Development and optimization of the laser shock wave adhesion test for composite bonding quality assessment

Romain ECAULT\textsuperscript{1}, Nicolas DOMINGUEZ\textsuperscript{1}, Hubert VOILLAUME\textsuperscript{1}, Benjamin CAMPAGNE\textsuperscript{1}, Laurent BERTHE\textsuperscript{2}, Michel BOUSTIE\textsuperscript{3}, Fabienne TOUCHARD\textsuperscript{3}

\textsuperscript{1} Airbus Group Innovations, France
\textsuperscript{2} CNRS, PIMM, Arts et Métier ParisTech, France
\textsuperscript{3} CNRS, Institut PPRIME, France

Contact e-mail: romain.ecault@airbus.com

Abstract. Bonding quality assessment is a key issue for the deployment of bonding for aeronautics primer structures. Therefore, characterization of bonding strength has become an important field of investigations, especially for the detection of weak bonds. Laser Shock Adhesion Test (LASAT), whose most recent developments are presented in this work, is one of the most promising techniques to assess bonding quality. Indeed, this technique enables to generate mastered tensile stresses within the assembly, including an interface to test. It can be used as a proof test to reveal the presence of weak bonds, without inducing damage into good ones. These investigations mainly focus on typical bonded CFRP for aeronautical applications. In this paper, characterizations of the composite dynamic response to laser shock are first presented. It is a key step to the development of a reliable test. For that, experimental data and numerical modelling have jointly been used to bring deeper the phenomenon understanding, and master the test parameters. Results for bonded composites have shown a good sensitivity of LASAT to discriminate weak bonds from correct ones. They also highlight that different degrees of weakness can be detected thanks to the test. Moreover, the LASAT has been optimized using numerical modelling, to be more sensitive and more efficient. Several modalities are proposed and discussed in this paper, targeting various industrial applications.

Introduction

Composite bonding is an important step toward the development of lighter aeronautic structures. It enables to significantly reduce the global mass, by replacing the conventional assembly techniques. It can also lead to faster production, since large panels can be bonded in once. Aircrafts eco-efficiency can be increased, during their production and during their life time. However, the mechanical quality of bonding must be ensured. It requires a good knowledge of the materials and a good mastering of processes. The bonding quality should also be quantified, which is so far not possible with the existing technologies leaving a risk of weak bonding. A weak bond is a mechanical weakness of the joint which cannot be detected by conventional NDT. Such bonds can result from poor curing or from a specific contamination prior to bonding process for example.
These years, several techniques are developed for this purpose. ENCOMB European project (Extended Non-Destructive Testing of Composite Bonds) is a good example of the research efforts dedicated to NDT of bonding (www.encomb.eu) [1-2]. In this context, the Laser Shock Adhesion Test (LASAT) has been pushed forward. Thanks to laser-induced shock waves, it enables to load the bond with a given level of stresses, thus giving a quantification of its strength. The technique capability has already been shown for various applications, mainly thanks to experimental works [3-7]. Especially, the technique enables to discriminate different levels of contaminations [8-9]. Recent work relies on a global methodology including experiments and modeling, to adapt and optimize the test for aeronautic composite bonding application [10]. In this paper, recent highlight results are given. The principle of the laser shock technique is first explained. The associated methodology is then detailed. Characterization of CFRP and bonded CFRP under laser shock loading is then presented. The corresponding numerical modelling results are also given and explained. The current technology performances are presented on the basis of experimental results obtained on bonded CFRP of various strengths. Finally, a first optimization solution is discussed. Paper is concluded on the steps to progress forward.

1. Laser Shock Adhesion Test Principle

1.1 Principle

![Fig. 1. a) Schematic description of the laser shock principle and main laser characteristics, b) 1D time/position diagram showing the principle of tension generation by laser-induced shock waves.](image)

The principle of laser shock technique is described in Figure 1. To generate a shock wave within a given target, a high power laser is focused on its surface. This irradiation leads to the ablation of few µm of the surface, and creates a plasma. Its expansion results in a shock wave generation by mechanical reaction (see Figure 1.a). Laser parameters are usually about few 10ns pulse width, few joules energy, and wavelength can be 532 nm or 1064 nm. A sacrificial layer and a confinement medium are generally used to generate a mastered pressure pulse, whose characteristics depend on the interaction properties [11].

Once generated, the wave propagations can generate high tensile loading in the material (see in Figure 1.b). These tensile stresses are of interest for the adhesion test to reveal the presence of weak interfaces. Concretely, the described pressure pulse leads to the propagation of a shock wave (rising edge), followed by a release wave (falling edge). Propagation depends on pressure level and on the material properties. When reaching the back free surface, the shock wave is reflected into a release wave for energy conservation reasons, and then crosses the coming forward release wave (see a 1D description in Figure 1.b). This crossing of release waves can lead to tensile stress generation. Several cases can
then be considered: 1. The generated stresses are above the global damage threshold of the assembly, creating damage where the rupture criteria are overpassed. Such damage is also called spallation [12]. 2. The stresses level is under the damage threshold of the assembly, thus no damage of the bulk materials is generated. 3. In addition to the previous conditions, a local weakness such as a weak interface is present inside the assembly. In this case, the tensile stresses enable to reveal the weakness by creating damage at this point. Under these conditions, the LASAT acts as a proof test to reveal the presence of weak interfaces. Another NDT have to be used afterward to detect the revealed weakness.

Despite this simple description, the shock propagation can be quite complex in case of composite material. Test parameters should be adapted to the tested assemblies to ensure a non-destructive testing. For that, a specific methodology has to be used.

1.2 Methodology

To address different application cases with different materials and/or different thicknesses, the LASAT should be adapted. Especially, the shock parameters have to be optimized for a given application such as composite bonding. For that, a methodology has been developed as shown in Figure 2. It is made of three main steps: characterization, modelling, and optimization. It might need several iterations. The first step is experimental, and uses a first set of shock parameters. Its main objective is to characterize the dynamic response of the assembly under laser-induced shock. Complexity is progressively increased from bulk materials to the whole assembly. Secondly, laser shock experiments at various intensity levels can be used to identify the damage thresholds of the tested assemblies. For that, post-mortem inspections can be performed. These thresholds are at least valid for the used shock parameters. The second step is numerical, keeping the same progressive increase in complexity. Purpose is to develop reliable numerical models to be used to deeper understand the shock propagation within the material. The numerical model validation stands as a complete work on its own, relying on comparison to experiments [13]. Once validated, the history of shock propagation can be analysed to map stress distribution. The quantification of the interfaces strength is thus possible through modelling. Finally, this analysis can be used in a third step to optimize the shock parameters for the assembly to test. For that, numerical modelling is used to optimize stress distribution by tuning the shock parameters. This way, more adapted shock parameters can be identified and specified for the targeted application.

In the next section, this methodology is applied to the composite bonding application. Selected case is typical from aeronautic. It is made of two T700/M21 composite laminates about few mm, bonded together with FM300 adhesive film. The bonding geometry is given in details in Figure 4. The experimental characterizations, conjointly with the numerical modelling results are given in Section 2. Disbonding threshold determination of various bonded CFRP is presented in Section 3. For this typical aeronautic case, a first optimization path is identified in section 4.
2. Characterization of CFRP and Bonded CFRP Under Laser Shock Loading

This section details the characterization of bonded CFRP under laser-induced shocks starting with a thin unidirectional CFRP - considered as an elementary constituent of the assembly - before working on the whole assembly. Note that no details about numerical models are given in this paper, but information can be found in [13]. The used laser source was a YAG laser, 1053 nm, 30 ns Gaussian pulse, under water-confined configuration. Energy is about 1 J. The focal spot on target is about 4 mm diameter.

2.1 Unidirectional CFRP

The investigated composite is about 500µm thick and is made of unidirectional plies. In Figure 3, this material is first characterized below its delamination threshold in Figure 3. a), and above the spallation threshold as shown in Figure 3. b). For such characterization, starting point is the experimental signal obtained thanks to Doppler velocimetry. In one case, several peaks can be observed, traducing the waves going back and forth in the laminate thickness. It is a no-damage signature. In the other case, the signal shows a clear sign of spallation with a change of frequency. This is the signature of spallation. This information on the composite behaviour under laser loading can usefully be completed by numerical modelling results.

The experimental and calculated velocities are first compared to insure that the model correctly describes the composite laminate behaviour (see in Figure 3.). This good agreement was obtained after a validation of the model [13]. Once reliable, results enable to deeper analyse the wave propagation using time/position/stresses diagrams. Position is the depth, along the axisymmetric axis of the propagation. In Figure 3 compression (in blue)/tension (in red) are displayed. In the first case, the diagram assesses the absence of damage through the whole thickness of the laminate. The back and forth period can be evaluated. In case of spallation, the tension rupture can be quantified about 200 MPa here. The position of the damage initiation can also be estimated thanks to the diagram.

![Figure 3](image.png)

**Fig. 3.** Characterization of a 0.5 µm T800/M21 unidirectional CFRP with a experimental velocity signal, the corresponding calculation, and a post-mortem inspection, without damage (a), and with damage (b).
To complete the set of results, post-mortem inspections were realized on the two shocked samples. The observation of the first sample does not reveal any delamination. A small transverse crack is visible, but is due to the bending of the sample in the setup holder, and not to the shock propagation. On the contrary, second sample is delaminated, which is consistent with the time-resolved characterization, and corresponding numerical modelling.

2.2 Bonded CFRP

Characterization of the bonded CFRP is given in Figure 4. The detailed geometry and lay-up can be observed in the micrograph. The pressure level was chosen to be below the damage threshold of the assembly. Since the velocity signal is harder to understand without modelling at first, 10 shocks were performed on the same sample to prove the absence of damage (average intensity 0.20 GW/cm²). Indeed, the 10 successive shocks result in behaviours quite close to each other. The mechanical responses between the first and the last shock being the same, it can be concluded that this assembly was not delaminated by the first tensile loading, neither by a fatigue effect below the damage threshold (until 10 shocks at least). This conclusion is confirmed by post-mortem observation presented in Figure 4, which did not reveal any delamination or cracks.

In case of the bonded assemblies, the numerical modelling is compulsory to understand the velocity signal, for it to be meaningful. The calculated velocity is presented in comparison to the experimental signals. Note that the model parameters are the same than the used ones for unidirectional CFRP modelling, using the correct orientations for composite plies. The agreement is quite good, but not perfect. Indeed, the bouncing velocity peak at 4.5 µs is stronger for the numerical calculation than for the experimental signal. This difference can be explain by modelling choices, and especially results from a lower attenuation in case of calculation [13]. Nevertheless, this peak is important for the response of the assembly. The time/position/stress diagram shows that this peak is due to second shock breaking-out after one back and forth of the wave. The presence of this second shock breaking-out and the corresponding velocity peak demonstrate that the first tensile wave, assumed to be the strongest, did not lead to any damage (tensile wave from 1.5 to 3 µs in red). A delamination occurring during its backward propagation would have

Fig. 4. Characterization of a 4 mm thick T700/M21 bonded CFRP below damage threshold, with 10 signals obtained after 10 repeated shocks, the corresponding calculation and a post-mortem inspection
prevented from a second shock breaking-out by “opening” the material. Once validated, the model can be used to investigate the current performances of the test, considering the used laser parameters. This point is discussed in section 4.

3. Revealing Weak Bonding

In addition to characterization, experiments have also been used to frame the disbonding thresholds of various assemblies with various bonding strength. Results are presented in Figure 5. Bonded composites were produced by IFAM in the frame of ENCOMB project. Before bonding, dip-coating of the thinner composite laminate in a release agent solution was used to modify the adhesion strength [2]. Four degrees plus a reference were produced. In Figure 5, they are displayed on the horizontal axis. A set of samples was mechanically characterized by University of Patras using GIC. Results are given as large red strips in Figure 5, referred by the left axis in J/m². Bonding strength decreases with the increasing level of contamination as expected. Another set of samples was dedicated to laser shock testing, using one sample per contamination degree. For each sample, 9 shocks were produced with an increasing intensity level, and post-mortem inspections have been performed to determine the presence or not of damage. Observation results are reported in Figure 5 using thin green strips, referred by the right vertical axis in GW/cm². Plain strips mean that no disbonding has been observed; hashed strips mean that there is a disbonding; space in between enables to frame the disbonding threshold. Note that this space is not uncertainty but just a consequence of discrete data. If looking to the trend, it can be concluded that LASAT enables to discriminate contaminated samples from reference. Considering the lowest contamination value, it is even more accurate than GIC. The test can also provide information on the different level of adhesion.

To complete the results given in Figure 5, some micrographs of the shocked samples are also presented. It shows that failure of weak samples is adhesive, which is consistent with the used contamination. These observations show that reference is not disbonded, when weak samples are. Some delamination in the back face composite is also visible for all the samples. It means that composite damage threshold has been also overpassed, and not only the disbonding threshold. To understand why, and to see how it can be avoided, numerical modelling can be used. It is presented in Section 4.

**Fig. 5.** Diagram showing the disbonding thresholds (thin green strips, right vertical axis) of various bonded composites (horizontal axis) in comparison to conventional GIC characterization (large red strips, left axis) – Post-mortem micrographs of the bonded samples at different data points.
4. A First Optimisation Solution

To explain the experimental results and insure a non-destructive test, two numerical calculations have been performed. They are presented in Figure 6. The pressure level was chosen to be below the composite damage threshold identified during the characterization step. In other words, the generated tensile stresses are just below the dynamic composite interlaminar strength. This way, composite laminate will not fail during the wave propagation, and non-destructive testing can be performed in case of interfaces weak enough to be opened by the remaining tensile level.

First, a cross has been added in the time/position/stress diagrams resulting from both calculations. This cross indicates the position of the maximal stresses within the assembly thickness. This position is the same in both cases because input pressure is the same. It can be observed that maximal stresses are located in the composite laminate, more or less in the middle. It is the reason why damage in the composite was evidenced during the shock experiments: the laser parameters are not well adapted to the tested assembly and shock configuration can be optimized to better distribute the stresses.

Knowing that better can be done, the current laser source testing capabilities can still be looked at. For that, two different interface strengths were tested for the bond to thin composite interface. In the first case, presented in blue in Figure 6, the bonded interface was set to 50% of the composite dynamic interlaminar strength. The numerical results show that the laser-induced shock does not lead to the failure of this interface. Indeed, the time/position/stress diagram shows two shock breaking-out, after one back and forth of the waves. The corresponding back face velocity also provides the same information, knowing that it has been understood thanks to modelling. This signal can be seen as the dynamic signature of a correct assembly, assuming that ≥ 50% of composite interlaminar strength is correct. In the second case, presented in red in Figure 6, the bonded interface strength was reduced to 40% of the composite strength, i.e. 10% weaker than in the previous calculation. This time, numerical results show a failure of the weak interface. In the diagram, the wave pattern changes when the propagating backward tension wave reaches the weak interface about \( t = 2\mu s \). Stresses are now high enough to open the interface, and reveal its weakness. As a consequence, waves remain trapped in both laminate one separated. The second shock breaking-out is thus not possible anymore, and cannot be
observed on the corresponding back face velocity signal. The back and forth of the waves trapped in the thin composite are now recorded at the back face. This is traduced by a change of frequency in the velocity signal which could be used as a time resolved diagnosis of the disbonds. A solution might be to compare such signal with a “no damage signature” such as the blue one in Figure 6 to reveal a disbonding.

Conclusions

The LASAT has now reached a maturity level in the laboratories. The methodology to develop and optimize the test is well mastered. Applied to aeronautic bonded composites, it enabled the characterization of bonded CFRP dynamic behaviour. Reliable numerical modelling helped to deeper understand the wave propagation within the assemblies, enabling optimisation. Testing capabilities have been demonstrated on various samples, showing that discrimination of various bonding strength is possible. Finally, the detection limit to insure non-destructive testing, especially regarding the composite laminate, has been numerically evidenced. Models should now be used to optimize the shock configuration to each application case, and bring the technology closer to industry.

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References