Laser impact modelling in order to assess composites bonding on aeronautical structures

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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 drilling process during which fibres can be locally damaged. For about 10 years, the LASAT (Laser adhesion test) technology appears to be a promising alternative. 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 so to calibrate the input laser parameters depending on the targeted results.

DynaS+ is working 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 automatized and numerical calibration tool to determine laser platforms input parameters depending on applications objectives (geometry, materials, targeted stress state)

This paper focuses on the numerical approach of this project and how LS-DYNA can be used to represent such phenomena. Analysis of laser induced shock waves propagation in representative structures will be presented in different configurations.

1 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 CO_2 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 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+ is working 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 so as to control the stress field mapping and anticipate the laser impact results
- Developing an automatized and numerical calibration tool able to determine laser platforms input parameters depending on the application and desired results (geometry, materials, targeted stress state)

2 Laser adhesion test technology

Choosing to assemble aeronautic structures only using bonding requires to be able to test the adhesive quality. 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.
The laser platform used in VANESSES is the “Hephaïstos” facility located in the PIMM laboratory in Paris. The PIMM (Procédés et Ingénierie en Mécanique et Matériaux) is one of Dynas+ partners in the project. The description of the “Hephaïstos” platform functioning can be found in many papers ([1] as an example). Numerical simulation is used to help understanding the mechanical phenomena generated by the laser impact by observing the stresses distribution and evolution through the structure thickness.

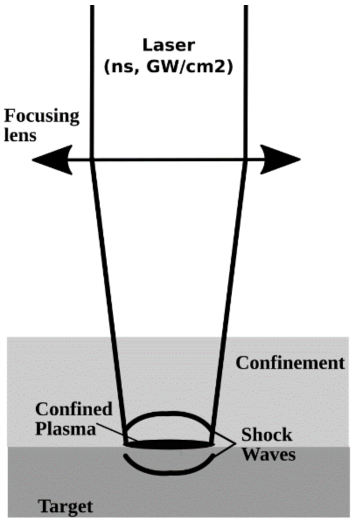

Fig.1: Laser impact phenomenon

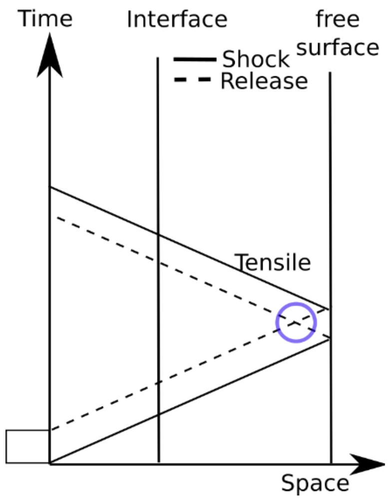

Fig.2: XT-Diagram of a propagating shock wave

3 Modelling strategy – Work on aluminium

The first works were made on Aluminium 2024 in order to gradually increase the complexity of the laser impact simulations. Indeed, composites are more complicated materials to characterize and model, and their anisotropy prevents from using 2D modelling. Another benefit of starting with Aluminium 2024 is the possibility of using the corresponding very detailed *MAT_TABULATED_JOHNSON_COOK developed by the “Aerospace Working Group”. Finally, the CEA, also working on laser shock modelling has developed an internal code, named ESTHER, enabling to provide the pressure loading profile depending on the laser characteristics when impacting an Aluminium plate. These pressure loadings

will be used as inputs in our simulations and will then be more precise when it comes to Aluminium impact.
As a consequence, using aluminium enabled us to quickly and reliably assess LS-DYNA capabilities in reproducing physical phenomena induced by a laser shock. Moreover, once numerical models proven to be representative and predictive, they were also used to perform many sensitivity studies in order to establish first modelling guidelines.

3.1 Numerical model

The Aluminium 2024 is an isotropic material and the laser loading being circular, a 2D axisymmetric model can be considered. Fully integrated elements have been used with non-reflecting boundary conditions. Spatial and temporal distribution of the pressure loading were given by the PIMM where experiments were performed.
In order to better visualise the stresses mapping evolution along the axis of the impact centre, DynaS+ has developed a program enabling to plot XT diagram. The figure below shows on the left the stresses through thickness versus time and on the right the superposition of experimental and numerical back face velocity versus time. Both results are positioned so as to facilitate the visualisation of shock waves propagation.

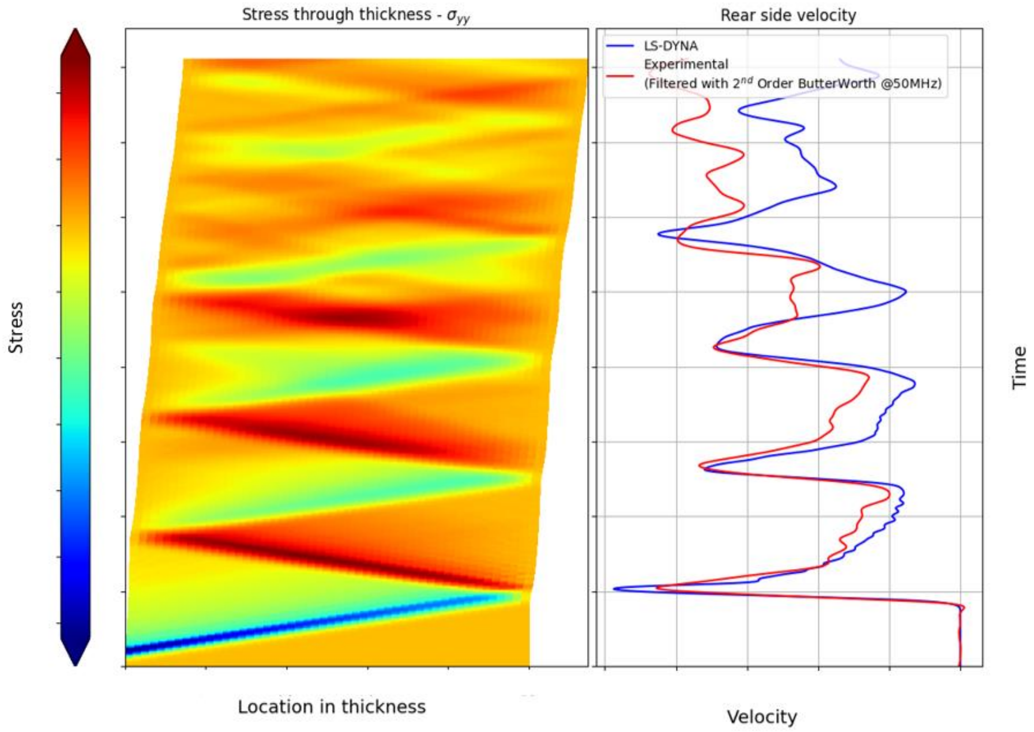

Fig.3: XT Diagram for the 2D axisymmetric model representing laser impact on Aluminium 2024

Results show a reasonably good agreement between the measurement of the experimental back face velocity and the numerical one. The signals periods are almost identical and the peaks magnitudes are really close for the fourth first peaks. However, it is harder to catch the experimental signal decreases and a rather significant difference can be observed between both curves after the third peak.
The juxtaposition between the stresses through thickness and back face velocity enables to well observe the matching between the shock waves propagation and the impacted sample behaviour. Each velocity peak corresponds to the moment when the compression loading wave gets to the rear side surface.
The visualisation of stresses through thickness and time also enables to know what level of stress undergoes the structure and where. The project final objective being to calibrate the laser input parameters to get a specific amount of stress in a targeted location, this tool will help in automatising the process and make it as precise as possible, especially as double impacts (symmetric or not) will later be considered in the project. Double impacts will enable to benefit from increased stresses when shock waves will cross each other, in a specific way so as to make them cross at interfaces locations for delamination purposes.

3.2 Sensitivity studies

Many sensitivity studies have been run in order to set a first modelling strategy. Some choices might change later when considering epoxy and composites materials but many numerical and physical analyses can already be run thanks to this reliable and fast model.

Two types of sensitivity studies can be considered to assess the model robustness and relevance. The “numerical” choices made for the reference model have been checked, among which:

- The model type choice. A 3D model has been created and results compared with the 2D one to ensure further analyses with the axisymmetric model can be reliable enough

- The mesh size so as to be sure results are converged and a good compromise is found between precision and computation time

- The meshing strategy to check how the way of meshing influences the results and identify a preferred strategy (simple homogenous grid pattern, butterfly design, use of a circular node line following the laser shape, use of bias to coarsen the mesh size as we move away from the centre…).

- The element formulation to choose the most appropriated one

- The insensitivity to the LS-DYNA version and parallelisation method (verification tests)

The “physical” sensitivity studies have considered:

- The boundary conditions and how experimental set up can impact the results.
    - It appears that the phenomenon is fast enough so that boundary conditions have very low impact on the back face velocity and shock waves propagation.

- The precise measurement location for back face velocity. Indeed, the experimental measurement is not a punctual value but made with a ~100µm diameter laser. Moreover, although the laser alignment is made with precision, the measurement might be slightly decentring.
    - Considering an averaged value instead of the centre node one has almost no impact on the velocity value. Also, even by taking into account a 200 µm offset from the impact axis results remain almost identical.

- The temporal loading and in particular the effect of the signal shape.
  The formula enabling to provide the temporal loading shape and magnitude does not get back down to 0 at its end. LS-DYNA would then directly consider 0 at the end of the curve. It is however quite unlikely and the influence of the curve final shape has been assessed by extending the curve more or less slowly back to 0.
    - The back faces velocities are first identical but start diverging after some time (when the final shape start changing). Differences remains really small and predictable. If the loading is applied on a longer time, even at very low level, it slightly increases the velocity.

  The code giving the temporal curve has been validated for pure Aluminium which is not our case here. Does the shape of this curve influence the shape of the back face velocity and can it enable to better fit the decrease not correctly catch in the reference model? In order to answer these questions some tests have been run. Among them simple ones are presented below. The figure shows three curves: the initial provided loading curve smoothly extending down to 0, another curve where only the signal tail shape has been modified to get a kind of plateau before decreasing to 0 and another one where the whole shape has been changed (magnitude of the peak, decrease and tail shape) while still being sensible. The blue modified curve leads to a slightly higher amount of energy delivered than the green one (around 5%) but in lower proportion than the difference between the green and red curve (around 8,5%).

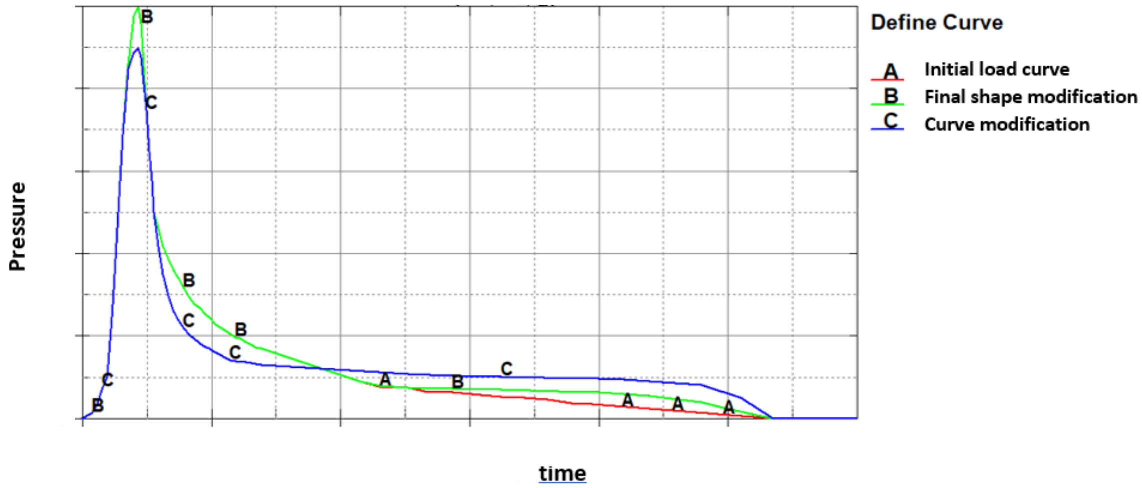

Fig.4: Different temporal pressure loadings

- The results show that the temporal loading shape has an influence on the back face velocity. The first peak magnitude is, as could be expected, linked to the pressure peak magnitude. The evolution in the decrease slope of the loading curve impacts the back face velocity decrease after first peak on a very similar way. The loading curve tail shape seems to influence the velocity profile after the second peak. The accuracy of the pressure loading curve shape is then important to better fit the experimental velocity results.

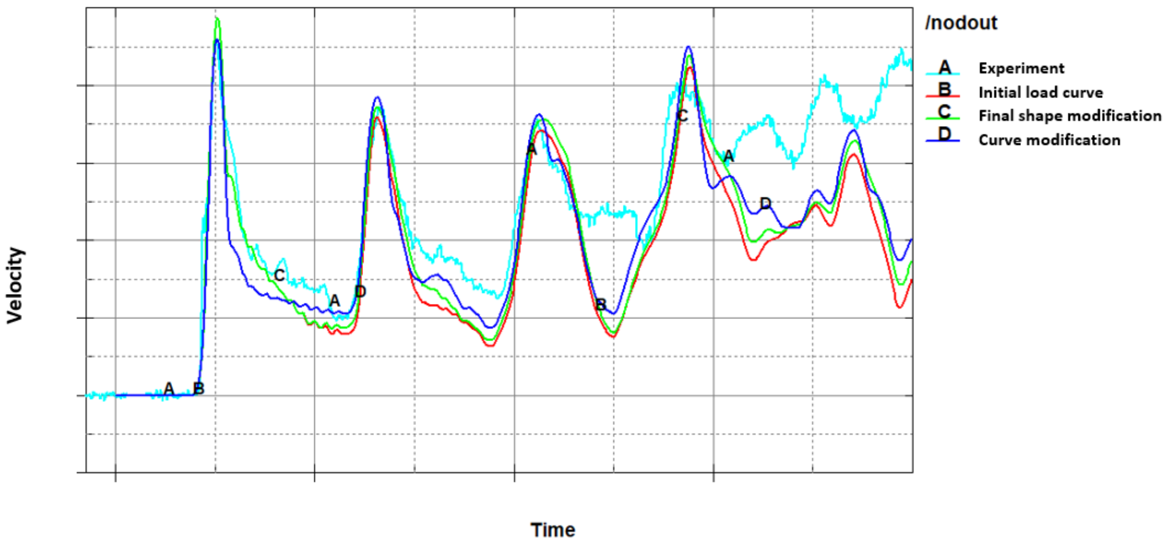

Fig.5: Back face velocity versus time depending on different pressure loadings

- The spatial loading, its precise shape and its method of application.
  The spatial distribution of the loading is influenced by the optical instruments of the laser platform. A quite accurate process is being used for several year and enables to get a rather smooth and constant application of the pressure on the complete circular shape of the laser spot. The hypothesis is made that the laser induced pressure is proportional to the light intensity. The spatial distribution is derived from this assumption. Then, the decrease in pressure on the spot perimeter is supposed to be almost linear expect at the very edge where it finished more slowly down to 0. Although sensible, this method can not be verified exactly. Consequently, a sensitivity study has been carried out. Few simple cases are presented on the figure below where the spatial curve has been modified on its edge to change the decrease slope, timing…
  - The results show that the spatial loading shape has an influence on the back face velocity. As long as the decrease in pressure starts at the same moment with a similar

slope velocity are almost identical (no matter the exact shape – smooth or stepped curve / sharp or finally rounded curve). However, the time at which the decrease starts and the slope of that decrease influence the amount of energy delivered at the spot edges and then the velocity curve shape, after the second peak (with an expected delay since it takes time for the edge effects to reach the centre of impact axis). The accuracy of the spatial loading curve shape is then important to be as representative as possible.

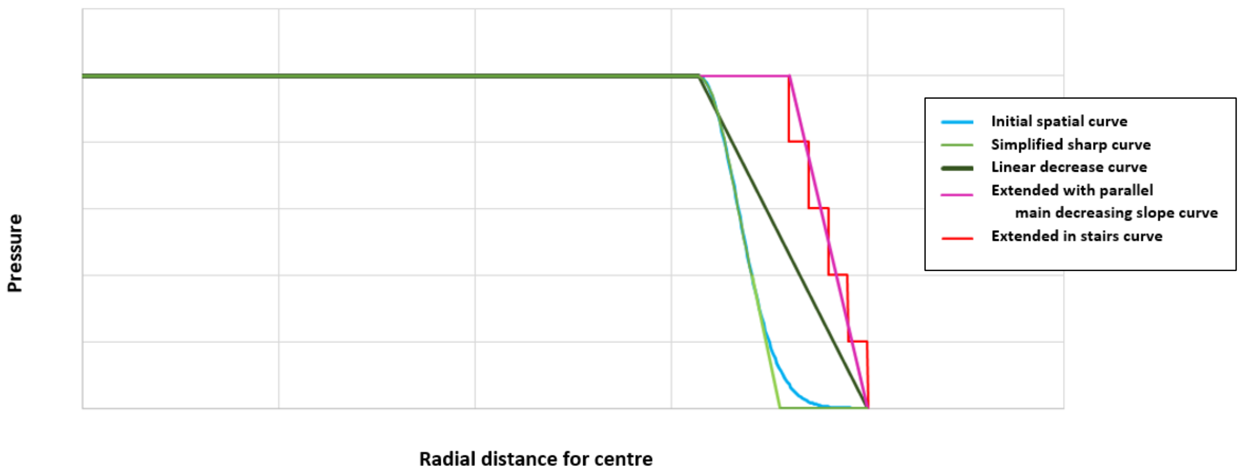

Fig.6: Different spatial pressure loadings

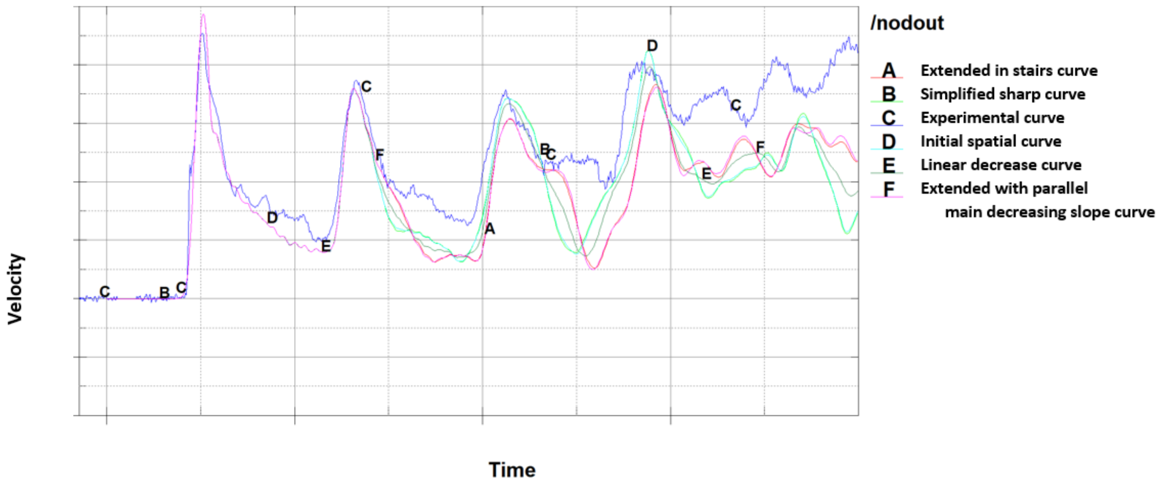

Fig.7: Back face velocity versus time depending on different spatial loadings

In the reference model the pressure is applied on the nodes lying in the laser spot area by using a function automatically calculating the right amount of pressure to be considered taking into account both spatial and temporal loading curves.

Finally, however the *MAT_TABULATED_JOHNSON_COOK was here identified to be the best choice, others material cards have been tested to quantify the influence of taking into account specific material properties such as the strain rate dependence, the discrimination between tension and compression behaviour, the need of an equation of state, the mathematical law used to represent the behaviour (tests were made with a Johnson-Cook for example) … Indeed, the *MAT224 is a complex law that implies to perform many material characterisation tests to get all the necessary data to fill the LS-DYNA card. It is quite unusual to be able to use such a precise but complex card. Other metallic material will probably be considered in further assembled structure, hence this additional work on Aluminium 2024.

Extra validation works have been carried out thanks to other experimental results. Once every sensitivity study performed and a first modelling strategy extracted from this work, analyses on composites have been realised.

4 First applications on composites

4.1 Numerical model

Composites material being anisotropic it is not possible to use a 2D axisymmetric model in order to reduce computation time. The unidirectional Carbon Fibre Reinforced Plastic (CFRP) considered here has its fibres oriented at 0° and 90°. A “fake 2D” model have been created: Only a slice on the composite is considered (one element through the slice extent) with 2 symmetry planes facing each other on each side of the slice. However not really correct this model is much faster to run than a 3D one and then enables to carry on multiple sensitivity studies quickly. Nonetheless a quarter 3D model has also been created to assess the reliability of the fake 2D model.

A *MAT_ENHANCED_COMPOSITE_DAMAGE is used to represent the composite plies and a *MAT_ELASTIC_PLASTIC_HYDRO with an Gruneisen equation of state is used to model the epoxy of the interplies. Material data are extracted from previous work on laser impact modelling but only quasistatic properties are considered.

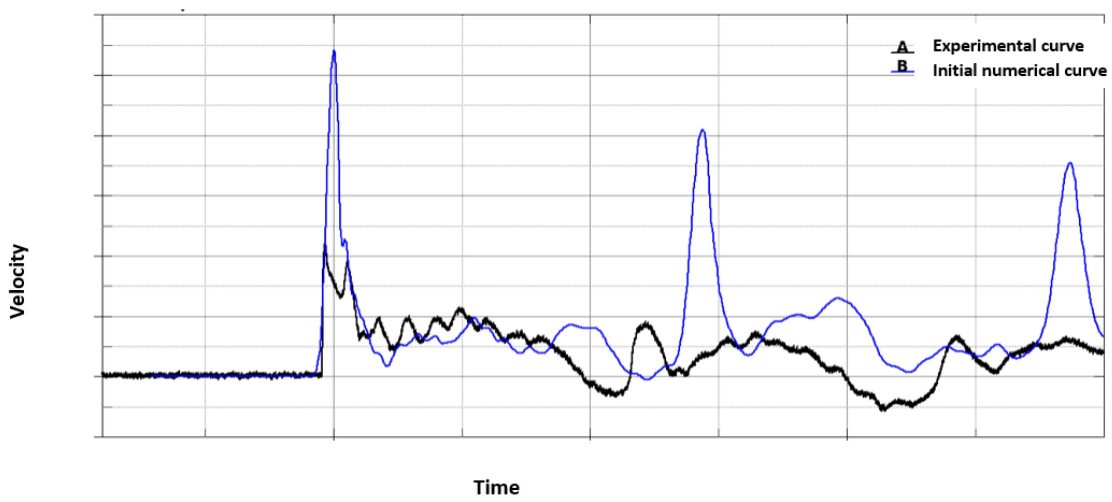

Fig.8: Comparison of back face velocities between experimental and numerical results on a composite plate

Using previously determined modelling strategy, the correlation between experimental and numerical back face velocities is not really good. The peaks magnitude is numerically far beyond the test one and the signals periods do not match either. This observation was expected since previous simulation work highlighted that strain rate effects have to be considered in order to fit the experimental results.

A first “manual” method has been employed (also used in previous works), which consists in applying scale factors to longitudinal and transversal Young modulus. Modifying the longitudinal modulus mainly influences the peaks magnitude, although it does not allow here to get close enough to the experimental magnitude while still applying sensible scale factor. Modifying transversal modulus mainly influences the signal period. By multiplying the initial modulus by 1,5 it is possible to fit the experimental curve period, as shown on the figure 7.

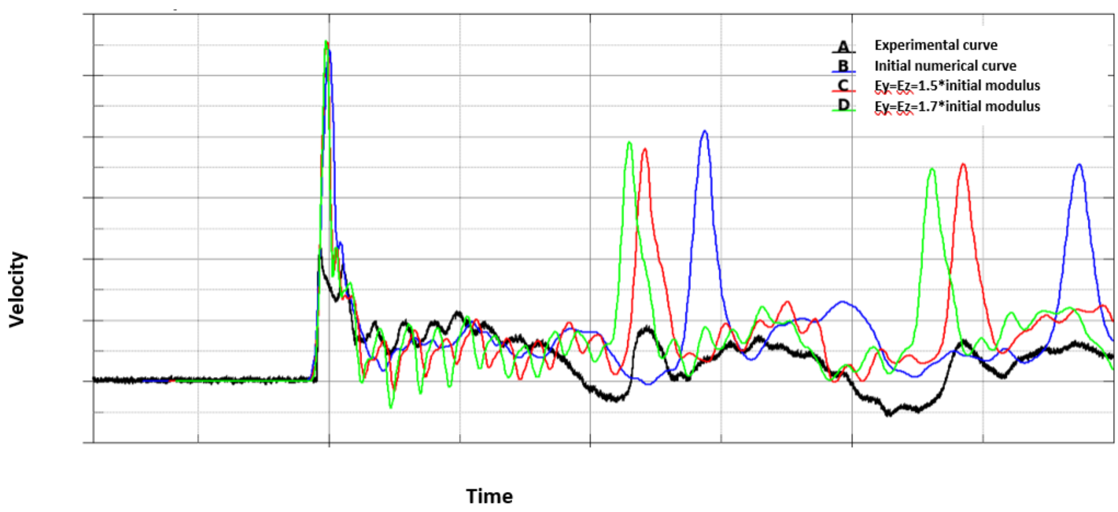

Fig.9: Back face velocity evolution depending on the composite transversal modulus value

The magnitude large difference remains and one can wonder if it does not come from the temporal pressure loading, validated on aluminium and not on composite. A thin aluminium layer is positioned on the composite top surface where the laser impacts the structure in order to protect the composite. However, the configuration remains quite different from the one considered to estimate the pressure loading. Moreover, the laser intensity used here is lower than the range of intensities for which the formula were validated. Previous studies showed that it was necessary to apply scale factor on the temporal loading profile in order to match the velocity first peak magnitude. The scale factor to be used so as to match the first peak magnitude in this case is equal to 0,38.

Additional validation studies on the same structure with different laser intensities or with different layer thicknesses have shown that these factors (on modulus and pressure loading) cannot be generalised and need to be determined for each particular configuration.

Using the previously identified scale factors, fake 2D and quarter 3D models have been compared. As it can be observed on the figure below, the 3D model enables to better catch the negative parts of the back face velocity signal and the second peak magnitude. The shock waves propagation in the direction normal to the slice plan (which is not correctly represented with the fake 2D) influences the results and improves the correlation with the experimental velocity. Considering the fact that the 3D model computation time on twice the number of CPUs is around 15 times longer than the fake 2D, the fake 2D remains interesting to consider for preliminary studies, especially as the corresponding results are not so far from the 3D ones.

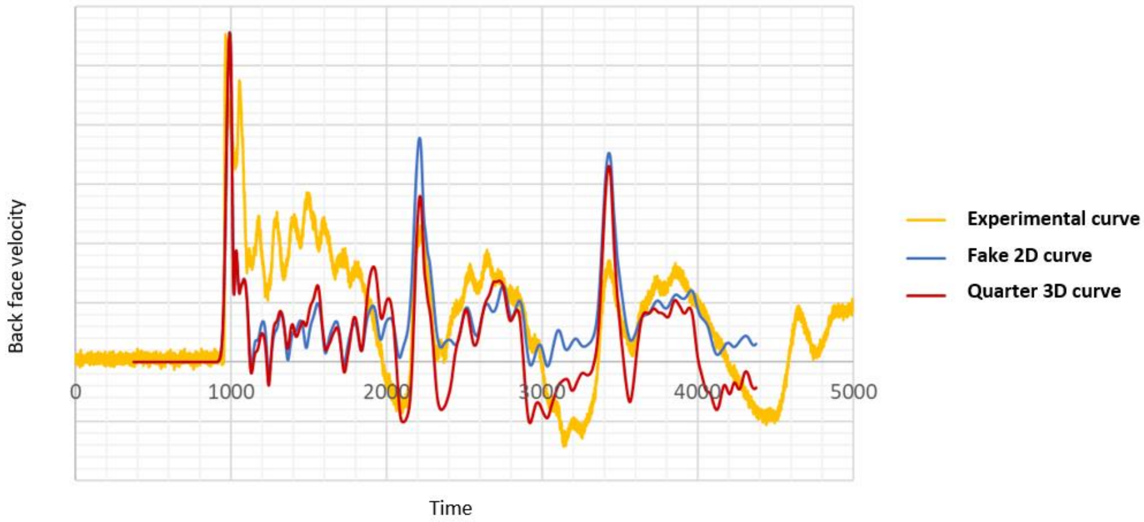

Fig.10: Comparison of back face velocities between experimental and numerical results depending on the modelling strategy

Other analyses have been performed but none has enabled to catch the "bump" that can be observed after the first peak. Different modellings of plies interfaces have been looked at but further work is being carried out on tiebreak contacts and cohesive elements in order to determinate the most appropriate strategy. This is especially important since one of the project objectives is to break adhesive interfaces between composites assemblies.

The figure 9 shows the XT diagram for the CFRP composite studied here. Once again, good accordance can be observed in between compression waves reaching the rear side of the sample and the back face velocity peaks. The intermediate smaller peaks coming from the wave reflections at each ply interface can also be observed.

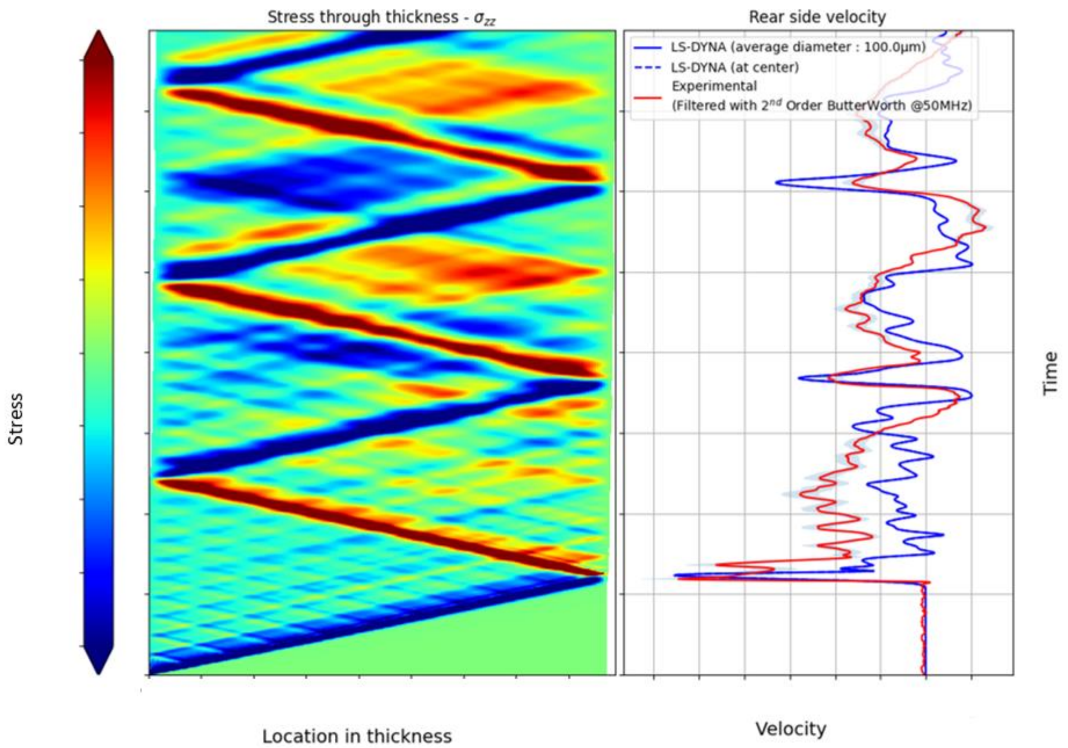

Fig.11: XT Diagram for the quarter 3D model representing laser impact on CFRP composite

5 Conclusion and perspectives

The LASAT technology appears to be 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 automatised 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…).
DynaS+ has started the project by looking at Aluminium plates in order to better understand the shock waves propagation phenomena and run many sensitivity studies so as to extract a first modelling strategy. Then composites have been looked at. New adjustments are necessary and work is still in progress in order to better fit the experimental data (adaptation of the temporal pressure loading…). Additionally, experimental tests have been performed on epoxy samples in order to better characterise them. Limited data are generally available for epoxy materials and their variability seems to significantly influence the waves propagation. Laser impact on epoxy have also been carried out. All these data are being investigated. In parallel, a work on the interfaces modelling within bonded structures is in progress. Comparison between tiebreak contacts, cohesive elements, their different options and how they influence correlation with experimental results will enable to choose the “best” strategy. Composites assemblies models will be fed by these studies and once validated thanks to further experimental tests, double laser impacts will be looked at. Indeed, they enable to increase the maximum possible stress within the structure and more surely position this maximum in the desired location (especially the symmetric configuration). Finally, DynaS+ is also working on developing new post-processing tools to facilitate the visualisation, understanding and analyses of the physical phenomena.

6 Acknowledgments

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7 Literature

[1] Sagnard, M.; Ecault, R.; Touchard, F.; Boustie, M.; Berthe, L.; Development of the symmetrical laser shock test for weak bond inspection. Optics and Laser Technology, Elsevier, 2019, 111, pp.644-652. 10.1016/j.optlastec.2018.10.052. hal-02063467

[2] Ecault, R.; Touchard, F.; Boustie, M.; Berthe, L.; Dominguez, N. Numerical modeling of laser-induced shock experiments for the development of the adhesion test for bonded composite materials. Composite Structures 2016, 152, 382–394. doi: 10.1016/j.compstruct.2016.05.032.

[3] Scius-Bertrand, M.; Videau, L.; Rondepierre, A.; Lescoute, E.; Rouchausse, Y.; Kaufman, J.; Rostohar, D.; Brajer, J.; Berthe, L., Laser induced plasma characterization in direct and water confined regimes: New advances in experimental studies and numerical modelling. Journal of Physics D: Applied Physics 2020, 54. doi:10.1088/1361-6463/abc040.

[4] Ansys LST, “LS-DYNA User’s Manual”, Vol. I, 2020