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LIGHTNING SURFACE EXPLOSION IMPACT STUDY ON DAMAGE GENERATION INTO COMPOSITE

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ABSTRACT

Lightning damage mechanism for composite aircraft structure is a complex multi-physical phenomenon. The lightning current entering into the surface metallic protection and the carbon plies generates Joule's effects and electromagnetic forces which both induce mechanical forces and surface explosion that produce a significant mechanical impact. The explosion of the lightning strike protection has been recorded through the measurement of the vaporization profile evolution in space and time using transparent glass epoxy substrates. In this paper, this profile is combined to shock wave model developed by the study of electric explosion on wire equivalent to web of ECF. The initial shock wave from the surface explosion has been injected into a mechanical model using Abaqus Explicit® with a pressure profile dependent on time and distance from lightning current injection. Results of the simulations are confronted with laboratory lightning tests for deflections and damages.

ACRONYMS AND SYMBOLS

A	Cross section of the ECF wires
CFRP	Carbon Fiber Reinforced Plastic
ECF	Expanded Copper Foil
GFRP	Glass Fiber Reinforced Plastic
I	Electrical current
J	Current Density
LSP	Lightning Strike Protection
P	Pressure
S	Cross section of metallic mesh filaments
SCF	Solid Copper Foil
T	Temperature
V	Electrical potential
WF	Waveform
σ	Electrical conductivity

INTRODUCTION

It is today difficult to predict the damage that could be generated by a lightning strike on a composite structure due to its complex phenomenology and the different forces involved [1]. The arc itself generates mechanical force as an acoustic shock wave and thermal constraints as a thermal flux transferred to the panel and thermal radiation from the arc. In addition, the lightning current of 100kA reached in about 20µs flowing into the structure (both lightning metallic protection and composite laminate) generates magnetic force (Laplace force) and Joule's effect. The different forces are illustrated in Figure 1:

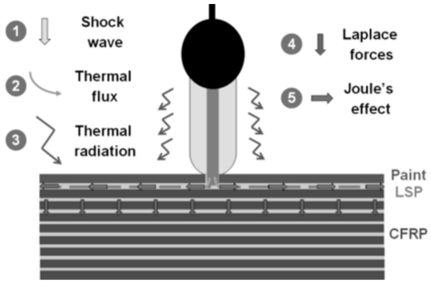

Figure 1 Lightning forces generation in composite structures

This latest phenomenon leads to a quick elevation of temperature of the LSP up to an explosion phase. The arc constriction due to the presence of a thick paint layer changes the current injection into the LSP and can lead to current injection into the first plies of CFRP that will explode due to Joule's effect. The paint is ejected lastly due to the gas expansion thus has enhanced the overpressure generated on the surface as presented in Figure 2:

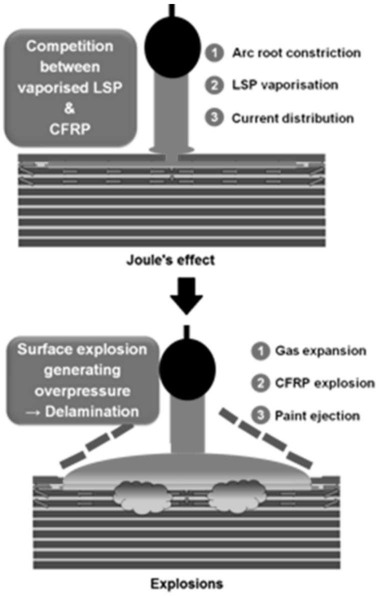

Figure 2 Lightning explosion proposed scenario

This will lead to important delamination into the composite structure in addition to the thermal damage which is important to predict aircraft structure safety.

Most of the works have been focused on the damage generated by a thermal process on bare CFRP panel [2-6], but the reality of the use of CFRP in an aeronautical context is very different.

The complexity of this phenomenon is enhanced by the fact that the damage is not only dependent on the structure configuration but also on the lightning strike protection and the paint thickness which are not part of the sizing of the composite structure against “nominal” stress loads. Indeed, those two parameters are of major importance in the surface explosion generation [7]. A continuous metallic protection like SCF will prevent any damage to the composite structure as a shield but usual LSP like is not efficient enough when combined with thick paint configuration.

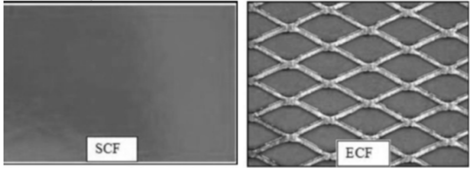

Figure 3 Lightning Strike Protection principle

For an identical structure and ECF, the increase of paint leads to a significant increase of damage as it increases the overpressure generated on the surface by its confining effect and the amount of current flowing into the CFRP. Figure 4 presents the damage evolution with paint thickness. On the right column, you can see the closest view of the visual damage and on the left column, the structural damage on the same scale (Panel in the circular frame Ø370mm).

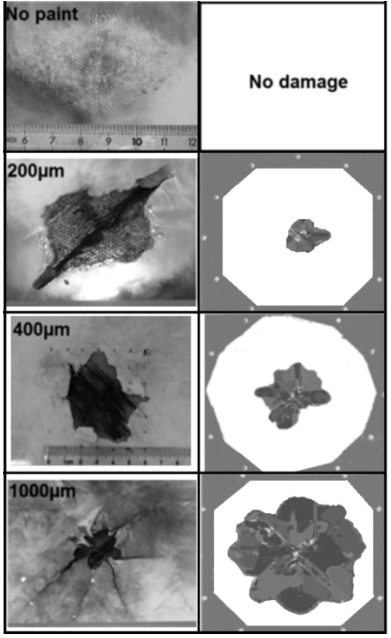

Figure 4 Detrimental effect of paint thickness

It is therefore important to understand the electrical current distribution impacted by the type of LSP and the paint thickness that will generate the surface explosion in order to create a representative loading on the structure.

For this purpose, the present study presents results of two experimental campaigns dedicated to the determination of the pressure generated by the vaporization of a simple wire, and to the evolution of the vaporized zone of copper wires in a lightning test. An analytical estimation of the pressure applied by the copper explosion is then proposed. An analytical expression of the pressure coming from the metallic web vaporization is then proposed. Validation tests are presented to explore the sensitivity of the pressure decrease on the composite panel deflection. Finally, a numerical model is proposed for Abaqus Explicit ® to prescribe this pressure using a user load. Results of rear face velocities and global delaminated surfaces are compared with experimental observations.

VAPORISATION PROFILE STUDY

The study of the vaporization profile is essential to understand how the arc root is constrained, how the current is distributed in the lightning protection and in the composite. All of this will allow determining an evolutionary spatio-temporal pressure profile, coupled with a rupture of the composite fibers, in order to be able to predict damage in the analytical model developed in parallel.

Lightning strike generated in laboratory is composed of a first peak of current of about 100kA reached in 17µs defined as waveform D in ED-84 [8]. This sudden and extremely high amount of current generates significant Joule’s effect in the metallic protection up to vaporization. The vaporization profile is dependent on the material properties and on the current density [9]. For an identical LSP, the vaporization profile will be modified by the presence of paint as it modifies the current injection from the confined plasma.

Lightning Tests

In order to simplify and decompose this complex phenomenon, specific samples have been manufactured replacing the CFRP panel by an insulating panel made of 11 plies of GFRP of 250µm thick each. The purpose of this configuration is to ensure that all the current will flow into the LSP installed on top of panel and focus only on the surface explosion. Indeed, arc root constriction due to paint leads to current injection into the CFRP composite when protected with ECF and the modified vaporized area is difficult to determine as illustrated in Figure 5.

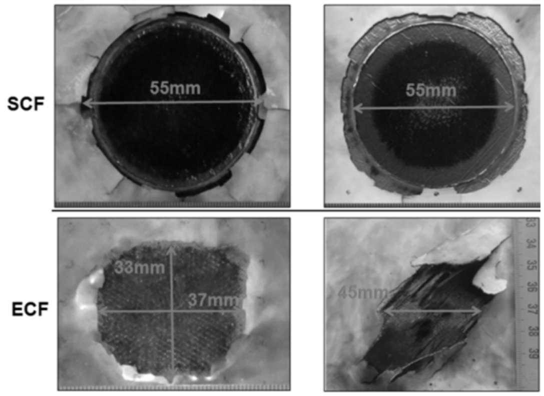

Figure 5 Vaporization profile on CFRP (right) vs GFRP (left)

It is important to notice that SCF profile is not modified when installed on CFRP which means that no current flew into the structure in opposition to ECF (see the upper series of pictures on Figure 5). Also, the profile of vaporized ECF is not a diamond shape for GFRP as shown in Figure 4, on the left picture without paint, when the arc is free but more symmetric when confined by paint.

Set up

Due to the high luminosity of the electrical arc, it is almost impossible to record the vaporization profile of the LSP from top view. The method developed with transparent fiberglass panels and a high speed camera (1Mfps) on the rear face allows following this vaporization profile as shown in Figure 6.

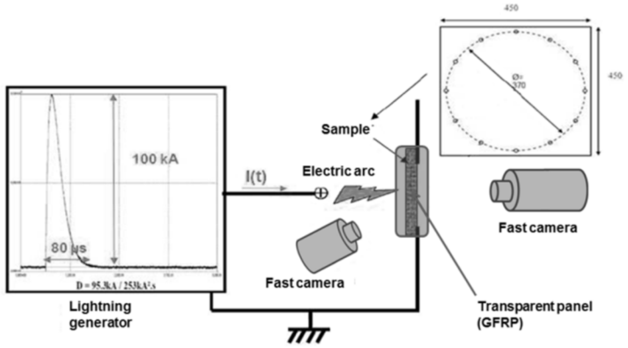

Figure 6 Vaporization profile set up

Lightning Tests results

Pictures of Figure 7 present white zones evolving from a small dot (top left) to a wide pale ring (bottom right) which diameter increases following the current injection. It is proposed by the authors that the white rings arise from the copper vaporization. The vaporization of copper will enhance the brightness of the plasma due to higher temperatures which explains why the profile is hollow even in presence of an arc on the top, as presented in Figure 7:

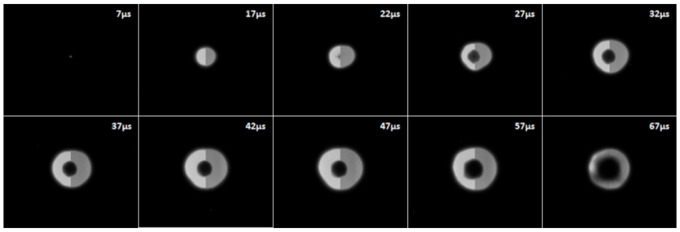

Figure 7 SCF vaporization profile

The vaporization profile evolution over time is measured from rear face observations, through the transparency of the GFRP panel. The mass of metal consumed is related to the section of metal and its physical properties in which the current flows. Here below is the Joule heating equation where the electrical and thermal properties are linked to a given metal and the current *i(t)* comes from the lightning arc with the chosen waveform:

$$m C_p dT = P dt = \left[\frac{1}{\sigma(T)} \int j^2(t) dv\right] dt$$
$$= \left[\frac{1}{\sigma(T)} \int \frac{i^2(t)}{A^2} dv\right] dt$$

In this case, the only main variable that can change the mass consumption is the cross section A.

For an isotropic protection as a homogeneous SCF, the current injection is the same no matter the direction or the paint thickness. This is why the quantity of metal vaporized will be the same no matter the arc interaction. But for anisotropic protection as ECF with diamond shape pattern, the situation is different.

This is confirmed with the study of the vaporization profile on the ECF which is anisotropic. The profile is certainly distorted: the higher the thickness of paint, the more the profile is symmetrical up to become circular despite the anisotropy of the lightning protection. So there is an impact of the paint on the constriction of the arc and the current distribution in the lightning strike protection as shown in Figure 8:

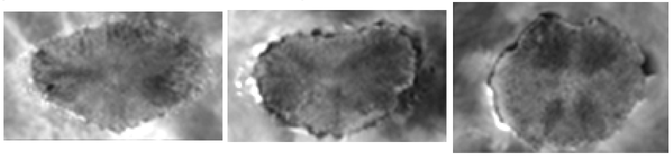

Figure 8 Paint impact on vaporisation profile (200/400/800µm)

SHOCK WAVE MODEL

Wire explosion study

As explained earlier, one of the main contributors is the overpressure generated by the quick vaporization of the metallic lightning strike protection that covers the composite aircraft surface in order to divert lightning current. This lightning protection is usually an Expanded Copper Foil (ECF) of 195gsm or 73gsm.

The lightning strike protection can be approximated to a web of wires of Ø125µm for ECF195 & Ø75µm for ECF73 (see Figure 3). Each wire is considered as a source of overpressure dependent on current density which is assessed as follows:

$$J_n = {}^{I_n}/_{S}$$

Equation 1 calculation of local injected current

With I_n, the total injected current at time *t* divided by the number of wires in intersection with the vaporization profile at the same time *t*, and S the cross-sectional area of the wire.

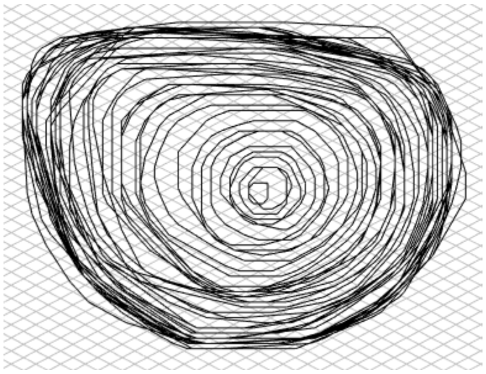

Figure 9 Example of vaporization profile with 400µm of paint distribution for current density assessment

The very quick and high amount of current that is injected in a thin copper wire generates a shock wave coming from, what we can found in the literature: an electric explosion [10-15]. This explosion comes from the sudden vaporization of a metallic wire heated by the important current flow in the small section creating Joule heating.

Lab test set up

In order to study the vaporization profile, a copper wire of 40mm is bonded between 2 electrodes with a coaxial return to ensure homogeneity. In order to validate the principle of vaporization profile, two waveforms have been considered. The first one called WF1 has a time to peak of 18µs and a time to half the peak of 84µs. The second one called WF5A has a time to peak of 54µs and a time to half the peak of 142µs. Those waveforms are slower than in the standard due to the impedance of our test set up. To support the study, several measurements have been performed:

- Current
- Voltage
- Picture at vaporization
- Pressure sensor at several distances from the wire

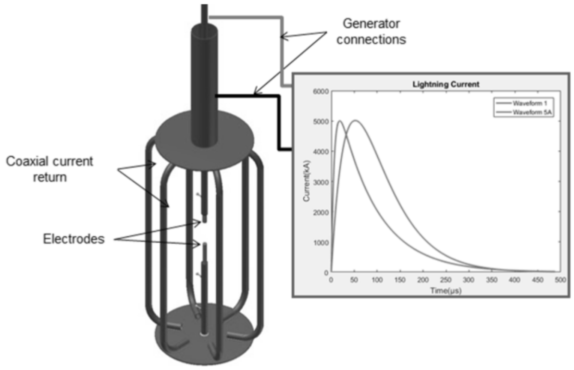

Figure 10 Wire explosion test set up

The shock wave expansion is first considered cylindrical from the wire and a quartz pressure sensor is installed perpendicular to the wire, in the middle to avoid boundary effects, at different distances from the wire. From pressure measurements at different distances and with different amplitudes and lightning waveforms, an experimental law was created to obtain the maximum pressure ΔP^+ at the wire neighborhood taking into account the damping effect of the air:

$$P_{wire} = P(r_{wire}) = \alpha(\Delta P^+) \times r_{wire}{}^{-x}$$

Equation 2 Reconstruction of pressure as a function of the wire section and distance

With r, the radius of the wire, α and x the distance to the wire axis determined from the test results as illustrated below in Figure 11:

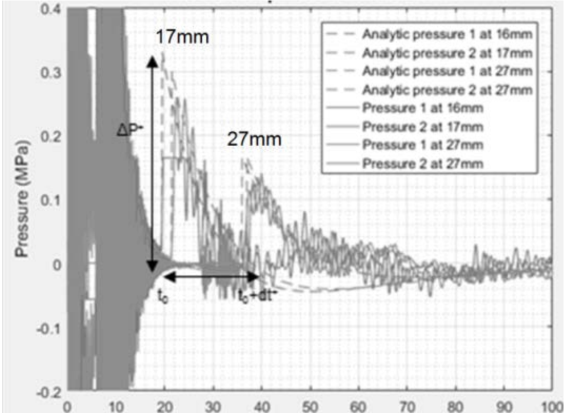

Figure 11 Pressure measurements at 17 and 27 mm for one configuration

Lab test results

Several pressure measurements at different distances from the exploding wire have been performed on different configurations. Those configurations are based on the variation of the waveform shape (WF1 vs WF5A), of the amplitude (5kA vs 10kA) and of the wire radius (Ø125µm for ECF195 vs Ø75µm for ECF73). In Figure 12, pressures plotted have been normalized to the pressure measured at 40mm. This is why only one spot is visible at 40mm and is equal to 1. The purpose of this normalization is to assess the pressure law independently from the pressure amplitude at the origin.

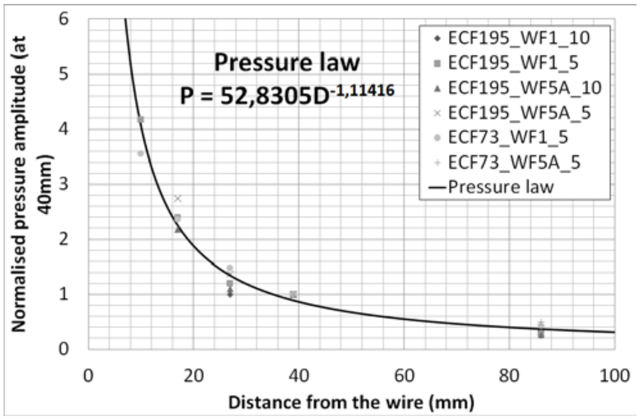

Figure 12 Pressure law from test measurement

Based on this law, it is possible to extrapolate the maximum pressure generated by different configurations with an extract presented in Table 1:

Table 1 Wire overpressure estimations with different lightning currents

	Pressure at the wire (MPa)			
	WF1 10kA	WF1 5kA	WF5A 10kA	WF5A 5kA
ECF195	290	160	218	127
ECF73	157	138	N/A	61

Wire explosion shock wave model

The pressure generated by the sudden vaporization of the wire is considered as a shock wave which is defined by the following equation for the positive overpressure:

$$P(t) = \Delta P^{+} e^{-(t-t_0)/_{dt^{+}}} \times (1 - {(t-t_0)}/_{dt^{+}})$$

Equation 3 Explosion pressure over time

With:

- Time of arrival (t_0)
- Maximum positive overpressure (ΔP^+)
- Positive phase duration (dt^+)
- Positive impulsion (I^+)

This specific pressure signature is illustrated in Figure 13 below:

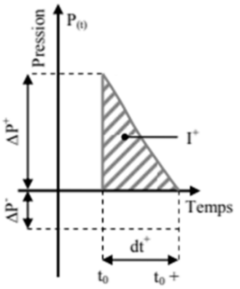

Figure 13 Shock wave pressure waveform

For ECF195, based on the test results of current density and pressure, an empirical model has been built. The overpressure ΔP^+ (MPa) generated by a wire explosion has been expressed as a function of the maximum current I_p (kA) injected in a section of equivalent wire with WF1:

$$\Delta P^{+} = a \times {I_p}^{b} + c$$

Equation 4 Explosion pressure as a function of current

In this configuration, a=80.3 (MPa.A^{-b}), b=0.64 and c=-62.88MPa.

SHOCK WAVE PROFILE LOAD

As already developed previously [16-20], mechanical numerical models are considered in order to simulate lightning strike as an overpressure on the composite panel. Most of them are considering a fixed surface of application or based on the theory of a free arc. We propose in this paragraph to use the previous established relations to prescribe a user defined load.

Load theory

In our study, the pressure model is dependent on time and space for the distribution and amplitude. For the distribution, an empirical model has been built based on the measurement of the vaporization profile for a given lightning strike protection with paint confinement effect. For the amplitude of the pressure, another empirical model is considered based on the measurement of shock wave generated by an exploding copper wire. The pressure has been related to the current injected to each wire and the assessment of this current distribution is made thanks to the record on the number of intersections between the vaporization profile and the lightning strike protection web. The combination of those models allows us to apply an evolving pressure on the surface of a composite panel in order to simulate the overpressure generated by a lightning strike in interaction with a metallic protection covered by paint: P(x,y,t).

Mechanical Model

Lightning damage to composite structure is a complex multiphysical phenomenon but there is clearly an interest to build a simplified approach with an equivalent mechanical model. In our study, we have considered Abaqus Explicit® in which user damage law thanks to VUMAT subroutine has been already developed by F. Soulas [21]. In addition, a VDLOAD subroutine has been developed in order to apply the pressure load on the top surface as defined previously: P(x,y,t). In order to validate this new subroutine, a first model without damage assessment has been built. Expected result considered for this validation step is the rear face displacement over time. In Abaqus Explicit, a single layer of shell finite elements (S4R) with GFRP elastic material properties (see Table 2), and a user defined load on the top surface have been implemented. This model simulates a GFRP panel bonded on a circular frame of Ø370mm which has been in a lightning laboratory lab with different lightning strike protection. The frame is considered by adding clamped boundary conditions at the border of the disk.

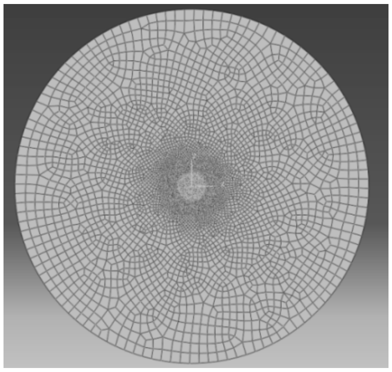

Figure 14 Abaqus model

Table 2 GFRP material properties

Density	1.88E-3 g.mm^{-3}
Elastic modulus E11	24 GPa
Elastic modulus E22	24 GPa
Elastic modulus G12	4.8 GPa
Elastic modulus G13	4.5 GPa
Elastic modulus G23	4.8 GPa
Poisson's ratio ν12	0.28

LIGHTNING DEFLECTION STUDY

Test results

Thanks to the stereocorrelation method developed in [22] using the set-up described on Figure 6, it is possible to measure the deflection of a panel.

As illustrated in Figure 15, the presence of paint has a significant impact on the deflection of the panel. Indeed, when there is no paint, the arc can move freely and the explosion generation by the sudden vaporization of copper on the surface can be freely evacuated in the air.

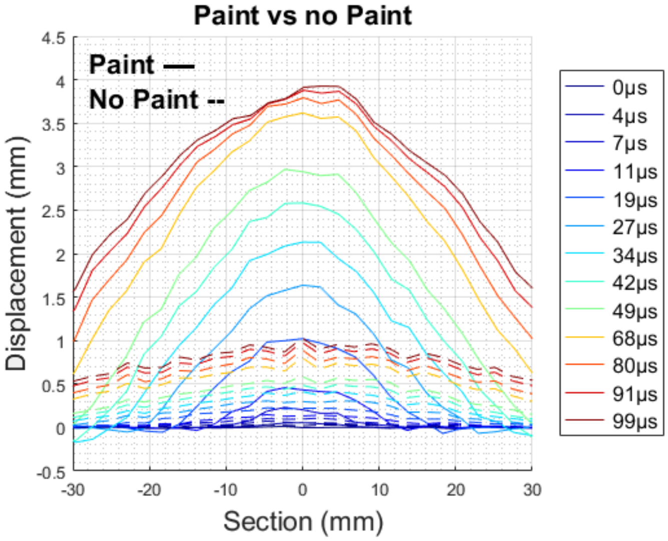

Figure 15 Stereocorrelation data comparison

On the opposite, when the panel is covered by paint with a thickness of more than 300µm, the arc is constrained which changes the distribution of current and thus the vaporization profile, as shown in Figure 8. And in addition, it confines the metallic gases generated by the surface explosion. The measurement of the deflection presented comes from a test of a GFRP panel of 3mm covered by ECF195 and struck by a lightning strike of waveform D (100kA). The deflection due to a strike of an unpainted panel is very limited (d<1mm after 100µs) and also very slow. A panel covered by around 400µm and struck by lightning will have a maximum displacement of more than 4mm at 100µs.

Indeed, the paint is not directly ejected by the overpressure generated by the explosion which leads to a slower decrease of the pressure compared to free space propagation.

Model results and analysis

The VDLOAD subroutine is used to apply a pressure profile dependent on time and space as described earlier. The only unknown is the decay of the pressure. We have thus simulated several loads configuration in order to assess the impact of the decay on the deflection generated on the panel.

The first configuration sets a uniform decay time dt^+ which follows the law defined in Figure 13 for all positions in space. The different decay times considered were 25, 20, 15, 10 and 3,2µs. The strain shown on Figure 16 is computed from the displacement using:

$$\epsilon(x_n) = [U(x_{n+1}x) - U(x_n)]/(x_{n+1} - x_n)$$

Equation 5 Definition of strain (elongation)

On Figure 16 and Figure 17, it is clearly visible that a constant decay time can't generate the equivalent overpressure. Compared to the test, the max strain is too important on the early stage as for the maximum displacement. The closest configuration to the maximum of displacement and strain in the latest stage is the configuration with 15µs of decay.

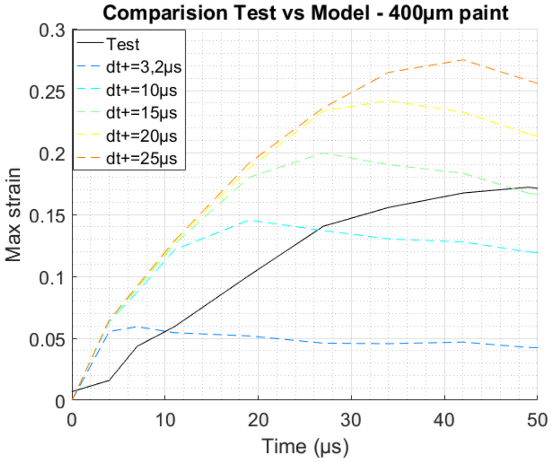

Figure 16 Overpressure sensitivity analysis of with constant decay – max strain

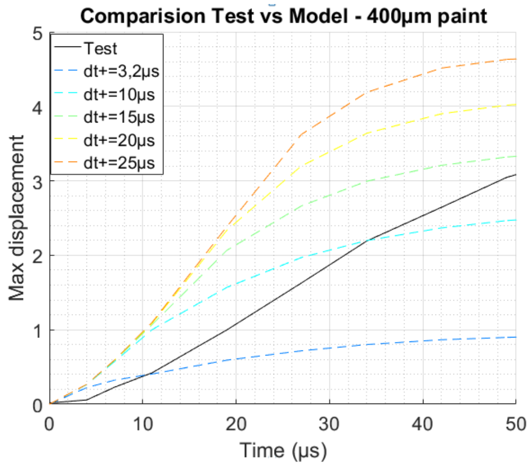

Figure 17 Overpressure sensitivity analysis of with constant decay – max displacement

This approach can not represent the overpressure generated on the surface. Indeed, the paint will be ejected depending on the stress generated by the overpressure on the paint. As this overpressure is decreasing with the current density decrease in the ECF, the paint will take more and more time to be ejected. The decay time will thus increase with the increase of distance in the center.

The second configuration considered has a decay time dt^+ which increases on the inverse of the pressure decrease. A priori chosen different values were considered: 1, 2, 3, 5 and 10µs. As presented in Figure 18, this law does not represent the decay dependency on the paint ejection. The closest configuration is the one with the minimum decay of 3µs in the center but again, the max strain and displacement is higher in the early stage.

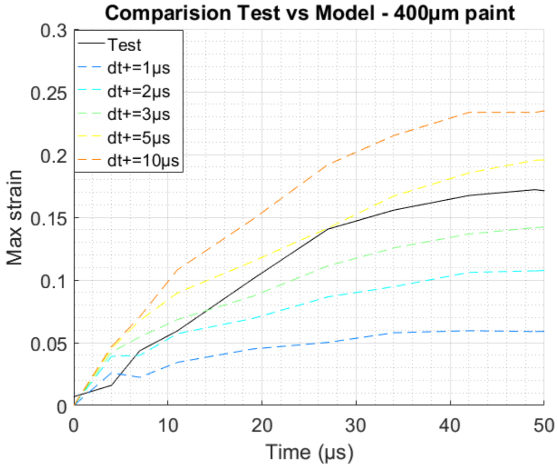

Figure 18 Sensitivity analysis of overpressure with inverse decay law – max strain

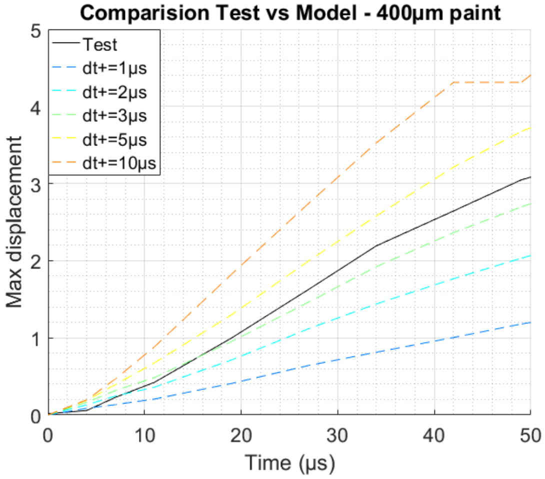

Figure 19 Sensitivity analysis of overpressure with inverse decay law - max strain

The maximum amplitudes of the explosion generated by each ECF wire are of first importance to determine the overpressure profile but it is also the case for the decay profile. The sensitivity analyses presented above are extracted from a modelling experience plan considering several decay laws. In order to build the representative law, it will be necessary to simulate the confining effect of the paint and the mechanical constraints necessary to eject the paint. For this purpose, mechanical characterization test of the paint and of the paint adhesive resistance are planned.

CFRP investigation

When struck by lightning, CFRP material presents an interaction with the arc. Indeed, as shown in Figure 5, we can observe dry fibers due to the flow of current into the CFRP layers. Contrary to GFRP which is made of fully insulating fibers, CFRP contains carbon fibers which are conductive enough to divert a small amount of current that should flow into the ECF. This amount increases with the paint thickness increase as the arc root can't move freely to follow the ECF vaporization profile. The arc attachment to the CFRP breaks the fibers locally, probably vaporizes the resin, and combined to the surface over pressure leads to an important delamination profile as shown in Figure 4.

The question is to know if the internal explosion in the CFRP will contribute to the global deflection, which is part of our validation process. For this purpose, we apply, in our Abaqus model, the same overpressure profile on a GFRP panel made of 11 plies, 250µm each, and on a CFRP panel made of 13 plies, 127µm each. Those 2 panel configurations have been tested in laboratory with the same lightning strike protection: ECF195 and the same paint thickness: 400µm. The overpressure profile chosen is the one providing the closest deflection profile compared to the test result with the GFRP panel. This configuration is interesting as there is no interaction between the lightning arc and the GFRP panel as it is completely insulating compared to the ECF on the top. The results are presented, in Figure 20, where we can see that the test deflection presents a more "protruding" profile than with the model.

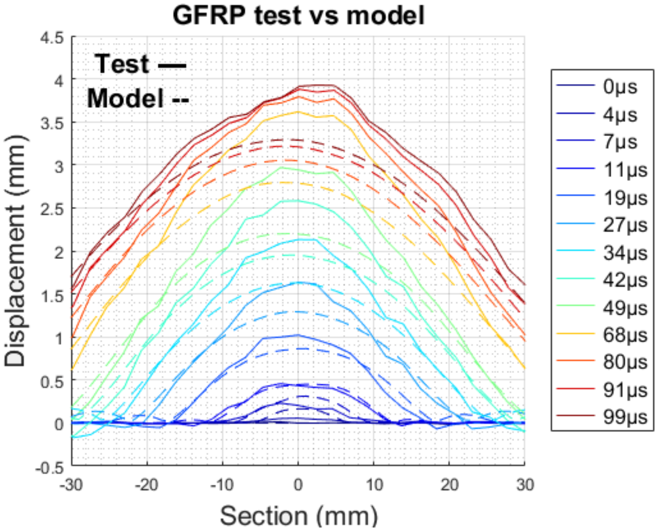

Figure 20 GFRP deflection profile: Test vs model

Even if not identical, this overpressure profile can be applied on the simulated CFRP panel in order to assess the contribution of the internal CFRP damage in the global deflection profile. Indeed, for a CFRP panel covered by thick paint, we know that there will be an interaction with the lightning arc which will create internal damages and explosions during the application of pressure on the surface. The results are presented, in Figure 21, where we can see again that the test deflection presents a more "protruding" profile than with the model. It thus presents similar differences than for the GFRP model.

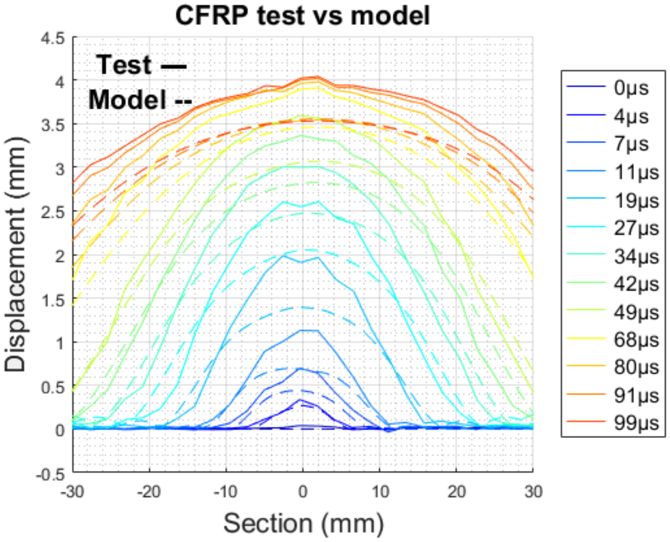

Figure 21 CFRP deflection profile: Test vs model

Even if important in the damage mechanism process, the internal explosion and fiber breakages have a negligible contribution in the global deflection profile.

This is an interesting information since it means that we can decorrelate the overpressure profile generated on the surface by the explosion of the metallic lightning strike protection and the internal fiber breakages and explosions. We will thus be able to validate the confinement effect on one side before adding internal damage due to current flow into the CFRP.

CONCLUSIONS

The objective of the work presented in this paper was to decompose the lightning phenomenon. Indeed, this is a really complex and multiphysical mechanism that generates the damage into a composite structure. The lightning arc itself is already complex to study, but it is even more complicated considering its interaction with the substrate which is not a simple homogeneous material. Indeed, this is a composite carbon panel covered by a thin metallic protection which vaporizes during the event and is, on top, covered by paint. This paint has 2 effects: to limit the arc root expansion and to confine the gas generated by the vaporization of the lightning strike protection.

For this decomposition analysis, a first part of the work has been focused on the arc interaction with the substrate: the lightning strike protection covered by paint. Based on a specific test set up, it is possible to know the vaporization profile and then associate to it an overpressure profile. A second part has then been focused on the electric explosion produced by the vaporization of the lightning strike protection by considering it as a web of copper wires. The explosion effect has been studied individually on wire in order to build phenomenological laws which relate the shock wave profile to the current density.

Finally, a mechanical model in abaqus with a vdload subroutine has been built in order to study the effect of the vaporization profile on the panel deflection which can be compared to lightning test results.

The limit of the current model is that gas confinement effect of the paint is not considered, thus it can't be a predictive model. For this purpose, mechanical characterization of the paint will be performed in order to add it in the model and assess the pressure profile associated.

As the deflection profile is mainly due to the surface overpressure, we will be able to validate it with the different lightning test results data and combined it to internal damage due to electrothermal effect.

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