A contribution to validation of SPH new features

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1 Introduction

Since 1998, the Smoothed Particle Hydrodynamics (SPH) method has been developed by LSTC in LS-DYNA®. This method is called a meshfree method because traditional finite elements are replaced by particles which are not physically connected but mathematically linked. It is an alternative to the classical Lagrangian Finite Elements method and is used to simulate problems where materials are submitted to hydrodynamic deformation modes, such as high velocity impacts. In order to improve the capabilities of SPH in LS-DYNA, LSTC recently developed several new functionalities available in the latest versions of LS-DYNA.

The first new feature is the possibility to choose a Lagrangian kernel for SPH particles, which means there are always the same neighbors for one SPH node (more stability in tension). The second option is Hybrid SPH / Solid elements, designed to couple the benefits of both SPH and Lagrangian finite elements. With these new Hybrid elements, it is now possible to switch from SPH to solid elements using certain criteria and to realize a better transition between SPH and finite elements areas (no more tied contacts needed).

This paper presents the DynaS+ contribution to the test and the validation of these new SPH options. Simple test cases and more complicated cases representative of industrial problems have been performed to assess the behavior and the interest of these new features. All tests have been conducted using LS-DYNA V970 R6.0.0 released in 2012. A comparison with older modeling ways will show the benefits they already bring, and the ones they will bring in the future, when their development will be completed.

2 New Lagrangian SPH formulations

The first calculation presented here deals with SPH formulation based on a Lagrangian kernel, in contrast with Eulerian one, which are historical SPH formulations in LS-DYNA. Lagrangian formulations appeared in recent versions in order to correct some limitations of Eulerian formulations.

With Eulerian ones, the smoothing length (support) of a particle changes through the calculation. As a consequence, the neighborhood of each particle needs to be updated at each time step. This operation takes quite a long time in the calculation process, and is associated with a recurrent problem in SPH: tensile instabilities which appear in areas where large deformations occur. In the case of a Lagrangian kernel, the neighbors'list of each SPH particle is defined in the initial configuration and remains constant throughout the whole calculation. It means that the support of a particle follows material deformations in order to always keep the same neighbors. It provides a solution to solve tensile instabilities but leads in exchange to a more limited use in the treatment of large deformations.

The work realized in this study tends to demonstrate the capabilities of formulations based on a Lagrangian kernel to overcome tensile instabilities. For that purpose, a simple model of a beam in 3-points bending has been defined as shown in the Figure 1 below.

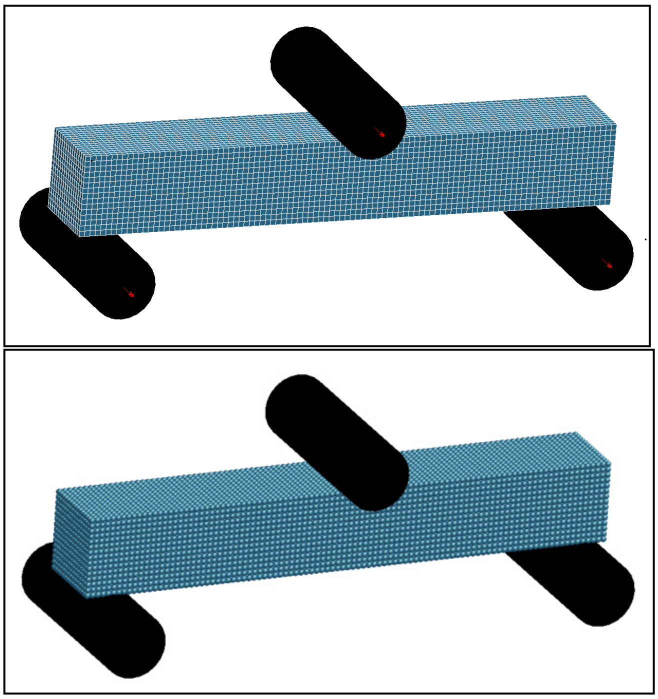

Figure 1 : models of 3-points bending in Finite Elements (at the top) and SPH (at the bottom)

A Finite Elements model has been realized in order to compare Eulerian and Lagrangian SPH formulations with a "standard" FE solution.

The beam is composed of steel associated with *MAT_PIECEWISE_LINEAR_PLASTICITY. The two cylinders under the beam are fixed and the third one is moving down, all are defined using *RIGIDWALL_GEOMETRIC_CYLINDER keyword.
Deformed views for the different simulations tested are presented on the Figure 2 below. We can clearly identify that a numerical fracture appears for the Eulerian formulation n°6 (fluid formulation with renormalization) on the lower side of the beam (beam area where the tensile stress is maximal) whereas the SPH formulation n°8 (Lagrangian with renormalization) reproduces correctly the deformed shape of the Finite Elements model.

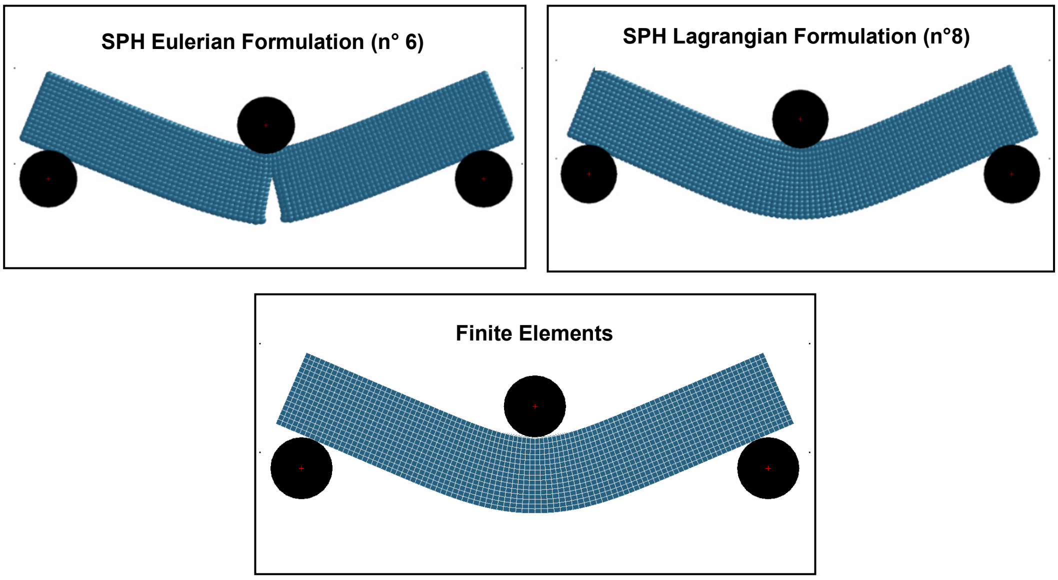

Figure 2 : views of 3-points bending simulations for different types of formulations

Every SPH formulations have been tested with this configuration. Among all formulations, only the two Lagrangian ones (n°7 and n°8) can get a result without numerical fracture.
Another way for detecting failure under the beam is to observe evolution of Von Mises stresses in the middle of the lower side of the beam (where fracture is supposed to appear) for the different formulations (see Figure 3). We observe that the curves D, E and F (corresponding to Lagrangian SPH formulations and Finite Elements) have the same ascending slope throughout the simulation whereas all other ones undergo a drop at a moment. That is linked to the rupture which releases some of the energy contained in the beam and reduces its stress state. We also remark that the curve E of formulation n°8 (renormalized Lagrangian) is particularly close to the reference, compared to the D (n°7, standard Lagrangian) which is farther away.

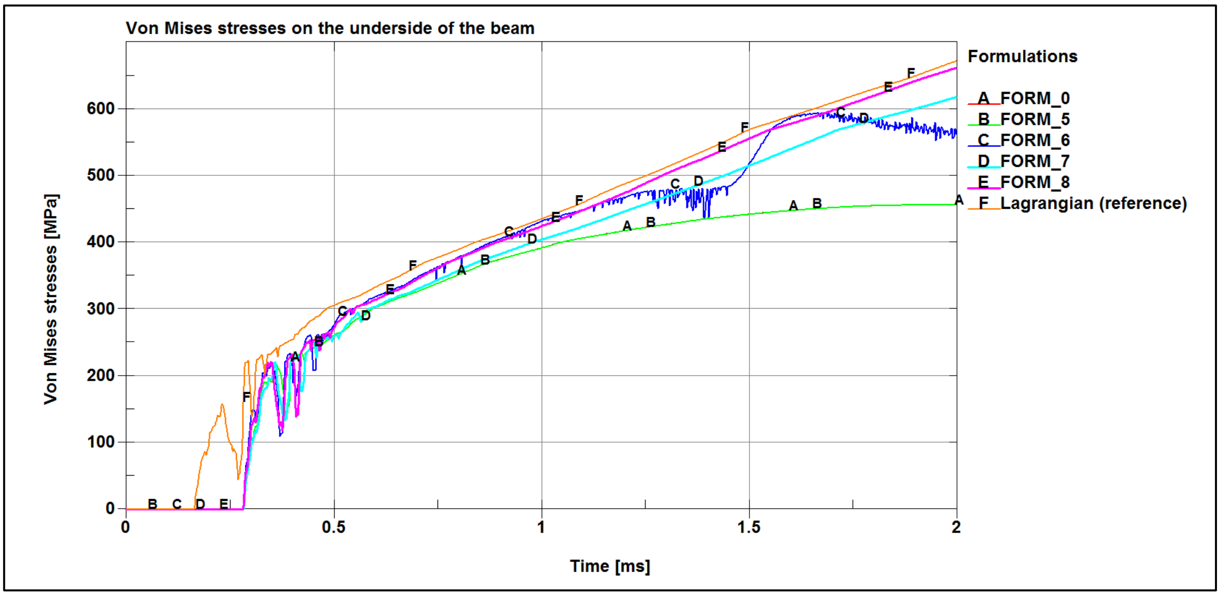

Figure 3 : evolution curves of Von Mises stress under the beam for different formulations

Finally, we also can compare the Von Mises stresses levels between the Finite Elements and the two SPH Lagrangian formulations to confirm the quality of simulations. Results for the standard Lagrangian formulation (n° 7) seem to be quite far from the Finite Elements reference but the renormalized one (n°8) shows very good match. Similar comparisons have been done with pressure and plastic strains level and lead to the same conclusions.

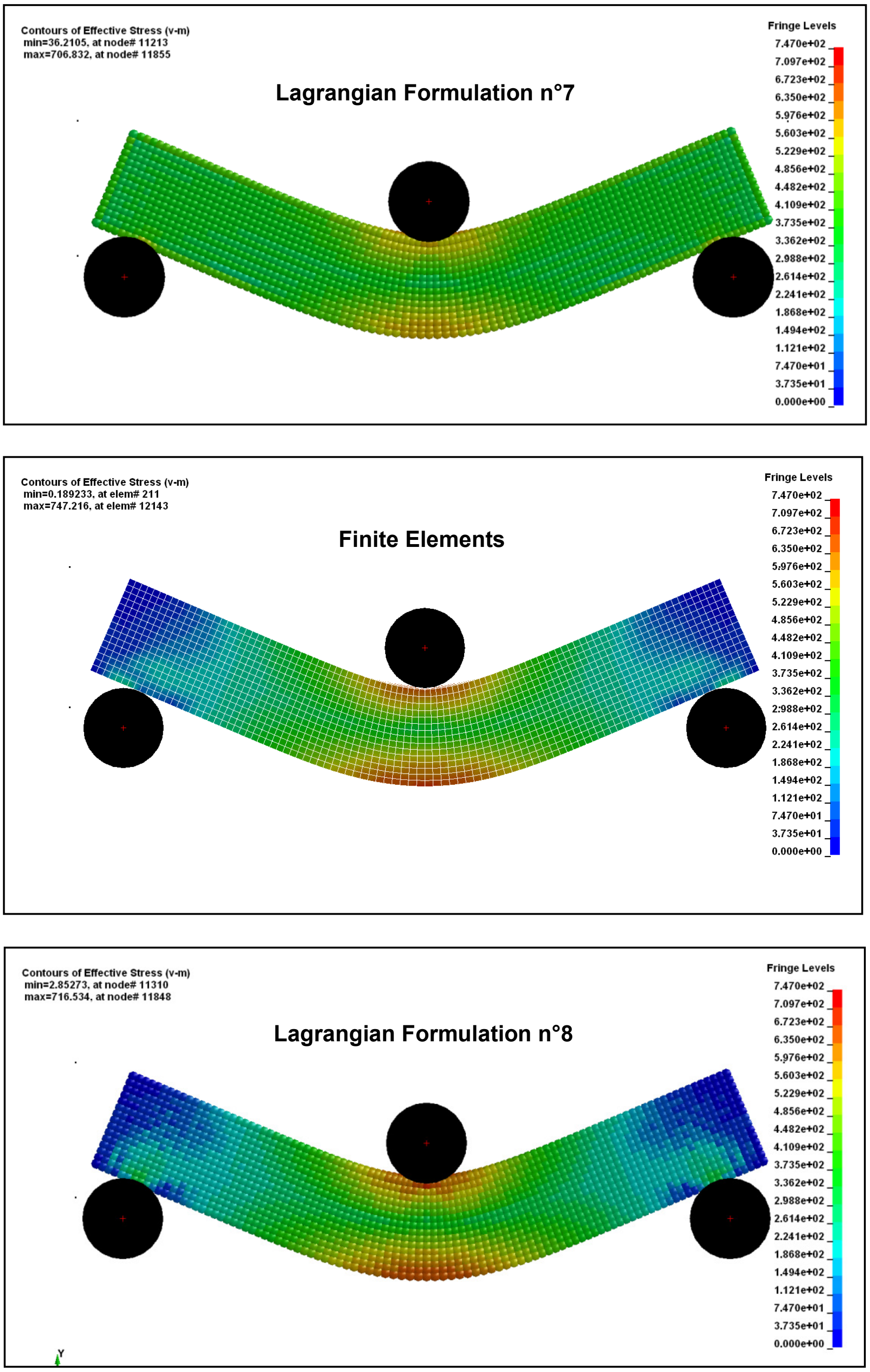

Figure 4 : Von Mises stresses for SPH and Finite Elements models

We can conclude that the new SPH formulations based on a Lagrangian kernel show very good capabilities to overcome tensile instabilities. Even if one of these formulations presents approximate results compared to a reference model built in classical Finite Elements, general results are promising and permit to be enthusiastic concerning the future of SPH method. These new Lagrangian formulations will have their full interest when the work in progress to allow a switch from Lagrangian SPH kernel to Eulerian SPH kernel during a calculation will reach maturity.

3 Hybrid SPH/Solid Elements

The second important SPH option implemented recently is the possibility to use hybrids elements coupling different behaviors and characteristics of both SPH nodes and Lagrangian Finite Elements in the same volume. This really innovative functionality can be used in two different ways: you can either couple the behavior of SPH and Finite Elements in the same physical space during the whole simulation, which is overall used to improve a transition area between pure SPH and pure Finite Elements, or you can switch from Finite Elements to SPH using a certain criteria. Two examples are developed in this paper showing the capabilities of this new SPH feature.

3.1 SPH/Lagrangian Finite Elements transitions

The first option investigated concerns transitions between pure SPH and pure Finite Elements. Historically, tied contacts are used to realize this kind of transitions but we can find some limitations with this method. Indeed the difference of behavior of the two entities implies that there can be some signal reflections at the boundaries of these domains. As a consequence, hybrid elements have been developed so as to realize better transitions.

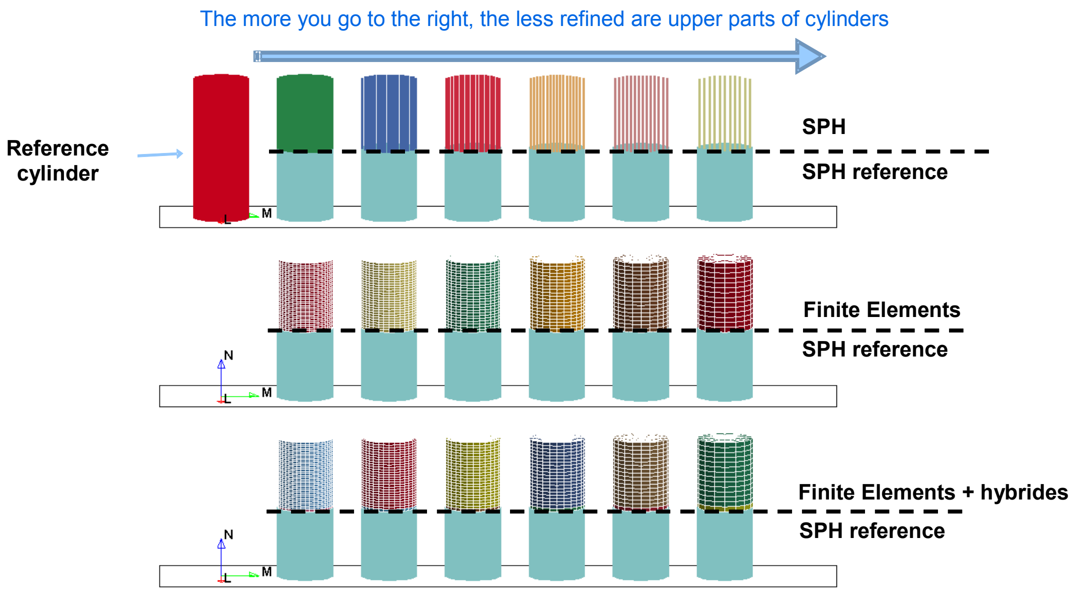

Figure 5 : Taylor impacts' model

The study carried out deals with a set of 19 metallic cylinders shared in 3 lines that we can see on the Figure 5 above. The construction of this model is quite complex and deserves an explanation. Except the reference cylinder (situated at the top of the image, to the left, in red), every cylinder is composed of 2 parts:

- The lower part is in SPH and is the same for each cylinder, with an inter-particle distance of 0.14 cm. It corresponds to the turquoise blue parts on the Figure above.
- The upper part is the one which makes a difference between all cylinders :
  - For the ones situated on the upper line, the upper part is composed of SPH. The cylinder the more to the left (with a green top), has an inter-particle distance of 0.14 cm like the reference. Then, distances between particles gradually increase when we move to other cylinders to the right, until the last one with an inter-particle distance of about 0.35 cm for its upper part.

- For cylinders situated on the second line, it is the same principle with upper parts in classical Finite Elements. Transitions are realized with a *CONTACT_TIED_NODES_TO_SURFACE_OFFSET. Mesh sizes also range from 0.14 cm to the left, to 0.35 cm to the right

- Finally, the last line of cylinders is quite similar to the previous one, excepted that cylinders all have a row of Hybrid elements between the SPH lower part and the Lagrangian upper part.

The aim of this model is to evaluate the quality of transitions with hybrids, compared to transitions with tied contacts only. For that, an initial downward velocity of 200 m/s is given to all cylinders to simulate a Taylor Impact on rigid walls placed at the basis of each cylinder. Then, the pressure signal received by the lower part of each cylinder is measured exactly at the same place on each cylinder (that's why all lower parts have to be strictly identical). And this signal is compared to the one received by the red reference cylinder entirely defined with one single SPH part.

First we can examine results for pure SPH cylinders (the ones on the upper line on Figure 5). We see that results are quite good: curves for different ratios of inter-particle distances are quite close to the reference curve A, except maybe for the two cylinders the more rough (curves E and F) whose curves' amplitudes are significantly different from the reference one. In all cases, the transition does not affect significantly the shape of the signal, it changes the levels obtained. This first result provides guidance when trying to make SPH / SPH transitions to limit the size of a model. To avoid disrupting too significantly the signal, ratio between the smoothing length of the finest part with that of the coarser one must remain low.

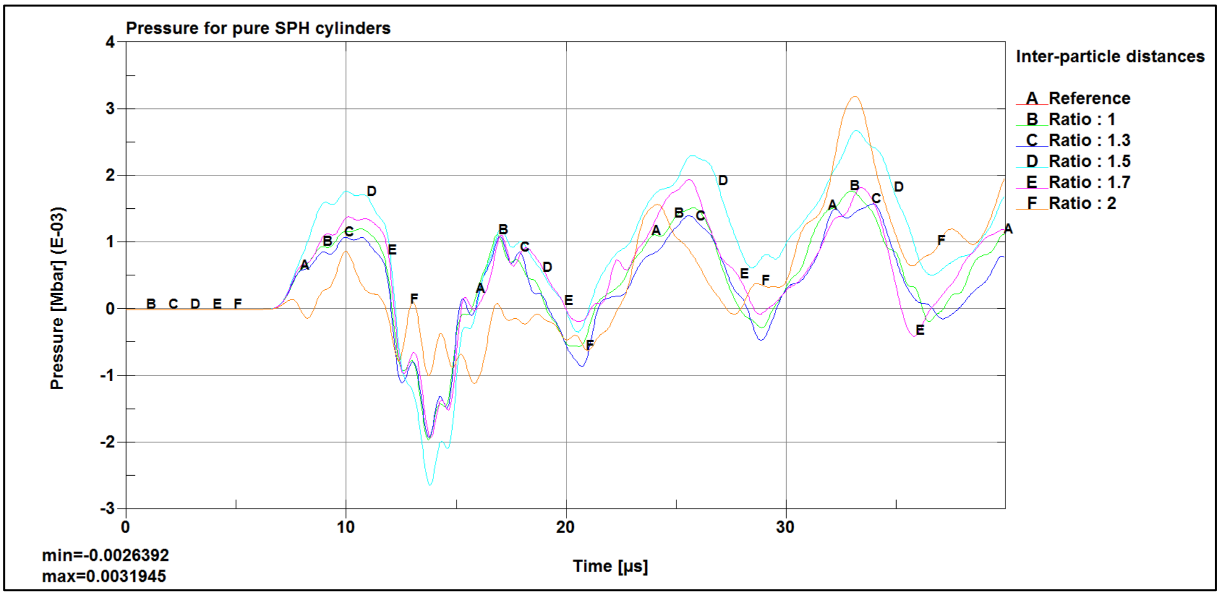

Figure 6 : pressure signal for pure SPH cylinders

If we now concentrate on other types of cylinders, we notice that for transitions done thanks to a tied contact, the pressure signal transmission is rather bad (see on the upper graph on Figure 7). Both signal shape and signal amplitude are largely affected by the tied interface. When we now look at the same graph for hybrids elements transitions (lower graph on Figure 7 below), we observe a real improvement concerning the signal transmission.

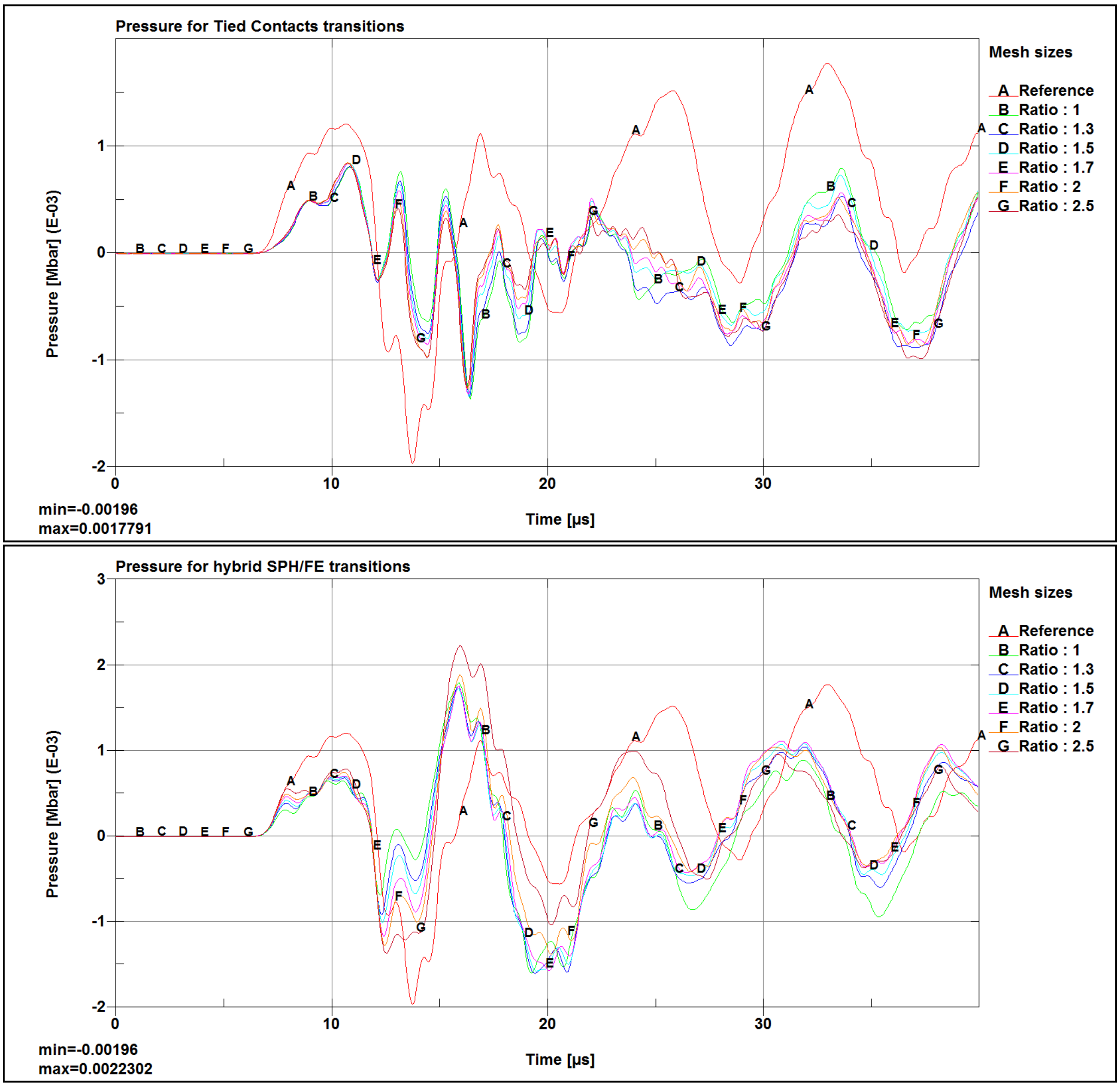

Figure 7 : pressure signals for hybrids and tied contacts transitions

As a result, we can say that the interposition of hybrid elements between pure SPH and traditional Finite Element have permitted to realize better transition between these two entities. Even if the wave shock transmission obtained with this new feature stays lightly less good than the one obtained with a pure SPH/SPH transitions (see Figure 6), the improvement compared to a transition realized with a tied contact is obvious and permits to bring some first elements for the validation of this new SPH option.

That is important to notice that these conclusions are valid for a certain range of velocity. Other investigations have to be done with higher velocities to validate totally this new functionality.

3.2 Switch Finite Elements / SPH

As said in the beginning, it is also possible thanks to hybrid elements to switch from Finite Elements to SPH using a certain criteria in order to couple the benefits of both types of elements. With this technique the "activation" of SPH particles happens once Finite Elements have reached a too high level of distortion to continue the simulation. At this moment, they are eroded (they disappear) and let particles take over to terminate the calculation. That is usually done so as to optimize computation times: SPH method is generally more expensive than Finite Elements to solve the same problem, so it is better to use it only when necessary, which means when deformation levels are too important. Consequently, the technique is to start a classical finite element calculation and then switch to SPH when it becomes necessary.
To illustrate this functionality, a 3D high velocity impact of a spherical projectile (in SPH, with an initial velocity of 2 km/s) on a thin plate has been realized in three different ways:

A. A pure SPH model
B. A model with only the middle of the plate (impact area) made in pure SPH
C. A model with the middle of the plate made in hybrid elements with a switch to the SPH at a plastic strain level of 10 % in the Lagrangian material.

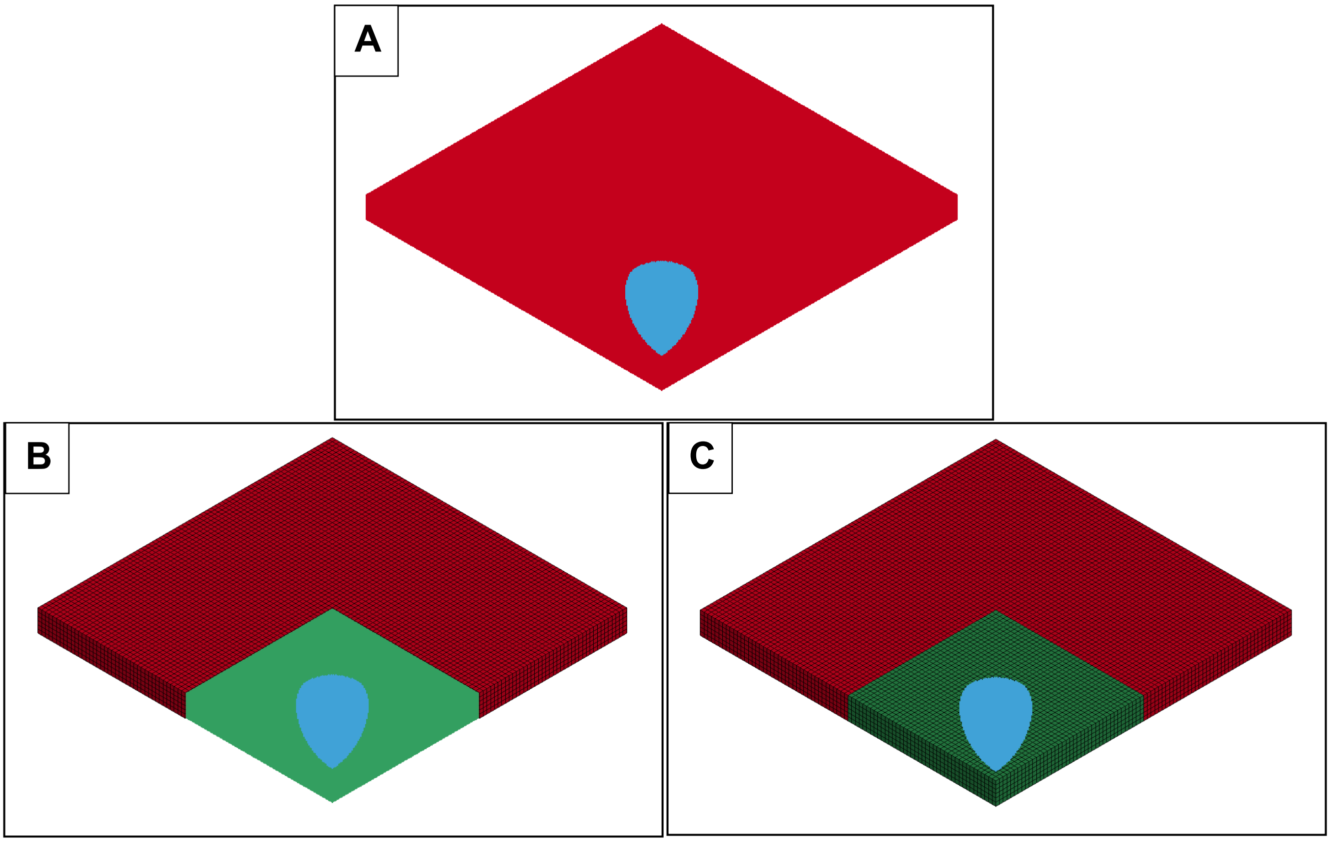

Figure 8 : different models of 3D Hyper Velocity Impacts studied

The aim of this study is the comparison of these three techniques in terms of computation times. Also, measurements have been done to validate the quality of models, on both dimensions of the hole in the plate after the collision, and the particles cloud generated by the impact.

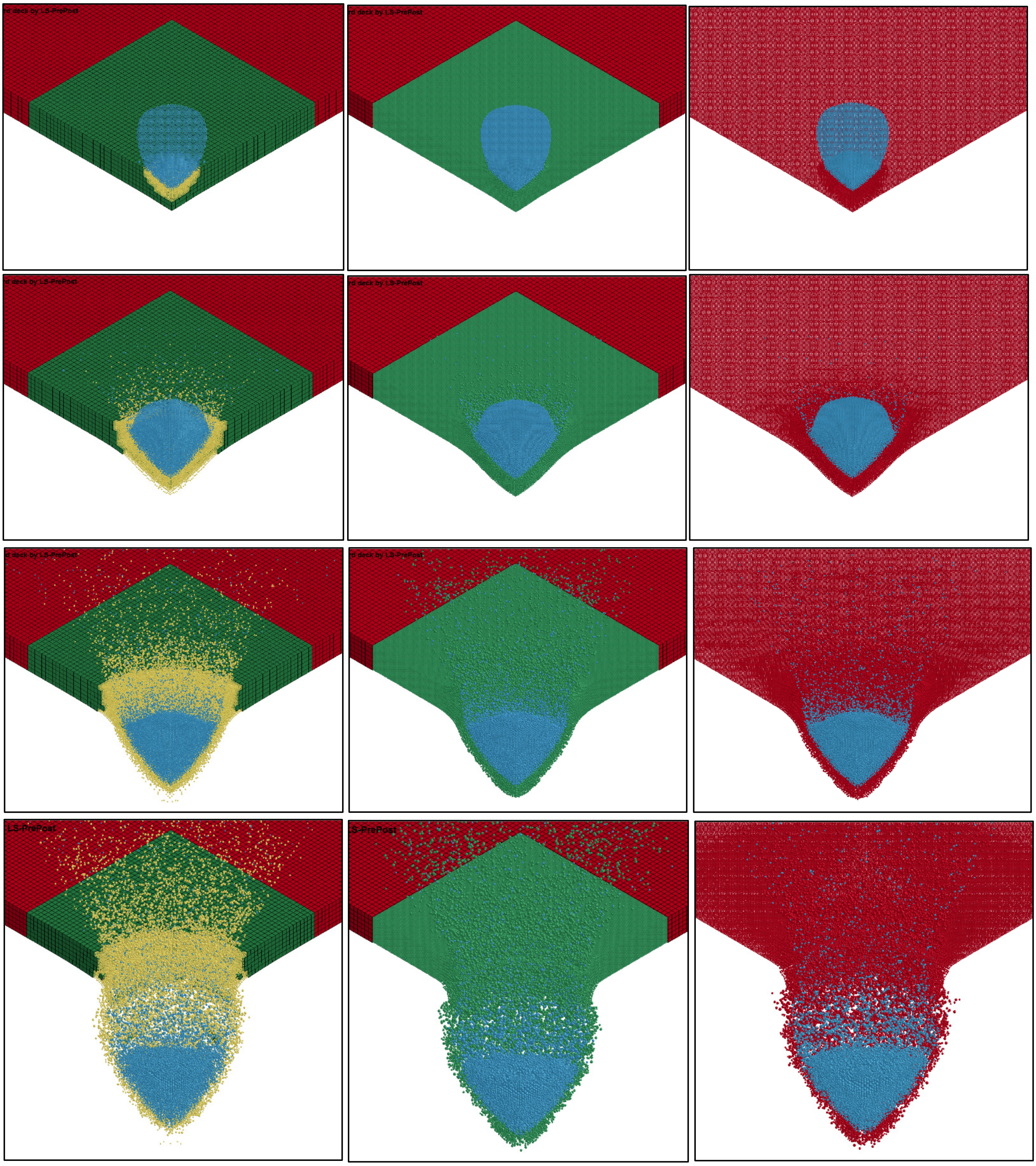

Figure 9 : Views of the three models of hyper velocity impacts

The Figure 9 above shows different views of the three simulations. The one with hybrid elements is the most on the left. We see that from the beginning of the contact between the projectile and the plate, some finite elements get eroded and particles appear to take over the simulation, which is perfectly normal since the high velocity of the phenomenon quickly implies distortion levels higher than 10%. Then, plate elements of the impact area continue to erode while the sphere perforates the plate.

Three distinctive features have been measured on final results of calculations (as shown on the Figure 10 below):

- Particle cloud width W generated by the collision
- Particle cloud length L
- Hole diameter D

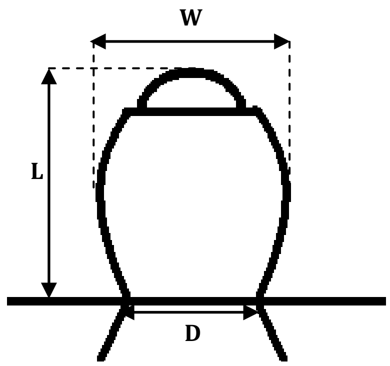

Figure 10 : measurements done on final results

We can see in the following table that results are very similar from a configuration to another. Except for the hole diameter, standard deviation does not exceed 0.04 which shows very good first results. We can explain the fact that the measurement about the hole diameter for the model C is a little more distant from other ones because the impact area in this case is made in Finite Elements with a mesh size of 0.05 cm, whereas it is made in SPH in models A and B, with a inter-particle distance of about 0.016 cm. As a consequence, measurements cannot be as accurate in model C as in other models, which can explain this standard deviation of 0.179.

	Pure SPH (Model A)	**SPH in the impact area (Model B)**	**Hybrids in the impact area (Model C)**	**Standard deviation**
Particle cloud width [cm]	3,019	2,943	2,992	0,039
Particle cloud lenght [cm]	2,981	2,952	2,989	0,020
Hole diameter [cm]	1,590	1,575	1,892	0,179

Table 1 : values measured on different models at the final state of the simulation

Concerning now computation times, we see on the Figure 11 below that the replacement of SPH particles by hybrid elements for the impact area permits to largely reduce calculation times which confirms the interest of this new technology.

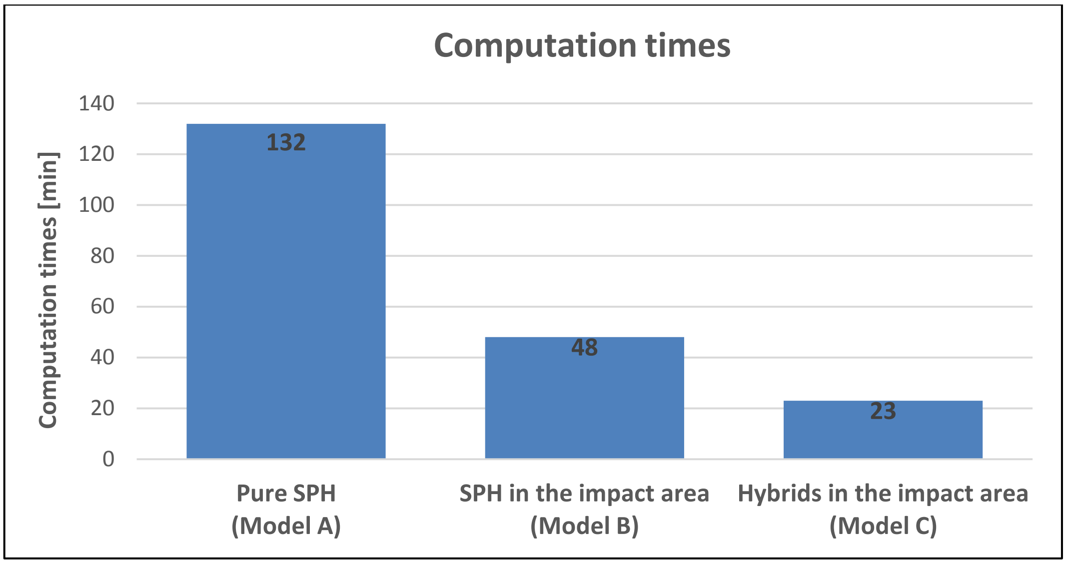

Figure 11 : computation times for three models studied

4 Conclusion

This paper aims to investigate the different new features appeared in recent versions of LS-DYNA and related with SPH method. Different tests were done to bring some elements in order to evaluate capabilities of these new technologies: SPH formulations based on a Lagrangian kernel and Hybrid SPH/Solid Elements. Results obtained allow to be enthusiastic, first because new SPH formulations shown good qualities concerning tensile instabilities which stays one of the major problems with SPH nowadays. Other limitations with this calculation method concern physical transitions with classical Solid Elements on the one hand, and calculation times on the other hand. That's precisely on that fields that new Hybrid elements are very interesting since we saw different types of applications where this kind of element bring obvious improvements. Large studies still have to be done to carry on the investigation of these options which should permit to SPH method to develop its applications possibilities in future years.

5 Summary

The aim of this paper is to bring a contribution to validate some new SPH options appeared in recent LS-DYNA versions so as to improve capabilities of SPH method. The first functionality is the possibility to choose a Lagrangian kernel instead of an Eulerian one, in order to avoid numerical fractures in areas with large tensile distortions. Simulations of beam in 3-point bending have been investigated as a consequence, and have shown very good results. The second option tested is the hybrid SPH / solid elements allowing first to improve transitions between these two different kinds of elements, and also to make a simulation with a “switch” between SPH and Finite Elements with a certain criteria in order to optimize computation times. Two types of simulations have been realized and show once again good capabilities of this new technology for both applications.

6 Literature

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