DESIGN OF MECHANICAL IMPACT TESTS EQUIVALENT TO LIGHTNING STRIKES

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Abstract

Lightning strikes of composite materials induce two distinct kinds of direct effects: surface and bulk mechanical damage. Bulk damage includes fiber-resin debonding, transverse cracks, fiber rupture and ply delamination. It results from the mechanical stress associated to physical processes which come with lightning strikes such as surface explosion or magnetic force generation. We propose a method to design mechanical impact tests representative of lightning tests in the sense that strain and stress applied to the material in both experimental situations are comparable. Then we compute the deflections of the samples expected for these representative impacts and we compare them with the ones measured during lightning tests.

1. Introduction

In flight, lightning strikes of aircrafts potentially induce electromagnetic perturbations on the on-board electrical systems as well as mechanical damage on the structural materials. The present paper focuses on such structural damage occurring in the vicinity of the lightning impact point on CFRP materials. This kind of damage is well characterized by in-flight experience and laboratory tests [1-3, 5, 10, 14, 16], but better understanding is desired to provide guidance in the design of future structural lightning protections and of test procedures. Lightning direct effects are usually modelled with coupled electrical and thermal formalisms [5-9]. In such models, energy is injected in the material by the Joule effect induced by the electrical current flow through the material and protection, as well as by heat transfer from the arc root. This energy input results in heating of the protection and material, possibly followed by melting and vaporization. The extension of the damage is assessed on the basis of the amount of these liquid or vapor phases.

There is however growing evidence that, in addition to these electrical and thermal phenomena, mechanical processes are also important contributors to the final damage, which can be analyzed as surface damage different from bulk damage [10, 14-16]. The surface damage corresponds mainly to removal of paint and metal protection but may also extend to the first CFRP ply. The damaged surface is the one which experiences large energy transfer from the arc root. Whereas surface damage is located near the lightning impact zone, bulk damage can shift significantly sideward and include large delamination areas. Surface damage typically results from thermal effects induced by metal protection layer melting or vaporization and possibly first carbon ply degradation (tufting, burning). Bulk damages are typically mechanical damage like fiber-resin debonding, transverse cracking, fiber failures, delamination and are similar to those observed in the context of low velocity impacts [4, 11-13]. These similarities suggest that bulk damage is generated by fully mechanical processes and that a purely mechanical impact test could be designed, such that it would produce bulk damage equivalent to the ones resulting from lightning strikes. Such an equivalent mechanical test would have several advantages over the standard lightning tests. From a fundamental point of view, by disentangling bulk damage processes from the surface ones, it would provide a clearer picture of the processes inducing damage and of the ways to control them. From a practical point of view, it would provide a simpler test set-up producing more reproducible results.

Previous studies have investigated such analogy with mechanical impacts [1], privileging injected energy (delivered by electrical or kinetic sources) and induced projected surface damage as criteria to be sought for assessing equivalence. Such attempts face a main issue since most part of dissipated energy during a lightning strike does not participate in damaging the material. As an alternative, the proposed approach here when designing an equivalent impact will consider the only external measurements available during strikes: out of plane velocities of the rear face of samples [10, 14-16]. Impact tests are then considered equivalent to lightning strikes if they provide similar plate deflections and speed.

The present paper is organized as follows. In section 2, we present the lightning test set-up and the measured speeds and deflections. In section 3, we describe a method to design an impact test which provides deflections comparable with those obtained from strikes. In section 4, we perform numerical simulations to compute the deflections expected from impacts, and compare them with strike deflections.

2. Lightning tests

Lightning strike tests were conducted using a lightning generator which injects current according to SAE standards [17]. Different combinations of continuous and impulse components can be applied on the sample, according to the location of the material on the aircraft skin. The present study is focused on D waveform component which is, in our particular test set-up, an electrical current impulse reaching a maximum in the range 94-98 kA within nearly 20 μs, and with a total duration of the order of 100 μs.

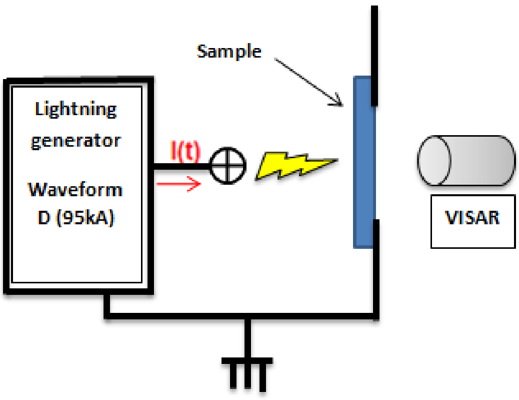


Figure 1: Set up for lightning strike test. Impulse in the form of an electric arc from a lightning generator hits the sample whose deflection is monitored by rear face visar and fast cameras.

The set-up is equipped with high speed cameras on the front side to monitor the damage dynamics and the electrical arc history and with a Velocity Interferometer System for Any Reflector (VISAR) at the rear side to measure deflections and speeds of the samples submitted to the strikes [fig 1]. This system covers a velocity range of a few cm/s to 3000 m/s with a precision higher than 1 %. In a few cases, stereoscopic techniques using two Photron SA5 fast cameras at a rate of 262500 frames-per-second (which yields a 128*128 pixel resolution) were implemented to measure deflection and speed of the 80*80 mm^2 central portion of the sample's rear face, represented by 16*16 facets each 5mm large.

The samples are 450x450 mm^2 squares made of eight CFRP1 or CFRP2 plies in a quasi-iso lay-up $[45°/0°/135°/90°]_S$. They are clamped on a circle ∅ 370 mm by twelve bolts on a metallic support. Four CFRP1 samples differ by their surface states: they can be covered with expanded copper foils of mass 195 g/m^2 (ECF195) or 73 g/m^2 (ECF73) or not (NoECF), they can be painted with a 200 µm thick paint layer (P200) or not painted (NoP). We thus consider four combinations for CFRP1 and for comparison one CFRP2 configuration as presented in Table I.

material	Sample #	surface state
CFRP1	1	NoECF-NoP
CFRP1	2	ECF195-NoP
CFRP1	3	ECF195-P200
CFRP1	4	ECF73-P200
CFRP2	5	ECF195-P200

Table I: Presentation of the studied cases

Results of the VISAR measurements are shown on fig. 2. Figure 2(a) and 2(b) show deflections and velocities at the center of the plate's rear face for the different cases. The samples 1 and 2 without paint on the surface exhibit both lower deflections and velocities than those with a layer of paint, shedding light on the detrimental effect of paint during the lightning strikes if low displacements and velocities are required at the rear face. These tests data also show the influence of the protection layer used. In fact for the same amount of paint, sample 4 (ECF73) reaches higher deflections than sample 3 (ECF195). This indicates that the metallic covering plays a benefic protection role because decreases the amount of energy dissipated at the surface thus lowering the remaining energy that is transmitted down to the rear face. It is concluded from fig 2 that rear face deflection and speed strongly depend on the surface state and can be used as representative parameters to characterize the sudden energy deposit on the surface, which results from the Joule effect associated to electrical current circulation in the sample as well as from heat transfer with the electrical arc located in the air gap between the generator electrode and sample.

For a lightning strike the energy delivered corresponds to the sum of the energy actually dissipated in the material, the one dissipated in the arc formation and the one returned to the ground. As the quantity to be determined is the energy dissipated in the material, two configurations arise from the previous analysis. In the case of samples with no surface paint the damaging energy seems to be the one actually dissipated in the material as expected. For our study the mechanical equivalent test is thus expected to give results similar to strike for the non-painted samples at short and large times. However in the case of painted samples, the surface state clearly influences the structural response of the sample. Regarding painted samples, similarity is expected only at short times as the surface state has been proved to be a contributor to the deflection of the plate.

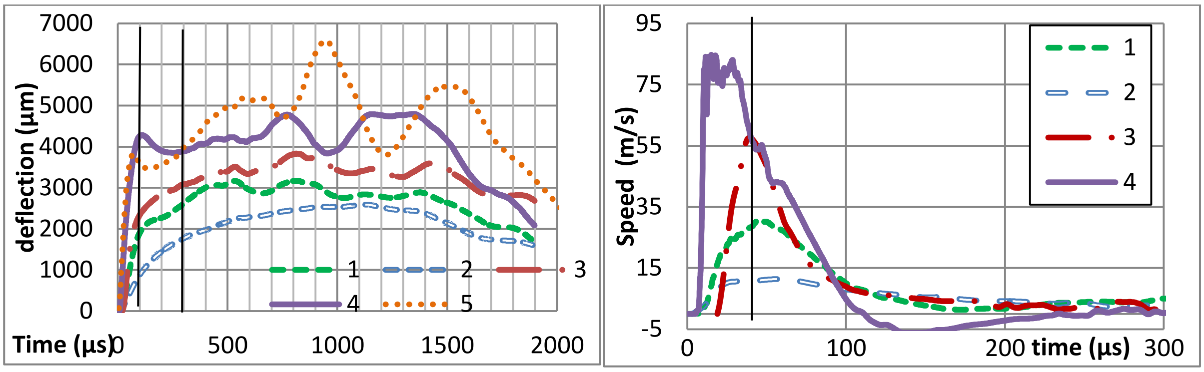


Fig. 2: (a) Deflection as a function of time of the central point at the rear side of the sample subjected to a D waveform lightning strike. (b) Velocities as a function of time for the first 4 samples.

3. Definition of equivalent impacts

The aim of the present analysis is to define impact test conditions which provide speed and deflection at the center of the rear face as close as possible to the ones measured in the lightning tests with no ECF and no paint. As a preliminary approach, it is assumed that impactors are spherical, made out of steel, do not deform, and hit the target normally. Thus, mechanical impacts are fully determined by radius r (thus mass) and velocity v of the projectile. The strategy is to find r and v by solving an inverse problem setting the equivalence of the energy dissipated between the energy deposit and the kinetic energy registered at the bottom face. To solve this inverse problem, we take advantage of the sudden character of the surface explosions to estimate the delivered strike impulse. As shown on fig. 2(b), the sample speed reaches its maximum, in the range 10-80 m/s, with a rise time ranging from a few µs to a few tens of µs (called "short times"). The speed decreases to small values within 100 to 150 µs, which corresponds to the duration of a lightning strike (called "strike time"), and is stabilized near zero at about 300 µs (called "large times"). On another hand, it is shown on fig 2 (a) that the deflections of the samples are dropping down after 1.4 ms and tend to reach zero at about 3 ms which is consistent with the natural vibration period T of these samples T=6 ms obtained from analytical computations. In the time range before T/2, the sample does not suffer from its boundary conditions and can be considered as infinite. For large times, we can therefore use the well-known analytical formulation of the deflection of an infinite plate subjected to a mechanical pressure.

3.1 Impulse calculation from measured deflections at large times

. Calculations are made at large times (about 300µs) which are long enough to enable considering that the pressure has been fully delivered, and short enough to emphasize that the plate is free of boundary.
The Green's function gives the deflection at time *t* and radius $r=(x^2+y^2)^{1/2}$ for a delta-function impulse applied at time *t=0* at the center *r=0* of an infinite plate ([18], p. 124):

$$G(r,t) = \frac{1}{4\pi\sqrt{\mu D}}\left(\frac{\pi}{2} - Y(t)Si\left(\frac{r^2}{4\sqrt{\frac{D}{\rho h}}t}\right)\right) \qquad (eq.1)$$

where µ is the surfacic mass (kg/m^2) of the sample, *D* (N.m) the bending stiffness. *Y(t)* is the step function at *t=0*, *Si* the sinus-integral function : $Si(z) = \int_0^z \frac{\sin(t)}{t} dt$. The Green's function is useful to obtain the deflection $d(x,y,t)$ at the point *(x,y)* and time *t* for any external applied pressure field *P(ξ,η,t)* with the convolution product:

$$d(x,y,t) = \int d\tau \iint d\xi d\eta G\left(\sqrt{(x-\xi)^2+(y-\eta)^2}, t-\tau\right) P(\xi,\eta,\tau) \qquad (eq.\,2)$$

At times large with respect to the impact duration, the deflection reaches a constant value d_∞ which can be obtained from insertion of an asymptotic form of eq. 1 into eq. 2:

$$d_\infty = \frac{I}{8\sqrt{\mu D}} \qquad (eq.\,3)$$

where I is the impulse resulting from the integration of the pressure field applied on the sample: $I = \int d\tau \iint d\xi d\eta\, P(\xi,\eta,\tau)$.

In practice, we proceed as follows: due to the particular lay-up selected, the samples can be considered as quasi-isotropic, the equivalent in-plane Young modulus and Poisson ratio are obtained from standard laminate theory (Exx=46.2 GPa and ν_{xy}=0.29 for CFRP1 and Exx=57.6 GPa and ν_{xy}=0.32 for CFRP2). The corresponding bending stiffness $Dxx = \frac{Exxh^3}{12(1-\nu xy^2)}$ are 33.6 N.m (e=2 mm) and 18.0 N.m (e=1.5 mm), surfacic masses are µ=3.1 kg/m^2 and 2.3 kg/m^2, for CFRP1 and CFRP2 respectively. The deflection at large time is extracted from fig. 2b and the corresponding impulse from eq. 3. With this procedure, the applied pressure P(ξ,η,τ) and integrated impulse I are surface state dependent, although no explicit model of the metallic and paint layer is performed. The impulse is then associated to the momentum *mv* of the impactor reaching the sample.

3.2 Impactor initial mass and speed evaluation

The impactor initial velocity is set to the maximum speed measured during the lightning strikes by the visars (reached at the so called short times), and shown on fig. 2(b). The impactor mass is then given by: $m=I/v_{max}$. Finally, the impactor radius is obtained from its mass using the steel density 7927 kg/m^3. The results of these steps are shown on table II.

Sample #	surface state	d_∞ (mm)	$I=mv$ (N.s)	v_{max} (m/s)	m (g)	r (mm)
1	NoECF-NoP	3	0.24	30	8	6.2
2	ECF195-NoP	2	0.20	11	18	8.1
3	ECF195-P200	3.4	0.28	58	5	5.3
4	ECF73-P200	4	0.35	80	4	4.9
5	ECF195-P200	4.5	0.24	120	2	3.9

Table II: Characteristics of the mechanical impact equivalent to the lightning strike.

4. Numerical simulation of the equivalent impacts

ABAQUS-explicit Finite Element software is used to model the study cases defined in Table II, accounting for lightning samples' size and boundary conditions. The impactor is modelled as an analytical rigid body which is not meshed and thus not taken into account in the computation as a material. It is assigned a mass and an initial velocity and positioned at the center of the plate. In preliminary stages, when designing an impact configuration equivalent to strikes, composite samples are modelled using shell elements (S4R), under the hypothesis of small deformation, a homogenized elastic orthotropic material, and a refined mesh from the boundaries toward the center of the plate. The analyses are led on two materials CFRP1 and CFRP2 with the previous stacking sequence. Lightning test deflections (dotted lines) and numerical modelling ones (plain lines) measured and computed at the rear face center of the samples are compared in fig 3 for the five cases studied here.

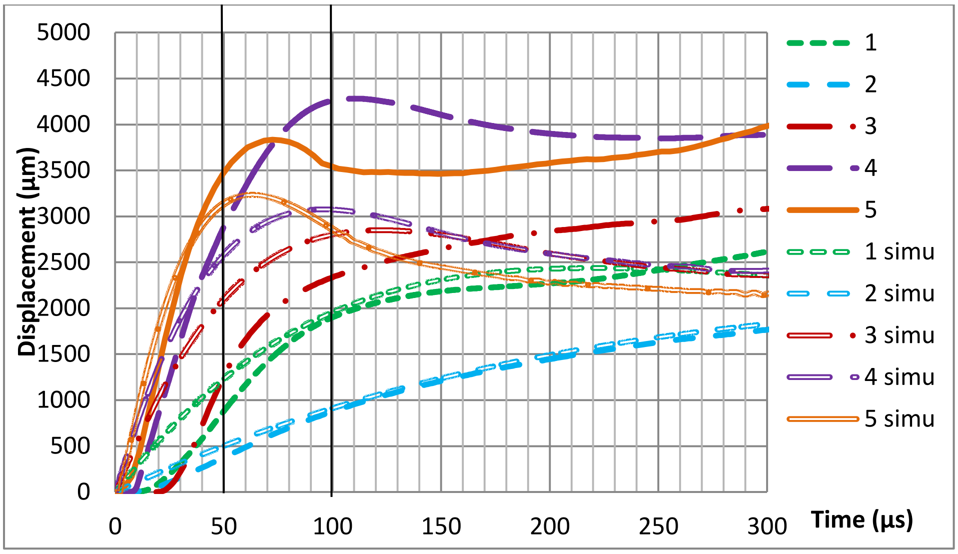
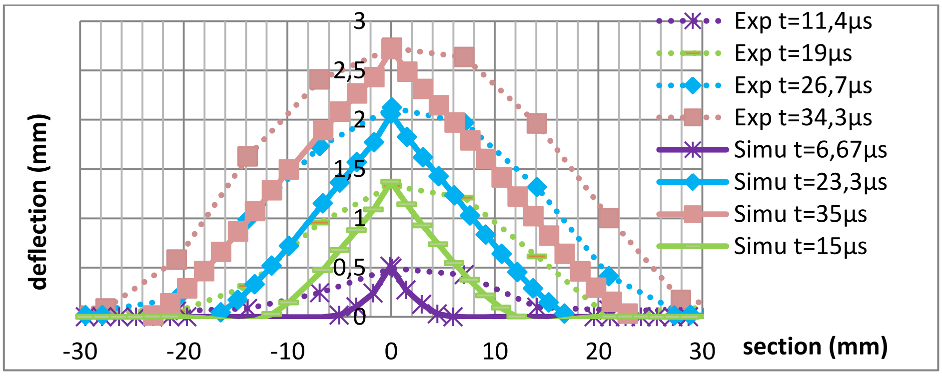


Fig. 3: Deflection vs time for the impact computations (full lines) and lightning strike tests (dotted lines).

The overall shape of the numerical deflections is as expected: a fast increase at short times controlled by the speed of the impactor, and a constant value at larger time such that the plate can be assumed infinite. The mechanical impact model shows good agreement with lightning test results for samples 1 and 2 which are unpainted panels, as predicted for both short (100-150µs) and larger times. In fact the constant deflection values d_∞ near 300 µs are well approximated by the model. In the case of the samples 3, 4 and 5, which are painted ones, the numerical model provides good results at short times as in the mechanical impact situation the projectile speed is transferred almost instantaneously to a small portion of the sample around the impact point. However the pure mechanical model fails at representing the large time deflections of these samples and the value of the constant deflection d_∞ is smaller in the impact models than in the strike measurements. This difference is concordant with the previous observation of the lightning results and confirms that in the case of painted samples the surface states influence the structural response of the impacted panels and that the numerical model is only fully representative in the case of unpainted samples.

Figure 4 shows profiles of the impacted sample along segments centered on the impact point. Measured profiles were obtained with stereoscopic techniques (see section 2) for CFRP1 and 2 impacted samples with different surfaces states. Computed ones were obtained for the corresponding impacts defined in section 3. The surface state appears to be a major parameter controlling the profile shape. In the absence of paint, the central portion of the sample is weakly distorted, the material recoils to the shock as a whole, which is an indication that the surface stress induced by the strike on the surface is rather diffused and has a large base.



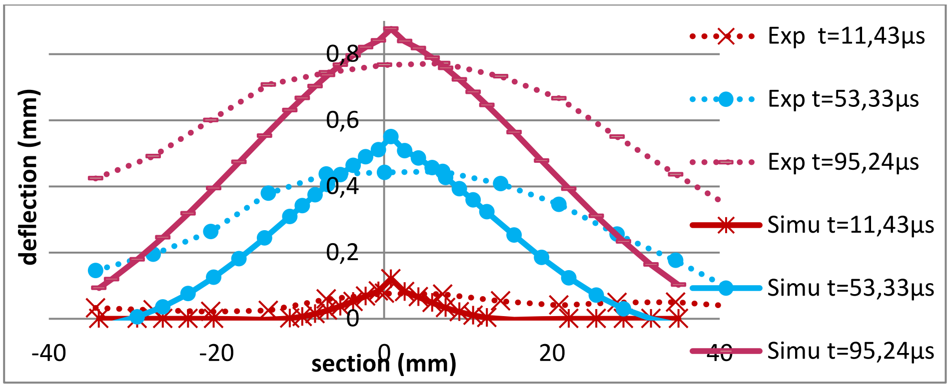


Fig. 4: Deflection of the central portion of the samples vs time. Full lines: impact simulations; dotted lines: lightning strike tests. Top: CFRP1, sample 2; bottom: CFRP2, sample 5.

By contrast, in presence of paint, there is some distortion of the sample, indicating a more concentrated surface stress. This should be related to a more confined surface explosion due to the strike in the experiment. The corresponding impact profiles also induce significant distortion of the sample. This indicates that the impact is expected to be more representative of the strike in absence of paint.

5. Conclusion

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 measurement of deflections and speed during lightning and mechanical tests. An equivalent impact using a simple analytical model has been designed and checked with numerical models. Several results arise from this study such as the representativeness of the impact which is better for unpainted samples but still correct at short times for painted panels. Next steps of the work will involve performing actual canon tests, comparing measured deflections in these impact tests with the predicted and the measured ones in lightning strike tests. From comparison of the obtained damage in both experimental conditions using C-scans or micro-cuts, it will be stated if preliminary hypothesis (spherical rigid impactor) are satisfactory or should be revised for improved representativeness of time and space distributions of incident kinetic energy; once designed, the equivalent impact tests will produce experimental data useful for both industrial applications (design of aircraft composite structures) and insights in lightning strike induced damage.

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