HOW TO DEFINE A MECHANICAL IMPACT EQUIVALENT TO A LIGHTNING STRIKE

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1 Abstract

Lightning strikes on thin monolithic composite materials such as aircraft fuselage skin induce two distinct kinds of direct effects: surface and bulk mechanical damage. Bulk damage includes fibre-resin debonding, transverse cracks, fibre rupture and ply delamination which are caused by mechanical stresses resulting from physical processes induced by lightning strikes such as surface explosion or magnetic force generation. We propose here a method to design mechanical impact tests wanted to be representative of lightning ones in the sense that strains and stresses applied to the material in both situations are comparable. The criterion of equivalence we rely on is thus the temporal evolution of the rear face deflection. Mechanical impact tests leading to deflections quite similar to the ones obtained during lightning tests have been designed using a simulation driven procedure and performed experimentally. A comparison between these two kinds of tests is then achieved, based on the two observables: rear face deflection for which we have a quite good matching for the first 100 µs and internal damage (delamination area and profile) for which we obtain an acceptable matching for the total delaminated area but very poor matching for the distribution of the delamination in the laminate.

2 Introduction

Extending the use of composite materials in aircraft structures exposed to lightning strikes to wings and fuselage demands specific designs allowing the attachment and conduction of high electrical currents. The optimization of such protection layers in the industrial context requires taking into account many constraints including damage reduction.

The present work looks at the possibility to find a frame of equivalence between a lightning test and a mechanical impact one. The interest of such a comparison is that it should provide some insight on the origin of the damage, a possibility to perform equivalent mechanical tests in a more reproducible way than lightning tests and ultimately to help in designing of lightning protection by the use of numerical modeling tools belonging to the field of mechanics.

Lightning strikes on protected Carbon Fibre Reinforced Plastic (CFRP) thin monolithic laminate materials such as aircraft fuselage skin induce two distinct kinds of direct effects: surface and bulk damage. Surface damage, defined as removal of paint and metallic protection as well as damaging of the first plies of the laminate, have an electro-thermal origin resulting from the circulation of an intense current [1-3]. Bulk damage, defined as damage in the depth of the laminate includes fibre-resin debonding, transverse cracks, fibre rupture and ply delamination. Bulk damage results from the association of various physical processes induced by the lightning strike such as surface explosion or magnetic force generation. This core damage has been compared from a phenomenological point of view to damage induced by mechanical impacts and was shown to be quite similar in shape and extent [4]. For clarity, we restrict in the following the use of the word "strike" to lightning and the use of the word "impact" to describe a massive projectile hitting the material under study. The resemblance of strike induced core damage with impact induced one leads us to assume an important mechanical contribution to lightning induced core damage, even if it may have at least in part a thermal origin [5-7].

Previous studies investigating such mechanical impact analogy [8] focused on the energy delivered by the electro-thermal phenomena or the kinetic sources as the key parameter defining this equivalence. However, we suspect this parameter not to be the most meaningful one as the largest part of the energy stored in the electrical system is dissipated in heating of the different parts of the electrical set-up, and not in damaging the material. We propose here another method, based on the transferred impulse, to design mechanical impact tests representative of lightning tests which does not suffer from this deficiency.
The criterion of equivalence we rely on is the possibility to obtain similar rear face deflection for both lightning tests and mechanical ones, resulting from comparable transferred impulse.

The present paper is organized as follows: in section 3, we present our method to obtain the equivalent mechanical parameters as well as the impact and strike test set-up. In section 4, we use this method to define impact conditions equivalent to strikes and we compare the damage obtained in both conditions.

3 Equivalent mechanical tests

The aim of this study is to design a mechanical impact test that would induce observable phenomena in the monolithic composite laminate equivalent to those produced by lightning strikes on the protected laminate. Indeed, lightning strike tests involve various kinds of physics such as plasma-material interactions, electromagnetism and electro-thermal effects that are not yet properly quantified and sometimes not fully reproducible. By using a pure mechanical impact, we propose a simpler and more reproducible method.

3.1 Equivalent parameters for mechanical tests

To study an equivalence criterion, we focus on the transferred impulse k (N.s). As a starting point, we assume that the panel subjected to the lightning strike has an infinite size and is subjected to an instantaneous load. The effect of this load is a recoil d of the whole plate which at infinitely large time tends toward the asymptotic value:

$d_\infty = \frac{k}{8\sqrt{\mu D}}$ (eq. 1)

where μ is the mass per unit surface and D the bending stiffness of the plate [9]. In practice, obviously, plates have a finite size L. However, they can be considered as infinite within a time window of the order D/C after the strike. This delay corresponds to the time taken by strain waves generated by the load at the centre of the plate to travel at speed C to its rim and reflect back. Such a delay is expected to be typically of the order of the millisecond, ten times larger than the duration of a lightning strike from an electrical point of view. There is therefore a time window between 0.1 µs and 1 µs where the instantaneous-impact-on-infinite-plate analytical model is expected to be a useful guide to interpret experimental results. Indeed, as shown in a previous paper [9], we do observe experimentally a plateau value of rear face displacement versus time in such a time window. Eq. 1 can then be used to obtain an impulse k from the measured deflection d_∞.

For the equivalent mechanical test, we consider a steel impactor of mass m which does not deform and hits the target normally with speed v. In this case, the transferred impulse is given by:

$k = m \times v$ (eq. 2)

Equalling this k to the impulse extracted from lightning test deflection plateau provides pairs of possible mass and velocity for the equivalent mechanical projectile. Usually, both are imposed by practical considerations, like the availability of the projectile (mass 4 g, ϕ9.8 mm diameter, in our case) and the velocity is consequently defined. Our experience taught us that the velocity thus obtained from this analytical model is not totally optimal. It is however a good starting for further refinements, which are performed by successive iterations using the numerical model described in section 3.2, tuning the projectile velocity until the computed mechanical impact deflection matches well the measured lightning strike one.

3.2 Numerical model

We now focus on the procedure used in this numerical refinement step. The ABAQUS-explicit Finite Element software is used to determine the behavior of nude composite plates subjected to projectile impacts. The model represents the samples, the clamped boundary conditions as in the lightning strike tests, and the projectile. The impactor is modelled as an analytical rigid body (analytical sphere). It is assigned an initial mass and a perpendicular velocity and is positioned above the center of the plate. A penalty contact without friction and damping is defined between the projectile and the target. For this preliminary stage of the study, where we design impact configurations equivalent to strikes, composite samples are modelled using shell elements (S4R), under the hypothesis of small perturbations and are set as homogenized elastic orthotropic material following the classical lamination theory. The mesh (see figure 1) is composed of rectangular elements in majority. Due to the sample geometry and in order to reduce the computation time, a progressive refinement mesh is prescribed from the boundaries toward the center of the plate.

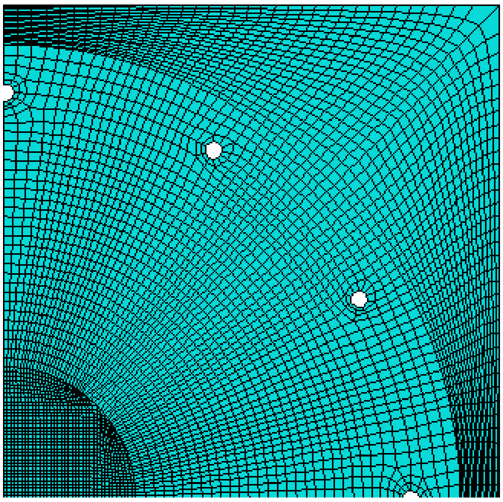


Figure 1: ¼ of the numerical model meshing strategy.

3.3 Application

The samples are carbon-epoxy square panels of 400x400 mm² made of 8 CFRP plies with the following lay-up: [45/0/-45/90]s. They are all protected by expanded copper foils of mass 195 g/m^2 (ECF195) in lightning strike tests. They differ by their surface states only: they are covered with expanded copper foils of mass 195 g/m^2 (ECF195) and can be painted with different thickness. A small hole of paint is artificially created on sample 107.

These samples have been tested to lightning on the EMMA platform at DGA-TA Lightning Lab in Toulouse. The electrical waveform D (peak 100 kA) with rise-times of the order of 20 µs and total duration 100 µs was used [10]. Deflections are measured during the test with an interferometry technique (VISAR).

Taking those measurements as inputs for our numerical model (see §3.2), we are able to compute impact conditions leading to deflections quite similar to the measured strike ones. The equivalent impactors to the three lightning test cases are listed in Table 1 which provides the equivalent projectile velocities calculated using equations (1) and (2) and subsequent numerical refinement.

Lightning sample	Surface state (paint + protection)	Calculated speed (m/s)	Projectile mass (g)
101	ECF195-P160	72	4
103	ECF195-P50	65	4
107	ECF195-P160	81	4

Table 1: Characteristics of the equivalent mechanical projectile to the associated lightning strikes.

An illustration of our result is given in Figure 2 which shows the comparison between measured strike deflection for sample # 107 and the one modelled for a mechanical impact with a projectile of 4g at a speed of 81 m/s. We see that the computed impact deflection is in good agreement with measured lightning strike ones at short times (<50µs). At larger times however, the lightning deflection continues to increase whereas the mechanical impact one reaches the expected plateau and then decreases. This indicates that some external force continues to apply on the material at late time of the strike which does not exist in the mechanical impact configuration. Notice that lightning strike ends at 100 µs from an electrical point of view. We speculate that this extra force must be related to possible thermomechanical phenomena occurring in the metal protection and paint layers at the surface and which are delayed with respect to the lightning strike. A possible model for these surface phenomena has been described in [7].

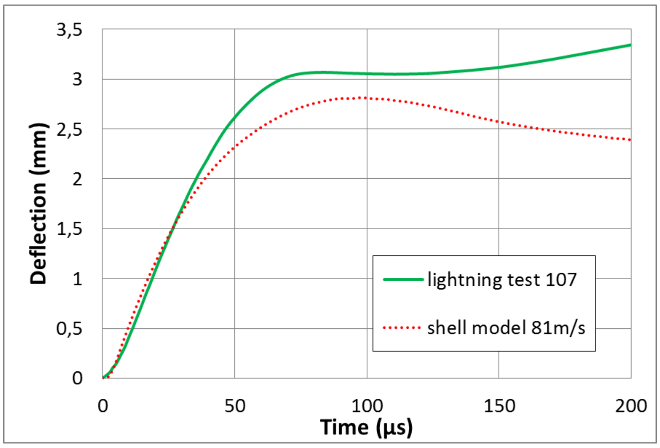


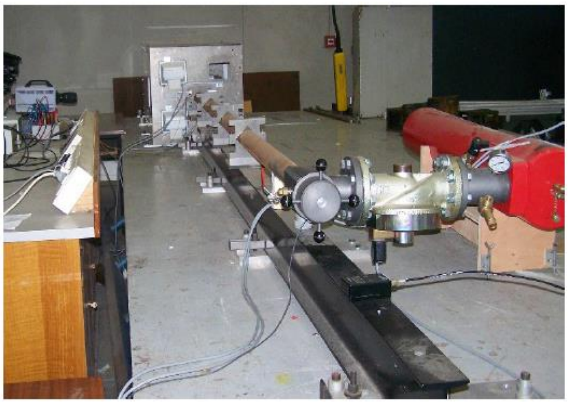
Figure 2: Comparison of rear face deflections between lightning strike (plain line) and numerical simulation with a steel projectile (dotted line).

We extend the use of this method to the 3 samples, as shown on table 1. The table provides the equivalent projectile speeds calculated using equations (1) and (2) and subsequent numerical refinement and for which good agreement with measured strike rear face deflection are obtained. Figure 4 ("shell model" and "impact test" curves) shows the comparison between strike-measured and impact-computed deflections for the cases # 101 and # 103, in complement to the case # 107 already shown on fig. 2. In the case # 101, there are significant differences even at short times, which suggest that further refinement may have been possible.

3.4 Mechanical set up

Once the mechanical equivalents were determined, impact tests have been performed at Institut Clément Ader Laboratory (ICA) in Toulouse, using the 4g steel sphere projectile, launched by a gas gun apparatus (canon) in a range of velocities from 50 to 150m/s. Illustration is given in Figure 3.a.

A clamping system (Figure 3.b) has been designed in order to reproduce the same boundary conditions than those of the lightning tests (12 bolts disposed in a circle of diameter Φ370 mm).

a


b


Figure 3: Gas gun apparatus: a): complete set-up with the pressure vessel; b): the metallic boundary ring on which is fixed the target square plate.

The set-up is equipped with a high speed camera which allows measuring the projectile velocity at the exit of the gas gun. Rear face displacements are measured using two displacement sensors (Keyence 20 kHz without contact).

Computed and real experiment velocities of the equivalent mechanical projectiles are compared in table 2. Experimental velocities are different by only a few percent from the required one.

Lightning sample	Computed projectile speed (m/s)	Measured projectile speed (m/s)
101	72	75
103	60	65
107	80	81

Table 2: Measured (obtained) versus computed (desired) velocities of the equivalent projectiles during gas gun impact tests.

4 Comparison between lightning and mechanical tests

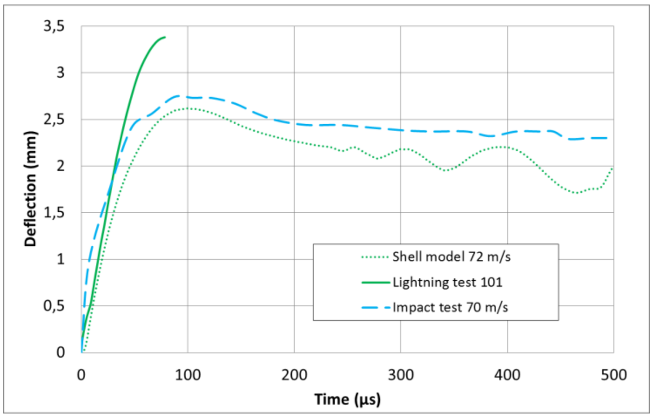
To determine whether the equivalence is efficient, rear face displacements from strikes and impacts are compared up to 100µs. In a second step, damage observed in the samples after impact tests is compared with strike damage. Both the shape and size of the projected delaminated area and the distribution of delamination in the depth of the laminate are examined.

4.1 Rear face displacement

We first check the accuracy of the mechanical model by comparing the computed and measured impact deflections in identical or close conditions. We can see on figure 4 that the experimental curves are in good agreement with the numerical predictions for both speed and deflection at short and larger times.

The experimental mechanical impacts systematically provide a slightly higher rear face deflection compared to the numerical predictions (about 4% at 72 m/s and 8% at 65 m/s). This result is consistent with the use of a homogenized elastic shell model which does not take into account damage induced by the impact. While the numerical model is too simplistic to represent these details, the obtained satisfying correlation shows that our modelling strategy of the mechanical impact is relevant.

In a second time, a comparison is made between mechanical deflections and lightning strike ones. The equivalent mechanical impacts provide quite good results at short times with lightning strikes results for samples 103 and 107: the initial slope of the curve is well reproduced as well as the first peak of deflection. The mechanical impact fails at reproducing the large time deflection observed in lightning conditions and the value of the constant deflection is smaller in the impact results than in the strike measurements. This difficulty for the impact equivalent to represent long time behaviour must be related to thermomechanical surface phenomena which result from the presence of the metallic protection and dielectric paint layer [7] and which are delayed with respect to the lightning strike itself. Such delayed phenomena cannot be represented by the fast mechanical impact processes.



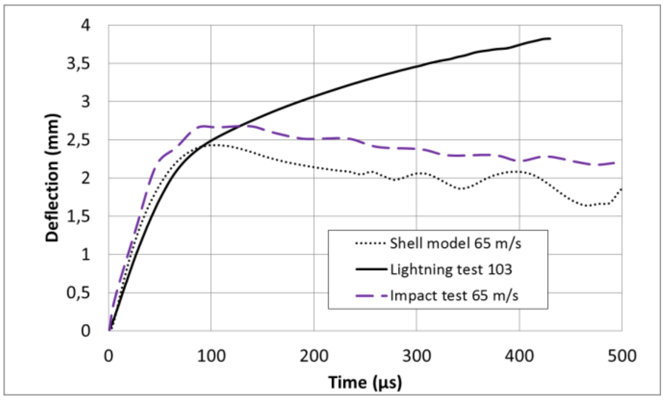


Figure 4: Comparison of mechanical impact result with numerically predicted one and lightning strikes results for 2 cases: top – sample # 101; bottom – sample # 103.

The displacement and maximum velocities at 50µs (mean instant of maximum velocity in lightning strikes) are compared in table 3. The agreement is good but of slightly lower quality for sample # 101, for which the chosen equivalent impact speed is presumably underestimated.

Sample	Strike displacement (µm)	Impact displ. (µm)	Relative difference	Strike max. velocity (m/s)	Impact max. vel. (m/s)	Relative difference
101	2827	2159	-23.6%	37.4	33.6	-10.1%
103	1726	1914	+10.8%	25.6	33.8	+32%
107	2626	2262	-13.8%	32.3	35.4	+9.6%

Table 3: displacements and maximum velocities at 50µs

4.2 Delamination extent and distribution

Table 4 presents the total delaminated area measured by ultrasonic C-scans for each lightning strike and its associated mechanical impact. Mechanical impacts produce delaminated areas in good agreement with lightning strikes for sample 107. Sample 103 is an extreme case which gives zero delamination for the lightning strike, and smallest, albeit non zero, delaminated area for the associated mechanical impact. Besides, the already mentioned underestimate of the equivalent impact velocity for sample # 101 induces an underestimate of the corresponding impact delaminated area.

Lightning samples	Impact speed (m/s)	Strike delaminated area (mm²)	Impact delaminated area (mm²)
101	75	2321	1626
103	65	0	630
107	81	1738	1746

Table 4: Delaminated areas for lightning strikes and associated mechanical impacts.

The distribution of delamination in the thickness of the samples is measured from micro-cuts. Figure 5 provides typical micro-cuts on 2 samples. A major delamination gap is visible in both cases between plies 3 and 4, counted from the impacted side. Simultaneously, surface damage is visible from the disappearance of the paint and metallic surface layers.

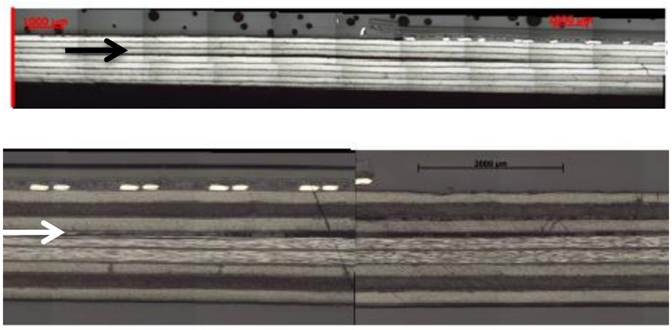


Figure 5: Microcuts of the # 101 (top) and # 107 (bottom) samples. The dashed lines on the top of the stack correspond to the metallic lightning protection; it has been removed by the strike on the right side which is the location of the surface damage. The white arrows show the location of the main delamination between plies 3 and 4. The cut line corresponds to a vertical line on fig. 7. The delaminated area is the one associated to the vertical ellipse on fig. 7. The scale of the picture is not the same in the # 101 and # 107 cases and can be given by the thickness of the 8 layer stack (1.45 mm in undamaged areas).

C-scans provide a more quantitative picture. In the lightning case, they are obtained only from the rear face, as shown on fig. 6, due to the too strong perturbations of the ultrasonic signals on the damaged impacted and protected side.

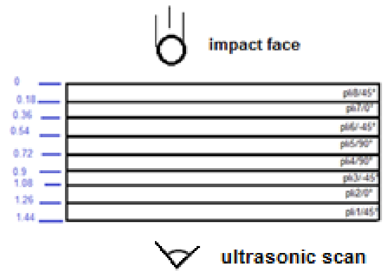


Figure 6: Two scales for ultrasonic testing method: left the thickness, right the fibre orientation

We compare in figure 7 the resulting C-scans for the mechanical impact at 75 m/s and for the lightning strike on sample # 101, which is considered to be the poorest comparison case and which is thus expected to be informative. The comparison of the two scans shows several differences. First the shapes of the two damage areas are significantly different although their magnitudes are of same order but somewhat larger in the strike case, as already seen on table 4.

The lightning strike damage area presents a very peculiar shape consisting of two zones around a 90°oriented delamination between the plies 3 (-45°) and 4 (90°). On the contrary, the ultrasonic scan of the mechanical impact presents usual characteristic features: a butterfly shape with a central vertical symmetry axis that is the axis of the projectile displacement, the wings of the butterfly being separated by two distinct visible cracks; the wings are limited by two series of cracks oriented on the fibre’s direction of the underlying ply (length) and of the upper lying ply (width). The large splinter oriented along the last ply orientation is typical of a mechanical impact damage which velocity is too high for the lateral dimensions and is a feature that we rarely encounter in lightning strikes. The butterfly shape of the delaminated area with its wings on both sides of a large 90° oriented delamination between the plies 3 and 4 (-45/90) shown on figure 7 is also a common feature of this kind of impact [11, 12].

The distribution of damage through the thickness is also different between impact and strike. This is clear on Figure. 8 where we see that for the lightning strikes sample, the damage stops at the double 90° interface and thus the damage area is confined in the first half (struck side) of the thickness of the laminate. The mechanical impacts on the other hand generate damage through all the thickness of the laminate following a classical helicoid cone which ends with the large splinter on the rear face of the samples.

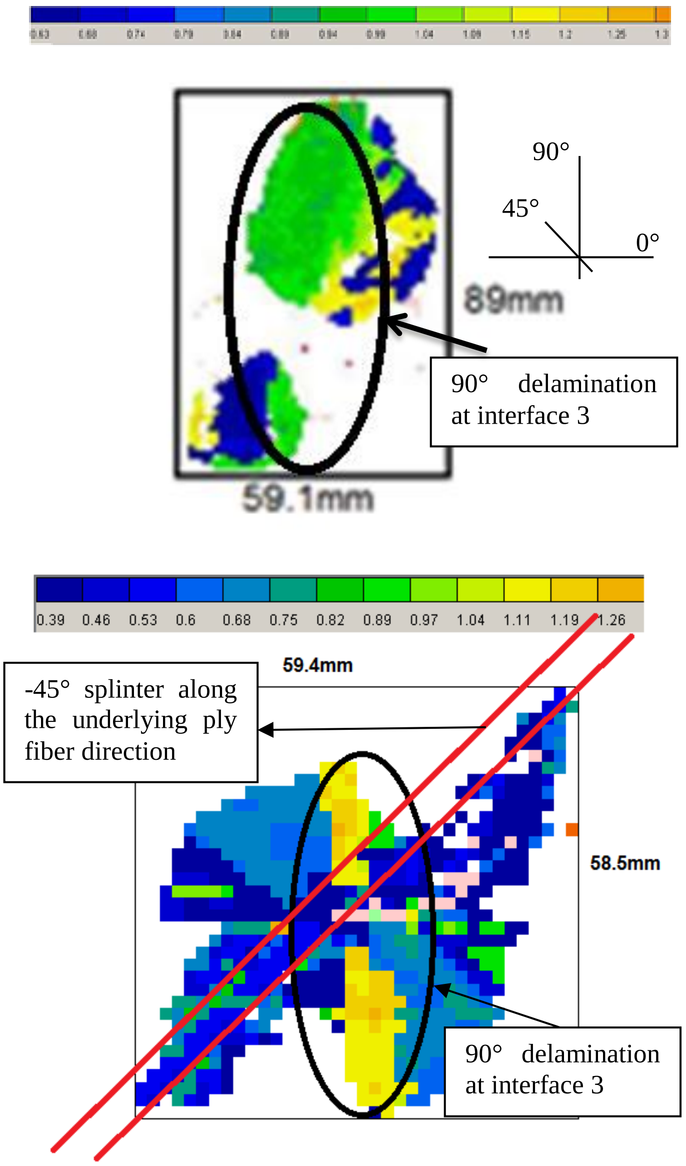
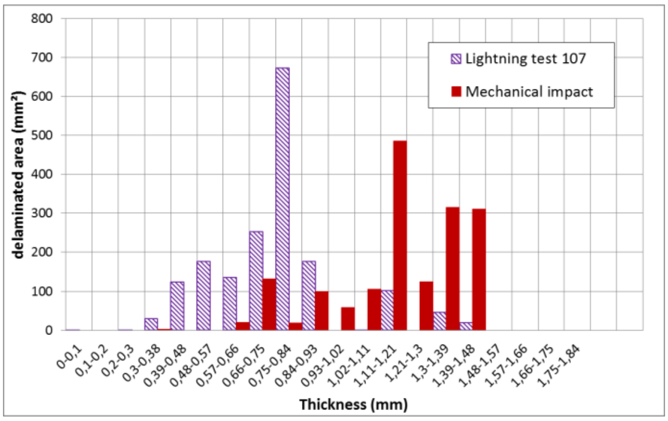


Figure 7: ultrasonic scans for lightning strike (top) and associated mechanical impact (bottom) at 75m/s for sample 101 at interface between plies 3 (-45°) and 4 (90°).



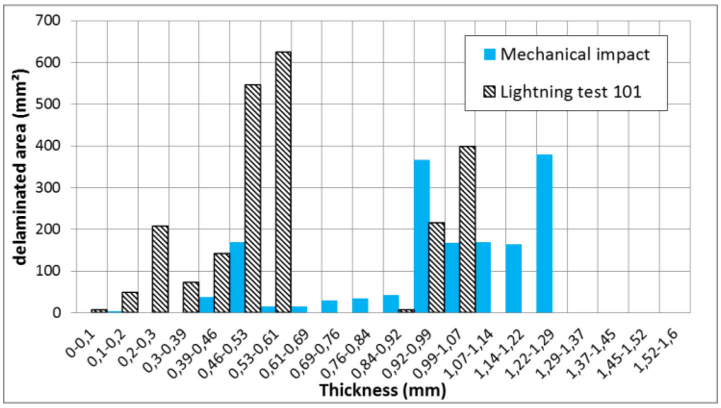


Figure 8: Histograms of the delamination as a function of position in the thickness (as defined in fig. 6) of the material, for # 101 (top) and # 107 (bottom) samples.

4.3 Analysis

From all the above analysis, it is demonstrated that our equivalent mechanical impact reproduces well the rear face displacement of a composite thin plate submitted to a lightning strike until the peak deflection is reached, as well as the induced total damage area. These observations form a basis to validate the proposed equivalence method. However, lightning strike damage distributions in the thickness of the material differ significantly from those obtained from mechanical impacts. Except for interfaces that hide the next interfaces, C-scans can be used to quantify properly the difference of damage distribution for each interface. Differences between mechanical impacts and lightning strikes damage are mainly due to the type of impulse created by the local contact of a small and hard projectile. We used steel ball with 4g mass and this small projectile launched at relative high velocities (about 70m/s) is known to create craters and rear face splinters localized around the projectile contact zone: surface craters appear, then by increasing further the impact velocity, penetration and perforation occur. Even if splinters also arise during lightning, they are not due to the same load distributions. In fact, the electrical arc expands radially during the strike and our steel ball is not able to reproduce such behaviour. The deflection behaviour at larger times may be better described with different types of projectiles allowing for longer contacts.

5 Conclusions

The present work is a first attempt to design a mechanical impact test representative of a lightning direct effect test. The analogy is made on rear face deflection and maximum speed measurements during lightning strike and mechanical tests. An equivalent impact using a simple analytical model has been defined and tuned with a numerical model. Actual canon test were performed to validate the numerical predictions as well as our equivalence method. The results were very satisfying regarding the kinematics of the samples. Indeed the canon tests results provide good correlation with the predictive numerical model and the lighting strike results at short times for rear face displacements and velocities. From comparison of the obtained damage in both experimental conditions using C-scans and micro-cuts, we have shown that the equivalent mechanical impacts and lightning strikes produced comparable total damage areas but fail to reproduce delamination distributions through the plies and thickness of the plates.

The work presented in the present paper is a first step which should be continued. First, representativeness of the impact should be improved along three lines. One is the long-time behaviour of the deflection, which could be improved by using different types of impactors allowing for longer contacts. A second line of improvement concerns the points at which comparison between strike and impact is performed. In the present study, we use a single point, typically at the vertical of the impact. We did not control the deflection at other points, what we should have done to obtain the correct deflection shape of the sample over a whole surface. Following these two lines, we should also achieve a better agreement between measured lightning and impact damage distributions in the thickness of the material. A third line is the improvement of the numerical model to compute the deflection resulting from the mechanical impact. It should include damage modes, this may have some effect on the computed deflection and thus on the definition of the equivalent impact. This of course simultaneously would provide estimate of the damage areas, to be compared with canon test results. Developments along this third line are presented in an accompanying paper at the present conference named "Core damage induced by a lightning strike and a mechanical impact: comparison" by the same authors.

Once the equivalence method will be fully operational, it will be used with benefits in industrial context. It will allow for instance for a fast estimate of the consequences of material design changes on lightning damage based only on virtual testing plans.

Acknowledgements

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