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Mechanical behaviour for aeronautical structures with embedded electric cables under low energy impact

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Abstract. *The work focuses on the mechanical strength of composite structures with embedded electrical functionalities submitted to low energy impact. This material is defined for aeronautical applications as multilayers of glass fibre composite with flat electrical cable layers embedded. The main question is about the damage involved by the low energy impact, and its influence on the electrical cables layer performances. The impact leads to failure with no external signs of damage and insulation degradation. The dynamic experimental campaigns are carried out on drop tower tests with hemispherical tool. localized damage mechanisms at conductor interfaces are observed and a finite element model is performed. A link between impact energies and loss of electrical performance of multifunctional samples is established.*

1. Introduction

Airbus Group has been working for a few years on the development of new, innovative and more robust avionics technologies so as to reduce the costs associated with wired network installation. In this framework, the integration of electrical wires within composite structures has become a major industrial stake. Indeed, the main advantage of embedding electrical wires inside a composite structure is to reduce time on the line as the installation and segregation of the wiring have already been pre-completed [1]. Besides, it confers protection to the electrical systems from environmental conditions and enables increasing the ratio of electrical functionality to volume, hence leading to significant mass and volume savings.

Ariane Group wished to investigate the replacement of conventional wiring solutions for space launcher applications (cf. figure 1). Such a technology would also offer the potential to carry synergies



for other applications on civil and military aircraft (pax floor, seat rails, replacement of electrical harnesses, etc.).

The foreseen multifunctional structure should consist in a composite beam embedding flat electrical cables mainly composed of wire gauges for power and data transmission. During its lifespan, it will be submitted to manufacturing and inspections operations, transport, storage, and assembly, waiting on the launching site, take off and flight.

The main defects affecting the electrical performances of aeronautical wires are short-circuits, broken cables, chafing, corrosion, connexion losses and insulation defects. Among the various causes of these wiring degradations, moisture, chafing, corrosion and chemical contamination are unlikely to occur with the multifunctional architecture due to the embodiment of the electrical cables within the composite structure [2].

Nevertheless, low energy impact in manufacturing, transportation or other can be very harmful to polymeric composite structures as they are likely to produce internal damage such as delamination and fibre/matrix cracking, leading to substantial mechanical properties degradation, including strength and stiffness [3] due to the new wiring architecture two types of electrical damage can occur: broken wires and insulation defects.

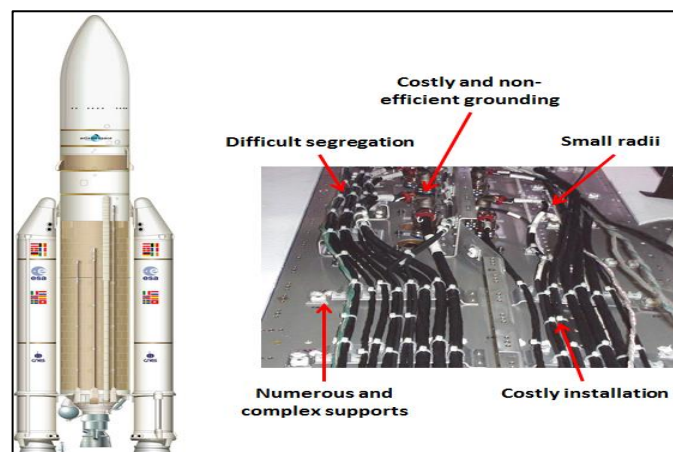


Figure 1. Installation and segmentation of the wire is time-consuming.

2. Presentation of multifunctional structure

2.1. Flat electrical cable definition

A flat cable technology has been selected and designed to replace the conventional solution and ease the integration of the electrical wires inside the composite structure. The chosen materials were a polyimide tape for the jacket, a fluorocarbon resin for the insulator, and AWG20 copper braided conductors for the wires.

The electrical cables have a nominal width of about 85mm containing 17 AWG20 electrical conductors with a width of about 3mm each once laminated inside the cable. Besides, it is worth noting that to ensure the electrical cable's flatness, the fluorocarbon resin sections were filled with two glass-fibres between every electrical wire, as shown in figure 2.

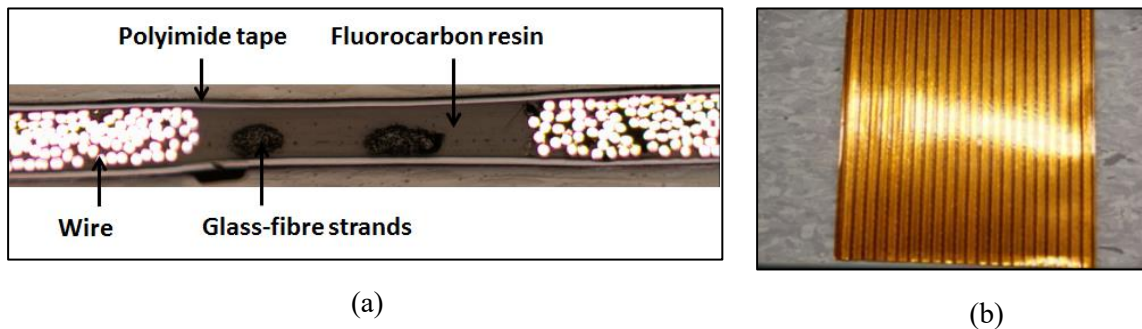


Figure 2. (a) Cross section of flat electrical cable, (b) sample of flat electrical cable.

2.2. Manufacturing of the Multifunctional structure

The solution investigated consists in superposing two flat electrical cables to have sufficient electrical wires for power and data transmission and return current functions. Hence, two flat electrical cables are laid one above the other within the composite structure. The distance between them is chosen according to the required characteristic impedance of the line. This divides the composite structure into three lay-ups of thickness h , with $h=1.5\text{mm}$. Additionally, two copper foils are laminated on the outer surfaces of the multifunctional structure for electromagnetic shielding purposes.

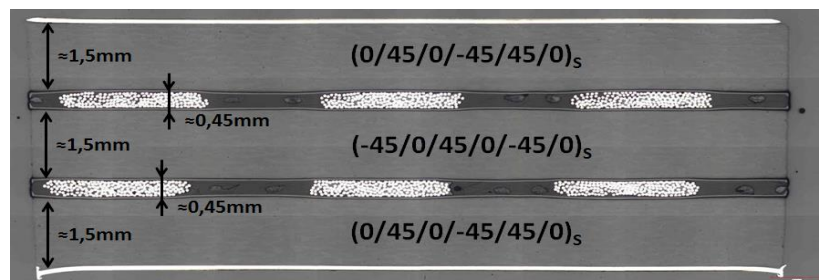


Figure 3. Cross-section of multi-layered composite functional structure.

The composite plies are glass preregs, i.e. pre-impregnated woven sheets of glass fibre with epoxy resin, that require a cure cycle of 180min at 160°C under pressure between 1 and 5 bar in an autoclave according to the manufacturer's datasheet. The curing environment is presented in Figure 4. The outer stacking sequences of composite plies are $[0/45/0/-45/45/0]_s$ and the inner stacking sequence is $[-45/0/45/0/-45/0]_s$. The composite plies, flat electrical cables and copper foils were manually laid up in this configuration while performing intermediate compacting and suitable surface treatment of the electrical cables (such as dry-cleaning) to ensure good interface properties between the composite and the cables. This manufacturing process was used to manufacture every plate and test specimens presented.

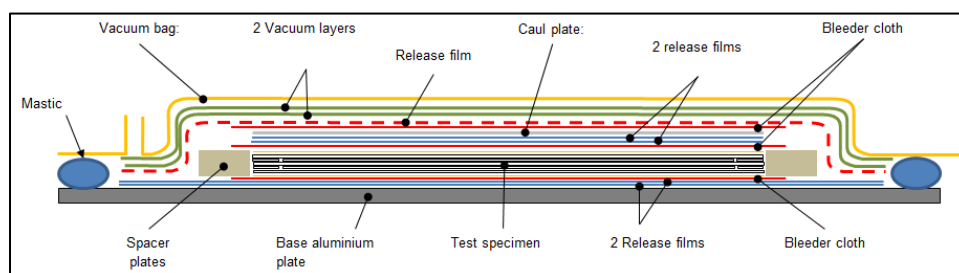


Figure 4. Curing environment of plates and specimens tested.

In addition, reference laminate specimens with the same stacking sequence without electrical cable embedded, named “Blank Specimens” are manufactured. these samples allow to quantify the behaviour of the electrical system embedded within the composite structure.

3. Mechanical behaviour of the functional structure under loading

3.1. Low energy test impact

Impact tests are carried out on an Imatek drop weight tower at 10J, 15J and 20J with a constant weight of 9,067kg dropped from a height varying from 0,11m to 0,22m to achieve the required impact energies. The impactor is made of hardened steel and has a diameter of 20mm. The test specimens have dimensions of 60x60mm² and are pneumatically clamped between two cylinders with $D_{int} = 40\text{mm}$ and $D_{ext} = 60\text{mm}$ (figure 5a).

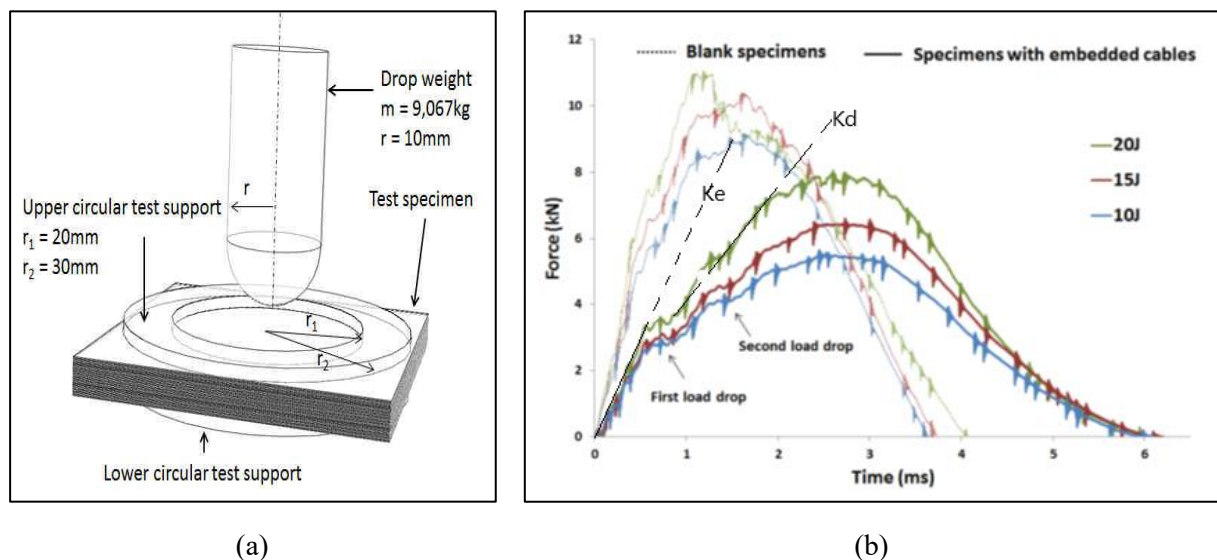


Figure 5. (a) Drop weight test impact setup (b) Comparison between the contact force histories of the multifunctional and blank test specimens impacted at 10J, 15J and 20J.

The contact forces recorded by a piezoelectric sensor at the bottom of the impactor are plotted for three test specimens impacted at 10J, 15J and 20J (Figure 5.b) for specimens without embedded cable (Blank specimens) and specimens with embedded cables. The curves exhibit a dome shape, while at 20J a more severe discontinuity appears at approximately 1,2ms for Blank specimen. In addition, it turns out that the impact response (contact force history and damage mechanisms) observed is very similar to what is described in the work of Xiao, et al. [4] where thick laminates have been impacted with a similar impactor and boundary conditions. Bi-linear behaviour can be deduced from the contact force history, where the initial linear behaviour (slope K_e) is followed by a slight drop and another linear behaviour (with a slope K_d and $K_d < K_e$ indicating losses of flexural and shear stiffness).

This is likely to be associated with local matrix cracks followed by initiation of delamination in a ring shape through the thickness of the laminates as observed in figure 6. Indeed, delamination initiation is mainly due to high transverse shear which are localized around the impact zone, hence resulting in a ring shape and propagating through the laminate due to the transverse shear loading. Once the delamination has propagated, fibre failure begins on the back face of the test specimens at 15J and 20J.

As compared to the blank specimens, these functional specimens show a much more dissipative behaviour with lower peak contact forces and higher impact durations. These experimental testings have revealed two main damage mechanisms that potentially hinder the electrical functionality of the structure:

- Slipping within the cables (observed under transverse dynamic bending), eventually leading to debonding within the cables (observed under transverse dynamic bending test)
- Tension-shear fibre failure of the composite plies at the interface with the embedded cables.

Compared to blank test specimens, the multifunctional test specimens seemed to exhibit better energy absorption and a slightly higher damage threshold. Nevertheless, the two main damage mechanisms observed at lower impact energies are more hazardous because they cannot be visually detected.

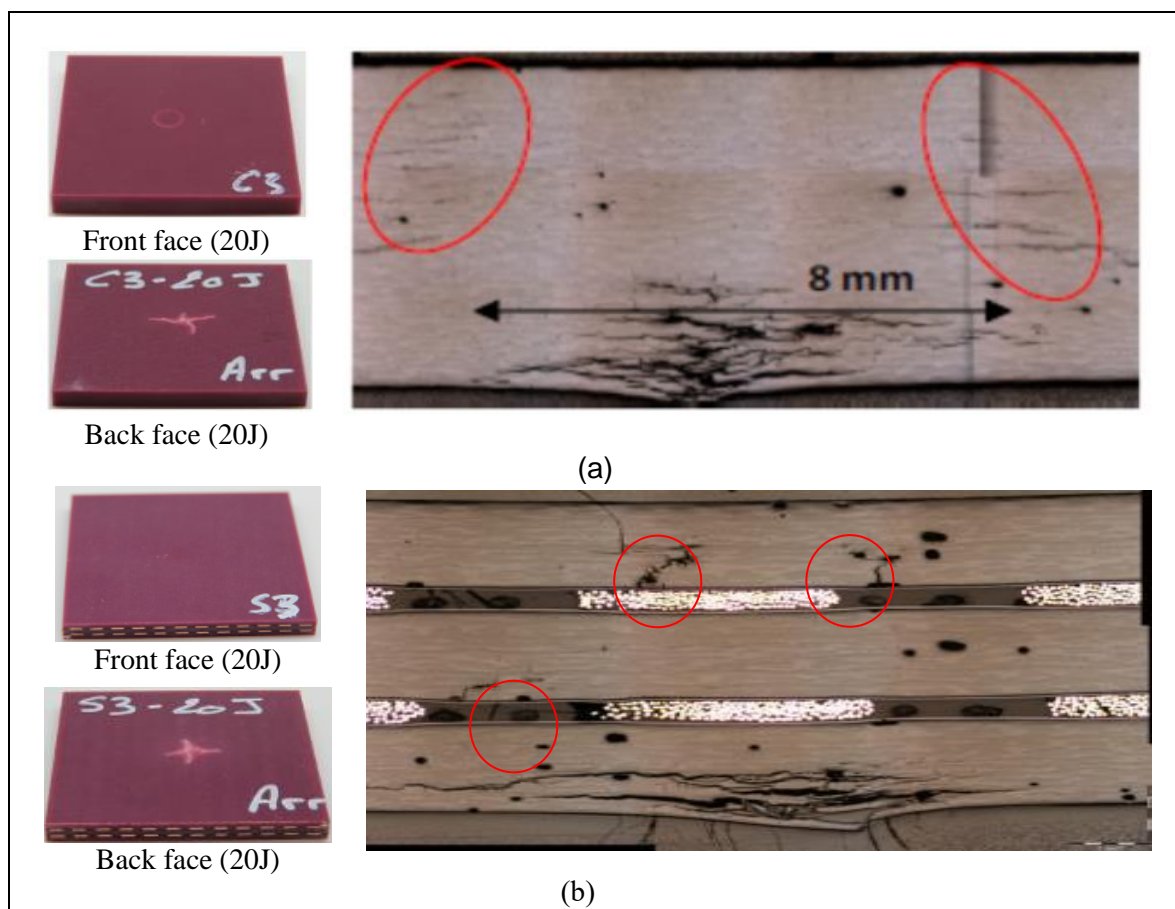


Figure 6. (a) Post-impact microscopic observations of the damage distribution within the multifunctional test specimens (b) microscopic observations within blank specimens.

3.2. Predictive numerical model

To reproduce the damage mechanisms observed experimentally, finite elements numerical modelling of the impact tests is performed under Abaqus. Eight nodes brick elements with reduced integration (C3D8R) are used to mesh the composite plies (one layer of elements per composite ply) and the embedded cables (three layers of elements per embedded cable). Penalty contact interactions with a normal and tangential component are used to define the contact interactions between the test specimens and the impactor as described in Figure 5.a. The impactor is modelled as a rigid body with a mass of 2,27kg (only a quarter of the test specimen is modelled). A user-defined constitutive law

based on the principle of progressive failure of Hashin [5] and damage mechanics of Matzenmiller and al. [6] is used to model the mechanical behaviour of the composite plies. The embedded cables are given a linear anisotropic behaviour and modelled similarly to a composite ply with the 9 classical engineering constants.

To reproduce the sliding inside the cables under inter-laminar shear strains, cohesive interactions are defined at the interface between cable and the composite plies, as shown in figure 7.a. When treated with a traction-separation relationship, damage initiation is related to the maximum traction on the load – displacement curve, (figure 7.b), and is followed by a softening phase that simulates the progressive decohesion of the interface with increasing damage [6].

The cohesive constitutive law used here is a classical bi-linear mixed-mode traction -separation relationship [7] which is already available within Abaqus CAE. Damage initiation is considered with a maximum stress criterion as in equation (1), and damage propagation is modelled with an energy-based Benzeggagh-Kenane (BK) criterion as in equation (2).

The maximum stress criterion is:

$$\max \left\{ \frac{\langle \sigma_{33} \rangle}{T}, \frac{\sigma_{13}}{S}, \frac{\sigma_{23}}{S} \right\} = 1 \quad (1)$$

The BK criterion

$$G_c = G_{Ic} + (G_{IIc} - G_{Ic}) \cdot \left(\frac{G_{shear}}{G_T} \right)^\eta \quad (2)$$

Where G_{Ic} and G_{IIc} are respectively energy release rate for mode I and II (fracture mechanics). T , S maximum normal traction and transverse shear stress for laminate and σ_{ij} are the stress tensor components.

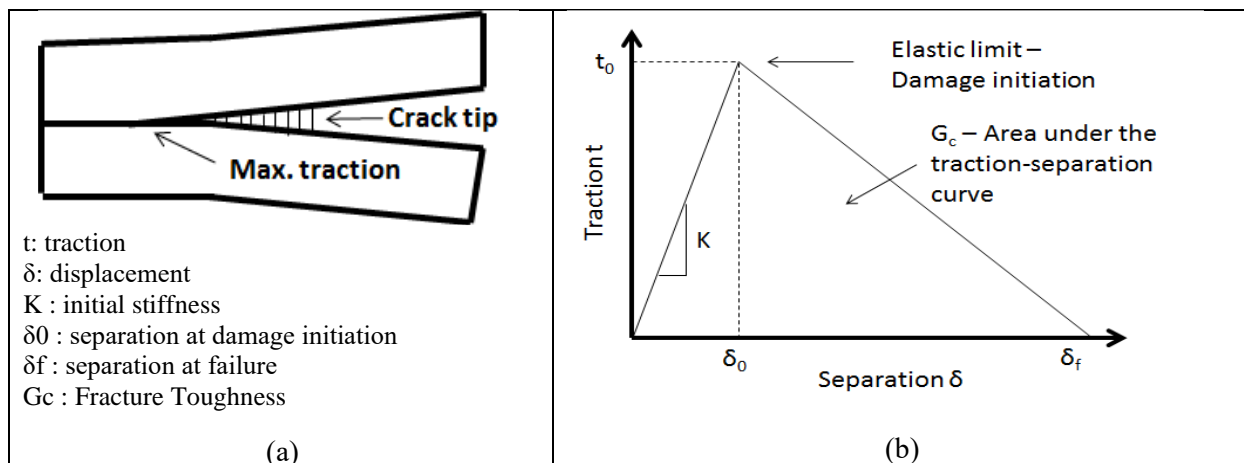


Figure 7. (a) Cohesive damage evolution at the interface, (b) traction-displacement curve behaviour.

In the numerical model, transverse shear strains seem to initiate inter-laminar damage and delamination at the interface of the flat cable layers in figure 8.a and identify in the contact force histories figure 7.b. It is observed that the fibre tension-shear failure which seems to initiate at the interface with the embedded cables is a consequence of the sliding that occurs inside the embedded cables. Indeed, sliding among the cables first occurs and is well reproduced by the cohesive surface to-surface interaction. This triggers the first load drop observed experimentally at 0,8 ms. It induces

higher inter-laminar and tensile strains on the adjacent composite plies, which leads to tension-shear fibre fracture captured at approximately 1,6ms.

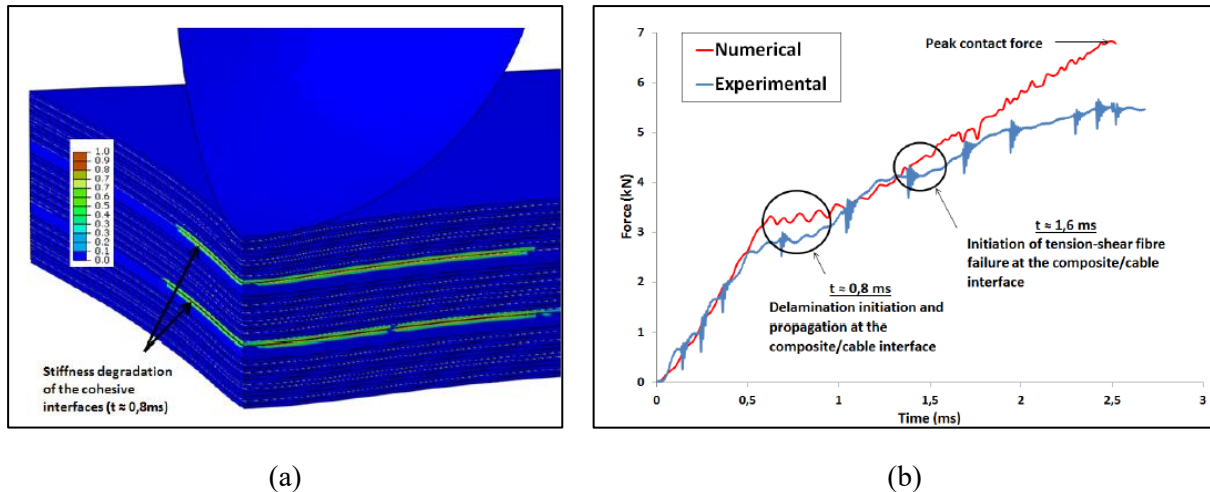


Figure 8. Numerical impact simulation of multifunctional specimen, (a) location of damage at interfaces, (b) impact force history comparison with experimental test.

4. Post impact electrical performances

In order to study the influence of such damage mechanisms on the electrical functionality of the structure, post-impact dielectric strength tests were performed. These measurements are expected to provide qualitative information about the insulation degradation of the cables [8].

The dielectric strength of an insulating material is the maximum electric field that a pure material can withstand under ideal conditions without breaking down (i.e., without experiencing failure of its insulating properties). Hence a dielectric strength test consists in measuring the breakdown voltage of a device under test while applying a differential of potential across the dielectric. A dielectric strength tester (also called hipot tester, flash tester, or high voltage tester) is used to measure this current. In this work, the system used for the measurements was a SEFELEC PR12NN with a maximum capacity of 12 kV. The work focuses on two types of electrical damage: broken wires and insulation defects (damage of the jacket and/or insulation).

Broken cables remain one of the critical scenarios to be avoided and occur due to excessive tensile strains on the electrical wires. In terms of electrical performances, this will induce an increase of the electrical resistance of the line, and ultimately a loss of data and power transmission. Insulation defects also appear to be critical since it has been shown that the insulator resin is the weakest interface inside the multifunctional structure. Indeed, insulation properties within the multifunctional structure are both a key design criterion and a major concern since a loss of insulation between two wires is likely to result in significant reduction of the breakdown voltage, and ultimately in short-circuits and electrical arcing.

Electrical shorting started occurring within the embedded cables for test specimens impacted at 20J under conventional impact test conditions as shown in figure 9.b. It always occurred between two conductors of the same cable (adjacent conductors of the top or bottom cable). Post-impact post-dielectric strength tests microscopic observations revealed that the electrical shorting occurred due to the internal tension-shear fibre failure observed previously. It is interesting to highlight that the resulting degradation was confined to the adjacent wires and did not spread to the other wires.

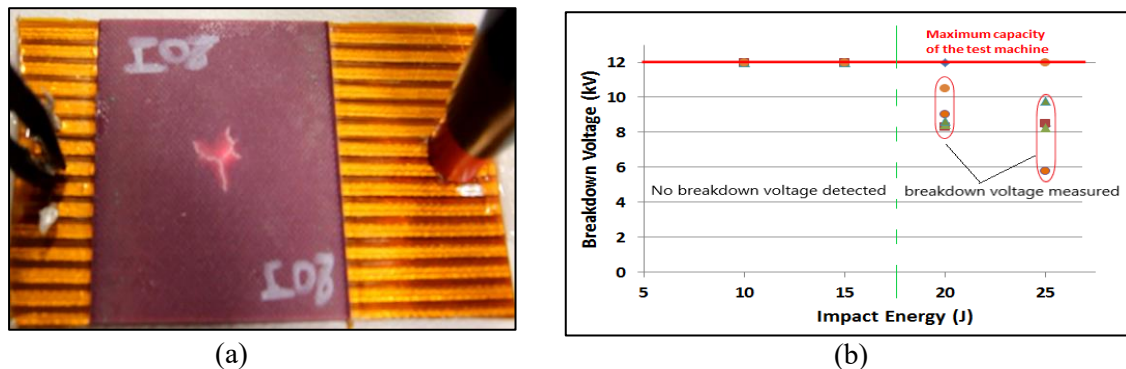


Figure 9. (a) Spark due to breakdown voltage localized in damage area (b) Identification of breakdown threshold versus impact energy.

5. Conclusion

Aerospace specifications combined with the expected weakness of such structures under out-of-plane deformations drove the need for investigations on the mechanical behaviour of such assemblies under low energy impacts (hails, drop tools, maintenance operations, etc.). Indeed, the structure appeared to be particularly weakened when loaded in bending due to the low shear stiffness of the embedded cables which induced higher internal shear strains. These shear strains led to induced both internal fiber failure of the composite plies at the interface with the embedded cables, and de-cohesions within the cables. In addition, they were shown to alter the electrical performances of the embedded cables as they result in insulation degradation between two adjacent wires, which was revealed by the post-impact dielectric strength tests.

For aircraft applications, electrical cycling (and thus, thermal cycling) should be investigated to ensure that it does not lead to delamination or de-cohesion within the cables due to the difference in thermal expansions between the various materials. In addition, mechanical cycling should not be neglected, including in-plane loads, since the mismatch of fatigue life between the composite and copper could lead to premature electrical failure.

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