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Edge glow: a combined voltage/power controlled mechanism?

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***Abstract*—The improvement of CFRP mechanical properties has led to the development of new materials in aeronautic industry. In the frame of engineering experiments for developing lightning strike protections, a phenomenon has been observed on edges of aircraft composite substructures, consisting in a bright glow combined with strong ejections. Uncertainties in the nature and the severity of this threat, so-called "edge glow", make necessary to consider it as a potential fuel ignition source and to implement appropriate lines of defense. Behind the most intense event that seems controlled by the voltage drop across plies, a second edge glow regime seems related to a thermal mechanism at pre-existing contacts on the composite edge. The context of this work is the mitigation of edge glow phenomena with appropriate protection designs and installation principles. This paper presents experimental investigations on generic test coupons that aimed at understanding how current distributes into a local assembly governed by non-linear contacts and how far it impacts edge glow occurrence and intensity.**

Keywords-lightning protection; edge glow; CFRP; conductivity

I. Introduction

The protection of composite fuel tanks against lightning direct effects is a major source of difficulty with large impacts in terms of mass, non-recurring costs (solutions development) and recurring costs (solutions deployment). The experience gained from previous aircraft programs suggests that significant benefits can be obtained from a consolidated methodology allowing for the determination of local constraints within an assembly. Conversely, the quantitative and absolute prediction of electrical hazards (e.g. sparking, outgassing or edge glow) based on theoretical or modelling approaches is considered as unrealistic due to the nature and complexity of the mechanisms involved. A more relevant approach consists in developing experimental characterizations of the influence of parameters identified as having key importance to electrical hazards. This knowledge allows mitigating industrial risks, orientating protection solutions and focusing certification stages on worst case configurations. In parallel, the identification of thresholds and mechanisms can be supported by the development of theoretical or empirical models with the objective of capitalizing and then extrapolating knowledge gained for future aircraft designs.

One of the electrical hazards faced by the aeronautical industry is the edge glow phenomenon. It occurs on composite edges of aircraft substructures when a fastener head is struck by lightning and consists of a bright glow combined with strong material ejections. A previous paper presented some experimental and numerical investigations in order to characterize the phenomenon in the case of low transverse conductivity CFRP materials [1]. The study case was simplified to a substructure in which a current waveform of a few kA was injected whilst monitoring both voltage drop between bolts and emitted light versus time to identify threshold conditions for edge glow occurrence as shown below:

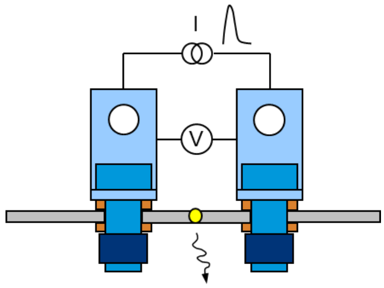

Figure 1. Test principles for preliminary edge glow characterization [1].

From this work, evidence has been made that edge glow is:

- an instantaneous event (few µs after the injection)
- an edge event (not an exhaust from an internal exothermic event)
- not only a local event (can occur on an edge up to 20cm from the impacted bolt)
- controlled by the voltage drop between plies (~200V threshold for the material considered)
- located at voltage drops maxima and rigidity minima
- sensitive to the action integral for its severity

These tests have been performed on substructure samples (no skin, no lightning protection) and on low transverse conductivity material (σ_z << 1 S/m). The material behaved as electrically isolated plies and broke via a voltage spark beyond a threshold of about 200V.

In the frame of more recent engineering tests, in addition to the presence of skin and Expanded Copper Foil (ECF) that tend to moderate the increase in voltage drop between bolts, it has been considered a substructure material having a conductivity of a few S/m in the transverse direction (σ_z ~ 5 S/m). Depending on the contact properties between the fastener and the lightning protection present on the skin, edge glow has been observed for lower voltage drops and with significantly reduced intensities. The purpose of this paper is to present the main results obtained from these recent test campaigns.

II. Description of Tests

A. *Several levels of complexity*

The real case we are considering here is a lightning strike on a fastener of a composite wing assembly composed with a skin and a substructure both in CFRP. The global current distribution (see (1) in Figure 2. is governed by material properties, aircraft geometry and lightning scenario (entry and exit points) and can be obtained using 3D numerical model.

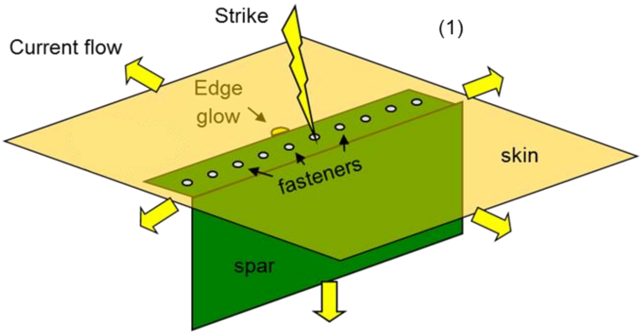

Figure 2. Current distribution at global assembly level.

At local assembly level, the current distribution is highly sensitive to contacts between the fastener struck and both CFRP parts and ECF. More specifically, the dynamic contact between the fastener and the ECF layer is highly sensitive to the seating depth of the bolt head with respect to the ECF bottom level. Depending on this parameter, the level of current, the voltage drop across carbon plies and the energy deposited into the substructure can significantly vary, at least during the delay necessary to have the fastener and the ECF in contact through a subsequent arc (2). This non-linear contact makes the prediction of the current distribution by a numerical model quite irrelevant and needs to be characterized experimentally.

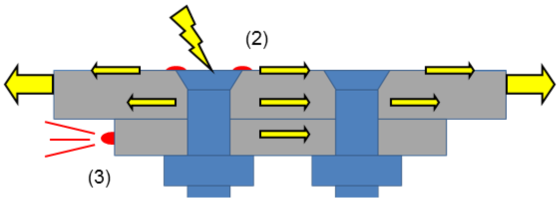

Figure 3. Current distribution at local assembly level.

Finally, the occurrence of edge glow at the substructure edge (3) is also a non-linear phenomenon, either a dielectric breakdown across plies or a possible thermally enhanced contact at the edge, which is difficult to predict quantitatively by numerical modelling [2].

While the preliminary test campaign only focused on the relation between the injected current into the substructure and the edge glow threshold, we aimed with this second batch of experiments to take into account of the real electrical stress applied to the substructure when considering the presence of the skin. In order to ease the characterization of both ECF-fastener dynamic behavior and the relationship between the current/voltage distribution into the substructure and edge glow occurrence, different types of test samples have been designed and are described in the following sections.

B. *Skin test coupons*

The first step consisted of characterizing the dynamic behavior of the fastener-lightning protection contact during the strike. As shown on the following figure, the galvanic contact between the fastener, (composed of a bolt and a sleeve) and ECF layer is only achieved when the seating depth of the fastener is such that the sleeve is directly adjacent to the ECF (not the case on the picture below).

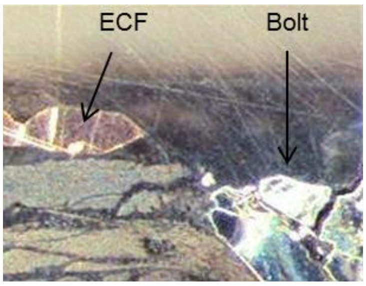

Figure 4. Micro-cut of the contact area between bolt and lightning protection

As this contact is critical to limiting the current that flows into the substructure, some experiments have been made on simple skin coupons consisting of a square CFRP laminate equipped with one single fastener at the center, while varying the contact height, h_c, as defined in Figure 5. :

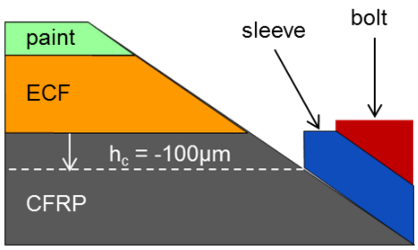

Figure 5. Contact height (h_c) of fastener with respect to bottom ECF layer.

Samples are made of a single fastener at the center of an 84mm×84mm square skin protected by an ECF layer. A pulse current waveform of 5kA peak is injected through a direct contact to the head to avoid any erratic arc movement (that could directly attach to the protection and thus short-circuit the contact we aim to study). The voltage drop is monitored between bolt and ground with a background loop that allows estimating the induced voltage that may be present on the measurement.

C. *Assembly test coupons*

The second step concerns the characterization of the full stack of the local assembly, i.e. the protected CFRP skin, the CFRP substructure and a second fastener allowing the current to flow back from the substructure to the skin. Reducing a large assembly composed of a row of tens of fasteners to only two is conservative as we overestimate the voltage drop between the impacted bolt and the adjacent one. Moreover, the objective of these tests is to assess the influence of the impacted fastener configuration (contact height) on edge glow occurrence, all other parameters being frozen. The two fasteners are installed in a staggered configuration that corresponds to a worst case in terms of resistance between bolts. In that configuration, shanks are not connected by carbon fibers through a direct path.

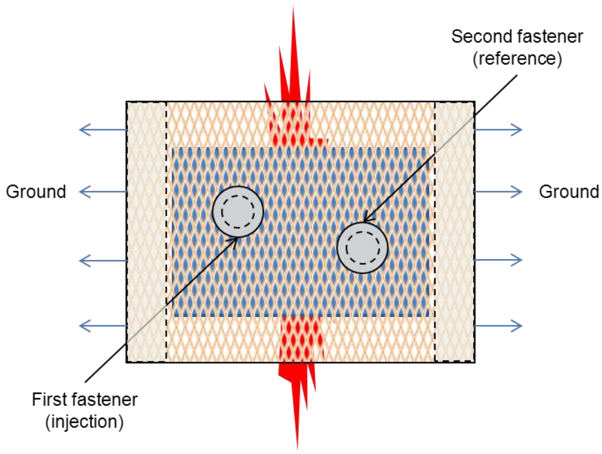

Figure 6. Assembly test coupons for edge glow analysis

The tests consist in a current injection on the "first fastener" head and an exit from the two lateral sides of the skin with different configurations of contact height for the first fastener from -200µm (deep countersink) to +300µm. The bolts are mounted in interference with the panel using Titanium sleeves. The second fastener is in nominal configuration, i.e. the contact height is +100µm. The injected current is a D waveform and diagnostics are included for resistance measurement before and after the shot, voltage measurement between bolts, still camera pictures of the whole event and capture of the emitted light versus time using optical fibers.

III. TEST RESULTS AND ANLYSIS

A. *Lightning protection to fastener dynamic contact*

Tests have been performed on samples with contact height going from -200 to 300µm. Except for samples having a contact height larger than 200µm, we can deduce from these tests that no physical contact exists between the sleeve and the ECF layer until an arc occurs (few µs after the injection starts), connecting the sleeve to the ECF layer. The arc enhances the sample conductance and reduces the voltage stress abruptly. The arc remains up to the end and acts as an electromotive force corresponding to the arc sheaths.

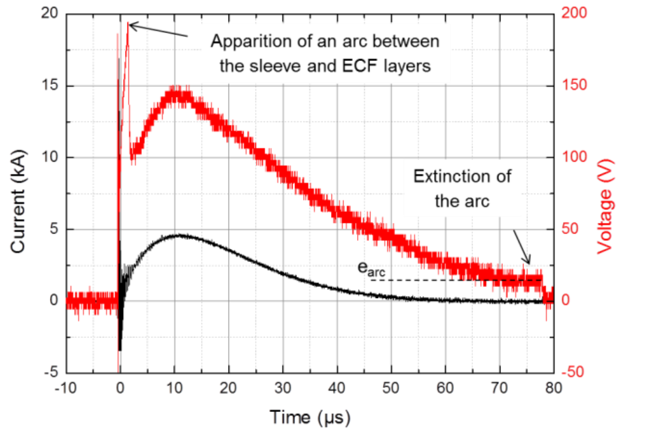

Figure 7. Current and voltage drop waveforms versus time for h_c = -45µm.

From these measured parameters, and after checking that inductive contribution was negligible, we have derived the sample resistance versus time, as shown in Figure 8.

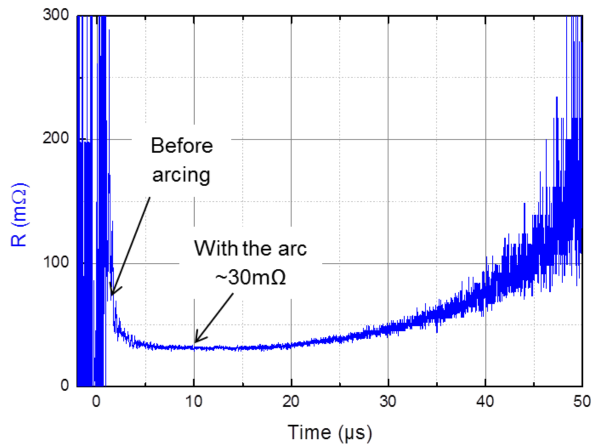

Figure 8. Sample resistance versus time for h_c = -45µm.

We can see that the remaining resistance after arcing is still high compared to ECF layer resistance. Once the arc is established, the surface impedance of ECF layer is not influencing both sample resistance and current repartition.

On the next figure, we report the resistance between the fastener and the ground, measured before and after shot, and we compare it to the one derived from in-strike measurements at peak current. For contact height h_c > 200µm, the resistance of the sample is very close to the one of 73gsm ECF layer after the shot. Note however that the galvanic contact was not achieved before the shot even when the sleeve was at the same height as the ECF layer. For h_c values lower than 200µm, there is no permanent contact after the shot and the sample resistance either before or after the shot is of the order or larger than the skin resistance (analytical estimation). As a conclusion, except for few cases at large contact height, there is no obvious relation between h_c and the sample resistance either before or after shot.

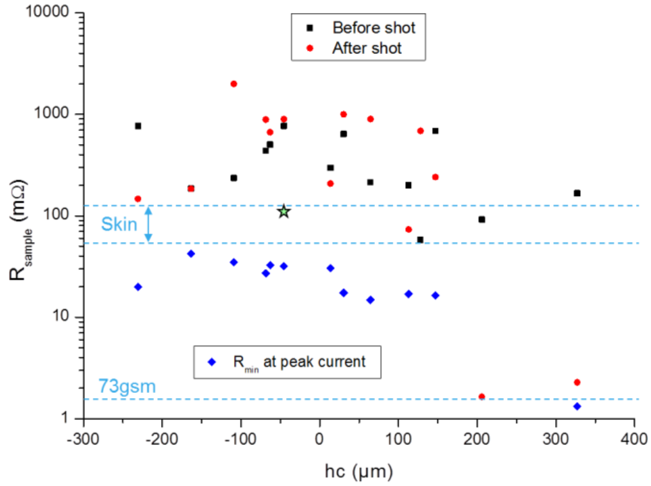

Figure 9. Sample resistance versus contact height of the fastener; ■ before the shot; ● after the shot; ◆ during the shot at peak current; ☆ before arcing

We have reported in Figure 9. the dynamic resistance at peak current, which corresponds to the minimum resistance. R_{min} is very close to the post-shot value and thus to the 73gsm level when h_c > 200µm. We can assume that the contact still exists during the shot, which is not the case for h_c < 200µm. Moreover, when h_c decreases, the resistance is higher. If we assume that the contact is ensured by a small arc between the sleeve and the protection, the arc is longer when h_c decreases, and thus more resistive to such an extent that R_{min} tends to the value of the CFRP skin resistance. We have also reported the resistance value measured just before the arcing (☆) is about 100mΩ, so within the estimated range for skin resistance. It allows estimating that the arc resistance between the fastener and ECF layer increases from 20 to 75mΩ when h_c decreases.

B. Edge glow experiments on local assembly

1) Dynamic behaviour of the assembly

We report on the next figures the injected current and voltage drop waveforms versus time for both positive (above nominal) and negative (deep countersink) contact height.

a) Above nominal contact height

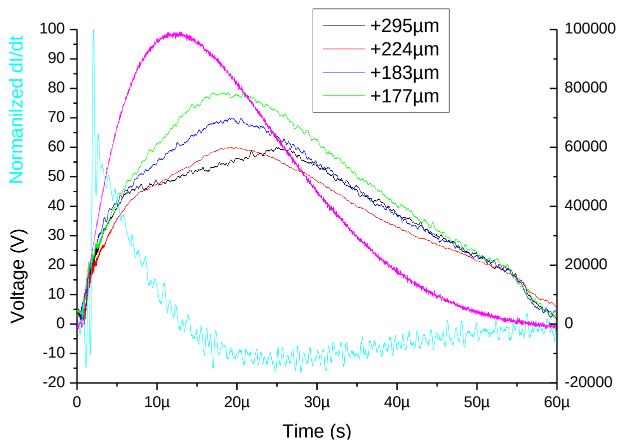

Figure 10. Current and voltage drop waveforms versus time for h_c > 170µm

- The peak voltage drop is significantly below the voltage threshold (~200V) observed previously [1].
- The effect of *LdI/dt* seems limited and can be estimated to few tens of volts at maximum.
- There is evidence of an arc with an electromotive force about 15V (as observed on previous tests).
- The voltage peak occurs after injected peak current, indicating that the current flowing between bolts is slower than the injected current (no explanation).

b) Deep countersink configurations

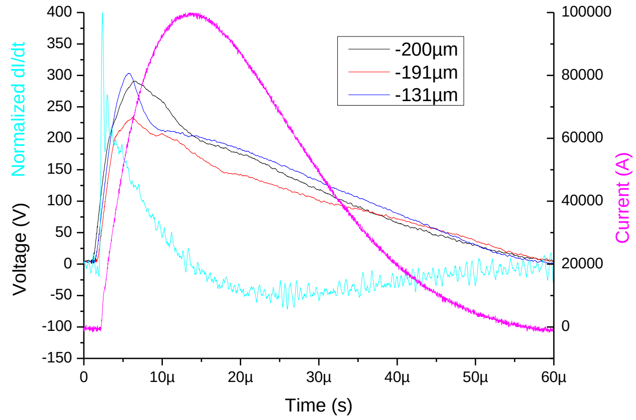

Figure 11. Current and voltage drop waveforms versus time for h_c < -130µm

- The peak voltage is of the order of the edge glow threshold observed in previous works (~200V).
- The voltage peak is not related to *LdI/dt* (estimated to few tens of volts previously).
- There is a linear decrease of the voltage drop with no evidence of an arc (electromotive force remaining when current collapses).

When decreasing the ECF density from 815 to 73gsm for a given contact height (~170µm), we observe that the voltage between bolts significantly increases, as shown on Figure 12.

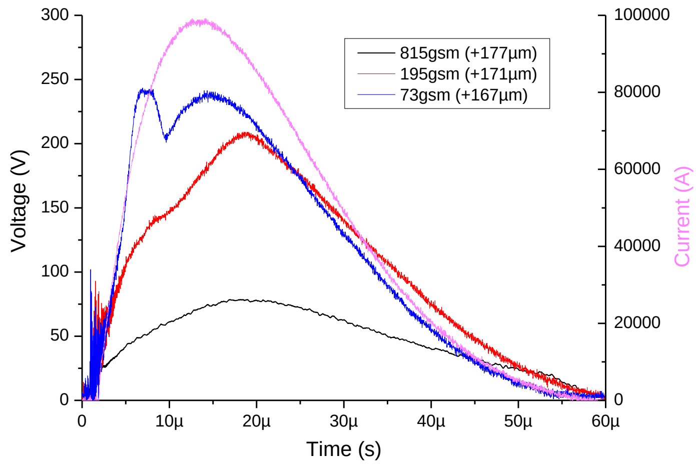

Figure 12. Current and voltage drop waveforms versus time for various lightning protection densities.

It is interesting to comment that in the case of 815gsm, there is a remaining electromotive force when current collapse, but it is not the case for lighter ECF densities. This would tend to confirm that the presence of 815gsm plays a role in arc trigger at bolt-ECF contact and no arc is created for configurations of lighter lightning protection densities or it collapses before the end of the current injection.

2) Observation of edge glow phenomenon

In previous works [1], tests on spar samples allowed to demonstrate that the edge glow was a voltage controlled phenomenon, with a threshold of 200V whatever the layup, bolt-to-edge or bolt-to-bolt distance and number of plies. The delay for edge glow apparition was due to the delay for reaching the voltage threshold while this latter seemed not sensitive to the voltage rise. Additionally, it has been shown that the spar transverse conductivity had no influence on the voltage threshold.

For the present test campaign performed on small assembly coupons, the voltage drop has been limited by the presence of the protected skin, and it remains below the voltage threshold when contact height is above 0µm. As observed for skin coupons, when h_c decreases, the voltage drop between bolts increases, as shown on Figure 13.

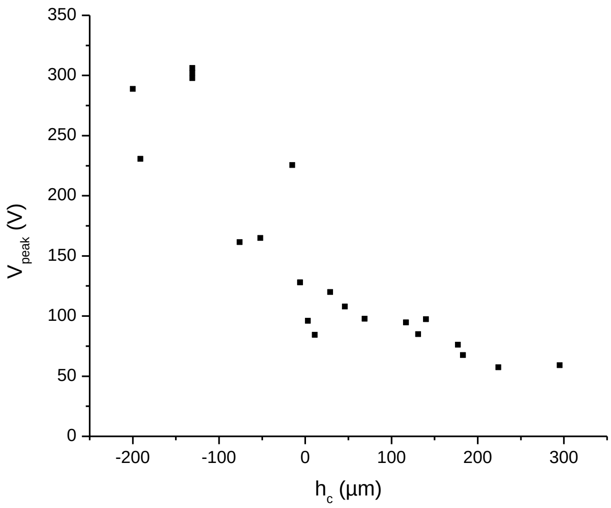

Figure 13. Peak voltage drop versus contact height of the fastener

We report in Figure 14. the voltage drop threshold for edge glow occurrence versus contact height, for various ECF densities. The apparent voltage threshold is about 45V for positive h_c values and it increases to 100V or more for deep countersink cases. This result is not in agreement with a voltage sparking mechanism ($V_{th\text{-}min}$ ~200/300V). According to Paschen's law, an isolated gap cannot break below 300V (even if this could be reduced in case of the presence of a dielectric surface bridging the gap – as epoxy resin – explaining why we obtained 200V for spar samples).

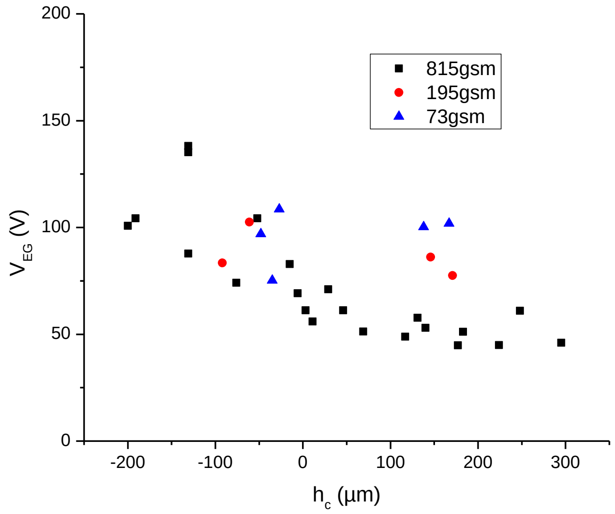

Figure 14. Voltage drop threshold for edge glow occurrence versus contact height of the fastener and for various lightning protection densities.

A second observation is that the voltage threshold is not constant but increases when h_c decreases → it suggests that it is necessary to have more voltage to produce an edge glow when h_c decreases, even when the current flowing through the spar probably increases (due to bolt-ECF contact degradation as h_c decreases). Finally, for a given positive h_c value, the voltage threshold increases when the ECF density decreases (that certainly induces also an increase in the amount of current flowing into the spar).

All these observations suggest that the voltage drop is not the only key parameter in the case of an assembly. As confirmed on the next graph, both h_c and ECF density influence the delay, which significantly increases from the deep countersink to the nominal cases (a factor of 12 when the voltage threshold only varies by a factor of 2 or 3).

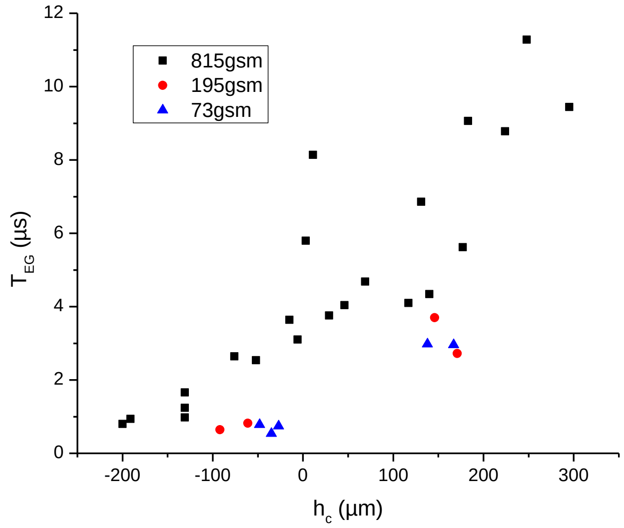

Figure 15. Edge glow apparition delay versus contact height of the fastener and for various lightning protection densities.

Two possible explanations can be considered to explain why voltage threshold is higher for shorter delays.

- When there is a rapid increase in voltage, such as the case in the deep countersink situation, a greater voltage is generally required for electric breakdown. However, the mechanism of voltage sparking does not seem to be relevant here due to the voltage levels measured at the time of edge glow.
- If edge glow is related to power deposited into the spar, then the rapid rise in voltage for the deep countersink situation allows the power threshold to be met earlier at lower injected currents.

As we didn't measure the spar current, we have supposed it is varying in the same proportion versus time as the injected current. According to the Figure 11. the injected current increases by a factor of ~2.5 between 2 and 12µs. In the same time period, the voltage threshold decreases by a factor of ~2.5. This tends to indicate that the key parameter would be the power deposited into the spar at edge glow occurrence as it seems to be constant whatever the delay, h_c and lightning protection density. As there has been no direct spar current measurement (and thus deposited power), it will be necessary to confirm this scenario by new tests with spar current monitoring.

The light emitted by edge glow has been captured by a still camera with high sensitivity and is reported on the picture below for various contact height values.

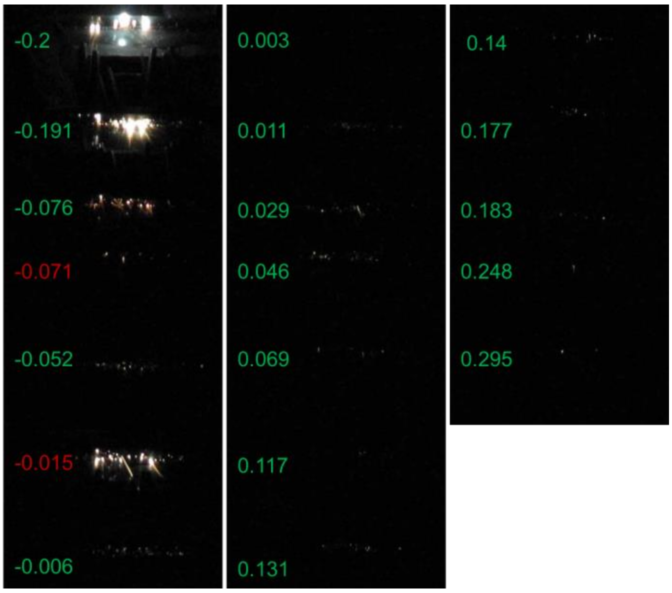

Figure 16. Still camera pictures, capturing the edge glow emission during shot, versus contact height of the fastener (indicated on each figure in mm).

The edge glow intensity is highly sensitive to the contact height. When h_c is positive, the edge glow intensity is very small. On the opposite, when contact height is negative, the emitted light intensity is significantly higher and is similar to the phenomena observed in previous work. The next figure gives a more quantitative assessment of the emitted light intensity and shows that its variation over the h_c range is up to 3 orders of magnitude.

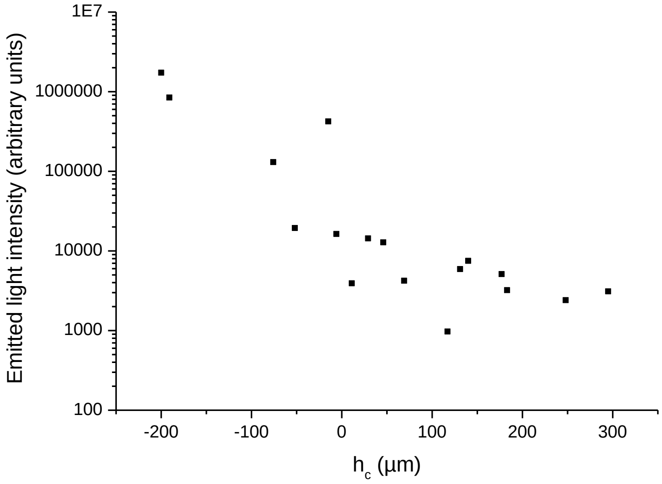

Figure 17. Emitted light intensity versus contact height of the fastener.

IV. Conclusion

We have presented in this paper the outcome of some experimental investigations on edge glow phenomenon on generic CFRP assembly coupons. At local assembly level, the dynamic contact between the impacted fastener and the skin protection during the strike highly influences the electrical stress induced into the substructure. This means the edge glow apparition is strongly sensitive to manufacturing detail such as the seating depth of the fastener with respect to the lightning protection. The contrast between previous and current work tends to suggest the existence of two edge glow regimes, i.e. two mechanisms or key parameters controlling the apparition of the phenomenon.

One occurs when the voltage drop between plies is over a voltage threshold, allowing a voltage spark whether there is a contact or not on the edge before the shot.

A second one seems to occur when the power deposited into the substructure, and thus into pre-existing contacts at the edge, is over a power threshold that produces visible heating (hot points). In that case, this mechanism would be sensitive to the transverse conductance at a micro level, i.e. to the way the "conductivity" is achieved locally. These hypotheses will be investigated more deeply thanks to a new test campaign in which substructure current will be monitored, combined with 3D numerical simulations to assess local current concentrations and temperature enhance.

References

[1] I. Revel, A. Hervé, G. Peres, M. Webster, R. Maddison and F. Flourens, "Understanding of edge glow phenomenon", ICOLSE, Seattle (WA), 18-20 September 2013

[2] R.B. Greegor, Q.N. Le, C.E. Anway, B.A. Whiting and A.C. Day, "Finite element simulation and experimental analysis of edge glow for a generic, 16-Ply carbon fiber reinforced plastic composite laminate" ICOLSE, Toulouse, France, 9-11 September 2015