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Experimental and Theoretical Evaluation of Aluminium Deflection due to Lightning Strikes

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This paper focuses on the displacement of aluminum plates subjected to the forces generated by a lightning current in order to compare modelling and experimental results directly. The electromechanical forces produced during lightning strikes can cause catastrophic damage and hence there is a need to understand the performance of existing and new materials under such extreme conditions in order to improve the ability to withstand these forces and minimize damage. Half-meter square 2mm thick aluminum plates were struck with a range of lightning currents from 40kA to 100kA. A computer model using a constant direct current input was used to predict the point of maximum deflection immediately following a strike which was compared to the measured maximum deflection from the corresponding experiment. Both model and experiment demonstrated an approximately linear relationship between maximum deflection and lightning current for aluminum. In addition, the experiment exhibited damped oscillation behavior following the maximum deflection and the extent of this was also related to magnitude of the lightning current. It was also found that, in the experiment, the test sample experienced an additional force, presumed to be due to air pressure, which could be corrected for. Overall, the static model and dynamic experiments showed close agreement with differences likely due to factors in each respective study.

Keywords: Lightning, static displacement, dynamic displacement, electromagnetic force, damped harmonic oscillation

I. Introduction

Lightning and its interactions with various materials are an increasingly important area of research, particularly in recent years. Notably, this is a critical area for the aerospace industry where much of the traditional highly conductive metallic sub-structure and skin have been replaced by modern non-conductive composite materials such as complex multilayer carbon fiber reinforced plastics. Other such applicable industry sectors include wind turbine structures, power infrastructure, and rail electrification, etc. Such materials are at risk of lightning strikes averaging 30kA that can reach around 30,000K associated with an equivalent electromagnetic force in the thousands of MPa delivered into an area of less than one square centimeter within a fraction of a millisecond. The ability of a material to withstand such an impact relies on how effectively it can translate the energy into other forms, such as light, heat and physical movement with minimal adverse effects. In the case of aircraft, a direct lightning strike can result in physical damage to the surface, internal structure and metal interconnections, resulting in burning, melting, vaporization and puncturing [1, 2]. Surface explosions and electromagnetic and electromechanical forces can became dominant contributors to bulk damage such as displacement, deflection and delamination of composite materials [1, 3]. The damage at the injection point or plasma arc channel can result in extreme destruction to localized metal and composite bodies compared to other areas [1, 5]. An illustration of such damage on both aluminium and carbon composite is shown in Figs. 1 and 2 [4]. In some cases, the force generated from such an event can be represented as a purely mechanical impact [3].

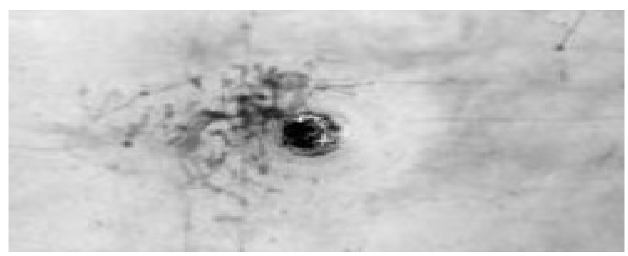


Figure 1: A puncture due to a lightning attachment point on an aluminum skin of an aircraft body [4].

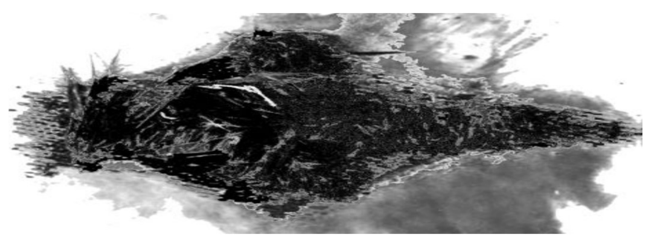


Figure 2: Surface damage at a lightning attachment point on a carbon composite material skin of an aircraft body [4].

Lightning-material interactions are often very complex, and the ability to model and predict accurately aspects of material behavior under such conditions is expected to lead to improvements in material research and design processes.

The Morgan-Botti Lightning Laboratory (MBLL) at Cardiff University is a new lightning direct effects research facility [6] which has the capability to generate the full A, B, C and D waveforms, and combinations thereof, as specified in EUROCAE ED84 standard [7]. Starting full research operations in January 2015, the MBLL team has initiated a range of lightning, lightning interactions and lightning phenomena investigations currently focused on applications in the aerospace industry. Recent studies have included the development of spectrographic and transient light measurement techniques [8, 9], the modelling of lightning-composite interactions [5], development of novel sensors and diagnostics, and lightning interactions with complex aerospace joints.

This paper outlines the development of a static model to predict the deflection of a half-meter square 2mm thick aluminum plate under different D waveform currents ranging from 40kA to 100kA. An experimental technique was developed to measure the physical displacement and related damped oscillation of an aluminum plate under the same lightning conditions. The maximum deflection point was used as a comparison to evaluate the accuracy of the model and the results are discussed. Future work will progress onto studies of a variety of lightning impacts on other materials, such as alloys and composites.

II. Direct Current Static Model

A. Numerical Model

The COMSOL Multiphysics Software package was used to construct the static model, which uses finite element analysis in three dimensions and includes solvers and simulation tools for various physics and engineering applications. The two interfaces used in this study were 'magnetic and electric fields' and 'solid mechanics'. Within the model, a 500x500x2mm 6082 grade (pure) aluminum plate was constructed with a Young's modulus of 70.3GPa, Poisson's Ratio of 0.34, and density of 2,700kgm^{-3}, with all edges grounded and assigned as fixed constraints. A copper wire of length 200mm was positioned perpendicular to the plate center, with one end in direct contact with the center point, representing the path of the lightning arc. The wire was assigned as a free node in the solid mechanics interface, meaning that there was no constraint on its boundary. A constant electric current was injected into the middle of the plate at 40, 60, 80 and 100 kA, and the maximum deflection value was measured. An illustration of the model setup is shown in Fig. 3. The model was static and only gave the maximum point of deflection, so no time-dependent transient or damped oscillation properties were included to account for any other responses of the aluminum plate due to lightning. No other forces or other external factors were included in the model.

The electromagnetic force can be calculated using the Maxwell surface stress tensor, F, referring to the electrical current, I_D, and developed magnetic flux density, B. The magnetic flux density generated around the copper can be calculated by using Ampere's law [4] as given in Equation (1),

$$B = \mu_r \mu_0 I_D / 2\pi r \quad (1)$$

where r is the wire radius, μ_0 is the permeability of free space and μ_r is the permeability of copper wire. The value of surface current density, J_s, depends on the current magnitude and surface area of the plate. As expected, the current density is much higher at the injection point and significantly decreases towards the edges of the plate. Thus, the force developed is not uniform and this can be calculated by equations (2) and (3) [5].

$$\overline{dF} = \overline{J_s}\, ds \times \overline{B} \quad (2)$$

$$\overline{F}_Z = -\iint \overline{J_s}\, ds \times \overline{B} \quad (3)$$

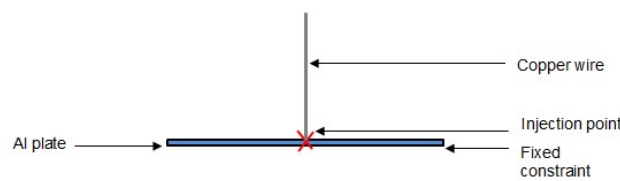


Figure 3: The model setup showing the current injected at the center of a 500x500x2mm aluminum plate

B. Computation Results of Panel Deflection

The results from the static model are given in Table 1, and an example showing the top and side views of the aluminum plate deflection at 100kA is shown in Figs. 4 and 5.

Table 1: Results from the static model for the displacement of an aluminum plate at different injected currents.

Current (kA)	Deflection (mm)
40	2.0
60	4.1
80	6.2
100	8.2

It can be seen that as the injected current and, hence, the force increases the extent of deflection experienced by the aluminum plate also increases; an injected current of 40kA results in a displacement of 2.0mm whereas 100kA results in 8.2mm deflection. This is as expected and occurs because of an increase in the current magnitude and magnetic flux density generated resulting in an increase in the applied mechanical force.

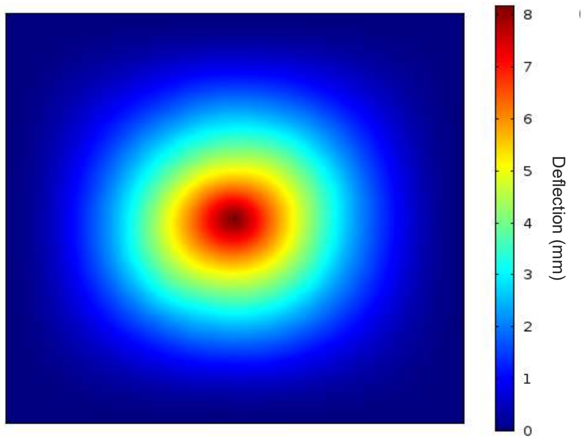


Figure 4: A top view of the displacement of an aluminum plate injected with a current of 100kA

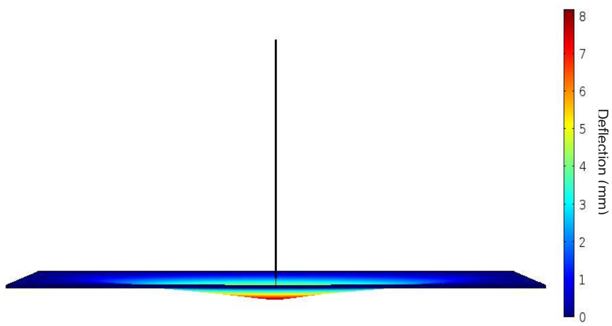


Figure 5: A side view of the displacement of an aluminum plate injected with a current of 100kA

III. LABORATORY TESTS

A. Experimental Setup

In order to measure the displacement experimentally during a lightning strike, a 500x500x2mm 6082 grade (pure) aluminum plate was bolted into a 215mm deep rigid frame below a lightning electrode, with the current flow injected at the electrode center and exiting at the edges of the plate. A fuse wire was used to guide the lightning arc to the center of the topside of the plate, whereas the underside was marked with a cross in white ink. A high speed camera coupled with a zoom lens was positioned to view the white cross from 2m meters away and at an angle of approximately 20 degrees. The camera had a resolution of 256x256 pixels, giving a spatial resolution of 0.12mm at the cross, and operated at 200,000fps over 5s, giving a time resolution of 5µs over one million frames. A reference image was taken by placing a ruler in the same plane as the white cross but perpendicular to the camera and capturing a single frame. The ruler was removed and the plate struck by lightning; the reference image was then used to measure the position of the white cross in each frame, thus plotting its movement over time during and immediately following the lightning strike. A Matlab-based procedure was developed to read and store the position of the cross from each frame for each experiment. All images were converted into binary code and a pixel threshold was set to identify the center of the cross from other artifacts within the image using a centroid condition within the software.

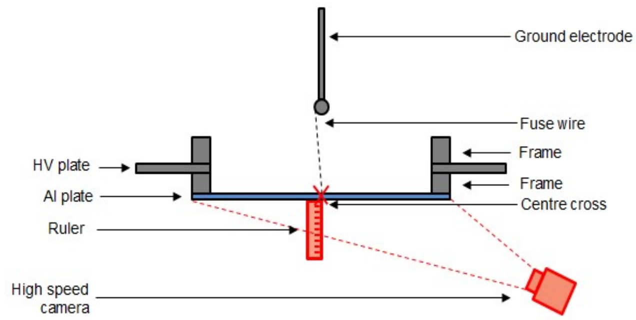
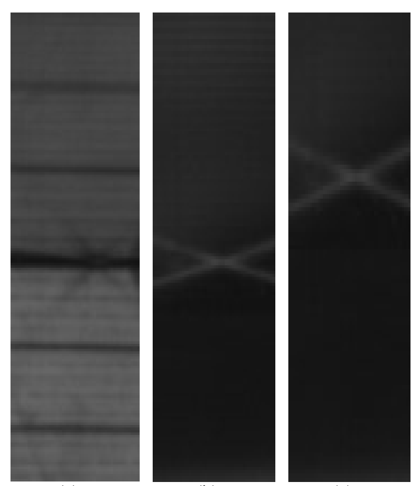


Figure 6: The experiment setup showing the current injected at the center of a 500x500x2mm aluminum plate with the displacement measured during the lightning strike with a high-speed camera. The ruler was removed before testing.

Each 40, 60, 80 and 100kA lightning strike experiment was repeated four times, with a new aluminum plate being used for each strike, with the average data presented here.

B. Test Results

An illustration of a references image against images taken at 1ms and 7ms after a 100kA strike is shown in Fig. 7. The full results for 40, 60, 80 and 100kA strikes are given in Fig. 8, with a comparison of maximum deflection points given in Fig. 9.



(a) (b) (c)

Figure 7: High-speed camera images showing (a) the reference image (black lines: 5mm, grey lines: 1mm, the top half of the image is a reflection of the ruler), (b) the position of the white cross 1ms after a 100kA strike and (c) the position of the white cross 7ms after a 100kA strike.

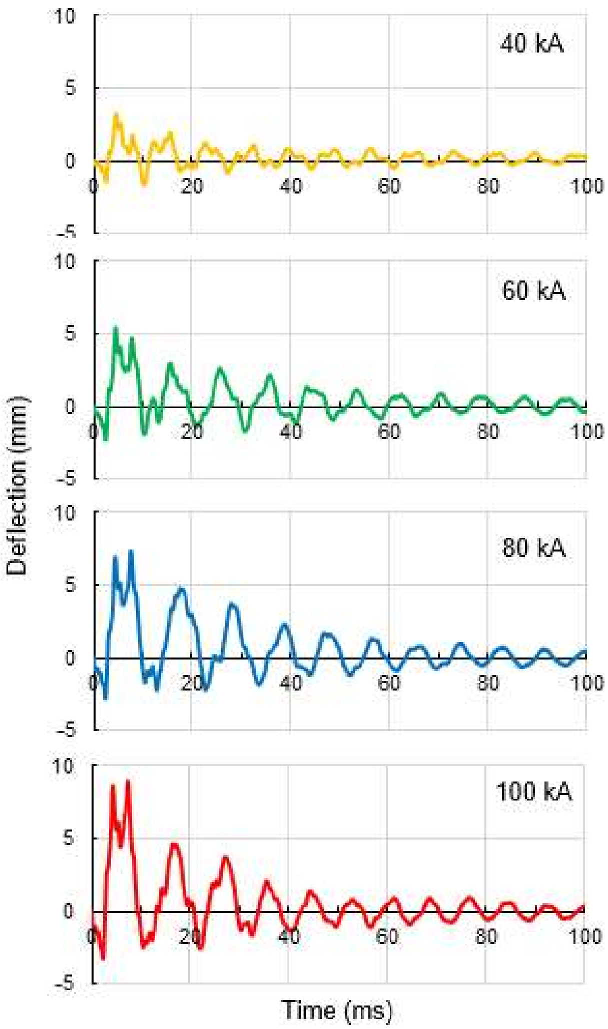


Figure 8: The dynamic deflection of aluminum plates injected with currents of 40, 60, 80 and 100 kA.

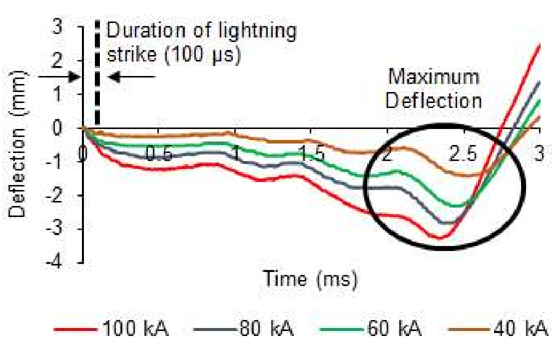


Figure 9: A comparison of dynamic deflection up to the first 3ms following a lightning strike, indicating the maximum deflection and duration of the lightning strike.

C. Maximum Deflection

All elastic materials, such as aluminum, will experience a level of damped oscillation when exposed to a large enough force. From the results, it can be seen that, in each case at approximately 3ms, each aluminum plate exhibits this behavior. Such materials also experience permanent damage if the stress developed during the application of the force exceeds the yield strength of the material which is presumed to occur within the first 1ms of a lightning strike. This was also observed with each consecutive strike, resulting in a plastic/elastic deformation, i.e. a dent, of 0.01, 0.04, 0.07 and 0.09 for 40, 60, 80 and 100kA. The large amount of noise within the results was examined by viewing the high speed camera footage and is a result of deflection/oscillation waves reflecting from the constrained edges of the plate back through the center measurement point resulting in constructive and destructive interference.

D. Subsequent Oscillation of Test Plate

In all cases, it was observed that the aluminum plates appear to experience a significant larger rebound in comparison to the maximum deflection and this is thought to be due to air pressure effects within the experimental setup. As shown in Fig. 6, the aluminum plate is essentially positioned at the bottom of a box which is only open at the top. During a lightning strike, the resulting pressure shockwave moves air away from the topside of the panel at a very fast rate, i.e. a shockwave, creating a pressure differential between this and the underside of the plate. The thin aluminum plate acts as a diaphragm and its equilibrium position quickly moves towards the area of low pressure. Due to the restrictions of the box, the air returns at a much slower rate to the topside of the plate and the equilibrium position of the thin aluminum plate will slowly return to its starting position. The resulting dynamic displacement, including the damped oscillation, is superimposed onto this change in equilibrium position. Given this, the maximum displacement is not the displacement of the plate in reference to the start position, but the displacement of the plate in reference to the equilibrium position at the time of the maximum deflection.

In order to calculate the true maximum displacement, the equation for damped oscillation was fitted to each result as given in equation (1) [9],

$$D = A_o . \sin(\omega t) . e^{-kt} \qquad (4)$$

where D is the displacement, A_o is the initial amplitude, ω is angular frequency, t is time and k is a damping constant. It was assumed that, by the time the aluminium plate had reached its maximum deflection, the shockwave had passed and air had already started to flow back into the box. Several mathematical functions were tried and it was found than an exponential fit worked best, as given in equation (2),

$$D' = \alpha e^{-\beta t} \qquad (5)$$

where D′ is the position of the equilibrium position, α is a constant and β is a decay constant. Combining equations (4) and (5), with the addition of an offset as a result of the dent, δ, gives equation (6)

$$D = A_o . \sin(\omega t) . e^{-kt} + e^{-\beta t} + \delta \quad (6)$$

Taking the 100kA dataset from Fig. 8 as an example, fitting equation (6) reveals the equilibrium position as given in equation (5), which is illustrated in Fig. 10. Here, it can be seen that the actual maximum displacement, d_{max}, is the sum of the displacement of the aluminium plate relative to the start position, d_1, and the equilibrium position at the time at which the maximum displacement occurs relative to the start position, d_2. The results for d_{max} can then be calculated along with relevant measurement and calculation errors, as given in Table 2.

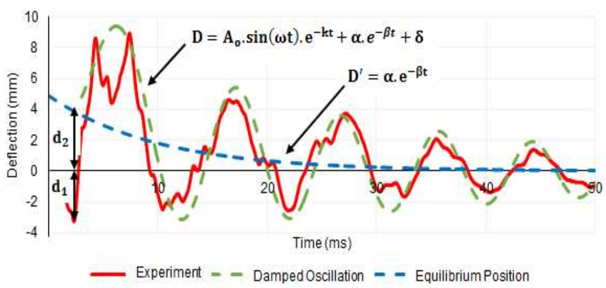


Figure 10: Mathematical fits to the 100kA displacement data revealing the equilibrium position.

Table 2: Results from data fitted to laboratory test measurements showing the displacement of an aluminum plate at different injected currents.

Current (kA)	d_1	d_2	d_{max}
40	1.43±0.06	1.20±0.48	2.63±0.54
60	2.30±0.06	1.98±0.48	4.28±0.54
80	2.82±0.06	2.84±0.48	5.66±0.54
100	3.25±0.06	3.79±0.48	7.14±0.54

IV. Discussion

The model and experiment displacement results from Tables 1 and 2 are plotted in Fig. 11. The model shows a clear linear relationship and the experimental results approximate to a linear relationship for injected current and maximum displacement. Both are in very good agreement with each other. However, the experimental results generally exhibit slightly less maximum deflection than the model. This may be because the model only considers the electromagnetic force developed at the centre of the plate and has no time dependant behaviour such as damped oscillations or the effects of shockwaves and air pressure. Conversely, the constructive and destructive interference seen within the experimental results may affect the accuracy of measurement, or there may be other factors not accounted for.

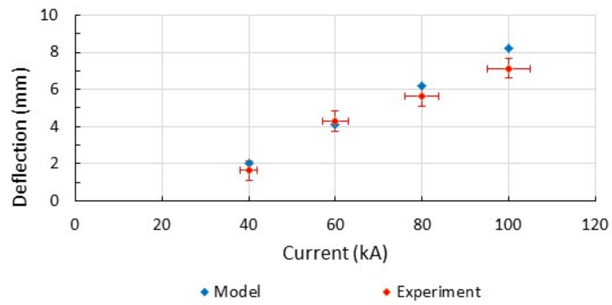


Figure 11: A comparison of static model and dynamic experimental measurements of maximum displacement.

Improvements could be made in both aspects to explore this work further. The model could be expanded to include other factors, notably by including time dependence, such as the shockwave, oscillation, constructive and destructive interference and the observed change in the equilibrium position. The experiment could be improved by minimizing air pressure and interference effects. Furthermore, the accuracy and resolution of the measurement technique could be improved.

V. Conclusion

A model was developed to predict the maximum deflection of an aluminum plate injected with currents of 40, 60, 80 and 100kA. An experiment was designed to measure the deflection under the same conditions, and the results were compared. The results showed very good agreement and were mostly within the measurement and calculation error margins of the experiment. The model only considered the electromagnetic force in a static condition whereas a number of additional factors were observed in the dynamic experimental results such as damped oscillation, constructive and destructive interference, elastic/plastic deformation and an air pressure effect.

Improvements can be made in both the model and experimental setups, but the close agreement of the results indicate that certain aspects of material behavior which may be related to damage and defect under lightning strikes can be modelled with satisfactory accuracy. Future work will progress onto the study of more complex materials, such as aerospace grade carbon composites.

Acknowledgments

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References

[1] B. Lepetit, F. Soulas, S. Guinard, I. Revel, G. Peres, "Analysis of Composite Panel Damages Due To A Lightning Strike", International Conference on Lightning and Static ElectricitySeattle, USA, pp.25.1-25.7, September 18-20, 2013.

[2] Y. Hirano, S. Katsumata, Y. Iwahori, A. Todoroki, "Artificial lightning testing on graphite/epoxy composite laminate', Composites: Part A, pp.1461–1470, 2010.

[3] Floriane Soulas, Bruno Lepetit, Christine Espinosa, Frederic Lachaud, Stephane Guinard, Yahann Duval, Ivan Revel, " How to Define a Mechanical Impact Equivalent to a Lightning Strike", 2015 International Conference on Lightning and Static Electricity, Toulouse, France, September 9-11, 2015.

[4] E. Rupke: 'Aircraft Skins: A Brief Introduction' in 'Lightning Direct Effects Handbook', Agate, pp.53, March 2002.

[5] N S Jamoshid, D Mitchard, H Griffiths, A Haddad, "Modelling The Deflection of Carbon Fibre Reinforced Polymer Materials under Lightning Strikes", 2015 International Conference on Lightning and Static Electricity, Toulouse, France, September 9-11, 2015.

[6] Simpson. H., Leichauer, P., Stone, C., Haddad, A., "Establishment of a lightning test laboratory for direct effects research", Int. Conf. on Lightning and Static Electricity, pp. 30, Seattle (USA), September 2013

[7] EUROCAE WG-31 and SAE Committee AE4L ED-84: "Aircraft lightning environment and related waveforms", 1997

[8] D Clark, D Mitchard, C Stone, A Haddad: "Spectroscopic characteristics of high-current arcs for a lightning direct-effects laboratory", 19th Int. Sym. High Voltage, Pilsen (Czech republic), August 2015

[9] D Mitchard, D Clark, D Stone, A Haddad: "Preliminary results for spectrographic lightning arc measurements", Int. Conf. on Lightning and Static Elecricity, Toulouse (France), September 2015

[10] George C.King, "Vibrations and Waves", A John Wiley and Sons, Ltd Publication, 2009, pp37