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Orbital debris impacts against spacecraft multiple shields: comparison of hypervelocity experiments and hydrocode simulations

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Abstract

Numerical simulations of Meteoroids and Orbital Debris (M/OD) hypervelocity impacts on spacecraft protection systems have been performed with the hydrocode AUTODYN-2D, using two different numerical techniques. Results of induced damage on a three-plates shield are compared with the Light Gas Gun (LGG) experiment data, and debris cloud expansion and mass distribution are compared with the pictures obtained by X-ray high performance camera. Differences in results between the two numerical techniques are underlined, and the influence of some parameters is discussed.

1 Introduction

A strong impulse has been given to the numerical and experimental study of hypervelocity impacts in recent years, because of the need to protect the International Space Station (ISS) from the M/OD environment in the Low Earth Orbit (LEO). The current strategy to manage the M/OD threat to the ISS is based on implementing state-of-the art shielding against particles up to about 1 cm diameter [1], [2].

Hypervelocity tests and numerical simulations are currently used to design M/OD protection shields. Projectiles fired by LGG in experiments can reach maximum impact velocities in the range of 6÷8 km/s, depending on the projectile mass: since the average debris impact velocity is 10÷11 km/s in LEO, numerical simulations represent a mean to analyze impact phenomena in the velocity range not easily accessible to launch facilities. This creates the need for previous calibration and validation of hydrocodes by correlating experiments and calculations, in order to gain confidence in the possibility to extend the computation philosophy to the high velocity range.

The Committee on International Space Station Meteoroid/Debris Risk Management has recently pointed out [2] the need to improve the current state-of-art of hydrocodes, in order to have an efficient tool for simulating hypervelocity impacts on space structures.

In this paper, two different lagrangian techniques are used to simulate experimental results of hypervelocity impacts against aluminum multiple shields with AUTODYN-2D. Firstly the conventional grid-based Finite Differences (FD) method with the erosion of highly distorted cells. Secondly the more recent Smoothed Particle Hydrodynamics (SPH) algorithm, born in 1977 to simulate astrophysics phenomena [3] and only recently implemented and applied to hypervelocity impact in AUTODYN-2D [4]. SPH is a lagrangian gridless technique, in which values and gradients of variables are estimated at some interpolation points based on known values at the neighbor points, by the use of a continuous and differentiable function (kernel). While retaining the advantages of lagrangian over eulerian techniques, such as computational time saving, better material interfaces definition and account for sophisticated constitutive models with rate and history effects, SPH does not suffer from the problem of tangling, that the large strains to which the materials are subjected in hypervelocity impacts cause to FD grids. In this way there is no need for non-physical erosion algorithms in order to obtain efficient solutions for problems involving high grid distortions. Even if SPH seems to be quite promising in the simulation of hypervelocity phenomena, it has to be said that it is relatively immature compared with standard grid based techniques, and still presents some problems of stability, consistency and accuracy. More studies and researches are needed before it becomes a fully fledged computational continuum dynamics technique.

2 Experimental results

The hypervelocity experiment to test the numerical simulations was performed at the Ernst Mach Institut in Freiburg, Germany, using a two-stage Light Gas Gun, during a test campaign to develop debris shielding for the European Module to be attached to the ISS. A spherical 1 cm diameter aluminum projectile (Al F37) was launched at 7 km/s against a 3-wall target, composed of an external Bumper Shield (1st BS) made of aluminum Al 6061 T6 and 2.5 mm thick, an intermediate Bumper Shield (2nd BS) made of aluminum Al 6061-T6 and 6 mm thick, and a backup wall (BW) representing the pressure shell to be protected, made of aluminum Al 2219 T851 and 0.32 cm thick. The spacings between the 1st and 2nd BS and between the 2nd BS and the BW are 9.0 and 4.2 cm respectively.

An X-ray picture of the expanding debris cloud between the 1st and the 2nd BS at 3.6 and 9.3 μs is shown in Fig. 1. The damage induced by the experiment, shown in Fig. 2, was a clear circular hole in the 1st BS, a large craterized area on the front of the 2nd BS with a little through hole and a large spalled area on its rear side, while the BW had a tiny hole with irregular cracks and large plastic deflection. Obviously, the irregular cracks cannot be reproduced by 2D axisymmetric simulations.

3 Numerical simulations

A normal impact test case has been selected as a benchmark for the performed numerical simulations because of the possibility of using the axial symmetry option, that makes 2D simulations equivalent to 3D ones on axisymmetric projectiles and targets but greatly reduces computation time. Since the simulations must run up to at least 100 μs in order to reproduce the damage induced on the three plates, computation time is a major concern for this problem, while it is not so important for the test cases of Ref. 4. The CPU time is therefore addressed in the discussion of results.

The FD technique, that uses a grid of nodes to simulate the impacting bodies, has already been used to reproduce a similar LGG experiment [5], and has been extended here to assess additional parameters. The projectile is modeled as a sphere with 40 cells along its diameter, while the number of cells along wall thickness is 10, 20 and 8 for 1st BS, 2nd BS and BW respectively, with a total number of 8000 cells.

As in very high velocity impacts cells tend to become extremely distorted until the computation becomes unstable, an erosion algorithm was utilized that removes cells when they have reached an established value of the geometric strain. It is worthwhile underlining that the erosion limit is a purely geometric value without any physical relation to the engineering strain of the material. According to Ref. 5 a value of 250% for this parameter was set in the present work. An option included in AUTODYN allows for the retention of the mass and momentum of eroded cells and this was used in the calculations. This option is very useful in hypervelocity impact simulations against multiple wall structures, to follow the behavior of eroded cells generated in the impact of projectile with the first wall that constitute the "debris cloud" impacting against the back standing walls. However, although mass and momentum are conserved, the energy of eroded cells is artificially removed from the problem.

Thanks to the lack of a grid, SPH is a suitable tool to model hypervelocity impacts, in which large expansive material flow occurs because of phase changes. On the other hand, since variable values at a given point are calculated based on those at neighbor points, the stability of SPH can be compromised if high material expansion causes a reduced number of neighbor particles in some zones. Two different particle sizes (indicated by A and B) were used to model the problem, in order to assess the dependence of SPH method on this parameter. Size A particle dimension was 0.5 mm for the 1st and 2nd BS, 0.4 mm for the BW (with a total particle number of 4728): this size was chosen as a preliminary model to test parameter influence, because of the very small computation time. For size B we chose 0.25 mm for the 1st BS, 0.3 mm for the 2nd BS and 0.4 mm for the BW (with a total particle number of 12610): this allows an exact number of particles (10, 20 and 8 for 1st BS, 2nd BS and BW respectively) along thickness. In fact, according to Ref. 4, SPH works best when particles are regularly spaced at distances of approximately their smoothing length. Furthermore, particle size B is the same as FD cells, allowing a comparison between the two techniques with the same spatial resolution (in general SPH is more diffusive than FD so one should expect to need more SPH particles than FD cells). Projectile particle size was always set equal to 1st BS size.

Material models

The material hypervelocity behavior is simulated in the hydrocode theory by the use of three main models: an equation of state (EOS) that expresses the value of hydrostatic pressure as a function of density and internal energy, a constitutive relation between the deviatoric stresses and strains that takes into account very fast dynamic phenomena such as work hardening, thermal softening and strain rate dependence, and a failure criterion to simulate the loss of load carrying capability of solid materials when shocked to very high energies.

The linear shock EOS was used in Ref. 4 for a single plate problem, while the Tillotson EOS was employed in Ref. 5. In this work both EOS were used to assess their influence by a comparison of results. The shock

EOS does not take into account any material phase change, and it is observed from experiments that a solid-liquid transition of aluminum starts to take place at velocities higher than about 5.5 km/s. The Tillotson EOS can simulate some phase changes, but it is not completely appropriate for the case under study because only solid-vapor transition is considered. The Steinberg-Guinan model for material strength has been used, in which the shear modulus and yield stress are expressed as functions of effective plastic strain, pressure and internal energy. The detailed formulations and constant values used in material models are reported in Ref. 6.

A tensile failure criterion was used to simulate the spall phenomenon, which causes material failure due to the reflection of shock compressive waves, generated during the impact, as tensile waves at the free rear surfaces of projectile and walls. The tensile (negative) value of hydrostatic pressure, over which the material is assumed not to bear any more tensile load, was set at $P_{min} = -1.2$ GPa.

The same material models have been used for the projectile and the three plates, as summarized in the following table.

CASE	NUM. TEC.	EOS	CONST. REL.	FAIL. CRIT.	SIZE
1	FIN. DIFF.	TILLOTSON	STEIN.-GUIN.	HYDRO TEN.	-
2	FIN. DIFF.	SHOCK	STEIN.-GUIN.	HYDRO TEN.	-
3	SPH	TILLOTSON	STEIN.-GUIN.	HYDRO TEN.	A
4	SPH	TILLOTSON	STEIN.-GUIN.	HYDRO TEN.	B
5	SPH	SHOCK	STEIN.-GUIN.	HYDRO TEN.	A
6	SPH	SHOCK	STEIN.-GUIN.	HYDRO TEN.	B

Table 1: simulation cases

Results

The following parameters were chosen for the comparison between simulations and the experimental data (summarized in Table 2):

-1st BS hole diameter

-Debris cloud shapes corresponding to experimental X-ray pictures

-2nd BS hole and spall zone diameters and BW hole diameter.

CASE	DEB. CLOUD AXIAL POS. 3.6 μs (mm)	DEB. CLOUD RADIAL POS. 3.6 μs (mm)	DEB.CLOUD AXIAL POS. 9.3 μs (mm)	DEB. CLOUD RADIAL POS. 9.3 μs (mm)
1	21.3	12.8	57.5	28.8
2	21.2	12.5	58.3	26.7
3	21.6	12.5	56.9	27
4	21.2	11.7	55.5	24.4
5	22.8	12.9	58.8	29.7
6	22.3	11.6	58.4	23.7
EXP.	23	11	58.7	21
CASE	**1ST BS HOLE DIAM. (mm)**	**2nd BS HOLE DIAM. (mm)**	**2nd BS SPALL DIAM. (mm)**	**BW HOLE DIAM. (mm)**
1	21.5	0.3	34.2	0.5
2	20.6	3.2	22.2	0.9
3	24.6-28.6	40	---	45
4	25-28.8	52.4	66.6	37
5	29	50	---	50
6	26-29	42	59	(*)
EXP.	21.6	4	60	3

(*) Not exactly determined because of local numerical instability

Table 2: simulation and experimental results summary

Debris cloud shape

The calculated debris cloud expansion agrees closely with experimental measures. In particular, the axial position is very well simulated irrespective of numerical technique, EOS or particle size.

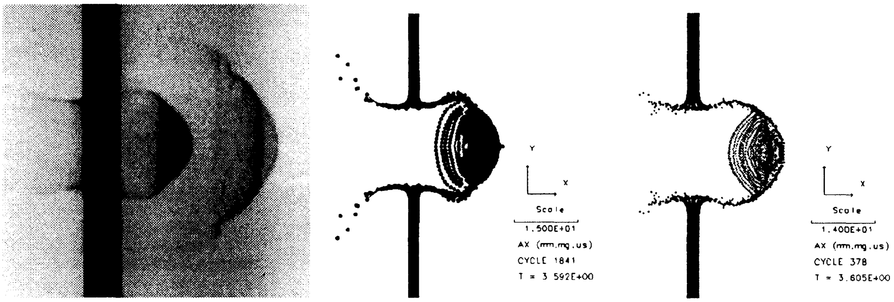

Figure 1: debris cloud shapes at 3.6 μs

The radial position is quite well simulated, with a slight overestimation for all cases, the SPH smaller size simulations giving the best predictions. In Fig. 1 the debris cloud shape at 3.6 μs is shown for experiments (left, with also the 9.3 μs picture), FD (case 1, center) and SPH (case 4, right) models.

Plate damage

The 1st BS hole diameter is well predicted by FD simulations. The final shape of the hole obtained with SPH cannot always be exactly defined, because particles tend to move away in the late stages of simulation, and for this reason some hole diameter ranges are reported in Table 2. Anyway the final diameter is always overestimated.

FD and SPH predictions of 2nd BS damage present marked differences. Cases 1 and 2 show a very small central hole on both 2nd BS and BW, but this is due to high velocity eroded cells concentration on the symmetry axis: this is a typical anomaly of axisymmetric simulations with erosion algorithm, without physical relation (see Fig. 3).

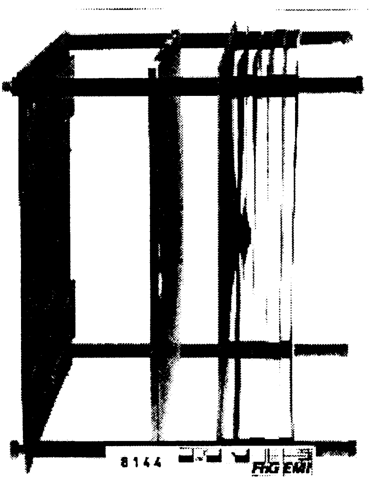

Figure 2: impacted target

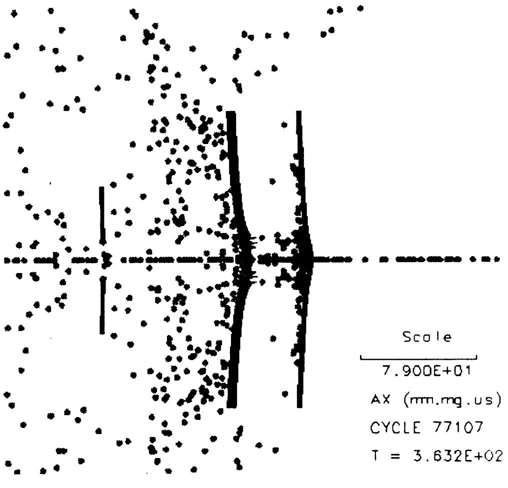

Figure 3: case 1 simulation at 363 μs

The spall diameter is underestimated, but with the Tillotson EOS a better estimation is obtained than with the shock EOS. With the FD technique, the spalled material tends to move away from the plate forming very narrow and long strips, that can also reach the BW before completely detaching from the 2nd BS (Fig. 4, left side), and this seems not to reproduce the physical phenomenon properly.

The spall phenomenon on the 2nd BS is not well simulated in SPH cases with the lowest spatial resolution: a large plate area detaches because of the debris cloud impact, consequently producing a serious damage on the BW that is not in agreement with the experiments. The calculated failure of the BW seems anyway to be incorrect beyond the effect of the material detached from the 2nd BS, with an unrealistic plastic deflection.

SPH seems to work slightly better increasing the spatial resolution. With size B the spall of 2nd BS rear face is well simulated in the initial phase, when a small hole is created and spall fragments clearly detach, travelling toward the BW (Fig. 4, right side).

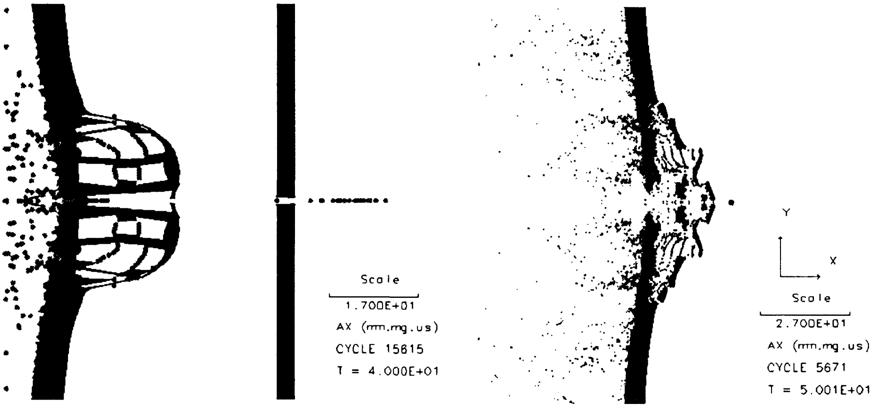

Figure 4: spall simulation for case 1 (left, 40 μs) and case 6 (right, 50 μs)

However, the remaining portion of the spalled zone initially attached to the plate, detaches at a later stage of the calculations and impacts the BW. The final spall diameter is in good agreement with the experiments, but the hole diameter is obviously greatly overestimated. The overestimated hole size may be due to numerical fracture of the remaining unspalled part of the plate; numerical fracture can happen in SPH solutions because of the well known problem of local instabilities.

The BW failure mechanism is unrealistic also in these cases. Particle number along BW thickness was not increased from size A to size B, and a higher spatial resolution may give better results. However, since the BW damage is strongly affected by the quantity of material detached from the 2nd BS, a finer modelization of the BW is not expected to improve the results, until the 2nd BS damage is correctly simulated.

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Computation time

The approximate computation time to carry out the different simulation cases up to about 100 μs, on a PC 200 MHz MMX 128 RAM Mb, is 30 hrs for FD, 2 hrs for SPH size A and 20 hrs for SPH size B cases.

Energy and momentum conservation

The global energy and momentum balance can not be compared directly to the experimental results, but their evaluation can be important to have a measure of the quality of the solution. With the FD technique two sudden drops of the global energy value were observed in correspondence to the projectile impact against the 1^{st} BS (zero time) and to debris cloud impact against the 2^{nd} BS (at about 13 μs). Energy remains almost constant during the movement of the debris cloud toward the 2^{nd} BS and then after the interaction until the end of the calculations. This is due to the erosion algorithm which removes highly distorted cells and the corresponding energy from the problem while keeping their mass and momentum, which is exactly conserved. Because of the low velocity of spall fragments, no cell erosion with relevant energy decrease was observed during their interaction with the BW. Energy and momentum balance could not be evaluated for the SPH simulations, because of the not straightforward behavior. It has to be said, however, that the SPH processor in AUTODYN is a beta version, and the implementation of energy and momentum balance is still under improvement.

4 Conclusions and further developments

The normal impact of a 1 cm diameter aluminum spherical projectile at 7 km/s against a double bumper aluminum shield was simulated with AUTODYN-2D hydrocode, using the axial symmetry option. Two different numerical techniques were used: a finite differences model with geometric erosion algorithm and the SPH method. The influence of two EOS (Tillotson and shock) and SPH particle size was examined. Numerical results were compared with a hypervelocity LGG experiment.

With the FD method, target damage is well simulated on the first plate but is underestimated on the other two plates. This technique shows the two non-physical aspects of high velocity eroded cells concentration on the symmetry axis and the inability to model detached spall material because of the grid-based nature.

With SPH the damage on the 1^{st} BS is slightly overestimated, and its precise definition is not easy because of the SPH particles irregular position after deformation. The spall phenomenon on the 2nd BS is not well predicted with the lowest particle size, and it seems reasonable with the highest one only in the first stages of failure process. Damage on the BW, that was always simulated with a coarse particle array, is not consistent with the experiments; one of the reasons is certainly the overestimated amount of material that detaches from the 2nd BS.

A good estimation of debris cloud shape was obtained in all cases.

FD technique, because of its inherent limitations, seems not to offer many possibilities of parameter variation in order to improve numerical predictions. On the other hand, even if SPH results are still far from a realistic prediction of the whole damage on a 3-wall target, it must be remembered that the study of SPH parameter influence is largely incomplete.

Future areas of study should concentrate on improving the prediction of 2nd BS spall failure (that is the phenomenon whose simulation is more uncertain but strongly affects the final ballistic shield performances), the use of an EOS that properly takes into account the solid-liquid phase transition (e.g. Sesame tables), the increasing of spatial resolution (which implies heavy penalties on computation time), the variation of the smoothing length (that is the distance below which SPH particles interact) and some other parameters such as the artificial viscosity coefficients and the spall stress.

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