# Development of a shock wave adhesion test for composite bonds by pulsed laser and mechanical impacts

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**Abstract.** Evaluating the bonding quality of composite material is becoming one of the main challenges faced by aeronautic industries. This work aims to the development of a technique using shock wave, which would enable to quantify the bonding mechanical quality. Laser shock experiments were carried out. This technique enables high tensile stress generation in the thickness of composite bonds. The resulting damage has been quantified using different methods such as confocal microscopy, ultrasound and cross section observation. The discrimination between a correct bond and a weak bond was possible thanks to these experiments. Nevertheless, laser sources are not well adapted for optimization of such a test because of often fixed settings. That is why mechanical impacts on bonded composites were also performed in this work. By changing the thickness of aluminum projectiles, the generated tensile stresses by the shock wave propagation were moved toward the composite/bond interface. The made observations prove that the technique optimization is possible. The key parameters for the development of a bonding test using shock waves have been identified.

## 1. Introduction

Lightness and enhanced strength are two major properties that make composite materials widely used in aeronautical structures. This success is clearly evidenced by the next aircraft generation such as A350 (Airbus) and Dreamliner (Boeing). Bonding the different composite parts together instead of riveting, welding or screwing the assemblies is the next step. It would reduce the manufacturing costs, as well as the assembly costs, meanwhile lightening the global weight of the structures. However, controlling the bonding mechanical quality in a non-destructive way is still a key problem. In this context, many studies are currently addressing the bonding quality of composite assemblies, and the problem of weak bonds. By definition, weak bonds are at least 20% less resistant than correct quality bonds and cannot be detected by conventional NDT (Non Destructive Test) such as ultrasounds. The adhesive weakness can have several origins such as poor surface quality, surface contamination or high degree of moisture in the composite before the bonding process… In this context and in the frame of ENCOMB European project (www.encomb.eu), several techniques are developed to enable the detection of weak bonds. There are mainly two ways of improvement: i) controlling the adherent surface quality before bonding, by evaluating the presence of chemical species, ii) quantifying the...
mechanical bonding quality with a non-destructive approach. In order to reach this last goal, CNRS (Centre National pour la Recherche Scientifique) is currently investigating the LAser Shock Adhesion Test (LASAT) [1], a technique based on laser-induced shock waves to test bonded composite. With the suitable shock parameters, this method enables to generate high dynamic tensile loading within the tested target thickness. These stresses could induce damage in an interface. Applied to the bonded composite adhesion test, and playing on the shock parameters, this technique can be used as a proof test. The shock propagation should not induce damage in the correct quality bonds but must break the weaker ones. In this work, laser shocks and plate impact shocks were performed on bonded CFRP (Carbon Fiber Reinforced Polymers) and weakly bonded CFRP in order to study the shock parameters influence on the assemblies’ response. Especially the debonding and damage thresholds were studied. To this aim, several post-mortem observation techniques were used: confocal microscopy, ultrasounds, optical microscopy. The damage resulting from the shock wave propagation was quantified and correlated to the shock parameters. The possibility of discriminating a weak bond from reference sample by laser shock is shown. Finally, the shock parameters influence on the bonded composite induced damage is discussed to lead to a more efficient laser shock test.

2. Shock wave adhesion test principle
The starting point is to generate an intense pressure loading on the target to test, by laser irradiation or plate impact for example. In case of laser-induced shock, the interaction consists in a high power laser irradiation of a target material surface. When focused on a material, it transforms the surface into a dense plasma gas. The plasma expansion, created on the material surface, produces a shock wave. The shock wave can also be created by a plate impact by sending a projectile thanks to a gas gun (see sketch in figure 1a). Then, the incident shock wave propagates through the thickness depending on the multilayer material characteristics and geometry (see in figure 1b for laser and figure 1c for plate impact). When reaching the sample back face, this incident shock wave is reflected into release waves propagating from the back face to the impacted face. These release waves can then cross the incident release waves coming from the front face and initiated by the end of the loading (see in figure 1b, 1c). It leads to high tensile stresses which could induce damage in the material if the local damage threshold is exceeded. A high level of damage is characterized by the spallation of the target material. Indeed, the resulting tensile stress level is directly linked to the laser shock amplitude [2]. In case of laser shock, the key parameter is the laser energy, whereas the projectile velocity is the one of plate impact shocks. The location of tensile stresses mainly depends on the material properties and on the pressure load temporal characteristics. As shown on the time/position diagram presented in figure 1.b, the laser pulse duration determines the position of the maximum tensile stress. For a given material and a given geometry, a short pulse (10 to 50 ns) would locate the first tensile stresses close to the

![Figure 1](image_url)

**Figure 1.** (a) Principle of the Laser adhesion test, Time/position diagram of wave propagation in the optimized case for laser shock (b), and for plate impact (c).
back face (about 50 to 250 µm), whereas long pulses (100 to 300 ns) could locate the stresses deeper inside the target (about 500 to 1500 µm). In Figure 1.c, the presented time/position diagram is showing the case of plate impact. In this case, the projectile plate thickness is the key parameter to locate the tensile loading. In case of the adhesion test, the optimized case occurs when the tensile stresses are located at the bond/ composite interface. Then, the laser energy or the projectile velocity can be tuned until the damage threshold of this interface, as it changes the stress amplitude. Therefore, the bonding quality can be controlled. Recently, the technology has been used to test bonded aluminium sample and different composite assemblies [3-5].

3. Experimental procedure and set-ups
Shocks were performed on different bonded CFRP samples using a laser source and a gas gun. The used material samples for investigation were symmetrical CFRP samples. These samples are made by two CFRP parts of pre-impregnated T700/M21, bonded together with a FM300 adhesive film. The two composite parts are identical. They are about 1.5 mm thick, and are made of 6 plies 

$[0°/0°/90°/90°/0°/0°]$. The bond line quality was degraded by using a release agent solution (Frekote) which enables the deposition of a certain amount of Si [6, 7]. An untreated reference sample was also tested for comparison with the weaker bond results. Airbus made the contamination process as well as the quasi-static GIC tests for checking the loss of adhesion in case of the contaminated bonded composite [7]. The laser source was a Nd-Glass source, 1053 nm, which can deliver up to 20 J and whose pulse duration is about 30 ns. On the target, an aluminium painting sacrificial layer was used to generate a well-known and stable laser-matter interaction. Water confinement was also used to increase the pressure and the duration of the loading. The plate impact experiments were performed with an air-gun system. A tank filled with compressed air between 5 and 20 bars, and then opened with a command valve, allows pushing a projectile fixed in a projectile carrier up to 90m/s. After experiments, samples are recovered in both cases to be analysed by different techniques.

4. Experimental results

4.1. Laser shock results
A representative overview of the resulting damage from laser shock on an adhesively bonded composite assembly is given in figure 2. A water-confined laser shock about 2.55 GW/cm² was performed on the samples front face. Three main types of damage induced by the shock wave propagation can be observed: i) Transverse cracks between the fibers and the matrix, through the ply thicknesses. These cracks are mainly due to the flexural component of the laser loading. ii) Delamination between the plies: they are initiated by the high tensile stresses, generated by the propagation of the laser induced shock wave inside the composite. The delamination location in the composite plies is due to the 30 ns pulse duration of the laser used which leads to a maximum of

![Figure 2. Representative micrograph and associated confocal microscopy measurement of damage resulting from shock wave propagation inside a bonded CFRP with a very low adhesion rate (water confined laser pulse, $I = 2.55 \text{ GW/cm}^2$).](image-url)
tensile stresses in the composite part of the assembly. In these experiments, the laser irradiation did not yield to spallation of the sample because the stresses were not high enough. That is why an elliptical blister can be observed by Interferometric Confocal Microscopy at the back face (see right chart in figure 2). This measurement allows quantifying the residual back face deformation of the shocked composite sample. Since the delamination occurred between 90° and 0° plies, the back face deformation measured by ICM is oriented in the 0° direction. iii) Debonding of the bonded interface: this debonding was possible thanks to the tensile loading propagating from the back face to the front face after the crossing of release waves. Even if some fracture energy was dissipated inside the composite, enough energy remained to initiate the debonding since the adhesion was really weak.

In order to evaluate the potential of the laser shock wave technique to evidence the presence of a weak bond, the same laser shock as the one presented in figure 2 was produced on a reference bonded composite target. The resulting damage from the laser shock wave propagation in this target and the produced damage in case of a weaker bond are compared in figure 3. Indeed, it can be observed in the micrographs that, even if the shock intensity was the same in both cases, damage patterns are different. In the reference sample, no debonding can be observed whereas it is clearly evidenced in the micrograph taken from the weaker bond sample. This result is encouraging because it shows that the laser shock technique can be used to discriminate a weak bond from a strong one. Nevertheless, it can be observed that in both cases, the composite part has been delaminated (see in figure 3.). This is due to the shortness of the laser pulse which induces maximum of tensile loading in the composite part of the assembly, close to the back face. Two comments can be made about this observation: i) almost no difference concerning the composite fracture was observed between the two samples. This is consistent with the used method to contaminate the composite and create the weak bond sample. Indeed, it is a surface contamination, which cannot affect the already cured composite strength. So there is no reason for the composite laminate quality to be different from one sample to the other. ii) For the industrial applications for which this method is developed, this is an important issue which should be solved by the optimization of the technique. As explained in the introductive section, the key parameter to avoid this composite fracture is the laser pulse duration. This parameter is correlated the position of the tensile stress maximum through the bonded composite thickness. Assuming that the local bondline damage threshold differs enough from the composite local damage threshold, the use of adapted pulse duration parameter should enable an optimized test without any failure in the composite sample. This hypothesis has been verified by plate impact experiments.

Figure 3. Comparison of the damage resulting from laser shock wave propagation in a correct bonded composite material and weaker bonded composite material by cross section observations.
Plate impacts were performed on the weak bond samples to show that the optimization of the shock adhesion test technique was closely linked to the pulse duration characteristics. As explained in the introductive section, the position of the tensile stresses maximum can be adjusted by changing the plate projectile thickness. It has been verified by producing two different plate impact shocks, at a given impact velocity, meaning constant pressure, but with two different plate thicknesses. The resulting damage on weak bond composite sample is shown in figure 4a). In the first cross section, the aluminum plate thickness was of about 1mm and no damage can be observed in the bonded composite. The maximum of tensile stresses was located in the composite and was not high enough, compared to the local damage threshold of the composite part, to produce cracks or delamination. The second plate impact was produced at the same velocity, but with a plate thickness about 3 mm. In this case, a full debonding has been observed, with almost no damage in the composite part (see in figure 4a). Indeed, the shock velocity in aluminum at this pressure level is close to 5500 m/s, when the shock velocity in composite can be considered in the range [2500 m/s – 3000 m/s] depending on the material quality, resin contents… Using a 1D acoustic approach, it appears that a 3 mm thick plate enables to generate maximum of tensile stresses close to the bondline, which is located 1.5 mm deep in the bonded composite sample. This is due to the factor 2 on the shock velocity (see figure 1c). Finally, the pressure was not really different than the one generated during the first impact. This time, the maximum of tensile stresses was better located and the damage threshold of the bondline was low enough for debonding. This result demonstrates that tuning the shock duration has an influence on the position of maximum of tensile stresses. It enables to avoid inducing damage in the composite material. Considering laser shocks, the pulse duration is clearly the key parameter to optimize the technique. Of course, the pressure is also an important parameter, because the tensile stresses have to be high enough for the bondline damage threshold to be exceeded. This is shown by the results presented in figure 4b. Indeed, the two plate impacts presented were performed with the same projectile thickness. The thickness was chosen to be equal to 3 mm, which corresponds to the optimized case for the bonded composite tested. The first sample was shocked with a projectile velocity measured close to 30 m/s, which generated corresponding pressure and tensile stresses above the damage threshold of both composite and bondline. Indeed, no damage was identified on the cross
section observation (see first micrograph, figure 4b). The second shock was performed with a plate flying at 85 m/s. This time, the induced pressure was high enough to crack the bondline, as it can be observed in figure 4b, second micrograph. This result shows that the pressure applied to the bonded composite should be above the damage threshold even in the optimized case.

5. Conclusions
In this study, the development of the laser shock adhesion test technique for the detection of weak adhesive bonds has been investigated. Laser shocks were performed on weakly bonded CFRP composite material. The resulting damage from the laser shock wave propagation has been quantified using confocal microscopy and cross section optical observation. It has been demonstrated that a weak bond can be discriminated from a stronger one. The laser shock technique is thus a good candidate to become an industrial proof test to detect the weak bond in assemblies dedicated to aeronautics. Nevertheless, the laser shock wave propagation also induced damage in the composite part of the assembly, highlighting the non-optimized shock configuration. Plate impacts have been realized with different projectile thicknesses to show that the key parameter to optimize the technique was the loading pulse duration.

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