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Effects of pulsed laser and electron-beam irradiation on protected aeronautical CFRP composite laminate to enhance the modelling of lightning-strike damage

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ABSTRACT

In this paper, damage produced by lightning strike, laser shock and electron beam deposition on a protected Carbon Fiber Reinforced Plastic composite laminate is studied in order to find analogies of effects and damage between these experimental means. As lightning strike physics on CFRP coated with a Lightning Strike Protection and paint is not fully understood, these analogies could be able to enhance lightning strike modelling by potentially uncoupling the physics at hand and having access to additional measurement instruments. The different experimental setups are briefly described before analyzing the damage response of the aeronautical CFRP protected using an Expanded Copper Foil and coated in aeronautical paint. Eventually the results are compared to build potential analogies able to enhance lightning strike modelling.

Keywords: Lightning strike, Laser shock, Electron beam, CFRP, ECF, Lightning Strike Protection, Paint, Experimental testing

1. INTRODUCTION

Lightning strikes airplanes at an average rate of once or twice per year per plane [1] leading to damage on the airplane hull requiring an extended period of time to repair. Lightning strike involves complex interlinked mechanical, thermal and magnetic phenomena. Thus, the current understanding of lightning strike physics fails to create models able to reproduce the damage produced by the lightning arc on Carbon Fiber Reinforced Plastic composite laminates, especially when a paint coating increases the damage dealt to the composite laminate due to the sublimation of the Lightning Strike Protection. However, the experimental damage observed with lightning strike on composite laminates is mainly composed of core and surface damage [2][3] as seen in Figure 1.

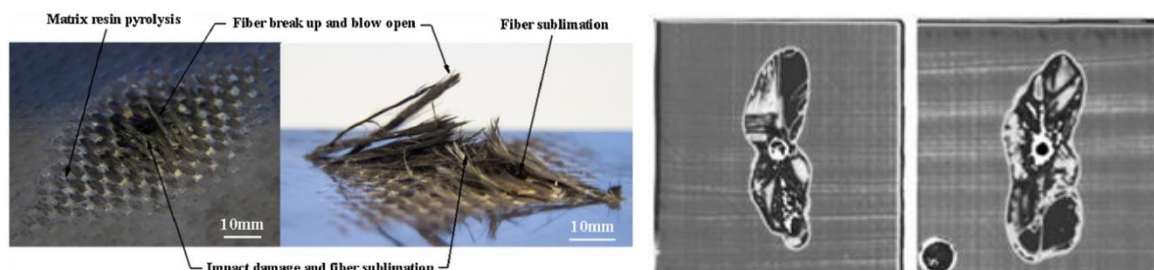


Figure 1 Surface [2] and core [3] damage of lightning strike on CFRP.

These damages seem to share some similarities with the damage observed with laser shock [4] and electron beam as seen in Figure 2 and Figure 3.

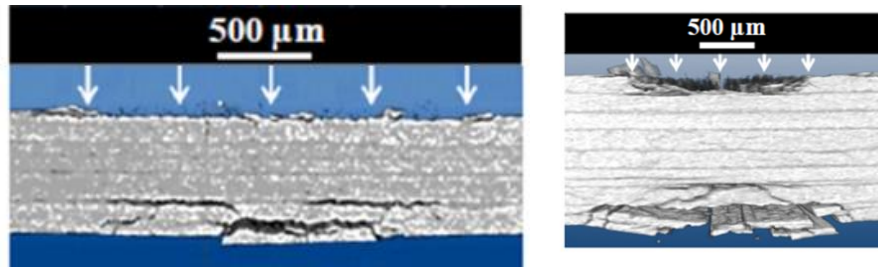


Figure 2 Typical damage produced by laser shock on CFRP composite laminate at low intensity (left) and very high intensity (right). [4]



Figure 3 Typical damage produced by electron beam on 35 mm diameter CFRP laminate. -a-: Front face, explosion. -b-: Back face spalling.

As laser shock and electron beam are easier to characterize experimentally, being able to reproduce a portion of the effects and damage of lightning strike on CFRP composite laminate with these experimental means in an instrumented and controlled area could help with the development of a lightning strike model.

This paper aims at studying the possible experimental analogies of effects and damage between laser shock, electron beam deposition and lightning strike on painted CFRP with an Expanded Copper Foil (ECF) as Lightning Strike Protection.

2. MATERIAL AND METHODS

2.1 Material

The aeronautic Composite Fiber Reinforced Plastic composite laminate of interest is composed of 13 plies of 127 μm thickness following the stacking sequence $[45/-45/90/45/-45/0/90_0.5]_s$ [1]. On the front face lays an Expanded Copper Foil (ECF195) which is made from a unique punctured copper foil that is then expanded. This ECF is coated in resin and topped by a 400μm thick aeronautic nonconductive white paint. The ECF dimensions as well as a cross-section view of a sample are shown in Figure 4 and Figure 5.

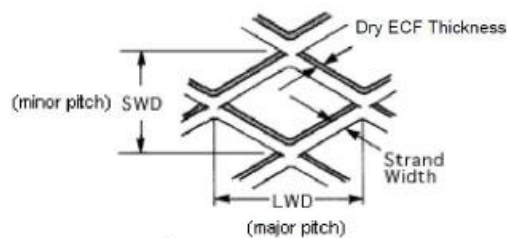


Figure 4 Shape of the Lightning Strike Protection : Expanded Copper Foil 195 (ECF195). Surface density = 195 g.m⁻², SWD = 1.23 mm, LWD = 2.54 mm, thickness = 76 μm, wire thickness = 178 μm. [1]

Three different types of samples are submitted to the laser shock and the electron beam : the bare CFRP, the CFRP with ECF and resin and the CFRP with ECF, resin and paint. These different samples are helpful to study the influences of the ECF and the paint on the observed damage.

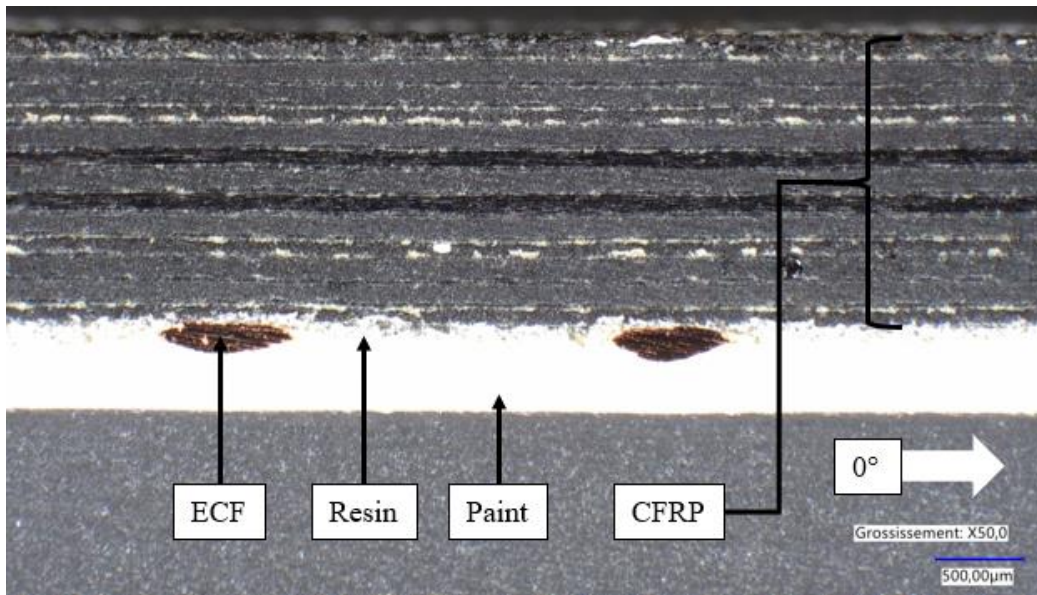


Figure 5 Cross section view of the CFRP coated with ECF and paint. Picture taken with a digital microscope with a magnification factor of 50.

2.2 Experimental setup

2.3 Laser

The BELENOS laser facility at Institut de Recherche Dupuy de Lôme (IRDL, UMR 6027 CNRS) is hosted by ENSTA Bretagne. BELENOS is a Nd-YAG laser of wavelength 1064 nm with a pulse duration of 7.5 ns. It is able to deliver a maximum energy of 3.7 J in an area of a few square millimeters [5] and a trigger allows for single shots with thermal stabilization. Either a water or glass confinement was applied on the target. The laser spot diameter ranges from 3 to 4 mm. To obtain a better noise to signal ratio for the back-face velocity signal measured with a PDV system, the back and front face of the samples are polished to reduce respectively the light and the load scattering. Furthermore, a thin layer of gold is sputtered by Physical Vapour Deposition to increase the reflectivity of the back face. As aluminum is the reference material for the laser matter interaction, an aluminum adhesive is placed onto the front face using a low vacuum of 0.3 bar to obtain an homogeneous bond between the adhesive and the sample.

2.4 Electron beam

The STAEL electron gun facility is hosted by the company NUCLETUDES. This experimental device focuses a flow of energetic electrons on a diameter of a few tens of millimeters. The circular irradiated area is adjustable thanks to a collimator placed in front of the target. For this reason, most samples are cut to a 35mm diameter disk shape and are irradiated on a 25mm diameter disk. In this paper, the experimental setup generates a shot of electrons of energy class between 200 and 600 keV on average for an impulse duration of around 100 ns and a fluence between 40 and 400 J.cm⁻². A reflective material is deposited on the back-face of the target to improve the quality of the recorded VISAR signal.

2.5 Lightning strike

Lightning strike experiments were not conducted as part of the work presented here. The sample of interest (CFRP+ECF+paint) was struck by lightning as part of a 2020 experimental campaign [1] aiming at producing a

theoretical and numerical model of lightning strike physics. Some samples were retrieved and analyzed to obtain the reference damage for the comparisons.

The 2020 campaign was conducted using the EMMA lightning generator of the “Direction Générale de l’Armement Techniques aéronautiques (DGA Ta, Balma, France)” facility. The sizing strike wave is defined by a peak current (100 kA), duration (20µs) and its action integral ($2.5 \cdot 10^5 \text{ A}^2\cdot\text{s}$) [1]. As the lightning arc path cannot be fully controlled, a copper wire is tied to the electrode to guide the current near the target. A lightning arc is produced as the current propagates through the wire before connecting to the target. The target is a 42*42 cm² CFRP+ECF plate coated with 400µm of paint on a 30*30 cm² area. Contrary to the Figure 6, the target was placed horizontally to account for the gravitational force.

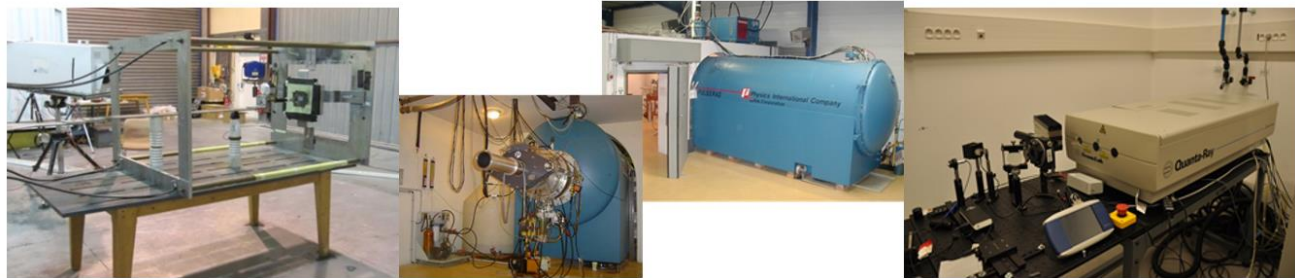


Figure 6 EMMA Lightning strike facility (left) [1], STAEL electron gun facility (middle), BELENOS laser facility (right).

3. RESULTS

3.1 Laser

Most of the samples submitted to laser shock show low damage on the back face (small blister or crack) and no surface damage due to the aluminum adhesive. These samples are analyzed using microscopic cross section view and microtomographic analysis.

The blisters seem to be due to a single delamination area as seen by the microtomography analysis of CFRP+ECF+Paint samples (Figure 7). Both of these samples used the maximum power configuration of the laser experimental setup, with a glass confinement. The microtomography view also shows a few transverse cracks in the last four plies that might be due to the combination of the bending of the sample under the shock.

Cracks are observed on some CFRP and CFRP+ECF samples that are currently being analyzed.



Figure 7 Microtomography cross section view of a post-mortem CCR+ECF+Paint sample submitted to a laser shot with a 1-centimeter thick glass confinement and a flux of approximately- 4.68 GW.cm⁻². Voxel size of 39.3 µm³.

3.2 Electron beam

Both low (15 cal.cm^{-2}) and medium (25 cal.cm^{-2}) fluences were studied with the electron beam. The results show a decrease of the surface damage with each added coating as presented in Figure 8 for 3 shots at medium fluence. Conversely the back-face damage increases with each added coating. The coating seems to act as a confinement for the thermal shock produced by the isochorous heating of the matter driven by the electron beam deposition.

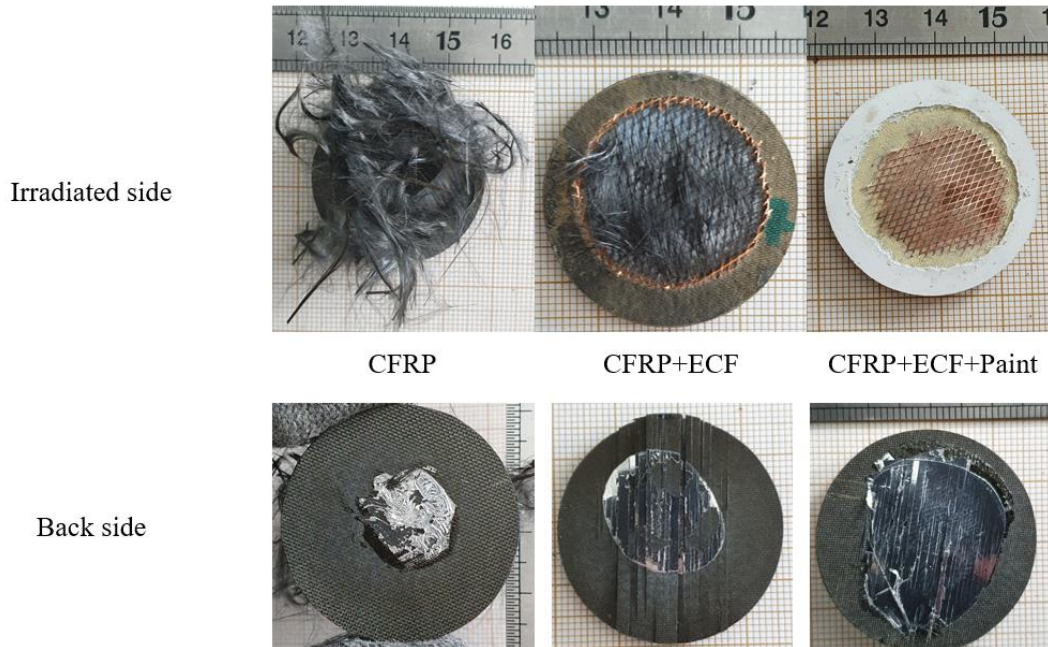


Figure 8 Post-mortem samples exposed to the STAEL electron beam at medium fluence (25 cal.cm^{-2}) for each coating.

The internal damages of the samples are analyzed using a microtomography as seen in Figure 9. The results depict two different damage area: the surface damage where the paint is sublimated and the ECF is untied from the resin and the back-face damage with damage due to mechanical effects with delamination and spalling. Contrary to the other coatings, only the paint has been sublimated. The ECF has been blistered while the resin around the ECF stuck to the CFRP (1 in Figure 9). The first plies (2) are undamaged contrary to the other coatings even if some cracks are visible beneath the resin (3) or in the resin where the ECF once stood (4). Conversely, with each added coating, the back-face damage is increased, from some delamination for the CFRP sample to multi spalling the other coatings (5).

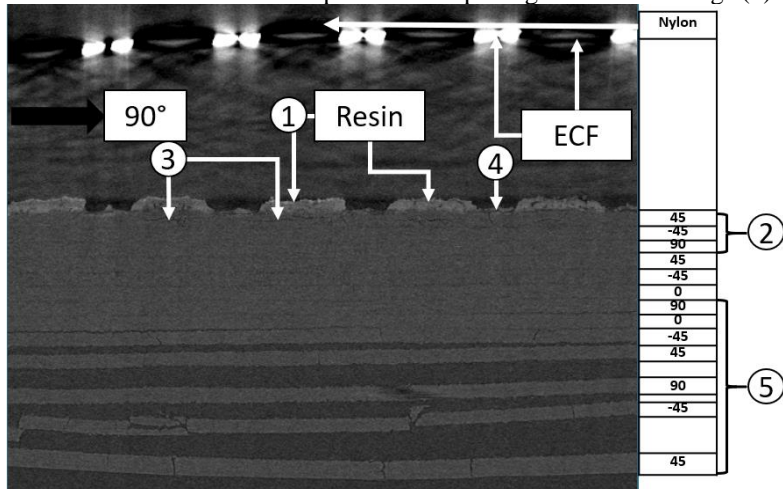


Figure 9 Microtomography local cross section view of a CFRP+ECF+Paint sample subjected to the STAEL electron beam at medium fluence. A nylon string is used to materialize the center of the front face. Voxel size of $64 \mu\text{m}^3$.

3.3 Lightning strike

The analysis of the lightning strike sample was made by coating the plate with resin to set the damage and by analyzing slices with a microscope (Figure 10). Due to the size of the plate, axis and peripheral damage are distinguished. The axis damage shows more surface damage with a mostly sublimated paint, ECF and resin and less core damage than in the peripheral area. The axis damage seems more linked to heat science and electromagnetics than mechanics contrary to the peripheral damage. The core damage of the peripheral area includes delamination of plies of the front and back-face as well as out of plane failure in the core.



Figure 10 Post-mortem lightning strike CFRP+ECF+Paint sample coated in resin and cut for the microscopic analysis. Slices 8 and 9 framed in red.

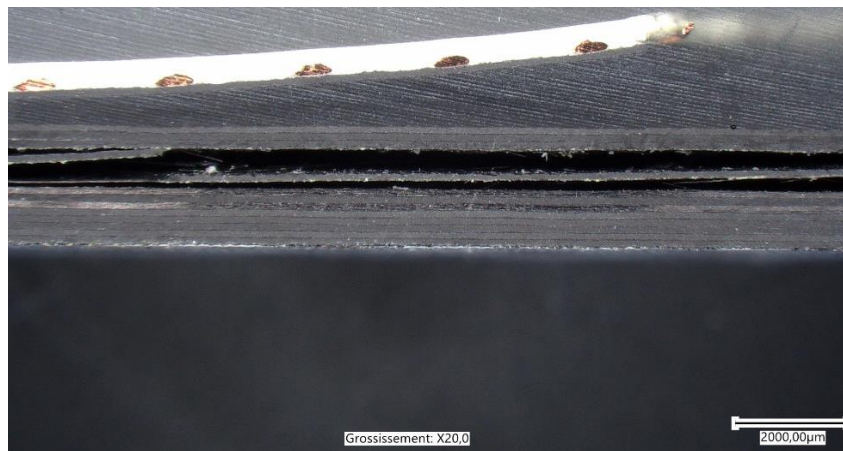


Figure 11 Microscopic view of the cross section in the rim of the lightning strike impact between slices 8 and 9.

3.4 Comparisons and analogies

Lightning strike experiments are difficult to instrument due to the discrepancies of the lightning arc paths between the copper wire and the target [1]. For instance, a back-face velocity measurement of the target cannot be properly performed due to the position of the impact varying for each lightning strike test. Thus, if other experimental means are able to replicate part of the effects or damage dealt to the target while being more controlled and instrumented, they could be the key to the improvement of lightning strike physics and model.

The damage produced on the CFRP+ECF+Paint samples by electron beam deposition share the distinction between thermal surface damage and mechanical core and back-face damage. However, the damaged volumes do not currently seem to share enough similarities to build analogies. One possibility could be that the damage of lightning strike varies between the area behind the impact and the peripheral area, a phenomenon that could possibly be reproduced with an increased radius of the electron beam sample.

The laser tests on the CFRP+ECF+Paint samples are able to produce limited mechanical damage in the core area of the CFRP but the volume of damage is far from the one observed with lightning strike tests. Thus, a more powerful laser is needed to increase the damage observed and potentially create additional types of damage due to the complex geometry of the sample. The current data collected can still be used to characterize dynamically the sample for high strain rates, providing better material properties than the quasi-static values.

Eventually, the data gathered with the laser and electron beam instruments are useful for defining a database for the numerical modelling of the dynamic response of the samples [6]. If loading analogies between the experimental means are found, this will help the improvement of the lightning strike numerical models as back-face velocity signals for lightning strike tests cannot be easily acquired. Back-face velocity signals for lightning strike tests could be measured only if the lightning strike is repeatable to place the VISAR at the correct location which means that the lightning arc has to be guided. Recent studies found that lightning arcs can be guided using lasers [6], so the data gathered here may be all the more useful.

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