Simulation of the ballistic perforation of aluminum plates with Abaqus/Explicit

Abaqus Technology Brief

Summary

Accurate numerical simulation of ballistic impact events can provide physical insights that cannot be captured by experiments. The high velocity perforation process is very complex and requires the use of reliable and robust constitutive models capable of simulating material response at high strain rates, high pressures, and with progressive damage.

In this Technology Brief, we describe Abaqus/Explicit modelling of the ballistic impact of metal projectiles on metal targets. An impact velocity range of ~0.4–0.9 km/s is considered and very good quantitative and qualitative agreement between the numerical results and experimental data is shown for both normal and oblique impacts. We will demonstrate the utility of Abaqus/Explicit as a tool for reducing the amount of experimental testing as well as assessing the projectile residual velocities and time-resolved kinematics.

Background

The inclusion of high velocity impact dynamics in engineering practice allows analysts to account for the effects of penetrating fragments, accidental loads, and collisions. Moreover, it allows for a more thorough design of lightweight protective structures for civil and military use.

Depending on the type and velocity of the impacting bodies, their structural response can vary from recoverable elastic deformation to material rupture with local state transitions. When a material is stressed by ballistic loading, shock waves are generated, and such waves are capable of creating pressure of a magnitude that can significantly exceed the material's strength. In these circumstances, a solid material at the early stages of the event can be considered as a compressible fluid, with strength effects appearing later [1]. Material damage develops prior to penetration and strongly influences its progress, and thus it should be properly accounted for in the analysis.

A simulation capability for high velocity impact events must therefore employ reliable and robust constitutive models capable of simulating material response at high strain rates, high pressure, and in a progressive damage framework. Abaqus/Explicit offers such tools and is therefore a natural choice for impact simulations.

The Abaqus/Explicit simulations presented here examine the perforation of aluminum plate specimens impacted with ogive-nose steel rods. The constitutive models used in the simulations account for the effects of strain, strain rate, and temperature on the material behavior. The geometry and material properties of the steel rods (projectiles) and aluminum plates (targets) were taken from [2].

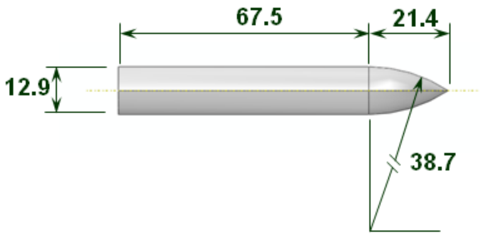


Figure 1: Schematic of the projectile (dimensions in millimeters)

Key Abaqus/Explicit Features and Benefits

- Mie-Grüneisen equation of state to model materials at high pressure
- Johnson-Cook plasticity model that accounts for strain rate, thermal effects and compressibility
- Johnson-Cook dynamic failure model within the Abaqus ductile damage initiation criterion for metals
- Progressive damage framework

The projectile is an ogive-nose rod with the 3.0 caliber-radius-head machined from 4340 Rc=44 steel rod stock (see Figure 1). The Young's modulus and the 0.2% offset yield strength of the material are 202 GPa and 1,430 MPa, respectively. The projectile's mass is approximately 81 gram.

The target is a 304 mm square plate cut from a single 6061-T651 aluminum plate of thickness 26.3 mm. The Young's modulus and the 0.2% offset yield strength of the material are 69 GPa and 262 MPa, respectively. Experiments in [2] showed this material to be practically rate independent. The results of the numerical simulations were compared with measured residual velocities and X-ray photographs of the perforation process [2].

Analysis Approach

The finite element models for normal and oblique impacts were created in Abaqus/CAE. In the latter case, the angle between the projectile velocity vector and the plate normal is 30° (see Figure 2). As noted in [3], the accuracy of any impact simulation strongly depends on: (a) the mesh;

(b) the constitutive model; and (c) the data used in the material model. These important simulation factors are discussed further.

Mesh details

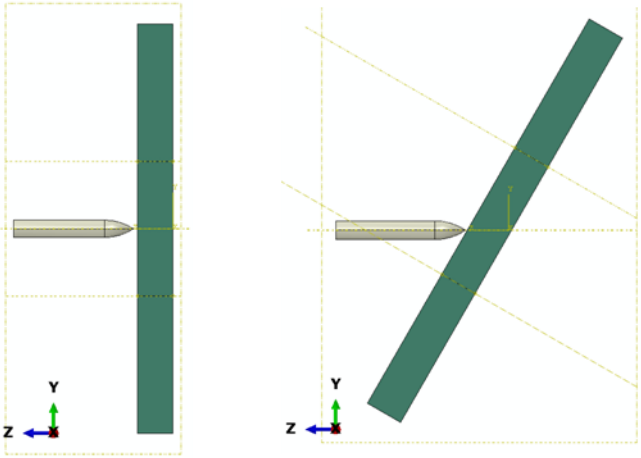
C3D8R elements were used to build the model: 12 elements along the projectile diameter and 26 elements through the target thickness. The resulting finite element model had approximately 7.5 million degrees of freedom.

Constitutive model

When the pressure generated by shock wave propagation exceeds the material strength by several orders of magnitude, the early stages of material response can be regarded as hydrodynamic; strength effects appear in the late stages of the event [1]. Therefore, it is assumed for both metal materials that volumetric behavior is described by the Mie-Grüneisen equation of state (EOS) model, with the deviatoric behavior described by the linear elastic and the Johnson-Cook plasticity models. Note that the Mie-Grüneisen form of the EOS model is suitable only for solids, and therefore cannot be used in simulations with impact velocities larger than 2 km/s, where solid-liquid-gas transitions occur in the material.

The EOS model requires the input of the: (a) reference density, ρ_0 ; (b) Grüneisen coefficient, Γ_0 ; and (c) parameters c_0 and s that define the linear relationship between the shock velocity and the particle velocity. The values of these parameters used in the present analysis are given in Table 1. Because it is not always possible to find the data for the required material, the parameter values in the table correspond to the materials with mechanical properties close to those used for the aluminum target and steel projectile. Providing the value of the specific heat allows for modeling the adiabatic heating of a material due to plastic dissipation through the analysis.

The Johnson-Cook model is an incremental elastic-plastic rate model that accounts for strain rate and thermal effects in the material and its compressibility. This empirical model involves several material parameters. The values of these parameters for the materials with mechanical properties close to those used for the aluminum target and steel projectile are provided in Table 2. Parameters A, B, and n represent the yield stress, hardening constant, and hardening exponent, respectively. Together with the values of the melting, θ_{melt}, and transition $\theta_{transition}$ temperatures of the material and the value of the thermal softening exponent, m, these parameters are provided as part of the metal plasticity material definition to model plastic hardening. Moreover, parameters C and $\dot{\varepsilon}_0$ are required to define Johnson-Cook rate dependence.



(a) (b)

Figure 2: Abaqus/CAE model of the normal (a) and oblique (b) impact

A comparison of the magnitudes of the yield stress, A, in Table 2 with those given previously for the target and projectile shows that the input parameters for the Johnson-Cook model should be calibrated before they can be used in the analysis. Using the true stress-strain experimental data for the aluminum target and steel projectile from [2] A, B, and n for both materials were calibrated so that a close fit between the experimental and numerical true stress-strain curves was achieved [8]. The calibrated input parameters used in the present analysis are given in Table 3. Note that the values of the parameters describ-

Table 1: Input parameters for the Mie-Grüneisen EOS model, [4, 5]

Material	Reference density, ρ_0 , [g/cm^3]	Grüneisen coefficient, Γ_0	Parameter, c_0 , [cm/µs]	Parameter, s	Reference temperature, [K]	Specific heat, [J/(kg K)]
Aluminum 6061 -T6	2.703	1.97	0.524	1.40	293.2	885.0
Steel 4340, Rc=38	7.83	1.67	0.4578	1.33	293.2	477.0

Table 2: Input parameters for the Johnson-Cook plasticity model, [5, 6, 7]

Material	A, [MPa]	B, [MPa]	n	θ_{melt} [K]	$\theta_{transition}$, [K]	m	C	$\dot{\varepsilon}_0$, [1/s]
Aluminum 6061 -T6	324.1	113.8	0.42	925	293.2	1.34	0.002	1.0
Steel 4340, C-30	792	510	0.26	1793	293.2	1.03	0.014	1.0

ing rate-dependency for the aluminum target were not used in the present analysis because, as was mentioned previously, physical experiments showed that the material is practically rate independent.

Failure model

The Johnson-Cook dynamic failure model is used as a specific case of the Abaqus ductile damage initiation criterion for metals. The Johnson-Cook failure parameters that were used in the present analysis for the aluminum target and steel projectile are given in Table 4.

It is important to note that the failure parameter d_3 is reported as being negative for a specific material in the literature. However, as explained in the documentation, Abaqus implementation of a Johnson-Cook general expression for the strain at fracture expects this parameter being positive. Failure to properly account for the sign of d_3 will lead to incorrect response. Besides the values of the failure parameters, the values of the melting and transition temperatures and the reference strain rate are required for a complete description of the initiation criterion. Clearly, the temperature values should be consistent with those used for the plasticity definition as given in Table 3. Choosing a zero value for the fracture energy, which is used as a data parameter for the damage evolution law, completes the settings of the failure model. Elements are deleted by default upon reaching maximum degradation according to the usual rules of the Abaqus progressive damage framework.

Initial and Boundary Conditions

The target was clamped along its perimeter, and an initial velocity was prescribed to the projectile. Due to high sliding velocities, frictionless contact was assumed between the target and projectile. Also, initial room temperatures (293.2 K) were prescribed for both the target and projectile. To preserve the projectile's nose from deformations and damage as observed in the experiments, the hourglass stiffness was scaled by 50 times for the normal impact simulations and 15 times for the oblique impact simulations.

Results

Normal Impact

Close agreement between the experimental [2] and simulated residual velocities for a range of striking velocities can be seen from Figure 3. Figure 4 illustrates the perforation process for each striking velocity presented in Figure 3 at the time instances for which the X-ray photographs were made in [2]. The results shown in Figure 4 are in close agreement with the time-resolved projectile kinematics in [2]. Note specifically that the projectile remains undeformed, which fully corresponds to the experimental evidence [2].

Oblique Impact

The experimental [2] and simulated residual velocities for a range of striking velocities are compared in Figure 5. The numerical and experimental results for lower striking velocities are farther apart than for the normal impact but, in general, the agreement between the simulation

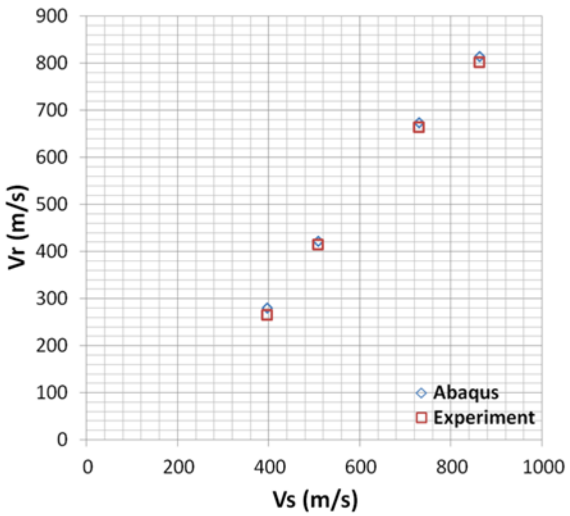


Figure 3: Experimental and predicted residual (V_r) vs. striking (V_s) velocities for normal impact

Table 3: Calibrated input parameters for the Johnson-Cook plasticity model

Model part	A, [MPa]	B, [MPa]	n	θ_{melt} [K]	$\theta_{transition}$, [K]	m	C	$\dot{\varepsilon}_0$ [1/s]
Target	262	162.1	0.2783	925	293.2	1.34	–	–
Projectile	1430	2545	0.7	1793	293.2	1.03	0.014	15.0

Table 4: Input parameters for the Johnson-Cook dynamic failure model, [5, 6, 7]

Material	d_1	d_2	d_3	d_4	d_5
Aluminum 6061 -T6	-0.77	1.45	0.47	0.0	1.6
Steel 4340, C-30	0.05	3.44	2.12	0.002	0.61

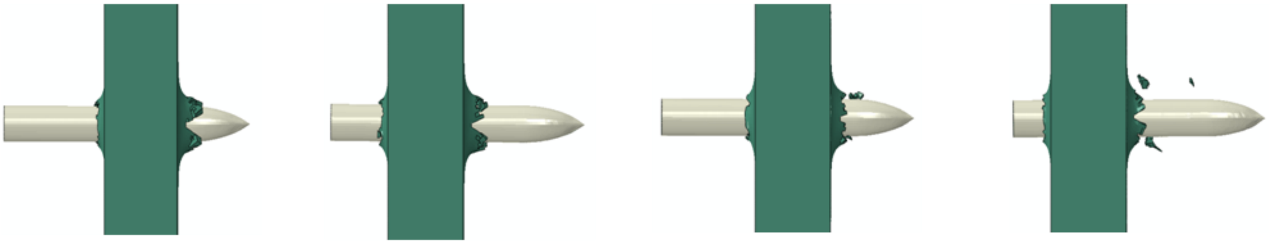

(a) (b) (c) (d)

Figure 4: Perforation process at various velocities and time instances: (a) V_s=396 m/s at 170 µs; (b) V_s=508 m/s at 160 µs; (c) V_s=730 m/s at 85 µs; (d) V_s=863 m/s at 95 µs.

and experiment is good. Figure 6 shows the perforation process for each striking velocity presented in Figure 5 at the time instances for which the X-ray photographs were made in [2]. The results shown in Figure 6 are in a close agreement with the time-resolved projectile kinematics in [2]. Moreover, it can be seen from the figure that the ogive nose remains undeformed, whereas the shank of the projectile exhibits visible bending, which is in accordance to the experimental evidence [2].

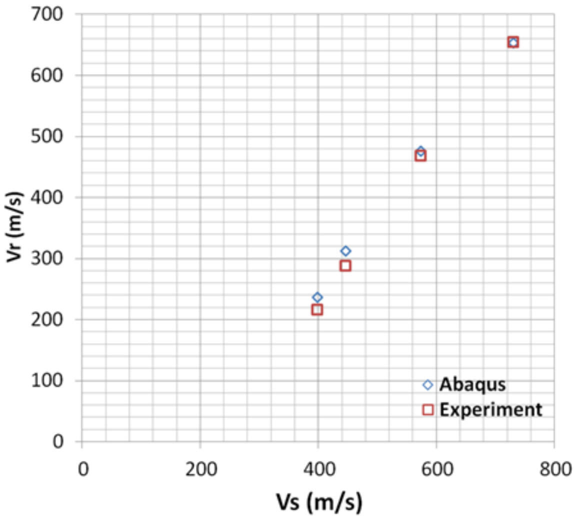


Figure 5: Experimental and predicted residual (V_r) vs. striking (V_s) velocities for oblique impact


(a) (b) (c) (d)

Figure 6: Perforation process at various velocities and time instances: (a) V_s=398 m/s at 220 µs; (b) V_s=446 m/s at 205 µs; (c) V_s=573 m/s at 165 µs; (d) V_s=730 m/s at 95 µs.

Conclusions

The Abaqus/Explicit simulation results of the ballistic perforation of aluminum plate specimens with ogive-nose steel rods show very good quantitative and qualitative agreement with experimental data for both normal and oblique impacts. Abaqus/Explicit may thus be used to reduce costly experimental ballistic testing.

References

1. Zukas, J.A., *Introduction to Hydrocodes*, Elsevier, 2008.
2. Piekutowski, A.J., Forrestal, M.J., Poormon, K.L., and Warren, T.L., "Perforation of Aluminum Plates with Ogive-nose Steel Rods at Normal and Oblique Impacts," *International Journal of Impact Engineering*, Vol. **18**, No. 7–8, 1996.
3. Zukas, J.A., "Some Common Problems in the Numerical Modeling of Impact Phenomena," *Computing Systems in Engineering*, Vol. **4**, No. 1, 1993.
4. Steinberg, D.J., "Equation of State and Strength Properties of Selected Materials," Lawrence Livermore National Laboratory, February 13, 1996.
5. Corbett, B.M., "Numerical Simulations of Target Hole Diameters for Hypervelocity Impacts into Elevated and Room Temperature Bumpers," International Journal of impact Engineering, Vol. **33**, 2006.
6. Johnson, G.R. and Cook, W.H., "Fracture Characteristics of Three Metals Subjected to Various Strains, Strain Rates, Temperatures and Pressures," *Engineering Fracture Mechanics*, Vol. **21**, No. 1, 1985.
7. Schwer, L., Aluminum Plate Perforation: A Comparative Study Using Lagrange with Erosion, Multi-Material ALE, and Smooth Particle Hydrodynamics, 7th European LS-DYNA Conference, 2009.
8. MATLAB 7.11.0, The MathWorks Inc., Natick, MA, 2000.

SIMULIA References

For additional information on the Abaqus capabilities referred to in this document please see the following Abaqus 6.12 documentation references:

- Analysis User's Manual
  - 'Johnson-Cook plasticity,' Section 23.2.7
  - 'Damage and failure for ductile metals,' Section 24.2
  - 'Equation of state,' Section 25.2.1

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