Meshless modelling of dynamic behaviour of glasses under intense shock loadings: application to matter ejection during high velocity impacts on thin brittle targets

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Abstract. The purpose of this study is to present a new material model adapted to SPH modelling of dynamic behaviour of glasses under shock loadings. This model has the ability to reproduce fragmentation and densification of glasses under compression as well as brittle tensile failure. It has been implemented in Ls-Dyna software and coupled with a SPH code. By comparison with CEA-CESTA experimental data the model has been validated for fused silica and Pyrex glass for stress level up to 35GPa. For Laser MegaJoule applications, the present material model was applied to 3D high velocity impacts on thin brittle targets with good agreement in term of damages and matter ejection with experimental data obtained using CESTA’s double stage light gas gun.

1. INTRODUCTION

The various instruments used in the Laser MégaJoule (LMJ) experiment chamber will undergo many aggressions resulting from target disassembly. In this study, the authors only focus on potential impacts of debris and shrapnel on fused silica optical debris shields. The Main Debris Shields (MDS) are placed in front of each laser way out and thin Disposable Debris Shields, DDS, might be used to stop droplets and substantially reduce very small shrapnel cratering on MDS. But ejecta from the rear surface and penetration through the DDS are likely to damage the MDS and seed new laser damage sites. Space agencies face to an equivalent problem with the meteoroids and space debris. Ejecta or secondary debris, can contribute to a modification of the debris environment. The large solar arrays involving brittle materials as well as the importance of the ejected mass let suppose that they might play an important role in auto generation processes of the space debris population.

To characterize matter ejection and to assess secondary impact threat, both experimental and numerical studies need to be performed. With the sight of modelling 3D impacts on brittle targets, the dynamic behaviour of glasses under intense shock loadings and phenomena that cause damages observed on impacted target need to be identified. CEA’s experimental facilities were used for the experimental part. On a numerical point of view, the severe deformations occurring in any high velocity impact event are best described by meshless methods since they offer advantages for modeling large deformations. To model matter ejection, the authors have chosen to derive and validate a material model coupled to Ls-Dyna/SPH method for both compressive and tensile loadings. This paper presents the dynamic behaviour of glasses, the material model derivation and its validation using an SPH method. Application to impacts SPH calculations are presented at the end of the paper.
2. DYNAMIC BEHAVIOUR OF GLASSES UNDER INTENSE SHOCK LOADINGS: EXPERIMENTAL RESULTS AND MATERIAL MODEL DERIVATION

2.1 Experimental observations and literature review

2.1.1 Dynamic behaviour of glasses under intense planar shocks

The dynamic behaviour of glasses under intense shock loadings has been widely studied since the existence of high explosive driving system and high speed optical techniques. Most of studies are dedicated to quartz or fused silica [1, 4] but all phenomena were observed on various glasses such as Pyrex glass (Cagnoux [2]) and can be summarized as follow: glasses are elastic under the Hugoniot elastic limit (HEL). For stress level over the HEL a change in slope of fused silica Hugoniot curve is observed (figure 1) and is attributed to fragmentation and densification of fused silica. This transition is responsible of the two-wave structures observed during tests ([1, 3]) which are similar to the yielding from elastic compression behaviour to plastic or fluid-like flow as observed on metals. Fragmentation originates from intense shear bands that results in multiple crack propagations modifying the macroscopic behaviour of the “damaged” glass. Some authors suspected a complete relaxation of deviatoric stresses above the HEL which comforts the fluid like flow described by Wackerle. For increasing stress levels a remarkable effect is a permanent increase in density of fused silica [1, 3 and 4]. Lalle identified indeed that rarefaction waves have different velocities than those calculated from Hugoniot curve in isentropic conditions. This remark can be correlated with observation of fine white powder on impacted sample. For stress level above 35GPa, another change in slope can be observed on figure 1. This corresponds to the behaviour of fully densified fused silica. It is suspected that a solid-solid phase change occurs in the above-mentioned region even if only a small amount of stishovite has been observed in the literature [4].

![Figure 1 Hugoniot curve obtained gathering results from different authors on silica glasses [3]](image)

2.2 Material model

With the sight of modelling glasses behaviour under high velocity impact condition for which compressive stresses easily exceed 50GPa all the characteristics of fused silica dynamic behaviour presented above need to be implemented in a material model. Such behaviour is particularly important during the first phases of penetration and for fragmentation of impacted targets. Tensile failure criteria causing spalling also play an important role in ejection phenomena and must to be taken into account.

2.2.1 Compressive behaviour

The two principal parts of the material model take into account the fragmentation phenomenon (strength model) and densification (equation of state). For compressive loadings up to 20GPa the strength model is inspired from a JH2 material model [5] with an isotropic damage that decreases the
strength from an intact to a fully damaged state. Such model has already proven its capability to reproduce particle velocity profiles for stress level just above the HEL. According to observations on the deviatoric relaxation, it has been chosen to reduce strength to 0 for highest pressures as presented in figure 2. The equation of state is a third order polynomial EOS for densities below the one of the fully densified material. The EOS of the densified material is linear with the bulk modulus of stishovite (figure 2) and non linear elasticity can be introduced for low compression levels. The maximum compression is stored for each particle ($\mu_{\text{Max}}$) when exceeding the compression at the HEL, the slope of the curves on release and on subsequent recompression differs from their initial shapes and depends linearly on $\mu_{\text{Max}}$. Numerical values were deduced from Lalle’s measurements of speeds of rarefaction waves [1]. Considering the sensibility of SPH methods to discontinuities, all changes in the behaviour (EOS and strength) are realised assuring the continuity of the derivative (cf. figure 2).

2.2.2 Discussion on tensile failure criteria/surface

Tensile failure criteria are particularly important for brittle material. Tension states can be obtained from different loading conditions. In present material model, it has been chosen to separate tensile and compressive damages. We considered that effects of tensile failure are extremely short and act instantaneously on stresses and strength whereas compressive fragmentation occurs gradually via the damage parameter. For this reason, a principal stress criterion and a Mohr-Coulomb failure surface have been added to the model. Different techniques can be used to affect particles but the simplest are often the most interesting in term of calculations time and implementation. Thus, we have chosen to deactivate particle in tension with the possibility of rehealing on recompression.

3. VALIDATION OF THE MATERIAL MODEL COUPLED TO LS-DYNA SPH METHOD

3.1 Basics on the Ls-Dyna Smoothed Particle Hydrodynamics method (SPH)

SPH method is a grid less Lagrangian technique allowing to bypass the requirement for a numerical grid to calculate spatial derivatives. This avoids the severe problems associated with mesh tangling and distortion which usually occur in Lagrangian FE analyses involving large deformations. The calculation cycle is similar to that for a FE computation [7]. SPH is often limited to application uses such as hypervelocity impacts and dependency of material model on the numerical method is often neglected. Here, we have chosen to validate the material model and the numerical method for two different glasses under planar shock loadings and to apply both to high velocity impact cases.

3.2 Material model validation for planar shocks in fused silica and Pyrex glass

In this paper, we decided to focus our study on fused Silica glass and Pyrex glass for two main reasons: fused silica has been widely studied since the 60’s and experiments realized by Lalle in 1991 [1] reached stress level up to 35GPa for which permanent densification is observed. As a
consequence, reproducing Lalle’s experiments allows us to validate the material model for a wide range of stress. With the sight of application of the model to impacts on borosilicate glass plates, we also decided to calibrate a data set for Pyrex glass (Cagnoux [2]) which behaviour was assumed to be closer to borosilicate glass than to fused silica.

Lalle’s experiments consist in 13 tests involving fused silica for maximal stresses ranging from 3.6 to 34.7 GPa. Both particle and free surface velocity were measured and are used in this paper to validate the material model coupled to Ls-Dyna SPH method. 5mm thick fused silica target was meshed using 28800 particles (60 particles in the thickness) assuming 2D strain conditions. In term of particle velocities and maximal stresses, results obtained by Lalle and corresponding SPH simulations are gathered on figure 3 a: maximal stresses, particle velocities and compression levels are well reproduced. Figure 3 b illustrates the free surface velocity of fused silica targets for both experiments and SPH simulations. As it has been presented in 2.1.1, for stress levels over the HEL the ratio free surface over maximum particle velocity is lower than two. The results of numerical simulations hence show that the material model has the ability to reproduce effects of densification on free surface velocity with a very satisfying agreement. The reader must notice that a non negligible uncertainty is introduced due to errors in particle approximation at the free surface. This uncertainty can be reduced using renormalized SPH code.

In this paper, we also focus on plate impacts realized by Cagnoux in 1985. Such impacts loaded Pyrex glass to stress levels ranging from 3 to 22 GPa. Longitudinal stress profiles versus time at different thicknesses were used to validate the new data set and were complementary to Lalle’s results. 40mm thick fused silica target was meshed using 120000 particles. Figure 4 illustrates 3 stress profiles at respectively 5, 10 and 15 mm in the target for both experimental results and SPH numerical simulations. Once again, SPH curves are consistent with experimental.

Figure 3 a & b Stress versus particle velocity and Free surface velocity: comparison between experiment and SPH simulations

Figure 4 Stresses in Pyrex glass: comparison between experimental data and SPH simulations
4. APPLICATION TO IMPACTS ON THIN BRITTLE TARGETS

4.1 Steel projectiles impacts on 2mm thick glass targets: experimental results


**Damages observed on thin fused silica and borosilicate glass targets**

The case of thin brittle targets is particularly interesting due to the quantity of ejected matter during hypervelocity impacts. Spallation phenomenon is indeed the main source of ejection for any brittle target; further more, spallation occurs at both faces of the target even if there is no perforation. The question which should be raised consists in knowing if we will not generate more fragments and more secondary impacts on MDS by using DDS. To answer this, a MICA shooting campaign has been performed to study damages and matter ejection on DDS. Many 2mm thick DDS were impacted by steel projectiles (Ø=500µm) a 1km/s to 3.2km/s. As for thick brittle targets, damages consist of three main characteristics: a perforation hole (D≈2.5mm), a densified zone limited to close hole’s periphery and a wide spallation area which extends to a much larger surface zone. In all perforating cases, the spallation zone on the rear face (~9mm) is almost twice the one observed on the front face (~5mm).

**Matter ejection during high velocity impacts on thin fused silica targets and borosilicate glass targets**

To assess the potential threat of secondary impacts on MDS, impacted samples were scanned to compute the ejected volumes and collection setups were integrated to MICA launcher. The results obtained are gathered in table 1. At 1.35km/s, the total ejected mass is about 49mg (70% is due to rear spallation. For perforating cases, the total ejected mass is about 122mg and about 82% is due to rear spallation. The ejected masses and volumes are also much bigger than the impacting ones mostly due to rear spallation. This illustrates the potential danger of using thin plates. Considering this large amount of ejected matter, a characterisation of this matter in term of size, shape and velocity appeared necessary. Aerogel collectors as well as light paperboard coated with adhesives were located behind DDS: a wide range of fragments were collected ranging from 1mm typical size to a few dozen of microns [6]. The use of CEA’s high speed cameras on MICA launcher gave additional information on the ejection phenomenology and clouds geometry. Two main ejection processes have been identified on both faces of targets: during the first 10µs we observed high velocity jets made of micrometric fragments travelling at ~1km/s for a 3km/s impact; 50µs later clouds made of bigger spalls (Ø<1mm) were observed with ejection angles lower than 25° and ejection velocities lower than 100m/s.

**Table 1** Ejected masses and volumes for four impacts on 2mm DDS at various velocities

<table>
<thead>
<tr>
<th>Impact velocity</th>
<th>1350 m/s</th>
<th>1900 m/s</th>
<th>2200 m/s</th>
<th>3010 m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rear ejected mass</td>
<td>33.3mg (68%)</td>
<td>43.6 mg (68%)</td>
<td>68.4mg (72%)</td>
<td>100.4mg (82%)</td>
</tr>
<tr>
<td>Total ejected mass</td>
<td>48.8 mg</td>
<td>73.1 mg</td>
<td>95.3 mg</td>
<td>122 mg</td>
</tr>
<tr>
<td>Mass Ratio (Meject/Mp)</td>
<td>95.6</td>
<td>143.3</td>
<td>186.8</td>
<td>239.1</td>
</tr>
<tr>
<td>Volume Ratio (Vej./Vp)</td>
<td>338</td>
<td>507</td>
<td>660</td>
<td>845</td>
</tr>
</tbody>
</table>

4.2 SPH modelling of high velocity impact on 2mm thick glass targets

Calculations presented in this section concern normal hypervelocity impacts involving 500µm steel projectiles on 2mm DDS at velocities ranging from 0.5 to 3.5 km/s. A 3D quarter model made of 210.000 particles has been built using 2 SPH symmetry planes. Damage (hole and spalled diameters) and matter ejection have been measured to validate and assess the prediction capability of the model.

SPH simulations for V<1.5km/s gave satisfying results because we were able to reproduce damages on both faces of glass targets. Spallation limit (1km/s) and ballistic limit (V>1.35km/s) were close to those observed on impacted samples. This results are illustrated on figure 5 a. It can be seen that for impacts above the ballistic limit, SPH simulations reproduce the perforation hole dimension with acceptable error (~10%) as well as front and rear spalled diameters with satisfying agreement: cross section profiles obtained with numerical simulations fit experimental profiles except for area close to free surfaces probably due to the mesh density and local inconsistencies due to SPH approach.
In term of matter ejection for a 3km/s impact (figure 5 b), as it has been observed in 4.1 with high speed cameras, SPH simulations present two main ejection processes: high velocity clouds of deactivated particles and “intact” particle clusters. Notice that fragments are considered here as an extrapolation of particle clusters which results from contact loss between particles mainly due to deactivation of border particles. Ejection velocities of deactivated particles range from 250 to 1000 m/s and “spalls“ velocities range respectively from 60 to 170m/s for micro spalls and from 15 to 40m/s for big spalls. All these fragments are present on both faces. A conical cloud is observed on the front face during the first 10µs of the simulation then the spalls are ejected perpendicularly to the main plane of the DDS. On the rear face of the DDS, spalls have ejection angles ranging from 5° to 15°.

Figure 5 a & b Spall and ballistic limits for moderate speed impacts (a) and ejection clouds for high velocity impacts: fragmented material and intact particle clusters can be identified (b)

5. CONCLUSIONS AND PROSPECTS

The material model presented in this paper is based on experimental observation of glasses behaviour under intense shock loadings. Thus effects of fragmentation and densification above HEL which gradually modify mechanical properties of glasses can be reproduced for a wide range of stress levels (up to 35GPa) using the implemented model coupled to Ls-Dyna SPH code. With the sight of projectiles impacts to focus on matter ejection for which tensile failure plays an important role, failure criterion have been implemented and only affect particle behaviour under tensile loading. Application of the material model to 3D high velocity impact cases (V<3.5km/s) gives satisfying results because both spallation and ballistic limits were reproduced as well as damages experienced by the target. In term of matter ejection, main tendencies observed during MICA shooting campaign were also reproduced for clouds morphologies and ejection velocities.

Future work will mainly consist in improving interaction between material model and SPH code for tensile failure. Application of the model to impacts on multilayered solar cells is also planned.

References