In-Situ Characterization of Laser Shock Dismantling Process Using Ultrasonic Guided Waves Sensed by Bonded Piezoelectric Transducers

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ABSTRACT

Laser shock dismantling allows to selectively separate the various plies of a composite material in order to sort aged or damaged ones from virgin or healthier ones and to build new composite materials from these recycled plies. However, following in situ the laser shock process is in practice hard to achieve due to the very short laser pulse duration (around 10 ns) and to the large associated energy density (around 10 GW/cm²). Piezoelectric elements are low cost transducers that can be easily bonded to composite structures and that are able to sense ultrasonic guided waves propagating in such structures in the frequency range below 500 kHz. Consequently, if a composite coupon enduring laser shock dismantling is equipped with piezoelectric elements, those sensors should potentially be able to collect dynamical signals directly following laser shock. In order to validate this approach, an experimental campaign has been carried out where a composite coupon has been impacted by laser shocks of increasing intensity in order to achieve delamination damages. Dynamical signals resulting from those consecutive laser shocks have been measured by the piezoelectric transducers. The signal collected by the piezoelectric transducers during a laser shock are shown to be exploitable despite the short laser shock duration in comparison with sensor bandwidth and can be reliably used to locate laser shock position and to estimate its intensity. Such an in-situ process monitoring approach could thus allow to ease the deployment and practical use of laser shock technology for composite materials dismantling and recycling purposes.

KEYWORDS: *Laser shock dismantling, Ultrasonic waves, In situ process monitoring*

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INTRODUCTION

Composite materials are increasingly playing a key role in various sectors of industry, which poses challenges for the recycling of these materials. For example, in the aeronautics sector, around 6600 aircraft will soon reach their end-of-life [1]. Various methods are already applied to recycle or reuse composite materials, such as chemical, thermal, and mechanical recycling, in order to meet these challenges. However, these methods sometimes struggle to meet quality standards, are slow, and generate environmentally harmful dust [2]. This is where laser shock technology comes into play, as it dismantles composite materials more efficiently without damaging them. This is the background to the RECREATE research project (https://recreate-project.eu/), which aims to develop an innovative technology for the selective dismantling of laminated composites, layer by layer, using laser shocks.

However, following in situ the laser shock process is in practice hard to achieve due to the very short laser pulse duration (around 10 ns) and to the large associated energy density (around 10 GW/cm²) [3]. Laser shock dismantling is thus more or less currently applied blindly without a convenient and reliable mean to follow it in-situ. On the other side, piezoelectric elements are low cost transducers that can be easily bonded to composite structures and that are able to sense ultrasonic guided waves propagating in such structures in the frequency range below 500 kHz [4]. Consequently, if a composite coupon enduring laser shock dismantling is equipped with piezoelectric elements, those sensors should potentially be able to collect dynamical signals directly following laser shock and if those signals are exploitable they can be used for process monitoring purposes. The main issue to overcome here is that the laser pulse is very short (10 ns) in comparison with the piezoelectric elements response time (2µs for a bandwidth of 500 kHz).

In order to validate this approach, an experimental campaign has been carried out where a composite coupon equipped with four piezoelectric transducers have been impacted by laser shocks of increasing intensity in order to achieve delamination damages of various size at a given position. Dynamical signals resulting from those laser shocks have been simultaneously measured by four piezoelectric elements. The signals collected by the piezoelectric elements during a laser shock are shown to be exploitable and can be reliably used to locate laser shock position and to estimate its intensity. Such an in-situ process monitoring approach thus allow to ease the deployment and practical use of laser shock for composite materials dismantling and recycling purposes.

LASER SHOCK PRINCIPLE

Laser Shock Wave Technique (LSWT) involves using a high-power laser, with beam intensities ranging from one to several GW/cm² to irradiate a target [3]. The laser induces the creation of plasma on the surface of the sample, resulting in the formation of shock waves, inducing maximum stresses of the order of MPa to GPa. In order to increase these pressure levels, a confinement system is set up to slow down plasma expansion, which results in a pressure 5 to 10 times higher and a shock duration 2 to 3 times longer than without confinement. To avoid thermal effects caused by the plasma, a sacrificial layer, usually an aluminum adhesive, can be interposed between the sample and the confinement, as shown in Figure 1. Initially, due to the presence of a free surface on the back of the sample, the shock wave is reflected as a relaxation wave. Then, the incident relaxation wave, created by the material's return to its initial state at the end of the laser pulse, travels from the front to the back. The intersection of these two stressrelief waves within the material can create high localized tensile stresses. When these stresses are high enough, they can cause delamination at the point of maximum stress.

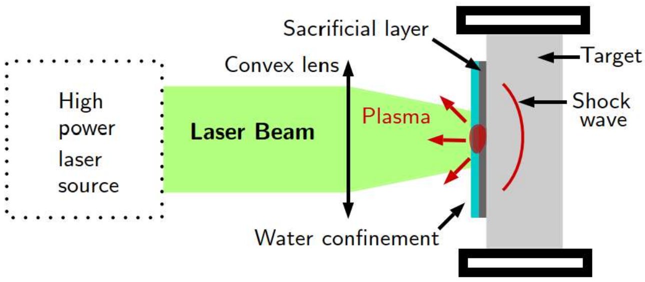

Figure 1: Laser shock principle (from [3])

In order to selectively separate the different layers of the composite, it could be achieved by directing the beam onto the material from both sides, thus obtaining a symmetrical laser shock, as shown schematically in Figure 2. By adjusting the delay between the two lasers, it then becomes possible to determine the location of the highest tensile stresses and position the delamination on the layer to be dismantled (denoted as D-SHM in Figure 2). If the maximum tensile stress is high enough, delamination occurs. The time delay is the parameter to set if we wish to offset the areas where we create damage. Without a time delay, delamination occurs in the middle of the sample [3].

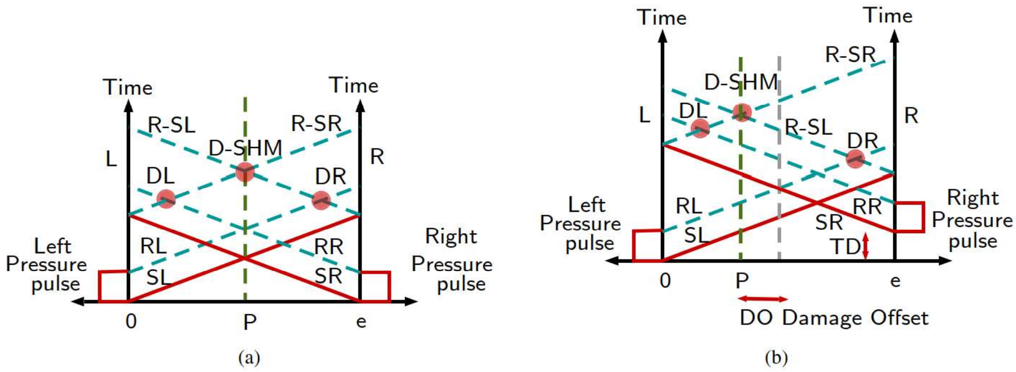

Figure 2: Spatiotemporal diagram illustrating symmetric Laser shock without time delay between laser pulses (a) and with a delay allowing to control damage depth (b) [3]

EXPERIMENTAL SETUP

Figure 3: Composite coupon sample equipped with four PZT transducers. The red cross denotes the position at which the laser shock has been achieved.

The composite material used consists of 2D woven carbon fibers and epoxy resin, with a total thickness of 2.1 mm and a size of 150 mm by 40 mm (see Figure 3). The composite consists of six plies, each ply 350 µm thick, with layers of carbon fibers oriented in 0°/90°. The epoxy resin used is renowned for its outstanding performance in terms of environmental resistance and mechanical behavior in hot and humid conditions, making a preferred choice in the aerospace industry for primary aircraft structures and helicopter blades. Small PZT transducers were used with a diameter of 15 mm and a capacitance of 8 nF. They are designed for use in a temperature range from -10°C to 70°C. We use a National Instruments module (USB-6366) to manage trigger signals and acquire signals with a CEDRAT Technologies amplifier having a gain of 100 [5, 6, 7]. The laser used is a THALES Gaia HP (Nd:Yag laser), with a pulse duration of 7 ns and a wavelength of 532 nm. The laser operates in symmetrical mode having two beams with an energy of 7 Joules each. To obtain an exact spot diameter of 4 mm, the distance between the lens and the focal point was set at 18 cm. The energy and parameters of the applied laser were all controlled by Thales software. An overview of the experimental setup is provided in Figure 4.

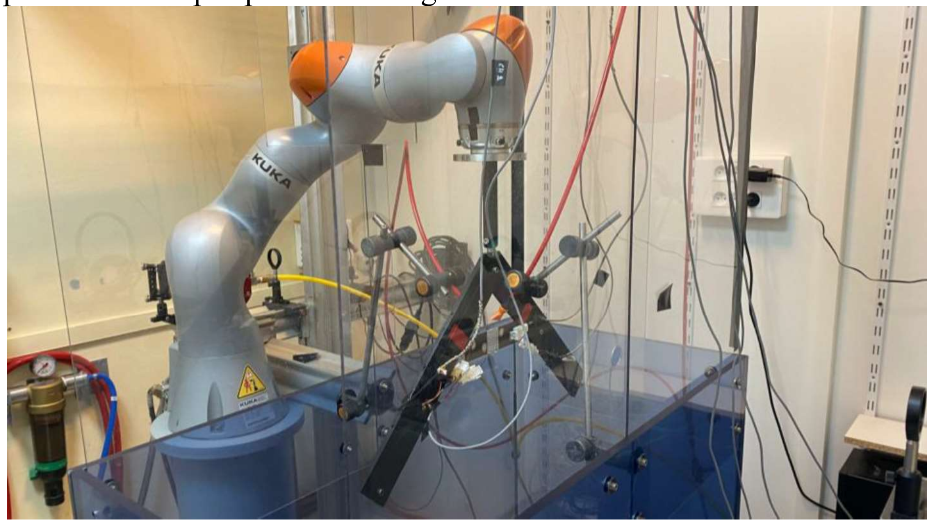

Figure 4: Overview of the experimental setup

We performed 10 consecutive shots by increasing the laser power at the same location in sample (see Figure 3). Table 1 shows the power density used for each shot. The threshold for the creation of delamination is the sixth shot. It was determined by ultrasonic A-scan tests, carried out before and after each shot, gradually increasing the laser power density. The ultrasonic data are acquired during each shot with a sampling frequency of 2 MHz. Delamination damage is created in the middle of the plate thickness using a symmetrical laser shot without delay.

Shot	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Power density (GW/cm^2)	0.39	0.83	1.43	1.79	2.16	2.69	3.03	3.73	4.05	5.01

Table 1: Power density associated with each shot

RESULTS ANALYSIS

COLLECTED SIGNALS EXPLOITABILITY

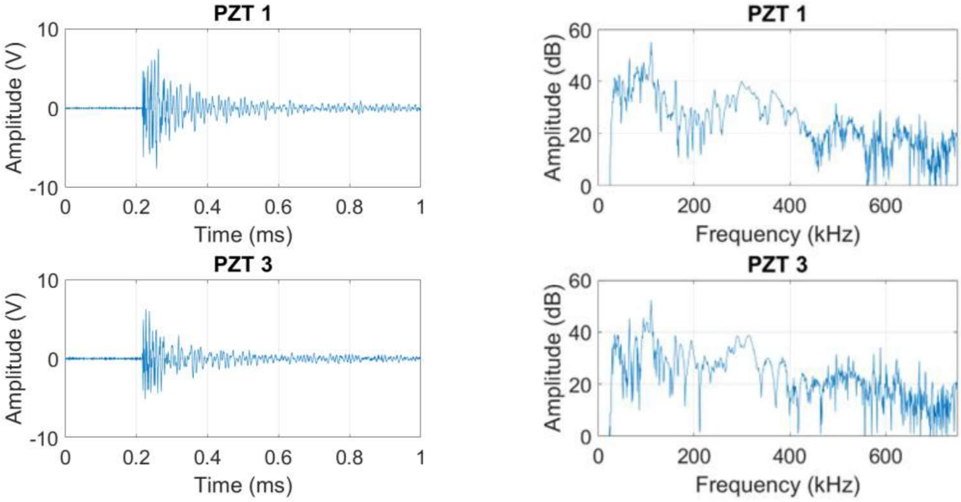

Figure 5: Experimental signals measured by the piezoelectric transducers 1 and 3 after the first laser shot: time domain (left) and (frequency domain (right)

As a first question, we can wonder whether the bonded piezoelectric transducers are able or not to collect any dynamical signals following the very short (10 ns) but energetic (several GW/cm²) laser shock that is much shorter that the piezoelectric elements response time (typically 2 µs if a bandwidth of 500 kHz is considered). The voltage signals measured for piezoelectric transducers 1 and 3 for the first and thus less energetic laser shock are plotted on Figure 5 after amplification by a gain of 100. From this figure, it can be seen that signals that are in the range of several Volts are measured, indicating that despite an apparent mismatch between the laser temporal scale (10 ns) and the piezoelectric transducers response time (2 µs), a reliable and exploitable dynamical information coming from the laser pulse can still be caught by the piezoelectric transducers and effectively measured. This response probably comes from the response of the structure (which is here the composite coupon) after it has been impacted by the laser pulse. By analyzing the signals in the frequency domain, it can be observed that energy below 400 kHz is present within the measured signals.

CORRELATION BETWEEN SIGNALS AND LASER INTENSITY

Then, the question arise whether or not the collected signals can be exploited in order to monitor the laser shock process by itself. As a first point in that direction, the energy and maximum amplitude associated with the signals measured by the four piezoelectric transducers have been computed for the varying laser intensity levels available (see Table 1). The results are shown in Figure 6. This figure clearly shows that a correlation exists between the energy or the maximum amplitude and the laser shock intensity. This thus potentially allows to estimate the laser shock intensity in situ from the collected signals. However, a dedicated calibration procedure should be a priori designed to achieve that goal. Furthermore, a kind of plateau can be observed for intensities larger than $\simeq$ 3 GW/cm². This value corresponds to the threshold value above which the composite material is being damaged. It thus seems plausible that laser shock energy is mainly being dissipated by the damage after the threshold is met, thus explaining the observed plateau.

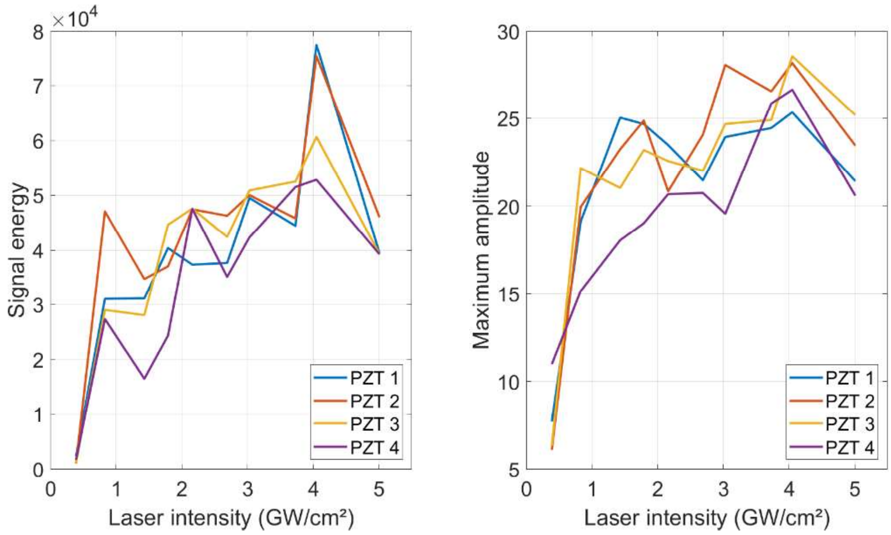

Figure 6: Evolution of the energy and maximum amplitude of the signals collected by the piezoelectric transducers as a function of the laser intensity.

CORRELATION BETWEEN SIGNALS AND LASER INTENSITY

Finally, as four piezoelectric transducers are available on the tested experimental coupon, it is also possible to try to locate the laser shock position using temporal information. In order to achieve this goal, standard triangulation methods (like the ones based on the time of arrival) can be used [8, 9]. These methods just require the measured signals to be available with a sufficient temporal resolution, and the geometrical positions of the piezoelectric transducers and the group velocity to be known. Here, given the composite plate material properties, the group velocity of the faster mode, the S0 one, can be estimated as 7050 m/s using the transfer matrix method for example [10, 11]. The piezoelectric transducers geometrical positions can furthermore be in situ measured. Using those information and by upsampling the measured signals by a factor 10, it is then possible to triangulate the origin of the impact events corresponding to the 10 laser shocks. The localization maps corresponding to those triangulations for the first 6 laser shocks are plotted on Figure 7. The maps provide a localization probability: the higher the probability the yellower the color is. From this figure, it can be seen that the impact events corresponding to the various laser shots are very correctly localized on the tested coupon sample. The resolution is far better horizontally than vertically due to the piezoelectric transducers positioning that is larger than higher. Alternate impact localization methods can also be investigated but the idea here is just to provide a proof of concept of the proposed approach.

CONCLUSION

Laser shock dismantling allows to selectively separate the various plies of a composite material in order to sort aged or damaged ones from virgin or healthier ones and to build new composite materials from these recycled plies. However, following in situ the laser shock process is in practice hard to achieve due to the very short laser pulse duration (around 10 ns) and to the large associated energy density (around 10 GW/cm²). Piezoelectric elements are low cost transducers that can be easily bonded to composite structures and that are able to sense and actuate ultrasonic guided waves propagating in such structures in the frequency range below 500 kHz (corresponding to a time response of roughly 2 μs). Consequently, if a composite coupon enduring laser shock dismantling is equipped with piezoelectric elements, those sensors should be able to collect dynamical signals directly following laser shock or the resulting structural response. In order to validate this approach, an experimental campaign has been carried out where a composite coupon have been impacted by laser shocks of increasing intensity at a given position in order to achieve delamination damages. Dynamical signals resulting from those laser shocks have been measured by the piezoelectric elements. It appears that the signal collected by the piezoelectric elements during a laser shock are exploitable despite the short laser shock duration and can be reliably used to locate laser shock position and to estimate its intensity. Such an in-situ process monitoring approach could thus allow to ease the deployment and practical use of laser shock technology for composite materials dismantling and recycling purposes.

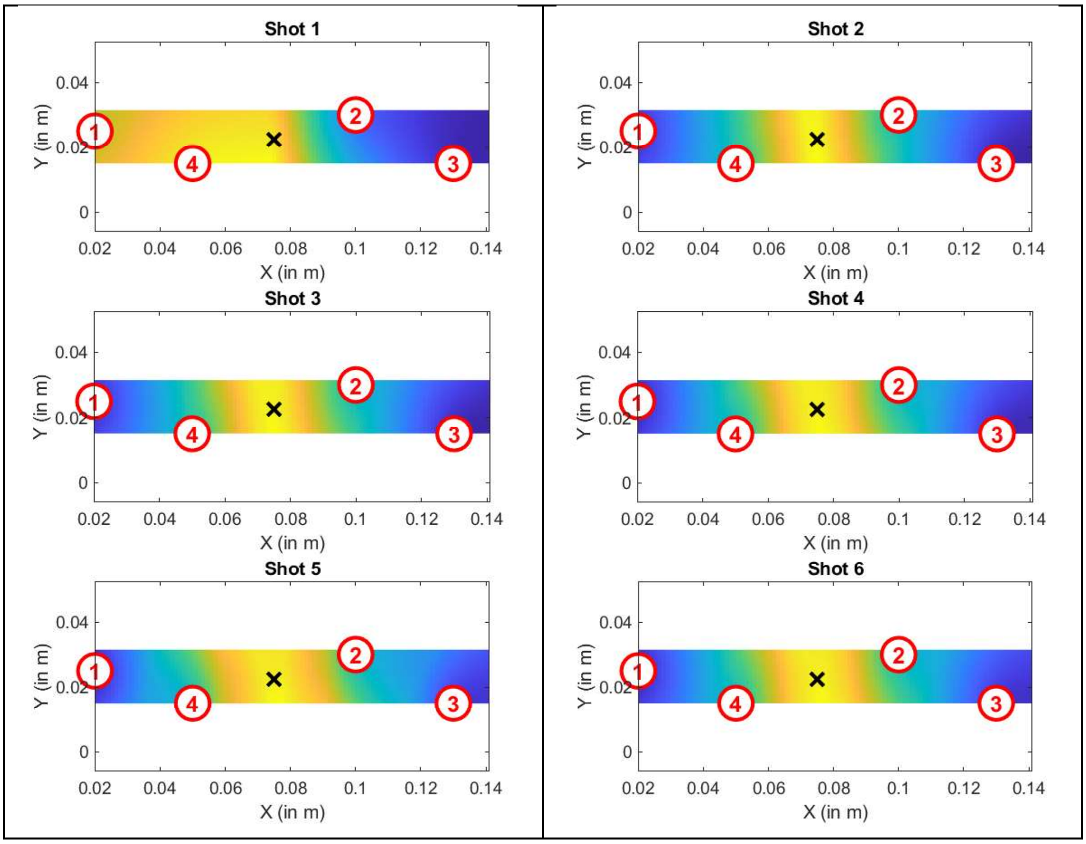

Figure 7: Localization by triangulation of 6 consecutive laser shocks. The maps provide a localization probability: the higher the probability the yellower the color is.

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REFERENCES

[1] X. Zhao, W. J. C. Verhagen et R. Curran, «Disposal and recycle economic assessment for aircraft and engine end of life solution evaluation,» *Applied Sciences,* vol. 10, p. 522, 2020.

[2] P. Kormpos, K. Tserpes et G. Floros, «Towards simulation of disassembly of bonded composite parts using the laser shock technique,» chez *IOP Conference Series: Materials Science and Engineering*, 2022.

[3] M. Ghrib, L. Berthe, N. Mechbal, M. Rébillat, M. Guskov, R. Ecault et N. Bedreddine, «Generation of controlled delaminations in composites using symmetrical laser shock configuration,» *Composite Structures,* vol. 171, p. 286–297, 2017.

[4] M. Mitra et S. Gopalakrishnan, «Guided wave based structural health monitoring: A review,» *Smart Materials and Structures,* vol. 25, p. 053001, 2016.

[5] G. Jaussaud, J. Rebufa, M. Fournier, M. Logeais, N. Bencheikh, M. Rébillat et M. Guskov, «Improving Lamb Wave detection for SHM using a dedicated LWDS electronics,» chez *11th Symposium on NDT in Aerospace*, 2019.

[6] M. Rebillat, M. Fournier, M. Thomachot et J. Rebufa, «Conception d'un système de SHM fonctionnant en modes actif et passif,» chez *16ème Congrès Français d'Acoustique, CFA2022*, Marseille, 2022.

[7] J. Rebufa, G. Jaussaud, M. Fournier, M. Logeais, N. Bencheikh, F. Claeyssen, M. Rébillat et M. Guskov, «Improving efficiency and robustness of structural health monitoring techniques based on lamb wave detection,» 2019.

[8] C. Fendzi, M. Rebillat, N. Mechbal, M. Guskov et G. Coffignal, «A data-driven temperature compensation approach for Structural Health Monitoring using Lamb waves,» *Structural Health Monitoring,* vol. 15, p. 525–540, 2016.

[9] M. Rebillat et N. Mechbal, «Damage localization in geometrically complex aeronautic structures using canonical polyadic decomposition of Lamb wave difference signal tensors,» *Structural Health Monitoring,* vol. 19, p. 305–321, 2020.

[10] S. Guo, M. Rébillat et N. Mechbal, «Dichotomy property of dispersion equation of guided waves propagating in anisotropic composite plates,» *Mechanical Systems and Signal Processing,* vol. 164, 2022.

[11] S. Guo, M. Rébillat et N. Mechbal, «Prediction of frequency and spatially dependent attenuation of guided waves propagating in mounted and unmounted A380 parts made up of anisotropic viscoelastic composite laminates,» *Structural Health Monitoring,* 2022.