# INVESTIGATION OF IMPACT INDUCED DAMAGE ON COMPOSITE PLATES BY ANALYSING THE ACOUSTIC RADIATION

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**Abstract**
The objective of this work is the analysis of the acoustic radiation caused by an impact on a composite structure and its use for non-contact detection and evaluation of the induced damage. This paper presents the design and the assessment of an appropriate experimental research bench. Tests are performed on carbon-epoxy laminates with several stacking sequences by mean of an instrumented pendulum impactor with energies up to 18 J. During impact, the radiated sounds are recorded by a microphone and analyzed in the audible frequency range (20 Hz – 20000 Hz). After impact, the laminates are inspected by means of an ultrasonic C-scan to quantify the damaged area extension. The existence and severity of damage is strongly linked to the complexity of the acoustic signals, described by an entropy based value.

## 1. Introduction

Carbon fiber reinforced polymer composites (CFRP) are widely used in advanced structural applications, including aircraft, automobile and marine structures. While composites have an advantage of high strength-to-weight and stiffness-to-weight ratios compared to metals, one limitation of many composite laminates is their low resistance to impact. Indeed, after a low-energy impact (usually under 40 J), visual inspection might not be enough to assess the structure integrity as severe internal damage can occur. Delamination propagation is one of the most common degradation mechanisms of CFRP laminates. The occurrence of delamination will lead not only to a loss of stiffness, but also to a significant decrease in the strength and expected service-life. Nondestructive techniques such as ultrasonic scanning are used to evaluate damage levels. However, parts have often to be removed from their original structure to be controlled [1]. On the other hand, local surface sensors such as accelerometers or acoustic emission sensors can collect real-time vibration data which can be used to monitor damage. However, these techniques require a contact with the monitored structure [2].

In some others domains, interesting non-contact methods have been developed to discriminate structure states. With principal component analysis, Pearson analyzed the acoustic radiation of falling pistachios to sort the closed-kernels from the open ones [3]. In the case of composite structures, Atobe and al. proposed a non-contact method for damage detection on sandwich panels based on force identification [4]. The impact force history is determined by analyzing the acoustic responses collected by a microphone antenna and using previously computed experimental transfer functions. Existence, location and severity of impact damage are accurately estimated.

In this study we investigate the use of the radiated sound field produced during impacts on composite materials for damage assessment. In order to scrutinize links between low-energy impact damage and acoustic indicators, an experimental bench has been designed and fabricated. Carbon epoxy laminates have been tested under different impact energies and acoustic signals have been compared to ultrasonic scans. Entropy-based damage detection and evaluation threshold is proposed for four stacking sequences.

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## 2. Materials and methods

### 2.1. Materials

The specimens are made from carbon/epoxy prepreg (STRUCTIL CTE115). The prepreg characteristics are shown in Table 1. The laminates were manufactured by hand lay-up according to four 24-plies stacking sequences detailed in Table 2. These stacking sequences were chosen so as to obtain different sensitivities to delamination. P1, P2 and P3 stacking sequences only contain 0° and 90° plies. Thicknesses differences are due to nesting and fiber rearrangement occurring between consecutive identical plies. Because of the plies anisotropy and of the different fiber orientations, bending stiffnesses differences occur at dissimilar plies interfaces. Delamination extension is greater as the bending stiffnesses mismatches are greater. Thus, as the number of consecutive identical plies in the stacking sequence increases, the delamination damage due to impact is expected to increase [5]. The last sequence is denominated "Fully Isotropic Laminate" (FIL) and provides specimens with quasi-isotropic quasi-homogeneous global properties [6]. The 400x400 mm$^2$ plates are cured in a hot press, and cut to provide four 200 x 200 mm$^2$ specimens for impact testing.

**Table 1.** CTE115 Material properties

| | | | |
|---|---|---|---|
| **Fiber** | TR50S | $\mathbf{E_{11}}$ | 118 GPa |
| **Fiber Weight** | 150 ± 7 g/m² | $\mathbf{E_{22}}$ | 6.8 GPa |
| **Resin Content** | 38 ± 2 % | $\mathbf{G_{12}}$ | 3.9 GPa |
| **Resin Type** | R367-2 | $\boldsymbol{\nu_{12}}$ | 0.37 |

**Table 2.** Stacking sequences

| Name | Stacking sequence | Thickness (mm) | Density (kg/m$^3$) |
|---|---|---|---|
| **P1** | $[0/90]_{6S}$ | 3.56 | 1500 |
| **P2** | $[0_2/90_2]_{3S}$ | 3.22 | |
| **P3** | $[0_3/90_3]_{2S}$ | 3.04 | |
| **FIL** | [0/45/90/-45/90/-45/45/<br>-45/0/90/0/45/0/45/-45/<br>45/90/0/90/-45/90/-45/0/45] | 3.52 | |

### 2.2. Design of the experimental bench

The experimental bench is presented on Figure 1. The main part is a heavy steel frame where the impacted specimen is clamped. Its geometry and mass properties are the result of a design led by two main criteria: decreasing the natural frequencies and allowing the best propagation of radiated sound in the measurement area. When in place, the free area of the specimen is reduced to 150 x 150 mm².

The impactor is not linked to the steel frame, in order to prevent transmission of unwanted vibrations between these two parts. It consists of a pendulum mounted on ball bearings. Its reduced mass at the center of percussion is 7.2 kg. The impactor nose shape is hemispherical with a 20 mm diameter. The impact force is measured with a force sensor (DYTRAN 1053V6) mounted behind the impactor nose. An inclinometer allows to precisely set the pendulum angle and thereby the impact energy by varying the drop height of the pendulum.

The radiated sounds are collected by a microphone antenna. It is composed of 5x5 microphones (type B&K 4935 – 30 mV/Pa) equidistant of 30 mm. The antenna is set on a plane 80 mm behind the tested

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plate and its center coincides with the plate center. This position ensures measurements in a plane where temporal and frequency content of sound radiation are sufficient and where microphones overloads are prevented. In the present study, focus is set on the central microphone signals but future work will use the antenna as a holographic network.

Force and microphones signals are recorded by a B&K spectrum analyzer. In time domain, sampling of the signal is fixed at 32.7 kHz. For the spectral analysis, signal processing of radiated acoustic signals is adjusted to ensure 6400 spectral lines on a bandwidth of 20 Hz to 16.4 kHz.

As it is very important to conduct the tests in a controlled acoustic environment, the experimental setup is housed in a hemi-anechoic room (6.40 m x 6.58 m x 2.74 m) that ensures a very low acoustic reverberation on the walls and the ceiling. This room has a cutoff frequency of 125 Hz, a reverberation time of 0.038 s and a background noise level of 17.2 dB. The temperature in the room during the tests is maintained between 18 and 19 °C to avoid any variation in sound velocity.

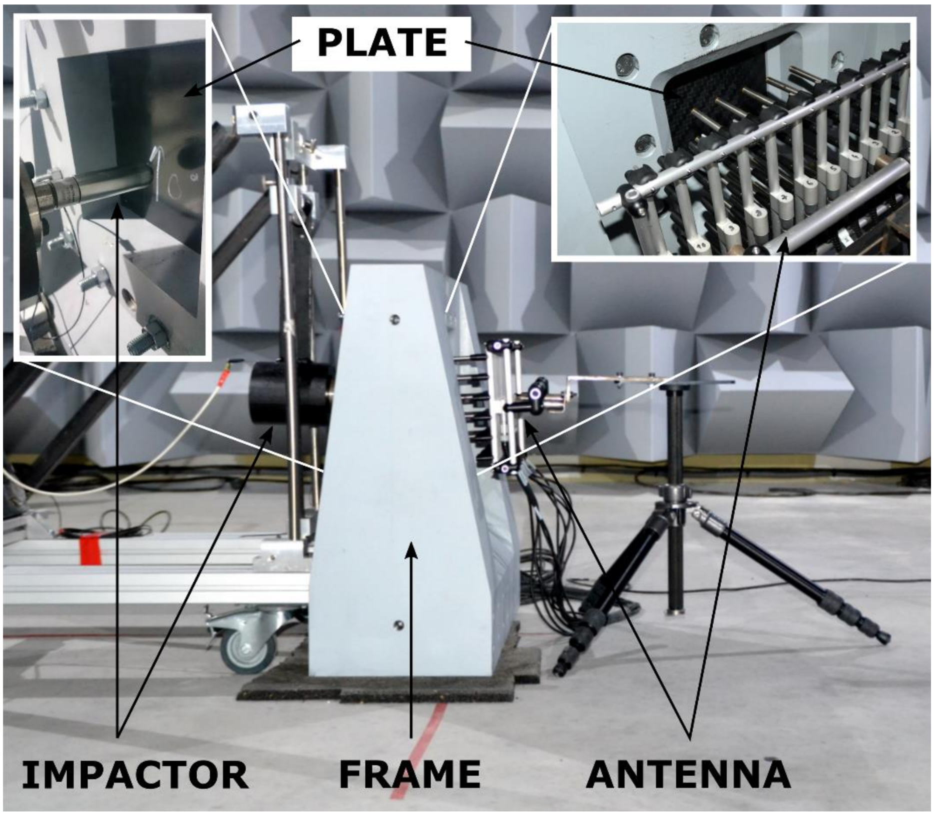


**Figure 1.** Experimental setup

## 2.3. Test procedure

Selected impacts energies are 2, 5, 10 and 18 J. Two impact tests are carried out for each energy level and each stacking sequence. The plates are clamped on their edges by mean of a square flange tightened with twelve bolts torqued to 50 N·m.

Each plate is impacted at its center. No rebound of the impactor is allowed. The data acquisition (force and acoustic pressure) is triggered by the force sensor signal. The signal are recorded during 500 ms. After impact, the specimen is removed from the frame and its damage level assessed by ultrasonic scanning. The specimens are scanned in an immersion tank (Physical Acoustics Ultrapac , IPRAD-210

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card) with a 15 MHz pulser-receiver focused transducer. Time of flight and amplitude C-scans are acquired. The damage severity is evaluated by measuring the total projected area of all damaged plies or plies interfaces.

### 2.4. Signal analysis

Given that force impact signal complexity increases as damage occurs during contact, Shannon's entropy can be a good indicator of the contained information [7]. This study aims at verifying that the consecutive acoustic radiation also contains enough discriminant information to detect and evaluate damage. For a random variable $X$ which is a function of the outcomes experiments, Shannon's entropy $H$ can be written as in Eq. 1:

$$H(X) = -\sum_{i=1}^{n} P(x_i)log_2(P(x_i)) \quad (1)$$

where $P(x_i) = P(X = x_i)$ is the probability measure of given variable $X$ taking the possible values $\{x_1, \ldots, x_n\}$. In probability theory and statistics, the cumulative distribution function $F(x_i)$ of a random variable $X$ is the function defined by Eq. 2:

$$F(x_i) = (X \leq x_i) \quad (2)$$

where the set $[X \leq x_i]$ defines an event of outcomes.

To build this cumulative distribution function $F$, it is necessary to define $N$ classes of amplitudes of the analyzed signal. This is equivalent to cutting the signal in magnitude. Once these classes determined amplitudes, the distribution function is constructed by counting the number of points in the time series contained in each classes. This count allows then to calculate the probability of occurrence of each classes of magnitude in the analyzed signal.

## 3. Results and observations

An overview of typical signals recorded during the impact by the force sensor and the central microphone is shown on Figure 2. For the acoustic signal, two time periods are distinguishable:

- Area A: the initial transient during the contact between the impactor and the plate (the force signal is non-zero);
- Area B: the free plate resonance occurring after impact.

Area A is the initial transient zone where damage caused by the impact appears. Figure 3 shows the trends in the first time period (area A) for all collected signals. In each case both force and acoustic signals are shown.

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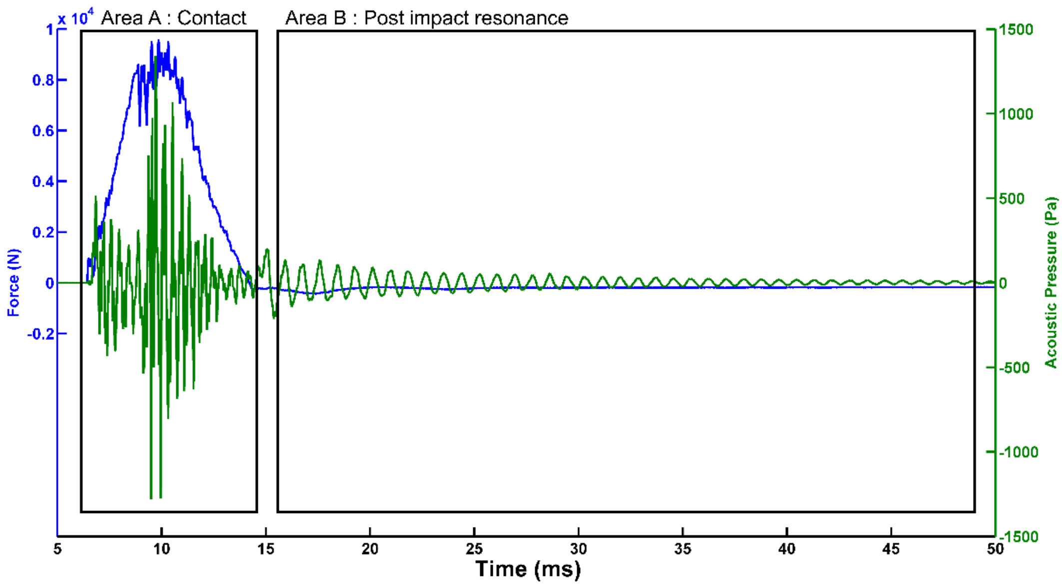


**Figure 2.** Force and acoustic signal for an 18 J impact test on FIL stacking sequence. Blue: force signal; green: acoustic signal.

In this study, we focus the analysis on the initial pressure peak as it seems to be influenced by the real time damage growth. All the initial transients from all tested energies and stacking sequences are isolated and shown in Figure 3. Figure 4 shows examples of damaged areas for four of the most damaging impacts. Average damage areas evolution vs impact energy is shown in Figure 5.

Synchronized disruptions occur in the acoustic and force signals. These disruptions in the force signal are signs of a created damage [4]. They are greater for highest energies, where ultrasonic scans reveal greater damage.

The P1 and FIL stacking sequences show very similar damage, lower than P2 and P3 for all tested energies. As expected, delamination extension is greater for P3 stacking sequence which has the highest bending stiffnesses mismatches. Damage areas larger than about 300 mm² (average damage area of the P2 specimens impacted at 10 J) seem to be linked to very high disruptions in the initial force peaks.

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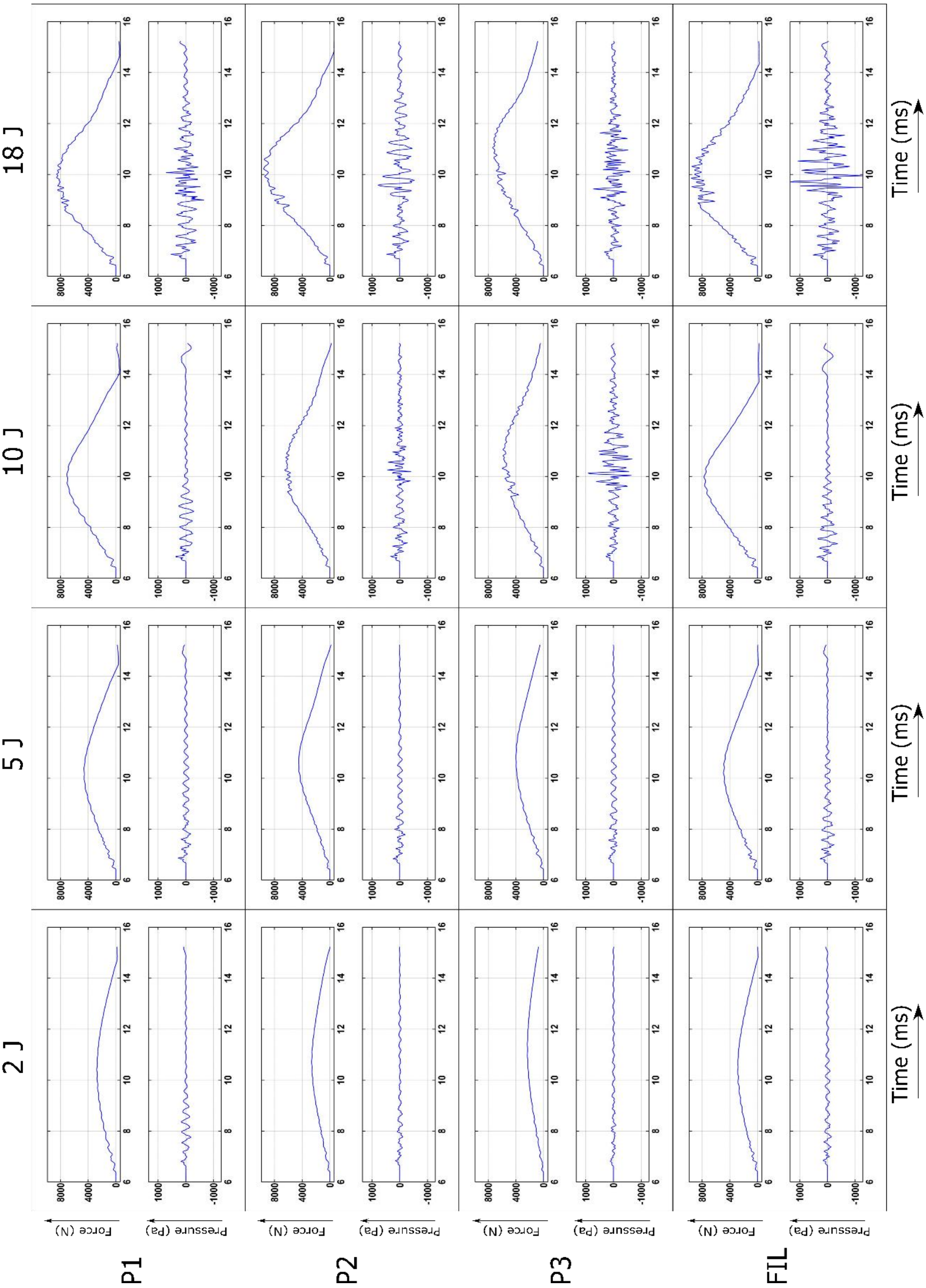


**Figure 3.** Trends of force and initial acoustic transients during contact (area A)

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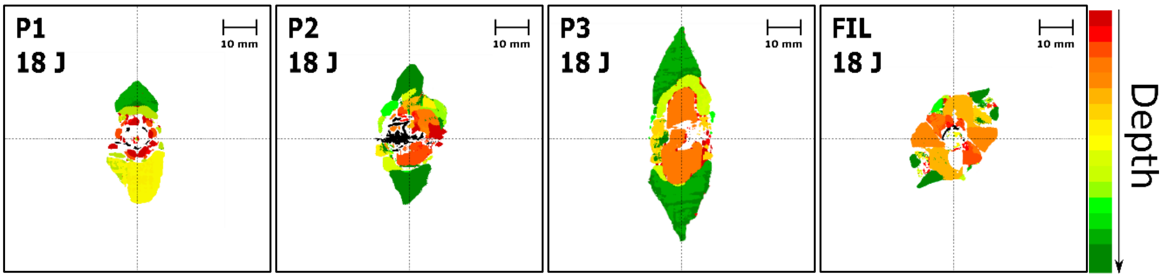


**Figure 4.** Post mortem ultrasonic scans: damaged areas for 18 J impacts on each stacking sequence.

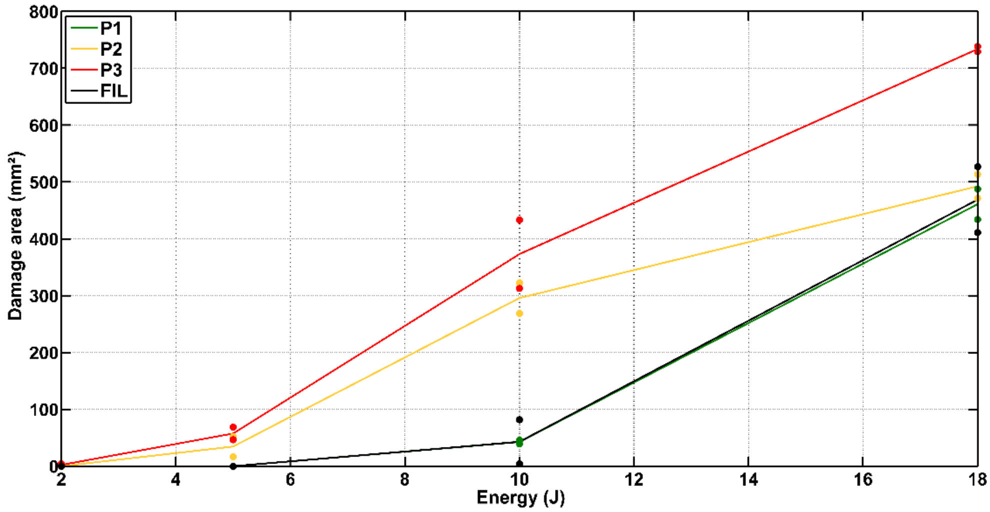


**Figure 5.** Average damage areas for all stacking sequences

Likewise, maximum sound pressures and sound complexities increase with the impact energy. With the objective of classifying damage using initial pressure peaks entropies (Eq. 1), the number of classes *N* used to calculate the probabilities must be defined. Classes range goes from the minimum to the maximum sound pressures over all the tests. Classes number *N* has been chosen so it maximizes the standard deviation between all computed entropies. For our results set, this method leads to a number of classes *N* of 103. Average damage areas as a function of the average computed entropies are shown in Figure 6. The amount of information contained in the initial pressure peaks globally increases as impact energy (and damage) increases. Results cluster in areas depending on the impact energies. For a given energy, highest damage areas do not necessary match with the highest entropies. Some significant damage can be found on the specimens whose computed entropies are above 2.4 (for 10 J and 18 J energy levels). This global threshold can be used to detect damage on these stacking sequences without the need for post-mortem ultrasonic scans.

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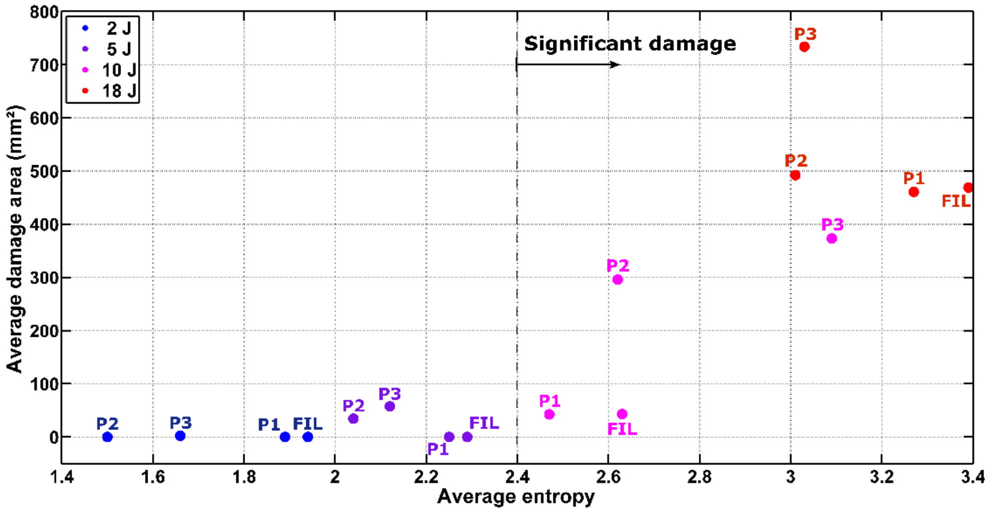


**Figure 6.** Average damage areas vs initial transients average entropies ($N$ = 103)

## 4. Conclusion

In this study, the design of an experimental impact bench has been presented. It allows the recording of radiated sounds from composites plates during impact. The damage extension has been measured by post mortem ultrasonic C-scans. The sound signal complexity has been estimated using Shannon entropy and compared between different stacking sequences. It is concluded that the evolution of damage with the impact energy is linked to the evolution of the transient radiated sound complexity. By putting the emphasis on the transient periods of the radiated sounds, an entropy-based empiric threshold has been defined to detect significant damage existence without post-mortem control. Further studies will use nonlinear time series tools in order to analyze inner recurrence patterns in the radiated sounds. Acoustic emission monitoring during impact will also be added to investigate the damage chronology.

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