Modelling of laser impact on typical composites aeronautical structures for bonding quality assessment

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1 Abstract

Massively used in aeronautical structures, composites are nowadays essential in the search for a more ecological and successful industry. Their low density enables weight reduction and then decreases airplanes consumption. However, the current composites assembly process represents a limitation in their use. In fact, we do not have any reliable, industrialized and non-destructive technology to control the adhesive quality. Then composites are also riveted which adds weight and a drilling process during which fibres can be locally damaged. For about 10 years, the LASAT (LAser Shock Adhesion Test) technology appears to be a promising alternative as a non-destructive control mean to asses bonding quality. The laser impact creates a plasma that induces shock waves propagation in the structure. The LASAT technology can also be used to generate damage anywhere in the assembly thickness. The experimental technology is mature but is lacking a numerical tool in order to calibrate the input laser parameters depending on the targeted results.

Dynas+ has worked, along with the PIMM (Procédés et Ingénierie en Mécanique et Matériaux) laboratory, CNRS - UMR 8006, and RESCOLL, on the VANESSES project, funded by the French Ministry of Defence, in order to:
- Create reliable and validated numerical models representing laser impacts and shock waves propagation on specific assemblies,
- Develop an automated and numerical calibration tool to determine laser platforms input parameters depending on applications objectives (geometry, materials, targeted stress state)

2 Introduction

The use of composites materials in aeronautic has been increasing for years. Their high mechanical properties but low weight enable them to be as competitive as metals while decreasing airplanes CO2 gas emission. Since the environment protection has become one of our societies priorities, optimizing the composites use is of real importance. One of these materials critical points is their assembling technique, between each other or with metallic materials. Bonding would maximize their potential but there is no reliable, industrialized and non-destructive technology enabling to control the adhesive quality. Composites are consequently riveted for safety reasons. Considering that rivets and assembly elements (such as screws, bolts…) can represent up to 12% of an airplane total mass, being able to suppress them by ensuring the bonding quality is a major challenge. Moreover, besides the cost and time savings of removing the drilling processes, it would also better respect the composites integrity, removing the risk of local damage and delamination.

Ultrasonics methods can detect the absence of adhesive or interface fracture but are inefficient when it comes to identify a “weak bond”. The latter corresponds to a zone where the bond exists but with lower adhesive capabilities than the targeted ones. The LAser Shock Adhesion Test technology (LASAT) could be the solution. Indeed, if well calibrated, the laser is non-destructive as long as the glue respects its nominal strength. This technology can also be used to generate damage in a specific and chosen location within a structural assembly thickness, enabling for example to disassemble bonded structures. Improved for years, the experimental technology is now ready to be industrialized. However, the absence of numerical tool enabling to calibrate the laser platform before the tests limits the efficiency of such technology. Indeed, the large variability of available inputs and possible applications makes the best set up research too long and expensive.

Dynas+ has worked on the VANESSES project, funded by the French Ministry of Defence over three years in order to create the numerical tool supporting the experimental laser platform. This project aims at:

- Creating reliable and validated numerical models able to represent shock waves propagation within assemblies in order to control the stress field mapping and anticipate the laser impact results
- Developing an automated and numerical calibration tool able to determine laser platforms input parameters depending on the application and desired results (geometry, materials, targeted stress state)

3 Previous results and modelling strategy

As a reminder, the LASAT technology allows to assess the bonding real mechanical resistance. The process consists in concentrating a laser (~GW/cm2, ~10-20ns) on one face of the assembly in order to produce a high-pressure plasma (GPa). The resulting shock wave propagates through the structure thickness, reflects and recombines on the internal or free interfaces (Figures 1 and 2). A confinement is also used to increase the laser impact resulting pressure in the material. As a result, the structure is subjected to tensile stresses which can induce failure if the stresses are high enough. It is then possible to detect the failure using technics such as non-destructive tests. In order to assess the bonding maximum capabilities, it is important to control the level and the location of the stresses generated by the laser shock. By doing so, it is also possible to use the LASAT technology to voluntarily induce damage or proceed to delamination.

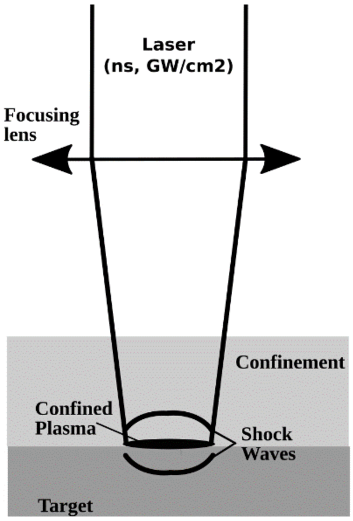


Fig.1: Laser impact phenomenon

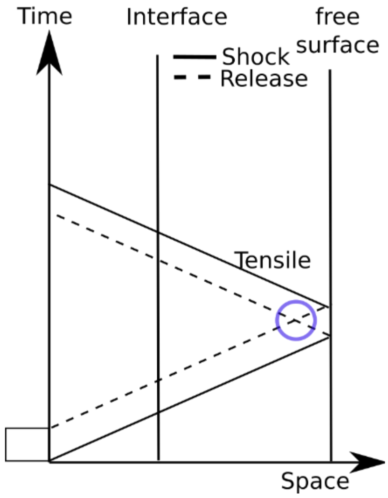


Fig.2: XT-Diagram of a propagating shock wave

First steps in numerical modelling of this process were done on Aluminium 2024. This kind of material is well known, allowing us to set a good modelling strategy for laser impact simulation. The previous work done in this project [1] has led to some LS-DYNA modelling choices: how to represent the laser impact using pressure loading (shape and time definition), mesh size requirements, limits of model type choice (Full 3D with symmetric planes versus fake 2D). Those choices were validated by experimental studies done by the project partners and global feedbacks.

4 Modelling epoxy and composite for laser impact

Considering the modelling strategy developed previously, improvements were needed regarding material modelling for composite. Indeed, initial numerical models used **`*MAT_ELASTIC_PLASTIC_HYDRO`** (**`*MAT_010`**) with a Gruneisen equation of state for the epoxy in the inter-plies and **`*MAT_ENHANCED_COMPOSITE_DAMAGE`** for the plies. The laser impact induces high strain rates range on the material, depending on the laser intensity. Since strain rate effects are not taken into account, those materials may not reproduce the right behaviour for all laser intensity with the same material parameters settings. One can set a scaled modulus for a specific laser intensity, as done in previous studies. Moreover, initial setup did not take into account possible failure between each ply.
The new stages of the project led to three main modelling points: epoxy material setup and composite and interface modelling. Combination of those new modelling strategies improve the representativeness of LS-DYNA model of laser impact on composites. Most of the following studies were done on a “fake” 2D model: One single solid layer between two symmetry planes. The optimal solution was then confronted with the equivalent 3D model to confirm the chosen strategy.

4.1 Setting up epoxy material model

Initially, the inter-plies epoxy was modelled using an elastoplastic model with an equation of state. Based on previous work found in open literature, the behaviour was relatively correct to reproduce epoxy under laser impact. In order to check and improve the numerical material setting, some experimental tests were performed by the PIMM on pure epoxy samples (produced by the partner RESCOLL). Different types of epoxy (constitution and chemical treatment) were considered and laser impact experimental campaigns were done for several laser intensities.
A study of the art on modelling epoxy material led to try another material law of LS-DYNA: **`*MAT_SAMP_LIGHT`** (**`*MAT_187L`**) [4]. This material allows a definition of young modulus as a function of strain rates and also includes a damping effect on elastic modulus (see figure below).

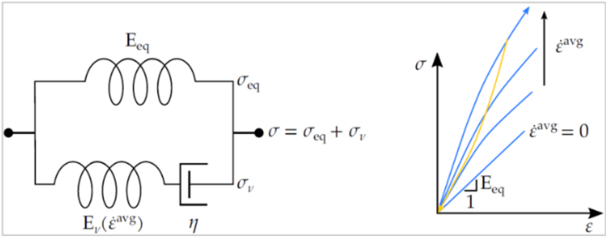


Fig.3: Rheological model of ***`*MAT_SAMP_LIGHT`***

Based on that, an optimisation study using LS-OPT has been done to correlate numerical result and experimental result of a laser impact on an epoxy sample. The starting value for the young modulus was the one set in the initial elastic-plastic material. To define the young modulus as a function of strain rates, an assumption was made: the young modulus is logarithmically penalised due to strain rates. Indeed, the logarithmic shape is quite simple to start with and can approximate stress-strain curves shape. Moreover, it has the benefit to reduce the optimization to only two parameters: one for the damping effect and one for the power law of the logarithmic penalisation of the young modulus. The LS-OPT study set to identify those parameters considered different experiment configurations (sample thickness, laser intensity). Since the velocity at the centre of the back face sample is extracted from the experiment, this time history curve was chosen as the target result. The objective function defined in LS-OPT study was the curve matching error between experiment and simulation.

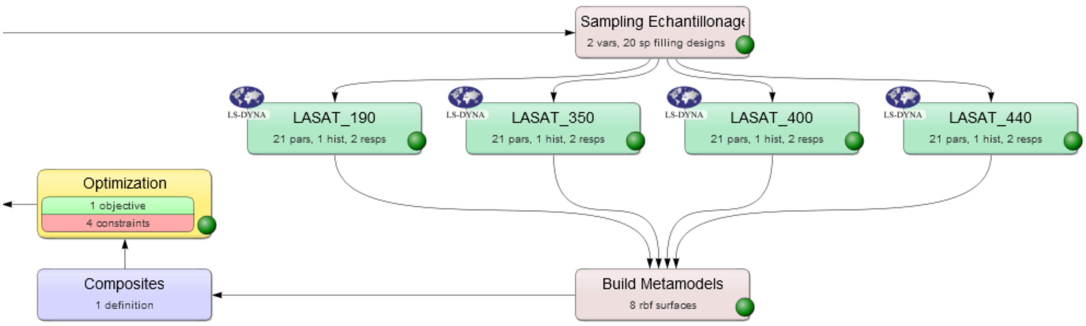


Fig.4: LS-OPT Study definition to identify epoxy law parameters

The result of this optimization was interesting, allowing the numerical behaviour to better approximate epoxy material. A comparison (figure 5) was done between the optimal setup and the initial material model of epoxy (the one using **`*MAT_ELASTIC_PLASTIC_HYDRO`** with a Gruneisen equation of state).

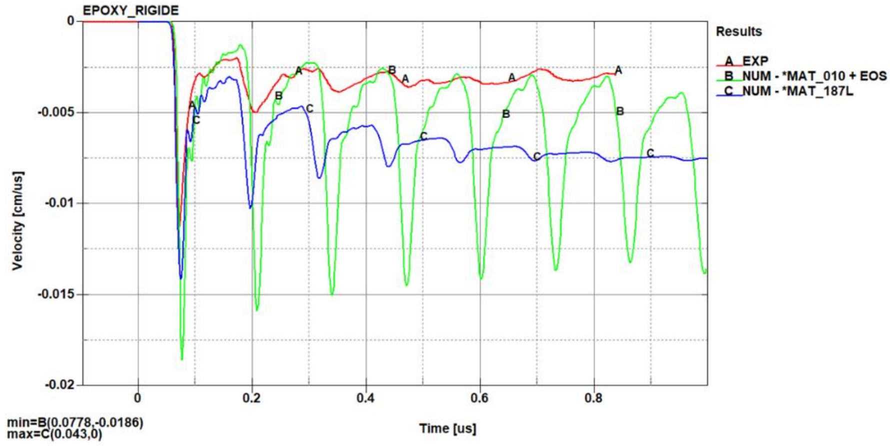


Fig.5: Different temporal pressure loadings

The initial solution (**`*MAT_010`** + **`*EOS_004`**) did not show such a strong damping effect on the back face velocity as it had been identified on the experimental data. The **`*MAT_187L`** with the optimized material parameters showed this damping effect and the first two high speed amplitudes were synchronous with the experimental curve. The amplitude difference between the numerical result and the experimental one may have been improved by changing the shape of the young modulus versus strain rate curve or by adding a plasticity behaviour in the material law in order to decrease the velocity after some waves propagation. These possibilities will be explored in further studies. However, considering the small thickness of epoxy layers within composite assemblies the LS-OPT study optimal result was good enough for the next stage of the modelling strategy.

4.2 Composite and interface modelling

At the start of the project, the **`*MAT_ENHANCED_COMPOSITE_DAMAGE`** material law was used to model composite plies. Since this law was not taking into account strain rate effects, the elastic modulus was manually updated as a function of laser intensity (using a scale factor on the quasi-static modulus) to represent the correct composite behaviour under laser dynamic loading. Considering our request, Ansys LST development team released a beta version with an upgrade of the material law. enabling to account for strain rates effects on the young modulus for solid elements. This new LS-DYNA version has been used for the following laser impact models. The goal was to have, for a defined composite, one numerical material law that can cover the full range of laser induced velocities.
Based on this new development and on some experimental data obtained with the help of our project partners, a LS-OPT optimisation study was done (figure below). In order to reduce the number of unknowns, composite samples with only one and two plies were produced by RESCOLL and laser impact tests carried out by the PIMM. As done previously, the back face velocity profile was extracted from the experiments and the simulations. The objective function of the optimisation study was the error between those two curves, as a curve matching function. Since the material characterisation is the same for one and two plies, the parameters calibration was done in the same LS-OPT study. To define the elastic modulus as a function of strain rates, as done previously for the epoxy, a logarithmic penalisation was considered here. Initial young modulus were the ones identified with a quasi-static tensile test and a transversal isotropic behaviour was assumed.

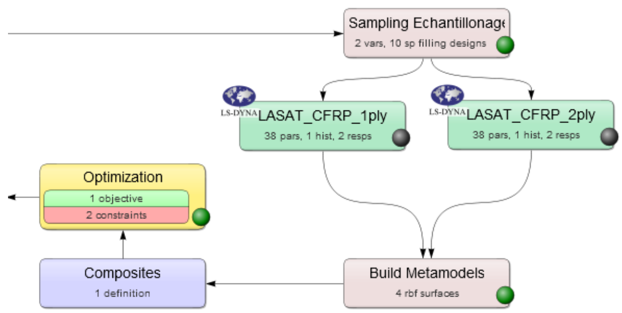


Fig.6: LS-OPT Study definition to identify composite ply law parameters

The optimization results showed a good representativeness of the composite behaviour. The figure 7 left image illustrates the obtained result for the 2 plies sample. Identified parameters to set the strain rates effects on young modulus are quite efficient in this case. Additional experimental data may be included in the optimisation study to widen the range of laser intensities applications: indeed, strain rates level is function of the laser intensity. However, some experimental limitation may be encountered (too high laser intensity may not be feasible on a thin layer of composite without damaging it). The LS-OPT optimal solution was then applied to a full ten plies composite. As shown on the Figure 7 (right) the material set up enabled to get a really good fit on the thicker sample, which validated the relevance of the LS-OPT parameters fitting and was really encouraging for further results reliability.

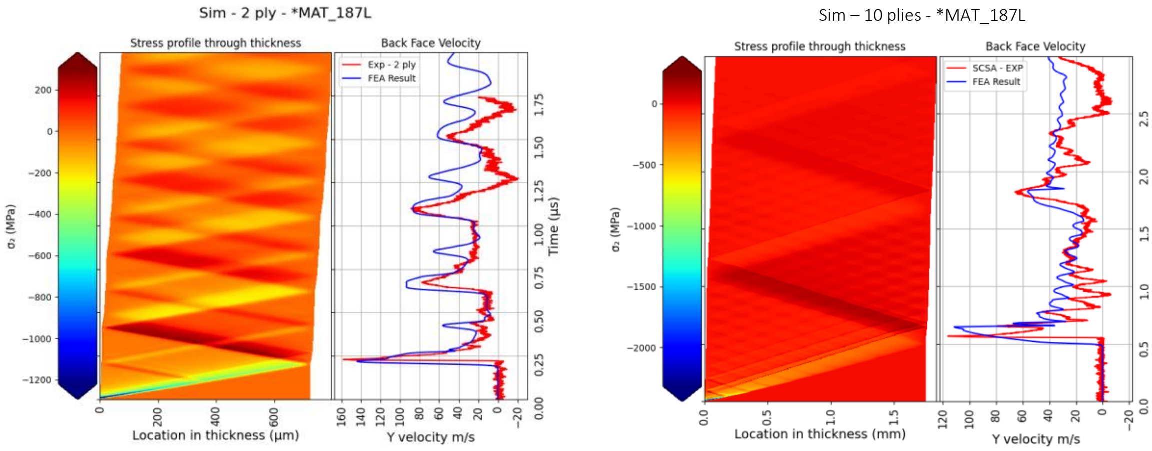


Fig.7: LS-OPT optimal result for a 2 plies sample (left) and 10 plies composite samples (right)

In addition to the material of each composite ply, some improvements on the interface modelling were required to simulate at the best the carbon fibres reinforced plastic behaviour during a laser shock. In LS-DYNA, two main strategies were identified: the use of cohesive elements or the use of tiebreak contacts.

The first one consists of adding a layer of elements between each structural layer. This cohesive layer can have a null thickness or a small one. It is mainly used in the case of delamination modelling, most of the time during a tensile test. This specific layer has to use a material law in LS-DYNA dedicated to cohesive elements. The choice of material depends on how the user wants to model the failure of the interface: using a tensile/shear force criterion, using an energy failure definition, … Several laws have been tested but with a main focus on the **`*MAT_138`** (**`*MAT_COHESIVE_MIXED_MODE`**). Nevertheless, whatever the chosen law, the cohesive element strategy has a limitation. Indeed, the mechanical load resulting from the laser impact is mainly in compression but the cohesive material laws do not enable to define a compression behaviour. Consequently, the cohesive elements reverse themselves when a compression load is applied to their boundaries. The adopted solution in that case was then to define a non-null thickness cohesive layer and define a penalty contact between the opposite surfaces of the cohesive elements. As a first check of this cohesive solution, a comparison between the initial modelling (merged nodes at the interface) and the one using the cohesive layer (multiple thicknesses tested) with no failure criterion defined was done in figure 8.

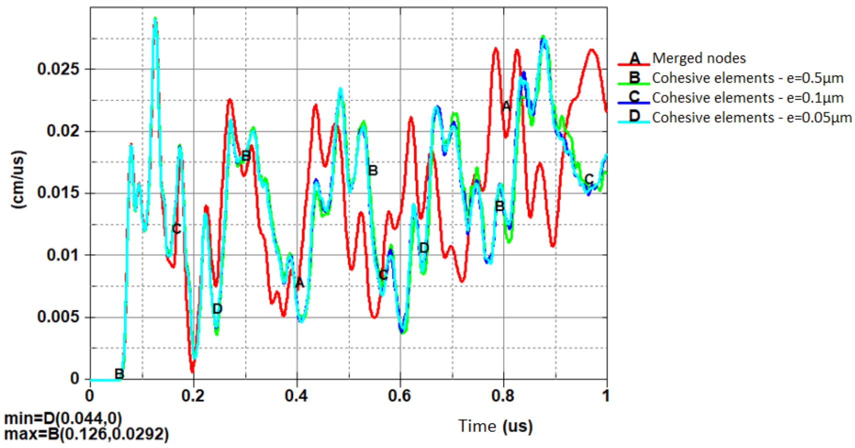


Fig.8: Back face velocity comparison between models with merged nodes at interface or with cohesive modelling solutions

As shown, the use of cohesive elements did not give the same result as the merged nodes (reference) solution. The first part of the signal is quite identical with all strategies, which corresponds to the first compression wave propagating from the front to the back face of the composite sample. However, when the tension wave comes back and a new compression wave comes in, back face velocity is dephased compared to the reference solution. Consequently, considering these results, the use of cohesive elements did not seem to be the best choice for this specific application.

The second option to model composite interface and debonding is to use tiebreak contact (**`*CONTACT_AUTOMATIC_option_TIEBREAK`**). In that case, glue has no thickness. Only failure criteria and possibly damage formula are defined for the interface. Multiple failure options are available with this contact. Some of them are quite identical to what is available in cohesive material law. Distance between tied slave node and master segment is maintained by a linear spring, for tensile and compression load, up to failure in tension. Doing the same comparison as for cohesive elements (figure 9), results were the same as the reference ones. Two failure options of tiebreak contacts were considered but no failure criteria were defined in order to compare with the reference (merged nodes).

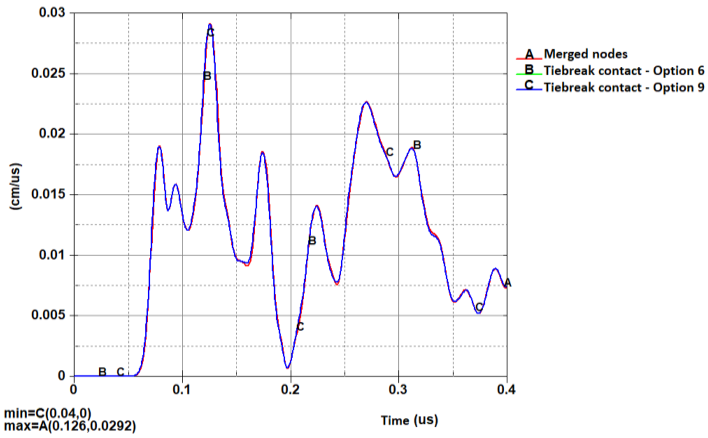
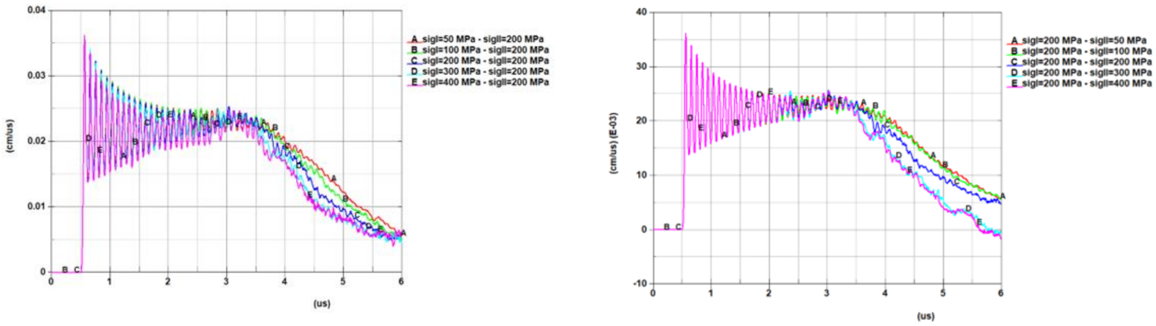


Fig.9: Back face velocity comparison between tiebreak contact modelling solutions

Compared to the cohesive method, the tiebreak solution showed the same result as the reference one. Very small differences on the back face velocity could be observed but were negligible. It was a good starting point in the case of laser impact modelling. For this modelling solution, a sensitivity study on the failure parameters was conducted. Three main parameters were tested: tensile (sigI) and shear (sigII) failure stresses, and critical distance for failure (CCRIT). As before, back face velocity history was used to compare the results. Tensile failure stress influenced the amplitude of velocity after the first peak: the higher it was, the more damped the oscillations were. Shear failure stress affected the velocity decrease after failure.



Influence of sigI   Influence of sigII

Fig.10: Influence of failure stress

In the case of critical distance, behaviour was quite different depending on whether the distance was set null or not. In case of a null critical distance, a brittle failure occurred. Just after the first velocity peak, oscillations were visible and were damped gently. By increasing the critical distance, failure was less brittle: interface damage was progressive and velocity history profile was more like when there was no failure.

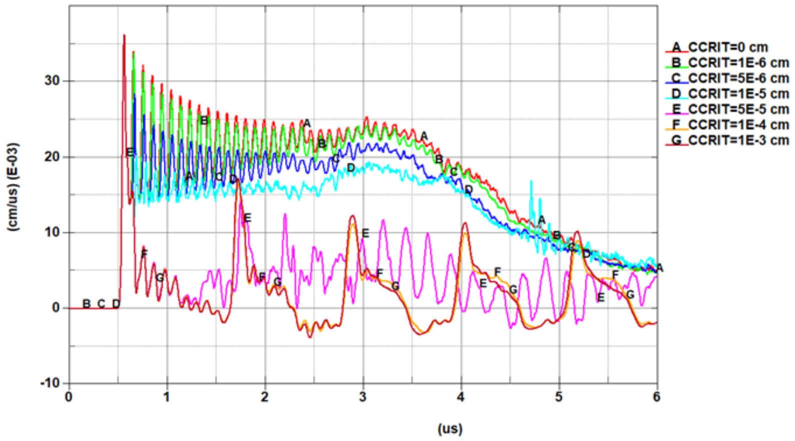
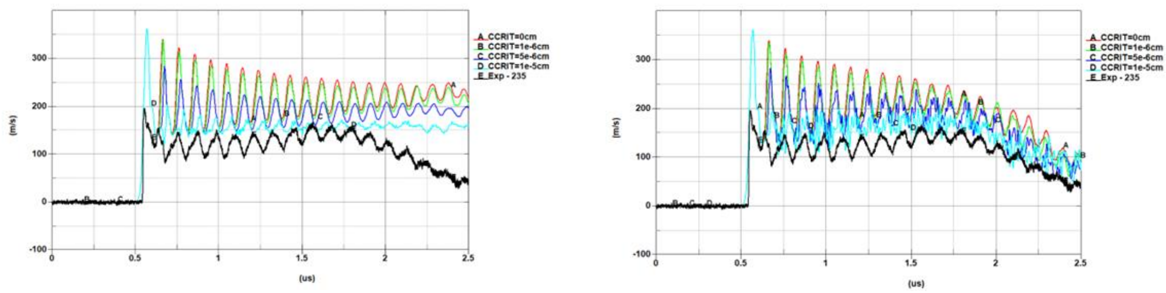


Fig.11: Influence of critical distance

Until now, simulations were made with the fake 2D strategy. It allowed to identify faster (up to 10 times faster) the best modelling choice. However, in case of interface debonding, the "fake" 2D may not have correctly represent the interface failure. A comparison between "fake" 2D and 3D strategies was done. It showed that the back face velocity history profile was quite equivalent between the two strategies. Indeed, failure occurred in both cases at the same time and led to almost the same velocity amplitudes for around the first dozen of the shock wave back and forth. However, the "fake" 2D model did not enable to catch the final shape of the experimental signal, contrary to the 3D model that showed the right behaviour. Then, the third direction needs to be correctly modelled if we need to reliably represent the complete signal shape.



Fake 2D model   3D model

Fig.12: Comparing modelling strategies for interface failure behaviour

With all those results, the preferred modelling strategy for composite under laser impact is now the following:

- Identify the material law parameters using experimental results on a composite without failure, using a “fake” 2D LS-DYNA model;
- Identify the interface failure properties by fitting experimental results with failure using a “fake” 2D model;
- Run a final check with a 3D model.

We then went to identify how to setup the laser parameters to induce failure at a specific interface.

5 Identify laser setting to induce failure

From all the work done previously, there was an efficient and robust strategy to model laser shock on composite structure. Final goal of the project was to identify the laser experimental settings to reach a certain stress level at a specific location through the composite thickness. It could be done iteratively from a baseline result and from experimental feedback but that method would be a long, expensive and tedious task, especially considering the variability of possible applications and the large parameters ranges. One of VANESSES objectives was to automat this process. The adopted solution was to use an optimisation study in LS-OPT enabling to identify some laser settings to achieve the targeted stress and location, The methodology was firstly adjusted on a well-known material (aluminium sample) and then applied to a composite structure loaded by a double laser impact, one on each sample surface.

5.1 Basic modelling on aluminium sample

From the beginning of the VANESSES project, aluminium was the best shot material to validate the modelling strategy. Material settings are fully known and the laser impact modelling options are well defined now. Aluminium models are predictive and reliable, reason why they were used to develop the LS-OPT strategy. To set an optimisation study, one needs parameters (laser settings ie. Laser intensity here) and an objective function. In that case, the user wanted to get a specific level of stress at a specific location through the sample thickness. The reference LS-DYNA model followed all predefined strategy options. To efficiently get a result, a “fake” 2D model was used (Figure 13). The optimal solution was checked with a 3D model thereafter.

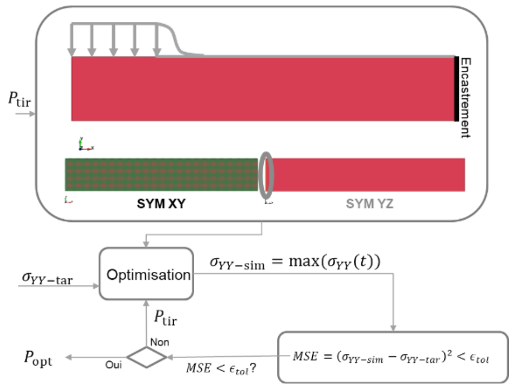


Fig.13: Optimisation study on an aluminium sample

The second step of the LS-OPT study was to run a robustness study in order to know if the obtained optimal solution was robust or not: did it correspond to a local optimum or would a small variation of the laser intensity only lead to a small variation of the stresses level and location? The study showed that with a relative variation of the laser intensity of more or less 5%, target stress ranged from -7% to 5%. The variation was quite good from a stability and robustness point of view.

5.2 Application to a composite assembly

Next stage of the laser parametric identification was to apply the previous process to a composite sample. It was a double side laser impact enabling to position the target stress wherever it was needed within the assembly (not obviously at the centre of the composite thickness). The laser intensity was the same on each sample face. The user could delay the impact between each side, depending on where he wanted the shock waves to cross and generate the targeted stress. Applying the previous process to the composite, the model gived a reliable result (Figure 14).

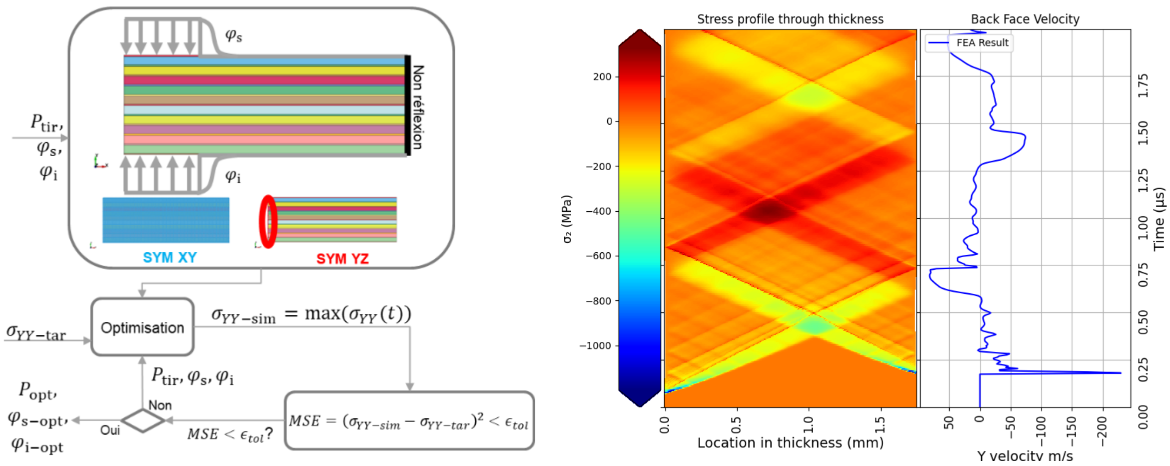


Fig.14: Optimisation study on a composite sample

The optimal result presented a maximum stress on a localized area through the thickness, at the targeted position. The maximum value was not shown outside the region nor at another time. The robustness study done on this optimal solution presented a small variation of the results: with a variation of 5% of the laser intensity or the phasing between front and rear impacts, the target stress was influenced by less than 7%. It was the same for the maximum stress position through thickness.

6 Conclusion and perspectives

The LASAT technology is an efficient solution to test adhesives quality in composites structures. Indeed, it enables to detect “weak bonding” while being non-destructive. However, for this technology to be efficient, the laser platform inputs need to be well calibrated in order to position the targeted level of stresses in the right location. Numerical simulation is necessary to support the experimentation and help the calibration. The aim of the VANESSES project is to create an automated tool giving the platform set up to be use depending on the structures properties (material, geometry…) and the desired objective (delamination of an adhesive interface…).
First step of the project was to look at Aluminium plates in order to better understand the shock waves propagation phenomena and run many sensitivity studies in order to extract a modelling strategy. Using that, composites have been looked at. Solutions have been found to correctly model composite and epoxy materials under laser impact. Work has also been done on bonding modelling with tiebreak contacts. Summing up all those results has allowed Dynas+ to identify the best strategy to optimise laser settings to target a stress level through an assembly thickness. This strategy has been written as a guideline to model laser impact and get the needed laser intensity to achieve a targeted stress level and induce failure at a specific interface. Finally, Dynas+ has also developed specific post-processing tools to facilitate the visualisation, understanding and analyses of the physical phenomena involved in laser shock modelling.

7 Acknowledgments

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8 Literature

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