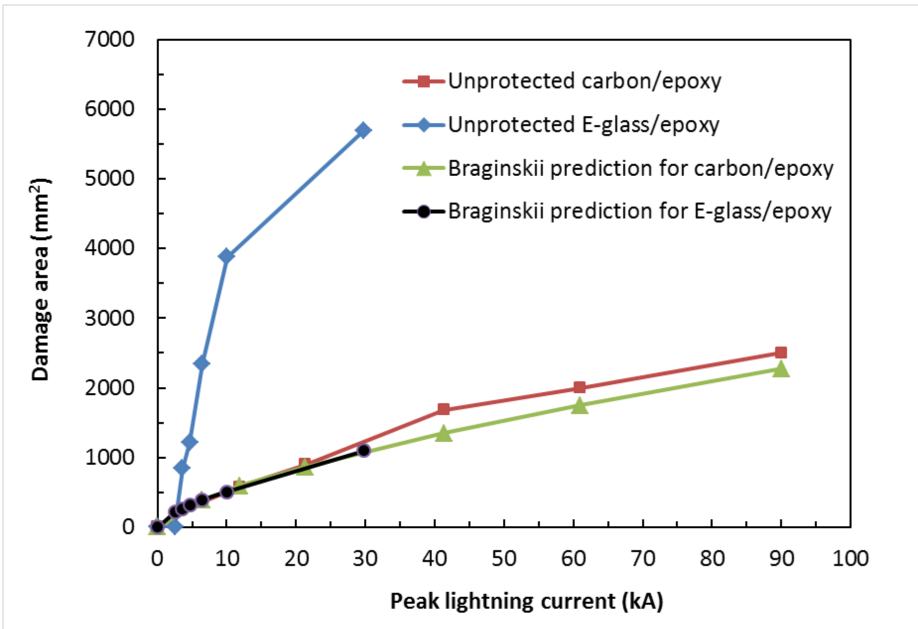

Figure 7 Relationship between lightning current and damage area for laminates

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5 Conclusions

The present experimental set-up of simulated lightning strikes aimed at creating the 'worst scenario' of the direct effects such that the electrical discharges resulted in not only Joule heating but also kinetic shock waves in both carbon/epoxy and E-glass/epoxy laminates. The damage characteristics in the struck specimens depended on the type of composite materials in addition to lightning current, AI and charge transfer and they appeared in the form of resin vapourisation, delamination and fibre tufting. The struck carbon/epoxy laminates were dominated by resin vapourisation 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 three plies. The damage characteristics of E-glass/epoxy laminates with a tiny hole were dominated by extensive delamination and fibre tufting due entirely to shock waves.

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