Design criteria for a High Power Pulsed generator for the delamination of laminate structures

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Abstract

Material assemblies combining composites, metals, and ceramics are increasingly used in structural applications due to their high strength-to-weight ratios and durability. However, disassembling such multilayered systems without damaging the constituent materials remains a challenge, particularly for recycling or repair purposes. Magnetic pulse technology offers a promising solution by generating transient mechanical loads through Lorentz forces induced in conductive layers. This paper aims to define the operating conditions of a high-power pulsed (HPP) generator capable of inducing controlled delamination in laminate structures. A simplified model of the current delivered by an HPP generator is introduced, and its temporal evolution is related to the mechanical load applied to the laminate. Previously established delamination criteria, derived from a one-dimensional wave propagation analysis using the method of characteristics, are reinterpreted to guide the design of an HPP generator. The required frequency and magnetic field amplitude are then expressed as functions of the laminate's acoustic and geometric properties. The results provide a set of design criteria for HPP generators in magnetic pulse disassembly applications, enabling effective and selective separation of bonded layers in multi-material systems.

Keywords

Magnetic pulse delamination, High-power pulsed generator, Laminate structures, Interfacial delamination

1 Introduction

Material assemblies are increasingly used in load-bearing composite structures, especially in high-value technology sectors (Ambaye et al., 2022; Clyne and Hull, 2019). Combining lightweight efficiency with durability, these assemblies face challenges in sustainably joining diverse materials like composites, ceramics, and metals, and require robust testing methods for quality assurance. Moreover, recyclability has become a critical factor for sustainable engineering.

Various tests exist to evaluate adhesion strength, primarily using acoustic waves to induce tensile stresses at material interfaces (Braccini and Dupeux, 2012; Mittal, 2014; Packham, 2006 ; Wang, 2011; Meyers, 1994; de Resseguier et al., 2009). Dynamic adhesion tests like the LASAT (Laser Shock Adhesion Test) are limited by very short pulse durations (~10^{-9} s), restricting their applicability to thin coatings and potentially causing surface damage (Tahan et al., 2020; Ecault et al., 2014).

Magnetic pulse technology offers a more suitable alternative, with longer pulse durations (~10^{-5} to 10^{-7} s), capable of evaluating thicker laminate structures without surface damage (Krongelb, 1978). The primary challenge in magnetic pulse disassembly remains accurately controlling interfacial tensile stresses. Unlike discontinuous LASAT testing, magnetic pulse tests require methods that account for continuous stress evolution to ensure reliable and predictable laminate disassembly.

Building on this context, the objective of this paper is to define the operating conditions of a high-power pulsed (HPP) generator suitable for the controlled delamination of laminated structures. The first part introduces the modelling of the mechanical loading induced by the generator. A one-dimensional wave propagation analysis using the method of characteristics, originally developed in previous studies, is reinterpreted to define the desired operating conditions for an HPP generator. From this, expressions are derived to relate the required magnetic field and pulse frequency to the laminate's properties.

2 Modelling and methodology

2.1 Loading tailoring

A high-power pulsed generator is an electrical device designed to deliver, electrical pulses of short duration that typically last from nanoseconds to microseconds as illustrated in **Fig 1**. Such generators primarily rely on high-voltage capacitors to store large amounts of electrical energy, which are then rapidly discharged through specialized high-speed switching components, including spark gaps or semiconductor switches (thyristors, IGBTs). Critical parameters of these generators include the pulse amplitude, current intensity, pulse duration, rise time, repetition frequency, and total energy delivered per pulse. These features make them particularly suited for applications requiring precise and controlled transient energy delivery, such as dynamic mechanical testing or electromagnetic processing techniques.

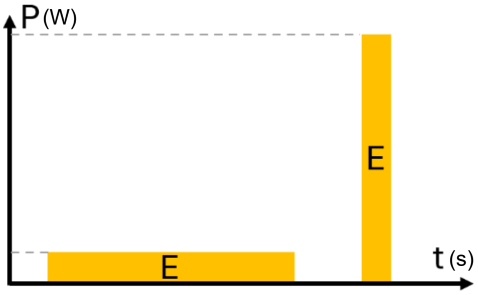

Figure 1 : *Power generated with quick energy discharge for the same energy*

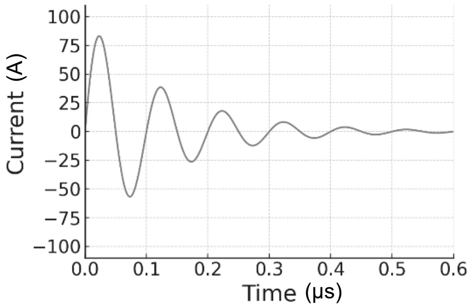

Figure 2 : *Time evolution of pulse generator's discharge electrical current*

The current delivered by a high-power pulsed generator typically exhibits a damped sinusoidal time evolution highlighted in **Fig 2**. This time evolution results from the interplay between the stored energy in capacitors, the inductance of the circuit (coils, connections), and resistances causing energy dissipation. An equivalent RLC representation of a HPP generator is illustrated in **Fig 3**. Consequently, the current briefly oscillates while diminishing exponentially, allowing precise and controlled electromagnetic or mechanical loading on the targeted material.

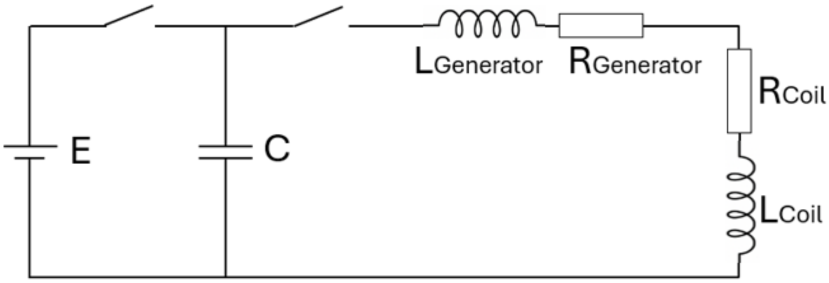

Figure 3 : *Magnetic pulse welding equivalent RLC*

Considering the characteristics of the generator namely capacitance C, inductance L, resistance R, and V_0 the initial voltage applied to the capacitor, the current can be expressed as :

$$I(t) = I_0 e^{\frac{-t}{T}} sin(\omega_0 t) \tag{1}$$

with $I_0 = V_0 \sqrt{\frac{C}{L}}$; $\omega_0 = \frac{1}{\sqrt{LC}}$; $T = \frac{2L}{R}$.

In most applications involving high-power pulsed generators, especially magnetic pulse delamination, the main interest lies in the initial current peak, as it predominantly governs the mechanical effects induced in the target structure. To simplify analytical or numerical analyses, this initial peak can effectively be approximated by a sinusoidal function. This approximation accurately captures the rapid rise of the current to its maximum amplitude, as well as its initial decay, facilitating the analysis of internal mechanical stresses and enabling precise predictions of dynamic behaviour, especially controlled delamination. Such a load, whose expression is given by Equation (2), is illustrated in **Fig. 4**.

$$\overline{P(t)} = \begin{cases} P_{max} sin^2\left(\frac{\pi t}{\tau}\right) & \forall t \in [0, \tau] \\ 0 & otherwise \end{cases} \tag{2}$$

where τ is the pseudo-period of the pulse. The pseudo period can be defined as the time between two successive maxima (or minima) in a damped oscillation.

Moreover, if the outer layer of the laminate structure is electrically conductive, the induced mechanical loading due to electromagnetic effects—specifically Lorentz forces—will follow a square sinusoidal evolution as the generated current which represents a reasonable estimate of the first half pseudo-period of the actual loading profile.

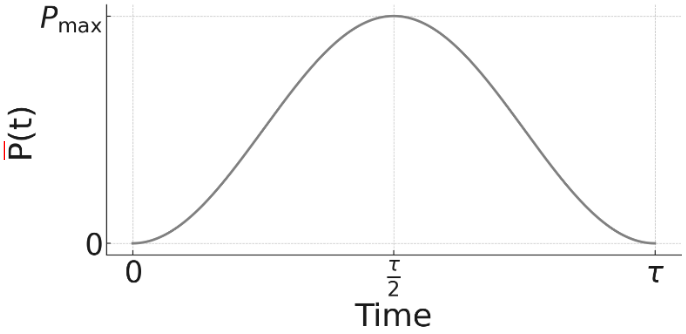

Figure 4 : *Time evolution of the applied pressure*

2.2 Dynamic Wave Propagation Effects

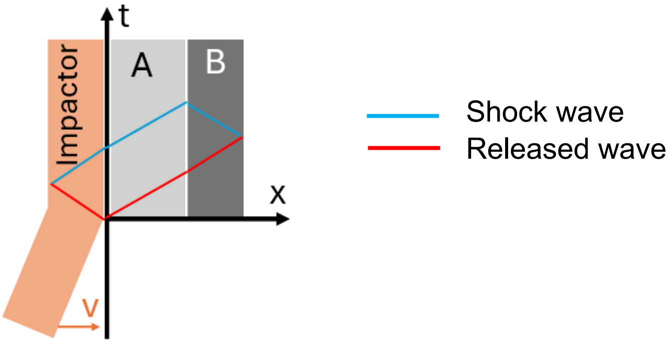

Figure 5 : *Analogy between Newton pendulum and plate impact on a bi layer (A,B) laminate.*

When an impactor strikes a laminate structure, stress waves are generated and propagate through both the impactor and the laminate. Then, tensile stress occurs at the crossing point of two reflected unloading waves. This behavior is depicted in **Fig. 5** through an (x,t) diagram, as typically employed in shock wave studies (Meyers, 1994). The precise location of these tensile stresses within the laminate depends on the wave round-trip time in the impactor and in each layer of the laminate. By carefully selecting the thicknesses of the impactor and back plate according to the relationship $\frac{d_{back\_plate}}{d_{impactor}} = \frac{c_{back\_plate}}{c_{impactor}}$ (Lagain et al., 2023), tensile stresses can be strategically localized at the desired interface, enabling controlled delamination of the targeted layer ; d_i and c_i being respectively the thickness and elastic longitudinal celerity of element i.

In plate impact scenarios, the generated mechanical load is discontinuous in time by nature. In contrast, high-power pulsed technologies provide a time-continuous and more sustained loading profile, making it possible to achieve controlled delamination of thicker laminate structures.

The magnetic pulse delamination method then aims to separate the interface between two bonded layers in a laminate structure without damaging them. It involves rapidly discharging electrical energy stored in a capacitor bank into an inductor coil placed near the laminate's conductive top layer. The resulting oscillating current induces eddy currents within the first conductive layer, generating repulsive Lorentz forces. These forces produce dynamic waves propagating primarily through the laminate's thickness.

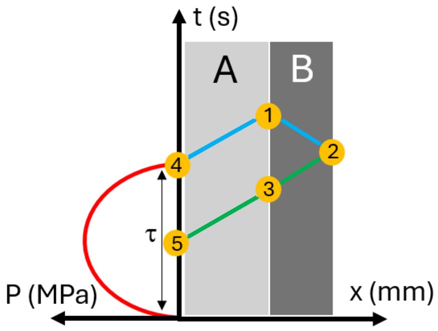

__Figure 6 :__ Characteristic plane (x,t) plotted with two layers (A,B). Few characteristics lines are plotted from the unloaded state (in blue) and from the maximum loaded one at the left side of the laminate in the three layers (in green).

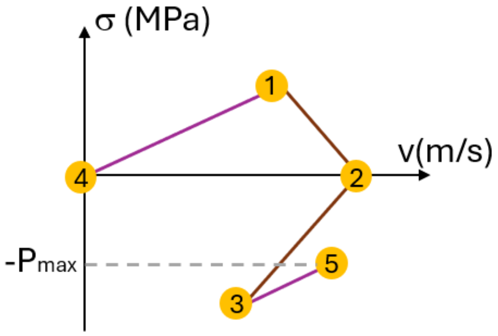

__Figure 7 :__ Plane (v,σ) associated with the characteristic plane shown in Fig 6. Lines in purple and brown are associated with the layers A, B respectively. The plot is here made in the case ZB>ZA.

The Lagrange diagram shown in **Fig 6** and the associated state diagram, shown in **Fig 7** highlight this process shows a few characteristic lines along which pressure waves travel through the laminate (Meyers 1664). In this diagram, the right boundary is considered a free boundary condition. The intersection of two unloading waves, at point 1 emerging from the intersection of characteristic lines 1-2 and 4-1, creates tensile stress as shown in Fig. 7, enabling delamination.

Based on the results developed by Lagain et al., 2023, where the method of characteristics has been used to express the interface tensile stress as a function of the properties of the laminate (Lagain et al., 2023, Fig 7), the period of the pulse should be equal to $\tau = \frac{4d_B}{c_B}$. However, considering a damped sinusoidal waveform, this condition imposes a pseudo period of discharge of about:

$$T = \frac{8d_B}{c_B} \tag{3}$$

Therefore, based on the work of Lagain et al., 2023, to reach the interfacial rupture stress, the maximum applied pressure must satisfy:

$$P_{max} = \begin{cases} \dfrac{(Z_A+Z_B)^2\sigma_R}{2Z_B\left(2Z_A+sin^2\left(\frac{d_A c_B \pi}{2d_B c_A}\right)(Z_B-Z_A)\right)} & if\ \frac{T}{8} \leq \frac{d_A}{c_A} < \frac{T}{4} \\ \\ \dfrac{(Z_A+Z_B)^2\sigma_R}{4Z_B Z_A} & if\ \frac{d_A}{c_A} \geq \frac{T}{4} \end{cases} \tag{4}$$

with σ_R the interfacial critical stress and Z_i the acoustic impedance of layer i.

3 HPP generator characteristics

Equation (3) provides the required period of the mechanical load for a specific structure. Assuming that the time evolution of the mechanical load matches that of the current delivered by the HPP generator, the generator must be able to produce a current with a frequency of about :

$$f = \frac{c_B}{8d_B} \tag{5}$$

If this condition is met, and considering that the magnetic pressure generated in this type of process is related to the magnetic field by $P_{mag} = \frac{B^2}{2\mu_0}$, then delaminating the last layer of the laminate requires that the magnetic field satisfies :

$$B_{max} = \sqrt{2\mu_0 P_{max}} \tag{6}$$

with μ_0 the vacuum permeability.

The generated magnetic field is influenced by multiple factors, including the impedance of the charge, the geometry and positioning of the electrodes, and the characteristics of the surrounding environment (such as materials, distances, and boundary conditions). These elements directly affect the distribution and intensity of the magnetic field, and therefore the mechanical loading induced in the laminate. As such, a dedicated application-specific study is essential to accurately characterize the generator and its configuration. This ensures that the system can reliably produce the magnetic field required to achieve the desired delamination effect under real operating conditions.

4 Conclusion

This study set out to determine the operating conditions that high-power pulsed (HPP) generator needs to perform controlled delamination of laminated structures. The analysis focused on the generation of interfacial tensile stress through magnetic pulse loading, with the goal of reaching the interface failure without damaging the layers.

Assuming that the mechanical loading follows the time evolution of the pulsed current, this leads to a target frequency for the generator, directly linked to the thickness and acoustic properties of the laminate. From this, an expression for the required magnetic field to achieve delamination was derived, taking into account the rupture stress and the acoustic impedance of a layers. This provides a practical criterion for estimating the minimum magnetic pressure needed at the interface.

It is important to note that the magnetic field produced in practice also depends on external parameters such as the geometry and positioning of the electrodes or the surrounding environment. Therefore, while the approach presented here defines the general design rules for an HPP generator, a detailed, application-specific study remains essential to ensure that the required load conditions can be achieved.

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Conflict of interest

The authors declare they have no conflict of interests.

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