High strain rate fracture behaviour of fused silica

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Abstract. Fused silica is a high purity synthetic amorphous silicon dioxide characterized by low thermal expansion coefficient, excellent optical qualities and exceptional transmittance over a wide spectral range. Because of its wide use in the military industry as window material, it may be subjected to high-energy ballistic impacts. Under such dynamic conditions, post-yield response of the ceramic as well as the strain rate related effects become significant and should be accounted for in the constitutive modeling. In this study, the Johnson-Holmquist (J-H) model parameters have been identified by inverse calibration technique, on selected validation test configurations, according to the procedure described hereafter. Numerical simulations were performed with LS-DYNA and IMPETUS-FEA, a general non-linear finite element software which offers NURBS finite element technology for the simulation of large deformation and fracture in materials. In order to overcome numerical drawbacks associated with element erosion, a modified version of the J-H model is proposed.

1. Introduction

Fused silica is a high purity synthetic amorphous silicon dioxide characterized by low thermal expansion coefficient, excellent optical qualities and exceptional transmittance over a wide spectral range. Because of its wide use in the military industry as window material, it may be subjected to high-energy ballistic impacts. Under such dynamic conditions, post-yield response of the ceramic as well as the strain rate related effects become significant and should be accounted for in the constitutive modeling.

Today, one of the most widely used constitutive model for simulating dynamic behavior of ceramic materials is the later version of the Johnson-Holmquist model [1], usually indicated as JH-2 ceramic model and available in a number of commercial codes. In this study, the identification of the JH-2 model parameters was performed following inverse calibration technique of selected validation tests. Numerical simulations were performed with LS-DYNA and IMPETUS-FEA, a general non-linear finite element software which offers NURBS finite element technology for the simulation of large deformation and fracture in materials. Model parameters were identified by optimization using multiple validation metrics as objective functions. In general, when critical damage is reached, the material strength is reduced to zero and the finite element is subjected to distortion with consequent reduction of the integration time step. In order to avoid excessive reduction of the integration time step, element erosion technique is commonly used. If from one side this technique helps the numerical simulation to continue, on the other side it causes the loss of mass, momentum and post-failure residual material resistance under compression. Alternative numerical techniques, such as element splitting, element...
separation, XFEM, etc., can be used to avoid these issues and simulate cracks formation in the material. In this work, the element separation technique, as alternative to element erosion, has been implemented for the fused silica in IMPETUS AFEA. This required the modification of the JH-2 model in order to control the element separation process.

2. Model parameters identification procedure
The identification of JH-2 model parameters has been carried out benchmarking the experimental results of selected validation tests. Taylor anvil impact and drop weight tests were chosen for the purpose. Taylor impact tests with velocity ranging from 3 m/s up to 100 m/s were carried out. Impacts from 20 m/s up to 100 m/s were performed using 40 mm gas-gun using air as propeller gas. Low velocity impacts (<20 m/s) were performed using a vertical gun in order to ensure normal impact condition. Drop weight tests were performed on different configurations of staggered fused silica tiles.

Both impact configurations were simulated with FEM. Model parameters have been varied in order to match selected validation metrics. At high impact velocity, no post-mortem measure was possible since the sample shattered at the impact. However, high-speed videorecording provided valuable information about the damage development and failure sequence that could be used to qualify numerical solutions. In particular, the propagation of the damage wave, the time and location of the appearing of spall fractures, in the rear section of the Taylor cylinder, have been used as validation metrics. In the drop weight test, the load vs displacement of the impactor was recorded and used as objective function for the model parameters identification procedure. Finally, model parameters identification was carried out using modeFRONTIER which is an integration platform for multi-objective and multi-disciplinary optimization.

3. Experimental and numerical simulation results
Drop weight tests showed that fractures develop in the fused silica tiles without penetration. The load vs displacement results showed not only considerable scatter, probably due to the initial distribution of pre-existing flaws in the sample, but also two different types of response indicating possible instable behaviour probably triggered by the interaction of the ceramic tiles and the backing surface. In figure 1 the comparison of the experimental data and calculated response is given. It is interesting to note that computational model is capable to predict with good approximation the different behaviour in the load vs displacement response, at different impact velocities, as a function of the geometry constraint associated with the staggered tile configuration.

In Taylor tests at high velocity, the fused silica is completely destroyed at the impact. As soon as the Taylor cylinder face comes into contact with the anvil, the material shatters. The damage wave proceeds along the cylinder axis eroding the material which turns into dust, figure 2. At the same time, as a result of the compressive pulse travelling along the cylinder axis and its reflection at the rear surface, clear spall fractures occur in the rear portion of the Taylor cylinder sectioning it into disk shaped slices. The impact velocity was progressively reduced in order to determine the threshold velocity below which no damage or fracture would occur. This quantitative information was also used in the identification procedure, [2].

In figure 2, the comparison of calculated deformed shapes at two different times for 83.3 m/s impact is given. Numerical simulation results were obtained with LS-DYNA using element erosion algorithm. Here, the threshold strain for element erosion was selected larger than the material failure strain in order to avoid that failure in the material would occur by erosion rather than by damage. The consequence of the erosion algorithm is clearly visible in figure 1b where the missing mass is clearly visible. Although the comparison seems to be qualitatively good, it has to be noted that the predicted spall in the rear section is much less than that observed in the experiments. This may be also a consequence of the loss of momentum associated with element erosion.
Figure 1. Example of different responses observed in the drop weight tests: a) v=1.1 m/s; b) v=1.5 m/s. Numerical simulations performed with LS-DYNA.

Figure 2. Comparison of deformation and damage at 83.3 m/s velocity impact: red indicates failed material. Simulation results were obtained using LS-DYNA. Here, the loss of material due to element erosion is clearly visible.

4. Material model modification

In order to avoid element erosion, the alternative use of element separation technique was explored. This technique consists in releasing the nodes connecting adjacent elements when a failure criterion is satisfied. This technique was implemented in IMPETUS AFEA. The solver is purely Lagrangian and all finite element and contact calculations are carried out in double precision using unique higher order element technology (isogeometric elements) well suited for processes involving extreme deformations. Green-Naghdi’s stress rate is used in all rate based material models. One key feature of IMPETUS AFEA is that the solver is adapted to the GPU technology allowing the possibility to solve large problems scaling the solution over a large number of graphic processors.

The element separation technique required some modifications of the JH-2 model in order to control the damage development and to improve model predicting performances. A first attempt has been done
as follows. For positive pressure (compression), the effective stress as a function of pressure is approximated with linear equation,

\[ \sigma_0 = A_0 + B_0 p. \]  

(1)

Damage scales down the material resistance according to:

\[ \sigma_y = (1 - D_c) \sigma_0 - D_c \sigma_f, \]  

(2)

where the completed failed material still maintain a residual resistance given by:

\[ \sigma_f = A_f + B_f p. \]  

(3)

Compressive damage is defined as

\[ D_c = \min\left(1, \frac{\epsilon^p}{\epsilon_f}\right). \]  

(4)

For negative pressure (tensile), spall damage is given by

\[ \dot{D}_s = \frac{1}{\tau_s} \left(\frac{\sigma_1}{\sigma_s}\right)^a \quad \sigma_1 \geq \sigma_s \]  

(5)

\[ \dot{D}_s = 0 \quad \sigma_1 \leq \sigma_s, \]  

(6)

where

\[ \sigma_s = [A_0(1 - D_c) + A_f D_c](1 - D_0). \]  

(7)

When tensile damage becomes critical a crack is introduced in the material using element splitting technique. Crack propagation can occur if the local stress intensity factor exceeds material fracture toughness,

\[ K_I > K_{IC}. \]  

(8)

This model formulation is based on the same physical background of the JH-2 model. The material behaviour under compression was simplified using a linear dependence of the material resistance with pressure. The major difference with respect to the JH-2 model is that damage in tension and compression was treated separately: the compression damage accounts for crushing while tension damage initiates by spall and propagates according to fracture mechanics. Tension damage rate accumulates with time similarly to Tuler-Butcher [3] brittle damage model which allows to account for different stress pulse duration.

In figure 3, the sequence of predicted damage development in Taylor impact at 89 m/s is given. Here, both material shattering at the impact surface and fracture development in the rear section are clearly visible. The sequence shows spall fractures development in the rear portion of the cylinder as well as particle separation in the front section crushed region. Qualitative comparison with high speed camera selected frames are in a fairly good agreement. Similar accuracy was also found for drop weight impact in terms of both load vs displacement response, figure 4, and fracture developments, figure 5.

Finally, the model was used to predict the occurrence of fracture in a steel ball impact test. In this simulated test, the impact velocity was increased up to fracture that was found to occur at 30 m/s. Later, experimental ballistic test was performed at two velocities: 25 m/s and 30 m/s. No damage was observed for the lower velocity while fracture occurred at 30 m/s as predicted by the model. A comparison of the predicted and observed failure mode is given in figure 6.
Figure 3. Example of different responses observed in the Taylor impact test at 89 m/s. Time goes from left to right. Simulation results were obtained with IMPETUS AFEA using improved JH-2.

Figure 4. Comparison of calculated (improved JH-2, IMPETUS AFEA) and measured response in drop weight test (impact velocity of 1.1 m/s).

Figure 5. Comparison of calculated (improved JH-2, IMPETUS AFEA) and observed fracture behaviour.
Conclusions
In this work, a procedure for the determination of JH-2 model parameters of fused silica, based on a reverse engineering approach, was used. Two types of test were used for the purpose: Taylor anvil and drop weight. Experimental tests showed that fused silica shattered completely at relatively high velocity impact (100 m/s) while it failed by spall at much lower velocity. Numerical simulation using JH-2 model in LSDYNA revealed that element erosion influences predicted material response and failure. Element separation technique was investigated as alternative to element erosion. This technique required the modification of the JH-2 model formulation in order to correctly predict material damage and failure. Preliminary results, using the modified model implemented in IMPETUS AFEA, seem to agree well with experimental finding observed in different impact test configurations.

References
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