

Validation of Abaqus Explicit – CEL for classes of problems of interest to the U.S. Army

P. Carlucci¹, C. Mougeotte¹, and J. Huidi²

¹U.S. Army – ARDEC, Picatinny Arsenal, Picatinny, NJ 07806

²SIMULIA – Dassault Systemes Simulia Corp. – 166 Valley Street, Providence, RI 02909

Abstract: In developing weapon systems for the warfighter, the US Army uses modeling and simulation tools to support the design, test and manufacturing of these systems. One of these tools is Abaqus/Explicit, including the coupled Eulerian-Lagrangian capability CEL. The addition of CEL in version 6.7EF-1 opened the door to a new realm of problems that could not be previously be modeled. With the addition of this new capability came the need for internal validation to establish a level of confidence for the class of problems of interest to the U.S. Army. Over the course of 2 years, several validation problems were modeled and the results compared to either experimental or analytical results. A few of these problems were selected for this paper, including the dynamic tensile extrusion of copper, JWL equation of state of explosive expansion, and compressible inviscid flow in a shock tube. The details of these analyses and comparison to experiment will be discussed along with their practical implications.

Keywords: Dynamics, Experimental Verification, Failure, Johnson-Cook, Explicit, CEL, JWL, Explosive, Ideal-Gas, Shock, Compressible inviscid flow.

1. Dynamic Tensile Extrusion of Copper

1.1 Description of Experiment

The Dynamic Tensile Extrusion test was developed at Los Alamos National Lab (Gray III, 2005) for the purpose of characterizing the influence of copper grain size on high strain rate/large strain response. A 7.62mm diameter copper sphere is launched at ~400 m/s into a tool steel die. Entrance angle is 80 degrees and exit diameter is 2.28 mm. The test arrangement is shown in Figure 1. This experiment was selected to be modeled in Abaqus/CEL for several reasons: a high rate, large strain problem that is not possible to be modeled well with a conventional lagrange technique; relatively simple geometry with a complex nonlinear result which is a challenge for any code to simulate properly; rates and strains that are in the range that are applicable to problems of interest to the U.S. Army; readily available experimental data for comparison and validation.

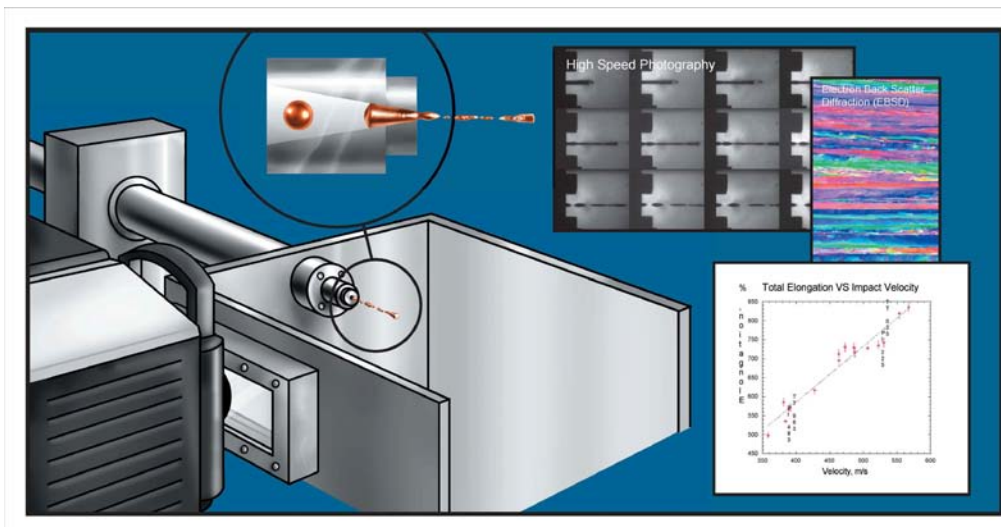


Figure 1. Dynamic Tensile Extrusion Test (courtesy of LANL).

1.2 Model Geometry and Model Mesh

The experiment as modeled for the analysis is shown in Figure 2, and was developed using quarter-symmetry. The conical die was modeled as a Lagrangian rigid body to reduce computational expense.

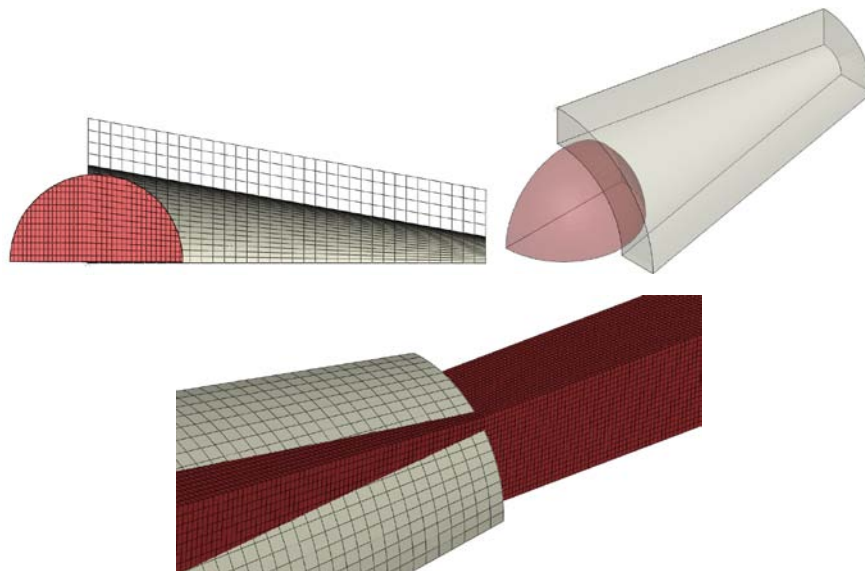


Figure 2. Dynamic Tensile Extrusion Test – model and mesh.

The complete assembly is approximately 170,000 elements, type EC3D8R linear reduced integration bricks with the default hourglass control for the Eulerian domain. The material constitutive model used for the copper is the Johnson-Cook plasticity and damage model. A predefined field was specified for the copper sphere initial velocity of 400 m/s. It is important to note that adiabatic heating effects were included since the Johnson-Cook plasticity and damage models include temperature dependency for material strength. This was necessary to capture the thermal softening that occurs due to the large plastic strains.

1.3 Analysis Results and Comparison to Experiment

Experimental results are shown for copper specimens of three different grain sizes in Figure 3. As shown by (Gray III, 2005), the extrusion of the copper sphere is dependent on the grain size of the copper. As is the case for almost all continuum material models, Johnson-Cook plasticity and damage cannot capture the effects of grain size on large strain dynamic response. Parameters for these material models are generally fit using standard experiments, and since stress-strain curves and Taylor cylinder experiments for the three grain sizes are virtually identical they would yield a single set of virtually identical parameters. Johnson-Cook material model parameters were taken from published data, and were not changed for the simulations shown here.



Figure 3. Dynamic Tensile Extrusion of Copper for grain size: (a) 65 μm , (b) 118 μm , (c) 185 μm .

For the purposes of model validation in this paper, comparison is made only to the coarsest grain size of 185 μm which showed good qualitative agreement to modeling. For the coarse grain tests, typically three or four individual segments would be expelled from the die, with a conical segment remaining inside. Figure 4 shows a direct comparison between one of the experiments and the Abaqus CEL model. High speed photographs are spaced 11 μs apart, starting from the top left and moving right. Viewport snapshots for the simulation are also spaced 11 μs apart. Since a common zero reference was not known, the 4th high speed video frame was used to synchronize the experiment to the model by matching the overall length of the expelled copper material to the edge of the die. Prior and subsequent simulation frames were then stepped by 11 μs from this reference. There is very good qualitative agreement in the shape of the expelled fragments, though the simulation produces three expelled fragments while the experiment produces four. In

this respect the simulation more closely matches the fragments recovered from the experiment shown in Figure 3 (c). More importantly, the position and state of the fragments matches with the time-steps of the high speed photography. The experimental velocity of the foremost fragment is ~ 780 m/s, while it is ~ 225 m/s for the rearmost fragment. Figure 5 shows a velocity contour plot for the simulated fragments, with the foremost fragment at 833 m/s, and rearmost at 278 m/s. The differences in the velocity from experiment are $\sim 7\%$ and $\sim 23\%$ respectively for the fragments.

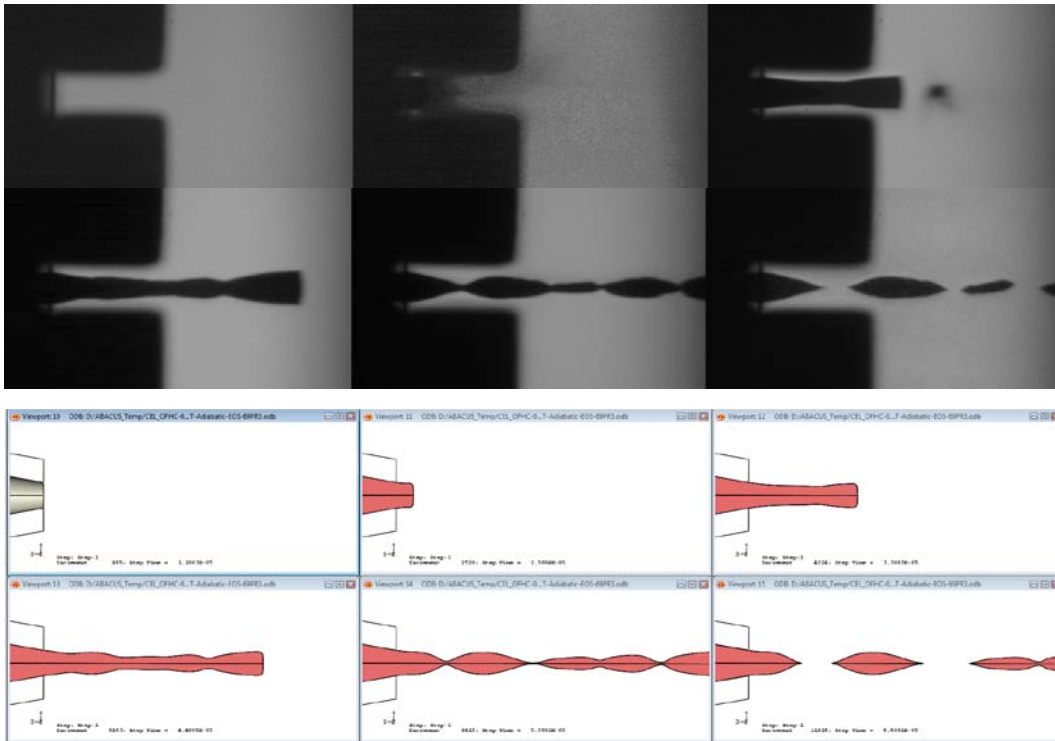


Figure 4. Comparison of test and CEL model results.

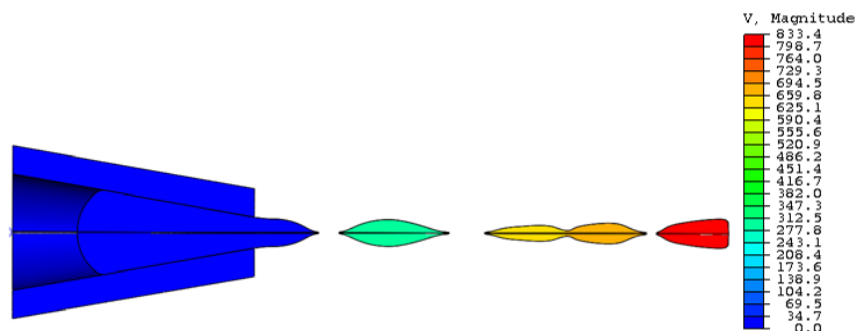


Figure 5. Velocity contour plot for expelled fragments in (m/s) – Abaqus/CEL.

Figure 6 is a contour plot of equivalent plastic strain, and shows the bulk of the fragments undergo greater than 300% plastic strain. This is consistent with the results presented by (Gray III, 2005). Overall the results demonstrate that CEL is properly handling the dynamic strength of solids including plasticity and damage. Through this validation activity came the confidence to use CEL for predictive analysis where experimental data was not available or cost prohibitive.

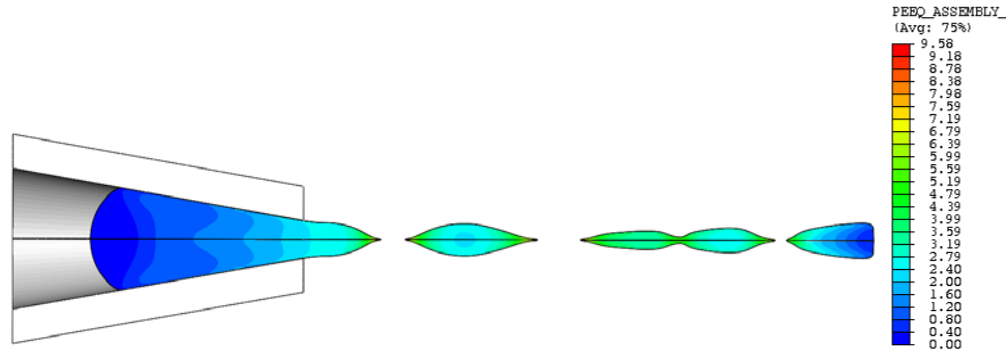


Figure 6. Equivalent plastic strain contour plot – Abaqus/CEL.

2. Explosive Loading – Validation using the JWL Equation of State

2.1 Description of Experiment

The JWL equation of state (EOS) allows modeling of explosive detonation products in an idealized and simplified manner. Though this EOS material model had been implemented in Abaqus/Explicit for some time, the addition of CEL and the Eulerian capability allowed the large displacements necessary for solution of these types of problems. Since explosively loaded structures and near field blast effects comprise a class of important problems for the U.S. Army, validation of the JWL EOS in CEL was necessary before using the capability.

The JWL EOS was first introduced by (Lee 1968), for the purpose of modeling explosives computationally. The paper contains JWL parameter fits for several common explosives, as well as comparison of original computational results to experiment. Two standard experimental test geometries were used, a hemispherical shell and a cylindrical tube both filled with high explosive. The geometries for these test arrangements are shown in Figures 7 and 8 respectively. For the hemispherical geometry the explosive is detonated by a point source at the sphere's center, while for the cylindrical geometry a plane wave detonator is used at the left as seen in the corresponding figure. The detonation of the explosive drives the metal shell, and experimental measurements are taken showing distance travelled with respect to time of the outside edge of the metal shell. For the cylindrical arrangement, the measurement is taken 20cm from the plane wave detonator. These experimental measurements will be used for direct comparison with models developed in Abaqus/CEL using the published JWL parameters for several explosives.

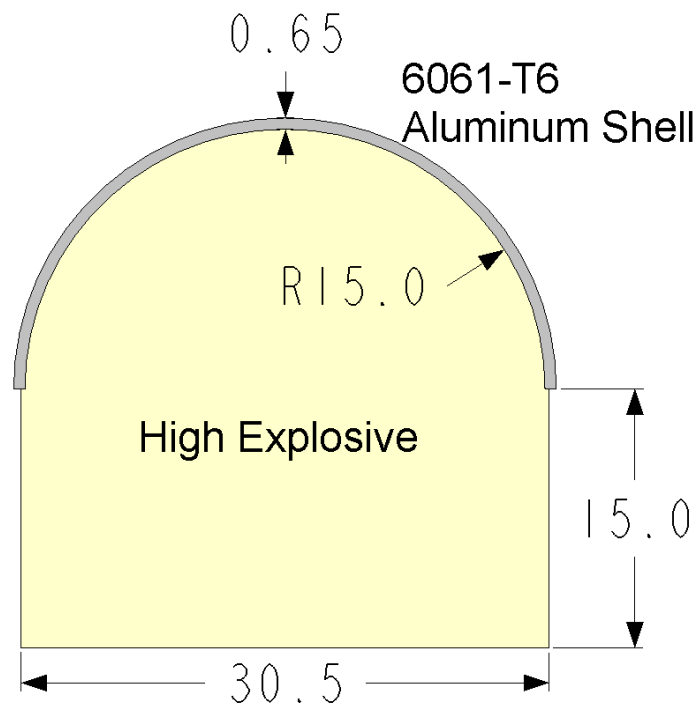


Figure 7. Hemispherical explosive experiment geometry, dimensions in (cm).

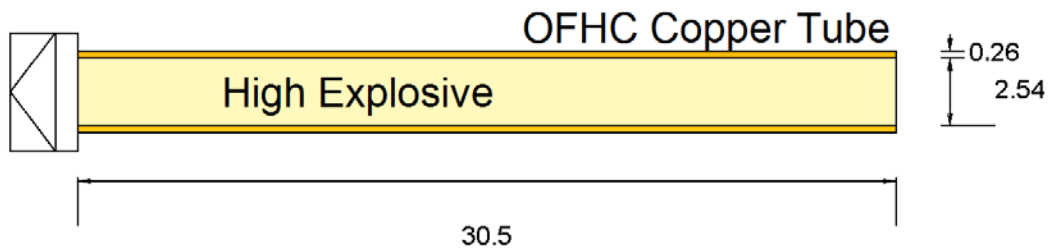


Figure 8. Cylindrical explosive experiment geometry, dimensions in (cm).

2.2 Model Geometry and Model Mesh

For the hemispherical experiment geometry, a CEL model was developed using spherical symmetry. The eulerian domain contains ~200 elements, leading to a very fast analysis time. The spherical aluminum shell was modeled as a Lagrangian solid. Johnson-Cook plasticity was used

for the 6061-T6 aluminum material. Figure 9 shows the modeled geometry and the Eulerian mesh.



Figure 9. Hemispherical explosive CEL geometry, spherical symmetry.

The model geometry for the cylindrical test case is shown in Figure 10. The Eulerian domain was modeled using quarter symmetry, and contains ~450,000 elements. The OFHC copper cylinder was modeled as a Lagrangian solid using ~5,000 first-order C3D8R elements. The material constitutive model used for the copper is the Johnson-Cook plasticity and damage model, and model parameters were taken from published data.

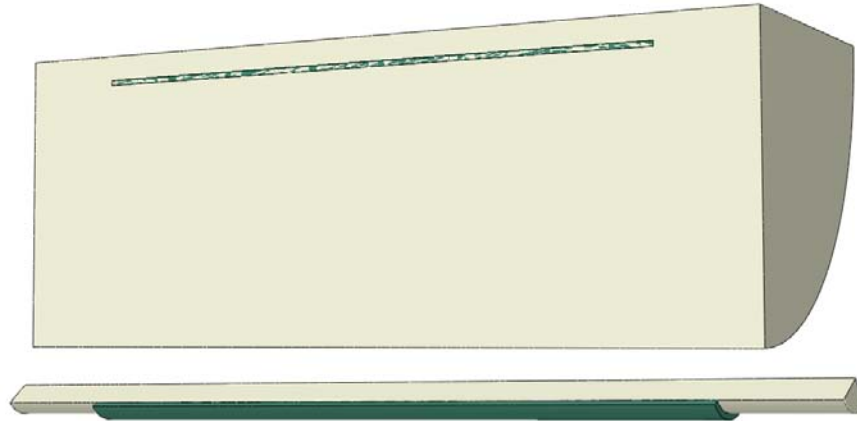


Figure 10. Cylindrical explosive CEL geometry, quarter symmetry.

2.3 Analysis Results and Comparison to Experiment

Shown in Figures 11, 12 and 13 are the comparison between experimental results and CEL analyses for the spherical arrangement. Comparisons are made for the following high explosives: Composition B, LX04-1, and PBX9404. For all three explosives, there is excellent agreement between CEL and experiment. Note that total time for these analyses is 50 microseconds.

Figure 14 shows pressure contour plots for the cylindrical arrangement, and is used to illustrate how the detonation wave moves from left to right. The reacted explosive products are behind the detonation front (to the left) while the unreacted explosive is ahead of the front. Figures 15 and 16 show the comparison for the cylindrical arrangement for Composition B and TNT, and the CEL analyses show very good agreement with the experimental results.

The CEL results show a small divergence that increases with time as compared with the experimental results. It is uncertain what is causing this diverging behavior. Helping to mitigate this is the fact that the shell material will fail before the effect of the divergence would significantly affect the results. For the typical engineering calculation that would be performed using the JWL EOS, the observed accuracy is more than adequate. This is reinforced by the statistical variation in actual explosive and metal properties that is considered normal for manufactured munitions. Overall the results compare favorably with those presented by Lee (1968), and the validation effort succeeded in providing the necessary confidence to use the JWL EOS a new tool for predictive analysis.

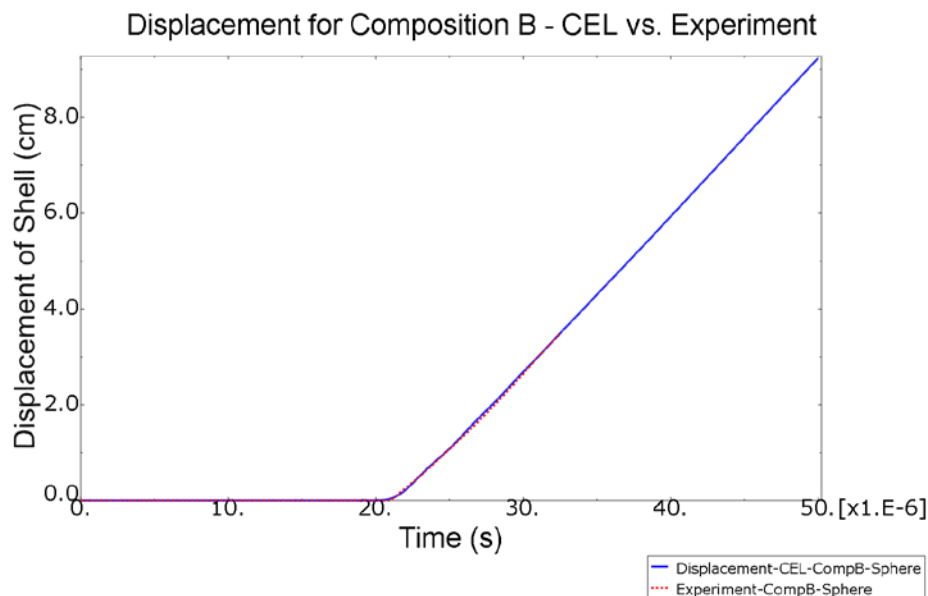


Figure 11. Spherical arrangement, CEL vs. Experiment – Composition B.

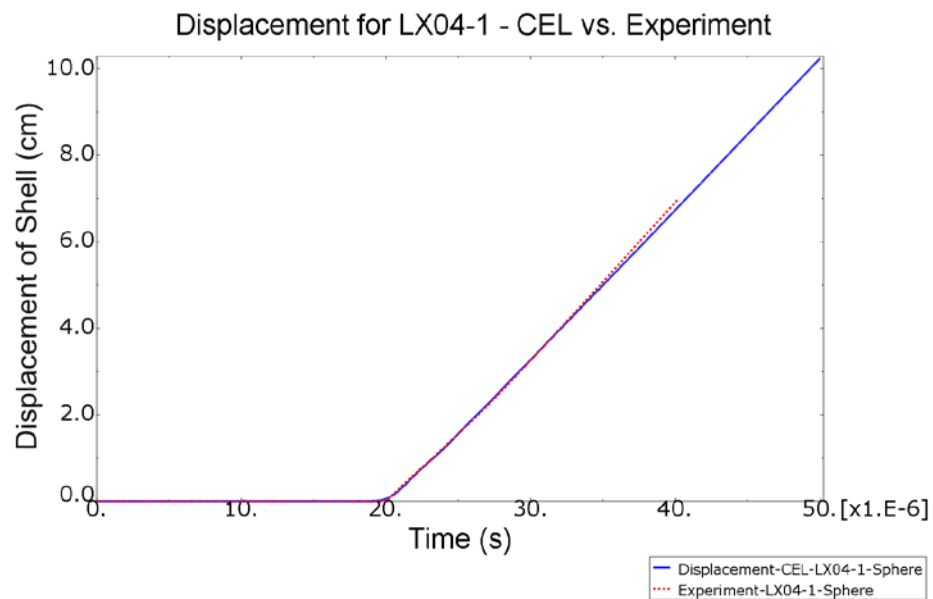


Figure 12. Spherical arrangement, CEL vs. Experiment – LX04-1.

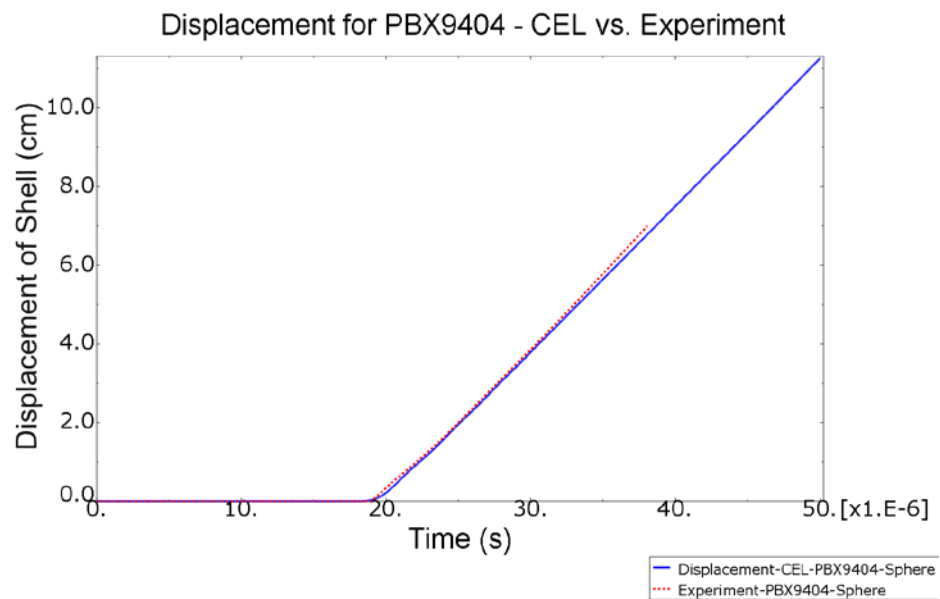
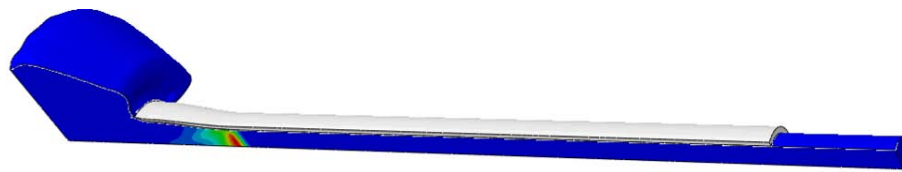
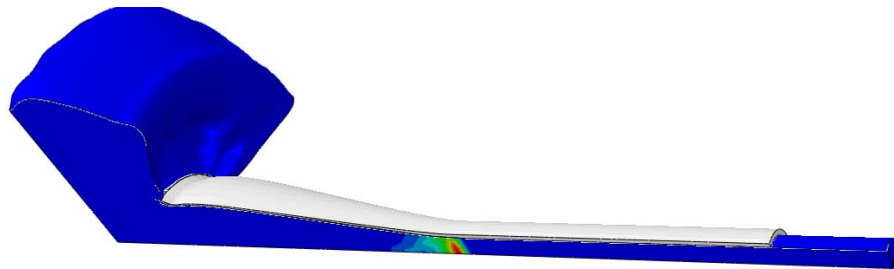


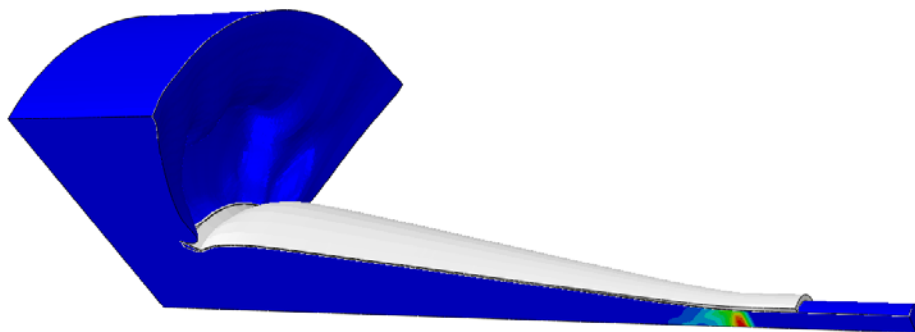
Figure 13. Spherical arrangement, CEL vs. Experiment – PBX9404.



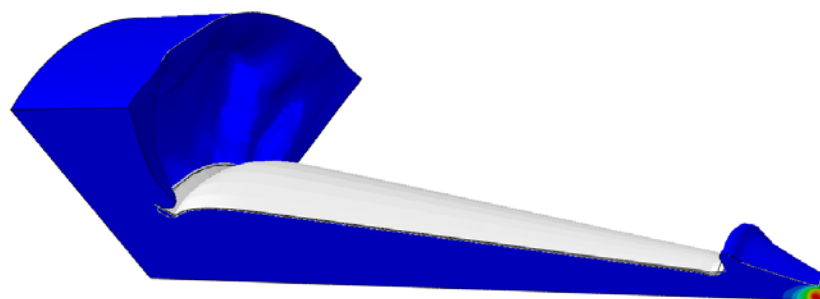
13 microseconds



25 microseconds



41 microseconds



51 microseconds

Figure 14. Cylindrical arrangement, contours showing detonation wave.

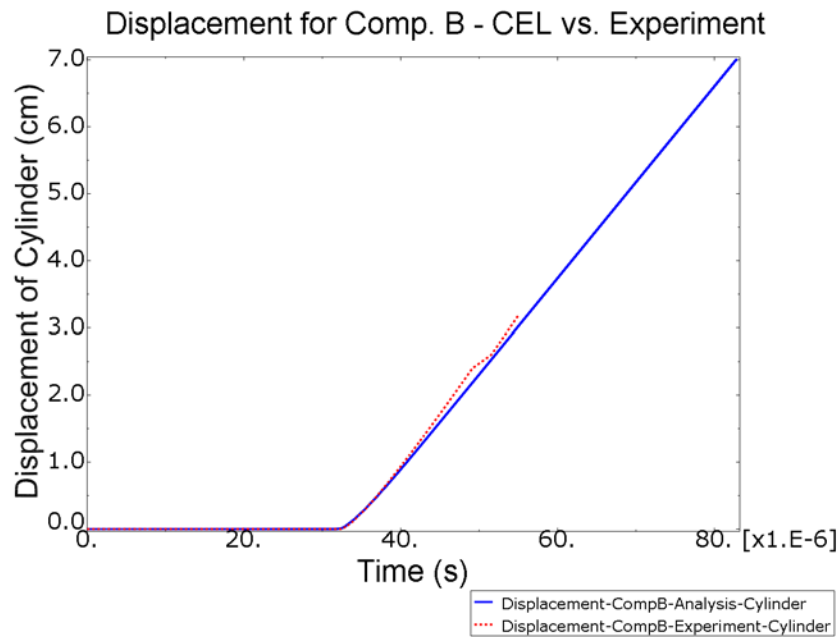


Figure 15. Cylindrical arrangement, CEL vs. Experiment – Composition B.

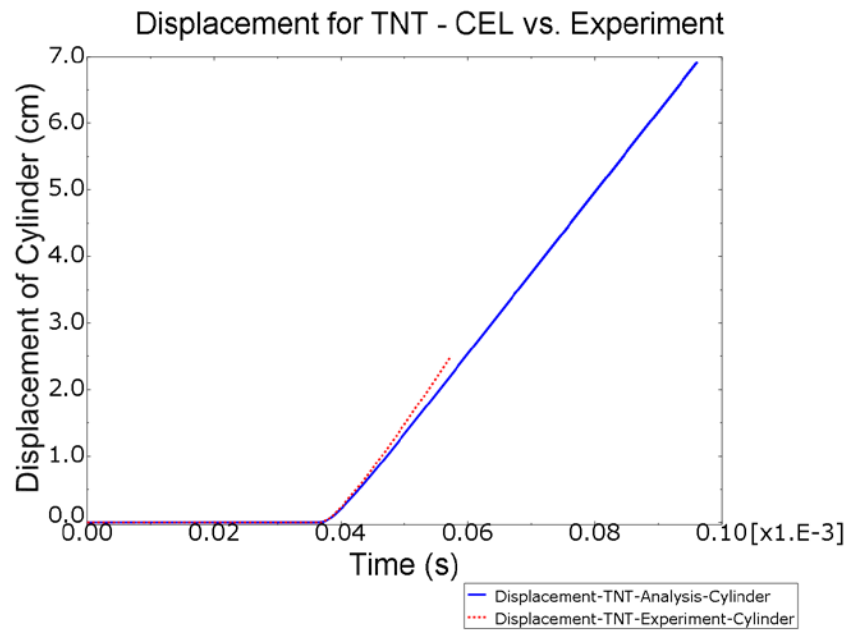


Figure 16. Cylindrical arrangement, CEL vs. Experiment – TNT.

3. Compressible inviscid flow – Validation using a Shock Tube

3.1 Description of Experiment

While compressible inviscid flow is applicable to a wide range of problems, the context of interest to the U.S. Army extends to blast loading of structures. While the JWL EOS describes in the preceding section is suitable for analyzing blast loading in the near field (the area that is in the immediate fireball of the high explosive blast), there are many problems that require analysis in the far field. In the far field the shock from the explosion has propagated into the surrounding ambient air, and it is this loading which causes the blast damage to structures. For this case, the inviscid compressible flow assumption is valid, and can be accurately used to model far field blast loading.

Traditionally, the solution for the compressible flow field would be accomplished by using a commercial CFD code, with idealized non-moving boundaries acting as the loaded structure. The calculated loads would then be applied in a dynamic FEA code (Abaqus/Explicit) to determine the resulting structural response. The introduction of CEL in Explicit allowed a direct coupling to solve this problem. The fact that the CEL implementation uses the full Navier-Stokes equations implied that it was able to handle inviscid compressible flow appropriately. It is important to note that CEL is not structured in the same way as a CFD code, and wasn't intended to fill this role. While it does include viscous effects with extension to laminar flows, it does not include any turbulence effects. But in the context of an air blast load, which is short duration and highly transient (with turbulence effects being of less importance to the structural loading), CEL would be well suited. Before using Abaqus/CEL to solve this class of problems, a level of confidence was necessary in the modeling of compressible inviscid flows, as well as with shock interactions.

A shock tube was chosen for the validation effort since the relevant analytical equations for the compressible flow are readily available (Anderson, 2003). Additionally, shock tubes are typically used to generate extremely high temperature and high pressure flows for very short time durations. This is very similar to the highly dynamic short duration air blast wave for far field blast loading. In general, a shock tube will have two chambers separated by a burst diaphragm. One chamber (the driver) will initially be filled with gas under high pressure. The other (driven) chamber will be filled with gas at low pressure (usually below atmospheric). To initiate the test, the burst diaphragm will rupture and a planar shock wave will begin to propagate into the driven section.

3.2 Model Geometry and Model Mesh

For the shock tube geometry, a CEL model was developed using ~120,000 elements. Figure 17 shows the Eulerian domain with associated initial conditions of the air in the "Driver" and "Driven" sections. The reason for not using a 1D model was due to the intent to place a Lagrangian object inside the shock tube for subsequent iterations. The ideal gas equation of state is used to model the air, along with specifying the specific heat and initial density. The desired initial pressure is specified indirectly by using a predefined field for the initial temperature (with pressure being the result from $P = \rho RT$). The goal was to create a shock wave of a particular strength in order to replicate a particular blast loading scenario. In order to achieve this, the density and temperature of the driver section were adjusted accordingly to give the initial pressure

that was desired. The driven section of shock tube was assigned ambient properties. It is unnecessary to simulate the burst diaphragm as the default interface between the two gases will behave as if the burst diaphragm had just ruptured at the start of the analysis.

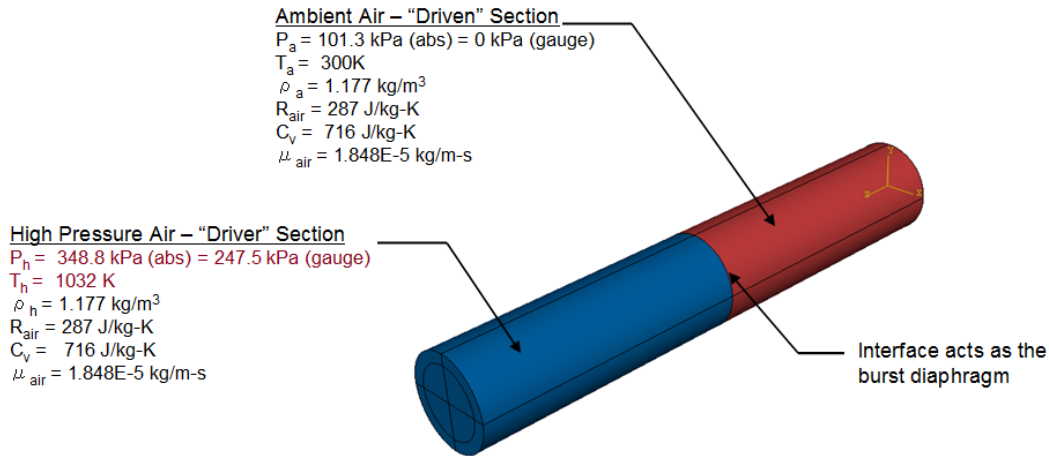


Figure 17. Shock Tube CEL geometry and initial conditions.

3.3 Analysis Results and Comparison to Experiment

For the CEL results, there were two regions of interest for comparison: the region behind the incident shock front (relevant to incident overpressure for blast waves), and the region behind the reflected shock front at the end of the tube (relevant to reflected overpressure for blast waves). Figure 18 shows the results from analytical calculations from the equations in (Anderson 2003).

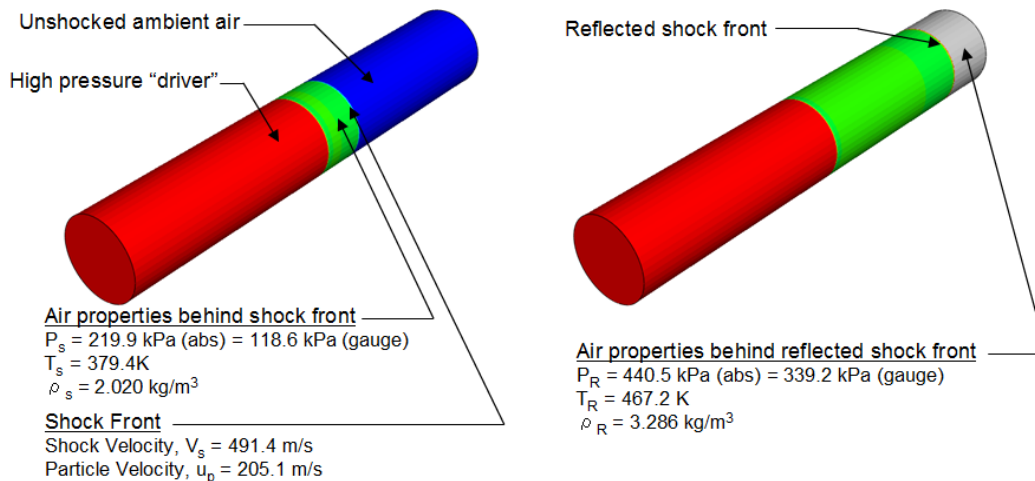


Figure 18. Shock Tube – Analytical Results.

Figure 19 shows the pressure contour results for the CEL model for the incident shock at 0.3 milliseconds and the reflected shock at 0.9 milliseconds. Also captured by the CEL analysis is the expansion fan that propagates into the “driver” section, and the characteristic widening of the expansion fan can be seen from the two contours.

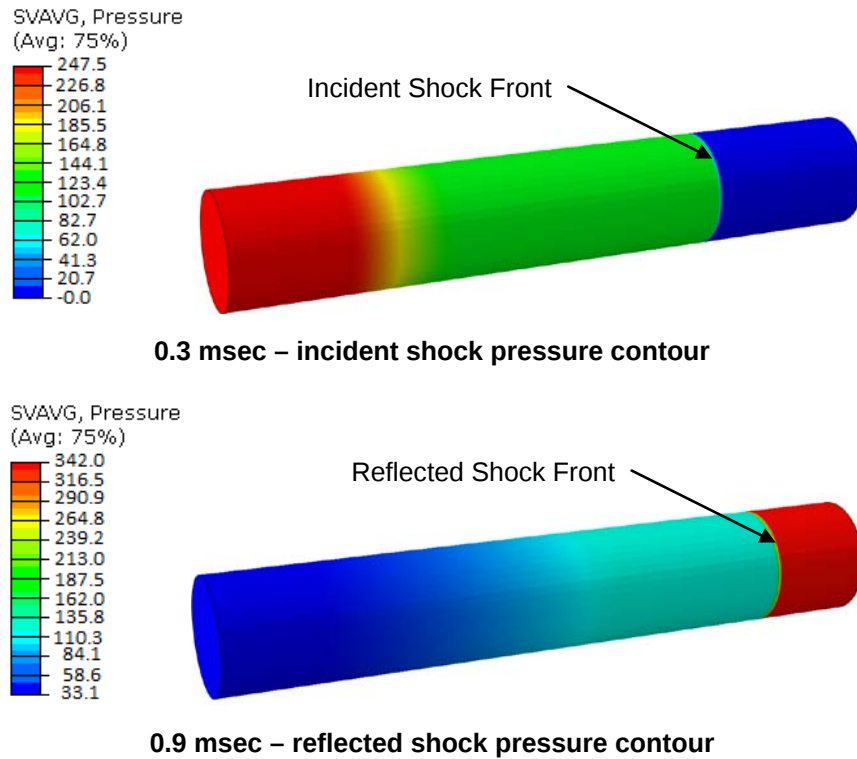


Figure 19. Shock Tube – CEL results, pressure contours (kPa – gauge).

A summary of the CEL results is contained in Table 1, which compares them to the analytical calculations and shows the computed error between them. There is excellent agreement between the analytical solution and the CEL results, with errors of less than 0.75% for all the relevant quantities compared.

Following this validation activity, CEL was used to accurately model far field blast loading on complex Lagrangian structures as shown by (Mougeotte, 2010), and to model the compressible choked flow into an artillery projectile’s base cavity (Stout, 2010).

Table 1. Shock Tube – comparison of CEL and analytical results.

Air Properties – Behind Incident Shock Front			
	CEL	Analytical	Error (%)
Pressure abs. (kPa)	219.7	219.9	-0.10
Temperature (K)	378.8	379.4	-0.15
Air Properties – Behind Reflected Shock Front			
	CEL	Analytical	Error (%)
Pressure abs. (kPa)	441.0	440.6	0.10
Temperature (K)	466.1	467.2	-0.22
Shock Front Properties			
Shock Velocity (m/s)	490.8	491.4	-0.12
Particle Velocity (m/s)	206.4	205.1	0.63

4. References

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5. Acknowledgements

The authors would like to sincerely thank Ellen Cerreta and George Gray of Los Alamos National Lab for providing the experimental data and figures for use in this paper, and for taking the time to answer questions with respect to the Dynamic Tensile Extrusion Test discussed in Section 1.