Simulating Underbelly Blast Events using Abaqus/Explicit - CEL

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Abstract: Accurate modeling and simulation of the effects of near-field blast events on vehicles and personnel is of interest to the Department of Defense. Applications include minimizing casualties and improving vehicle survivability from attacks using improvised explosive devices. The coupled Eulerian-Lagrangian (CEL) capability in Abaqus/Explicit was used to replicate experimental tests in which the structural response of varying metal panels subjected to the detonation of a buried charge was characterized. A Lagrangian representation was used for the test structure and panel and an Eulerian representation was used for the soil, explosive, and ambient air. The detonation of the charge was approximated using programmed burned techniques and its detonation products were modeled with the Jones-Wilkins-Lee (JWL) equation of state. A simplified hybrid elastic-plastic material model for geologic materials developed by the U.S. Army – ERDC was implemented as a VUMAT and used to describe the soil. The simulations agree favorably with the test results and produce higher fidelity solutions than traditional analytical or empirical blast models. It is shown that Abaqus/Explicit can be used to accurately predict the response of a structure subjected to a near-field blast event with specific application to underbelly blast events on vehicles.

Keywords: near-field blast, underbelly blast, fluid-structure interaction, hybrid elastic-plastic soil model, Jones-Wilkins-Lee equation of state

1. Background

1.1 Overview

In a near-field blast event, the explosive products are not fully developed and are directly interacting with the structure under consideration. This is in contrast to a far-field blast where a well-developed shock wave will be traveling through an ambient medium. Typically, the resulting shock on the structure is highly irregular spatially and temporally. Underbelly blast events add additional complexity because the explosive of interest is often buried in the ground. The resulting blast event consists of a complex fluid-structure interaction between soil, explosive products, and the structure under consideration. The extreme deformation associated with the expanding detonation products and soil surrounding the explosive lends itself well to an Eulerian representation. The response of the structure is typically of predominant interest and complex plasticity and damage models are often used to describe the material. As a result, a Langragian treatment of the structure is preferred. Therefore, a finite element solver with the capability of coupling the interaction between Lagrangian and Eulerian materials offers a substantial advantage in modeling the detailed fluid-structure interactions that dominates near-field blast events.

The coupled Eulerian-Lagrangian (CEL) capability in Abaqus/Explicit allows for this capability. The algorithm is a two part process in which all material is deformed with a Lagrange treatment in a given time increment. This is followed by a remapping step for the Eulerian material. Over-closures between Lagrangian and Eulerian material are handled using a general purpose contact algorithm.

A proposed technique for accurately modeling a near-field blast event is to use the CEL capability to model the explosive material and any ambient mediums that undergo excessive deformation (i.e. soil, air, etc.) as Eulerian material while modeling the structures of interest as Lagrangian material. In principle, Abaqus/Explict – CEL should be able to resolve the appropriate fluid-structure interactions and capture the loading imparted on the structure by the detonation products. For the specific application of modeling an underbelly blast, it is proposed that using a Jones-Wilkins-Lee (JWL) equation of state for the explosive products and a simplified hybrid elastic-plastic model for any geological material in which the explosive may be buried in will yield accurate results when coupled with the appropriate plasticity and damage models for the structure.

To assess the validity of this modeling approach, a benchmark problem was established. Specifically, an experiment designed to calibrate empirical blast models to underbelly blast events was replicated in Abaqus/Explicit. The particular experiment chosen encompasses the relevant physics required to accurately model an underbelly blast event. The entire model definition, with specific emphasis on the empirical constants for the relevant constitutive models was defined *a priori* and not adjusted to improve correlation with the experiment. This was done to replicate a realistic workflow in which a predictive solution is required from the finite element solution. The parameters for the constitutive models were acquired from well-established material databases within the U.S. Army.

1.2 Jones-Wilkins-Lee (JWL) EOS for Explosive Products

The Jones-Wilkins-Lee (JWL) equation of state is an empirical model useful in describing the thermodynamic properties (i.e. pressure, specific volume, and energy) of the detonation products of nearly ideal explosives. Equation 1 expresses the pressure of the detonation products as a function of the volume expansion from the initial state of the products ($V^* = \frac{v}{v_o}$), the relative internal energy ($E = \frac{e}{v_o}$), and empirical coefficients (A, B, C, R_1, R_2, ω). The isentrope describing the product gases is given in Eq. 2, which completes the equation of state. The JWL equation of state is readily available in Abaqus/Explicit and has been successful in replicating experimental cylinder expansion tests.

$$P = A\left(1 - \frac{\omega}{R_1 V^*}\right)e^{-R_1 V^*} + B\left(1 - \frac{\omega}{R_2 V^*}\right)e^{-R_2 V^*} + \frac{\omega E}{V^*} \qquad \textit{EQ-1}$$

$$P_s = Ae^{-R_1 V^*} + Be^{-R_2 V^*} + CV^{*-(\omega+1)} \qquad \textit{EQ-2}$$

Calculating JWL parameters involves conducting cylinder expansion tests and incorporating the resulting data into a thermo-chemical equilibrium code. The resulting parameters can be validated through replication of the cylinder expansion test results in a hydrodynamics code. It is important to note that since the JWL parameters are typically calibrated to cylinder expansion tests, their applicability outside of the volume expansions experienced by the detonation products during this test is questionable. A common expansion for detonation products during a cylinder expansion test is within the range of seven to eight volume expansions. Thus, beyond this expansion range, the validity of the JWL equation of state cannot be guaranteed. Note that in the limit of volume expansion, the detonation products will be approximated using ideal gas assumptions.

In addition to having an equation of state for the detonation products, it is also necessary approximate the detonation process when modeling an explosive material. Essentially, there needs to be some way to determine when a quantity of material converts from its solid un-reacted state to its gaseous reacted state. One of the simplest techniques to model the detonation process is through the use of programmed burn. In the programmed burn technique, the user defines the initiation points on the explosive. Knowing the detonation velocity of the explosive material, D_{CJ}, and the position vector of the nearest detonation point, $\vec{x}_o$, one can estimate the time of detonation, t_d, of a material point defined by its position vector, $\vec{x}_p$, through the use of Eq. 3. Note that the inherent assumption in this approach is that the detonation wave, from the point of initiation, travels straight toward the material point at a constant velocity. This assumption may not be geometrically valid in all cases.

$$t_d = \frac{\left\|\vec{x}_p - \vec{x}_o\right\|}{D_{CJ}} \qquad \textit{EQ-3}$$

1.3 Simplified Hybrid Elastic-Plastic Soil Model

The hybrid elastic-plastic (HEP) material model was developed by U.S. Army – ERDC to accurately describe the material response of geological materials subjected to high impulse loading (i.e. shock events). The hydrostatic behavior of the material is assumed to be a function of material compaction and its compaction history, as shown in Eq. 4 (referred to as the pressure-compression relation). Due to the history dependence of the pressure-compression the material response can differ if being loaded (along a virgin loading path), unloaded, or reloaded. Therefore, regions of hysteretic behavior can be accurately described. The model can easily accommodate linear and non-linear descriptions of the pressure-compression relation and divide it into piecewise regimes, such as a hysteretic crush-up region to the point of void closure followed by non-hysteretic behavior beyond void closure.

$$P = f(\mu, \text{history}) \qquad \textit{EQ-4}$$

The pressure-compression relation is able to capture such complex behavior because it consists of a series of empirical fits and detailed logic to determine which fit is applicable based on the history of the material. Typical fits used include linear, quadratic, and power but the model can be adjusted to accommodate any fit so long as the relevant empirical constants are known. Note that for a given material, a suite of testing is required to determine the appropriate empirical constants.

The deviatoric stress of the material is dictated by a variable shear modulus which is constrained to never be greater than G_{max}, as shown in Eq. 5. The shear modulus, since coupled with the local bulk modulus of the material exhibits comparable complexity to the pressure-compression relation. The Poisson's ratio of the material can also vary during unloading and loading conditions. Deviatoric failure is assumed to be coupled with the hydrostatic state of the material and is based on the second invariant of the stress tensor. Equation 6 shows that the yield surface, which is also empirically calibrated, takes the form of a pressure-dependent exponential function.

$$s_{ij} = 2\min\left[1.5\frac{dP}{d\mu}(1+\mu)\left(\frac{1-2\nu}{1+\nu}\right), G_{max}\right]\left(\varepsilon_{ij} - \frac{1}{3}\varepsilon_{kk}\delta_{ij}\right) \qquad \textit{EQ-5}$$

$$\sigma_y = A - Ce^{B_o P} \qquad \textit{EQ-6}$$

2. Model Definition

2.1 Problem Definition

Experiments were conducted by Defence R&D Canada (DRDC) – Valcartier in which aluminum and steel plates (i.e. the test articles) were subjected to the detonation of buried mines. The deformation histories of various points on the test article were recorded spatially and temporally. This data was used for calibration of the CONWEP and U.S. Army TACOM Impulse blast models. The experiment was designed to be representative of an underbelly blast event and so it serves as a natural benchmark problem to assess the validity of any methodology in modeling near-field blast events.

Figure 2 illustrates the overall configuration of the experiment. The target plate is a 6' x 6' plate and is the object of principle interest in the experiment. Tests were conducted using 1.25" thick 5083-H131 aluminum and 0.25" RHA aluminum plates. A SAE 1020 steel support stand suspends the target plate 16" above the soil surface. Approximately two inches below the soil (5 cm) is a charge of C-4 explosive. A box beam frame sits on top of the target plate which forms a

4’ x 4’ opening above the target plate. The box beam frame supports additional mass allowing the application of a representative vehicle weight on the test apparatus. In the tests conducted, a weight of approximately 234,000 pounds was applied to simulate the mass of a light-armored vehicle.

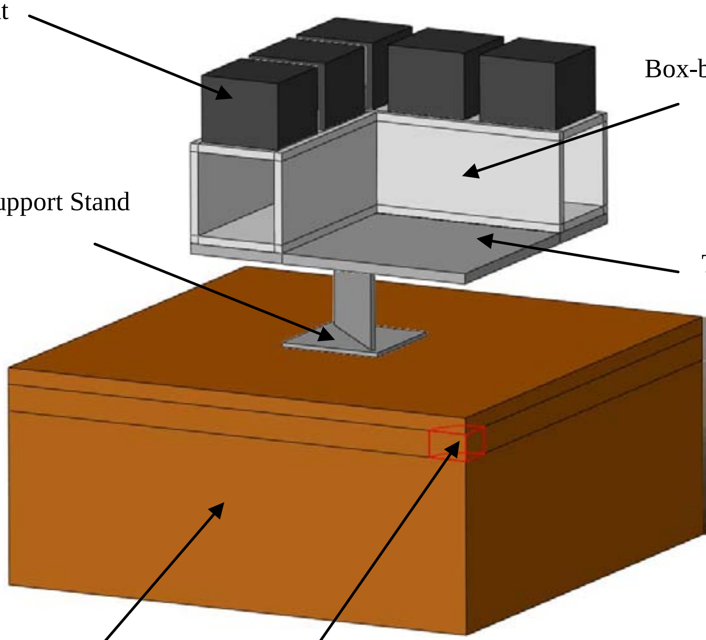


Figure 1. Overview of experimental setup as defined in Abaqus/CAE. Note that quarter symmetry is assumed.

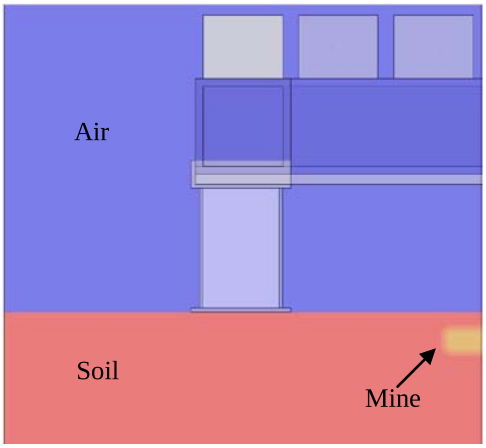
2.2 Finite Element Model

Due to the inherent symmetry of the experiment, quarter symmetry was assumed when developing the model. The computational advantages of applying symmetry to any finite element model are obvious but symmetry is especially useful in the context of a near-field blast simulation. In order for the general contact algorithm to resolve any over-closure between Eulerian and Lagrangian surfaces, the mesh resolution of the materials at the interface must be comparable. Since the Eulerian domain encompasses a large volume relative to the actual Lagrangian structure the resulting element count in the Eulerian domain becomes a significant factor in the computational requirements of the model.

General contact was used with the exception of the air with the Lagrange bodies, where contact was excluded. This was done because the Lagrangian parts are embedded within the Eulerian domain. That is, there are some areas in the model where the Eulerian and Lagrange meshes overlap. The result is that air is initialized within the test structure. This could be avoided if the volume-fraction tool was used in Abaqus/CAE, which would allow for void to be initialized within the Lagrange parts. However, this would be computationally demanding of the solver as the Eulerian surface reconstruction for the air would be more complex. In addition, the CEL contact algorithm would have to resolve significantly more contact over-closures in each increment. Since the interaction between the air and the solid structures does not dominate the physics of the experiment it is assumed to be negligible and omitted from the model.

The simulation was conducted on a high performance computing cluster with nodes composed of dual 6-core 2.67 GHz Xeon X5650 processors and 48 GB of memory. The analysis required the use of two nodes (i.e. twenty-four cores) over a period of five hours.

Part	Description
Support Stand	Treated as a rigid body. Meshed with 56,565 C3D8R elements.
Weight	Treated as a rigid body. Meshed with 800 C3D8R elements.
Box-beam Frame	Modeled as SAE 1020 steel with linear elasticity. Meshed with 88,816 C3D8R elements.
Target Plate	Modeled as a 1.25” thick 5083-H131 aluminum solid with linear elasticity, Johnson-Cook plasticity, and Johnson-Cook damage.
Soil*	Modeled using a simplified hybrid elastic-plastic model calibrated to a “sandy” soil at a density of 2300 $\frac{\mathrm{kg}}{\mathrm{m}^3}$.
Mine*	Explosive products modeled as C-4 using the JWL equation of state. Detonation process approximated through programmed burn calculations.
Ambient Air*	Modeled using ideal gas assumptions at standard ambient temperature and pressure conditions.



*Note that the soil, mine, and ambient air are all defined within the Eulerian domain, which was meshed with 795,982 EC3D8R elements. The assignment of these three materials within the Eulerian domain is shown above.

Figure 2. Overview of model assembly and mesh summary.

3. Analysis

3.1 Blast Event

The entire blast event, including the structural response of the plate takes approximately five milliseconds from ignition of the explosive charge. The dominating physics in this experiment is the interaction of the detonation products with the soil as well as the interaction between the soil and target plate. As the detonation products expand, the overlying soil is ejected into the bottom of the target plate. The impact of the soil into the target plate is the primary cause of deformation as the momentum transferred to the target plate is significant. The detonation products impact the target plate with velocities comparable to the ejected soil. However, an inconsequential amount of energy is transferred to the target plate due to the substantial expansion of the detonation products. Therefore, the interaction of the detonation products with the structure can be neglected.

The entire mine has detonated at 50 μs into the analysis. As a result there is no longer a solid phase associated with the explosive material and it has completely converted to gaseous detonation products. At this point the volume expansion of the detonation products is less than eight times the initial volume and so the JWL equation of state is expected to reasonably describe the thermodynamic state of the material. Although there is significant deformation within the surrounding soil, the detonation products are still confined.

At 100 μs into the analysis the surrounding soil begins to fail which will provide the highly pressurized detonation products with an escape path. Despite this, work will continue to be performed on the soil by the detonation products. Note that the corresponding expansion of the detonation products has exceeded the calibration bounds of the JWL equation of state. As the detonation products continue to expand, the resulting thermodynamic calculations will asymptotically approach ideal gas assumptions.

The ejected soil first contacts the target plate at 350 μs into the analysis. The velocity of the soil throughout the ejection process is predominately upward (i.e. perpendicular to the bottom of the test plate) and so the impact is focused on the center of the target plate. The initial contact area is approximately 10% of the linear distance from the center of the target plate to its edge. Additional soil which has yet to contact the plate will contact an additional 10% of this distance. Also at this time the detonation products have contacted the target plate. However, the momentum associated with the detonation products is not significant enough to affect the test structure. Instead, the detonation products are deflected along the bottom of the test plate.

At 400 μs into the analysis, the majority of the soil has impacted the center of the target plate and the resulting deformation is noticeable. The detonation products continue to expand but cease to have an appreciable effect on the final deformation profile of the target plate. In this sense, the detonation of the mine only affects the test structure for approximately half a millisecond after ignition. Note that this is the time required for the detonation products to eject the soil into the

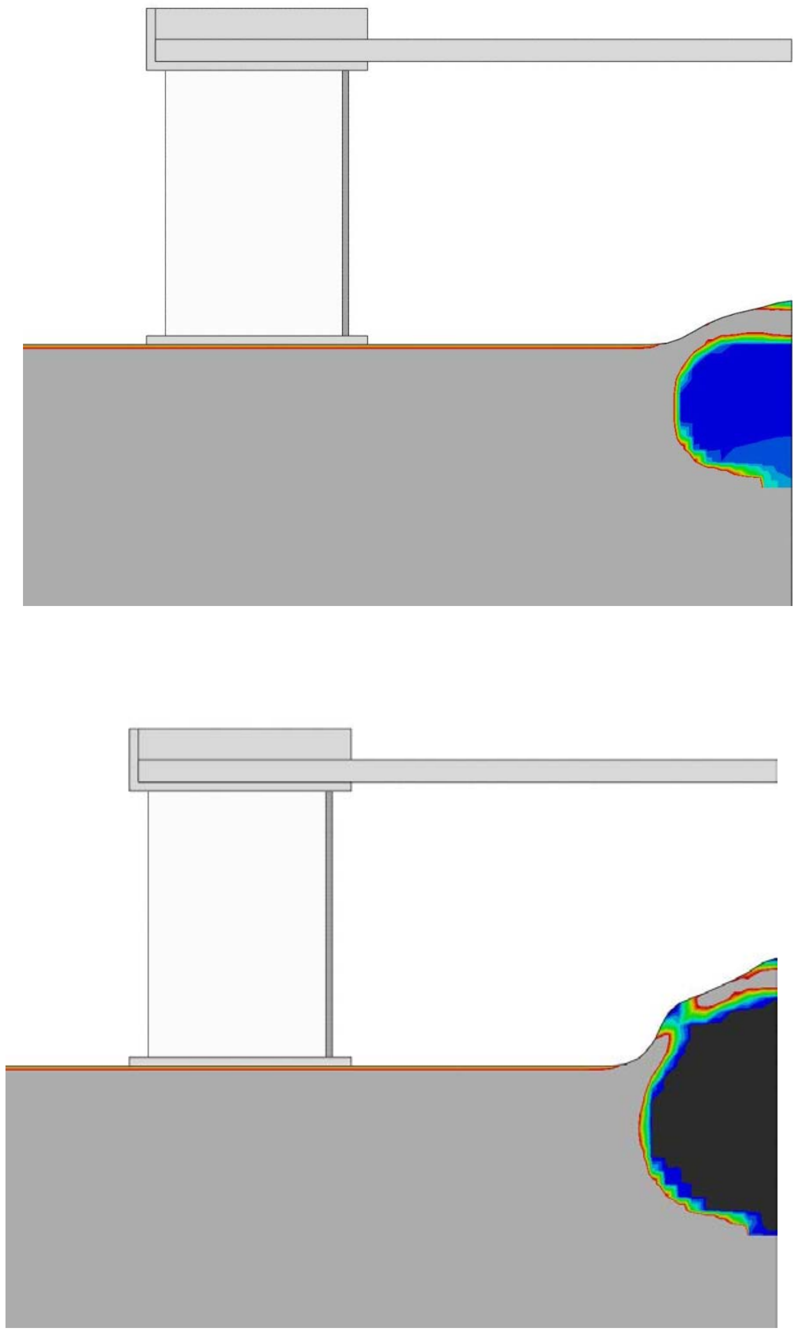


Figure 3. Density contours at 50 µs into the analysis (top) and 100 µs into the analysis (bottom)

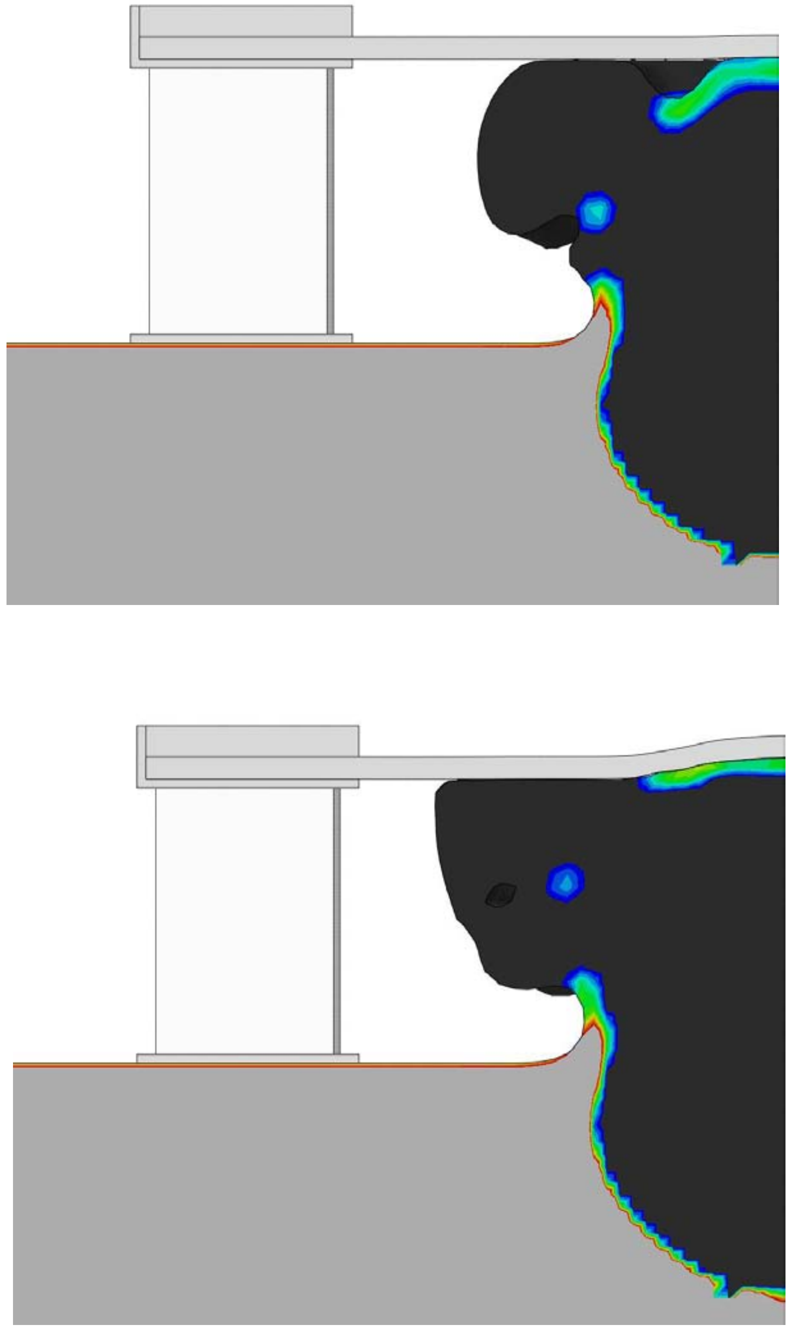


Figure 4. Density contours at 350 μs into the analysis (top) and 400 μs into the analysis (bottom)

target plate. The remaining 4.5 ms of the analysis consists of the test plate responding to the soil impact.

3.2 Structural Response

The kinetic energy of the soil impacting the test plate is significant. During the impact event, the test plate is plastically deformed. The maximum deflection of the center test plate was observed at approximately 2.5 ms after the onset of deflection. Afterward, the elastic strain energy in the test plate dissipated resulting in a “spring back” effect. The spring back was 4.2% of the maximum deflection. After 5 ms (from the start of the analysis) the spring back of the test plate had mostly dissipated. At this point, it was assumed that the test plate was in its final deformed configuration. The residual displacement of the center of the plate was recorded so that it could be compared to the experimental results.

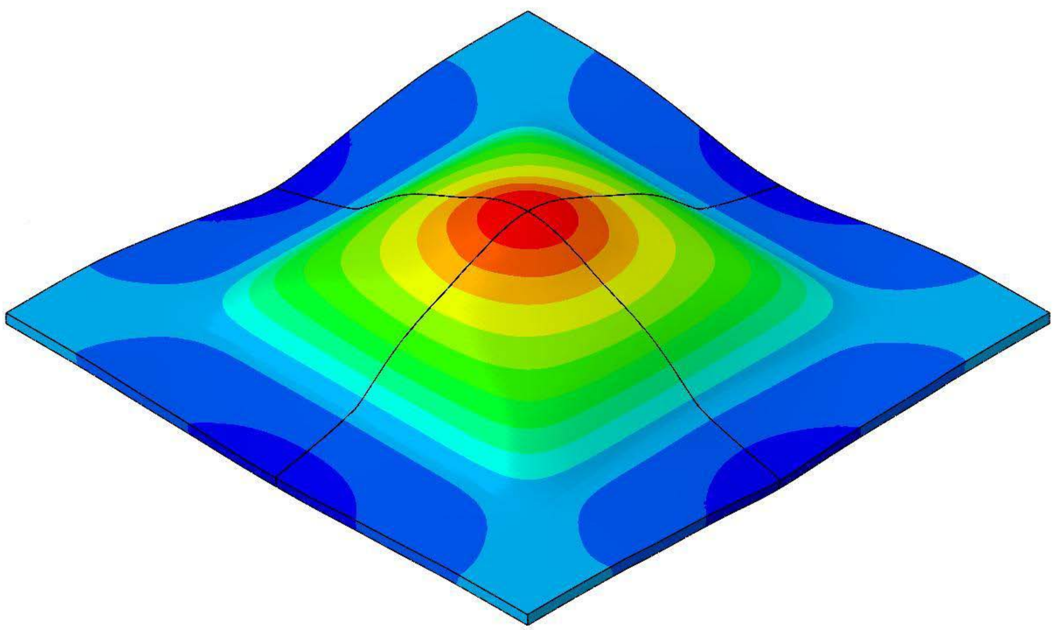


Figure 5. Final deformation contour plot of the target plate.

4. Discussion

4.1 Comparison with Experimental Results

The finite element model accurately predicted the residual displacement of the center of the test plate within 3% of the experimental results. In addition, the final deformation profile of the test plate along its symmetry plane shows reasonable agreement with the experiment. This comparison is detailed in Fig 6. Note that the error associated with the finite element solution becomes more pronounced away from the center of the plate as the total displacement is under-predicted.

The best agreement of the model with the experiment occurs along the predicted contact surface between the soil and target plate. The empirical coefficients for the simplified hybrid-elastic-plastic soil model were taken from a soil of comparable density but different constituent components (as test data for more representative soil was unavailable). Since the density of the soil is representative, it is conjectured that the momentum transfer between the soil and target plate is accurately captured. This would explain the model agreement in regions where a soil-plate impact was predicted. However, the dispersion and quantity of the ejected soil is suspect because the constitutive response is likely to be inaccurate. It is thought that in the experiment, a greater quantity of soil than predicted by the model was ejected toward the middle of the target plate. Such an event would produce a deformation profile that is more consistent with the experimental results.

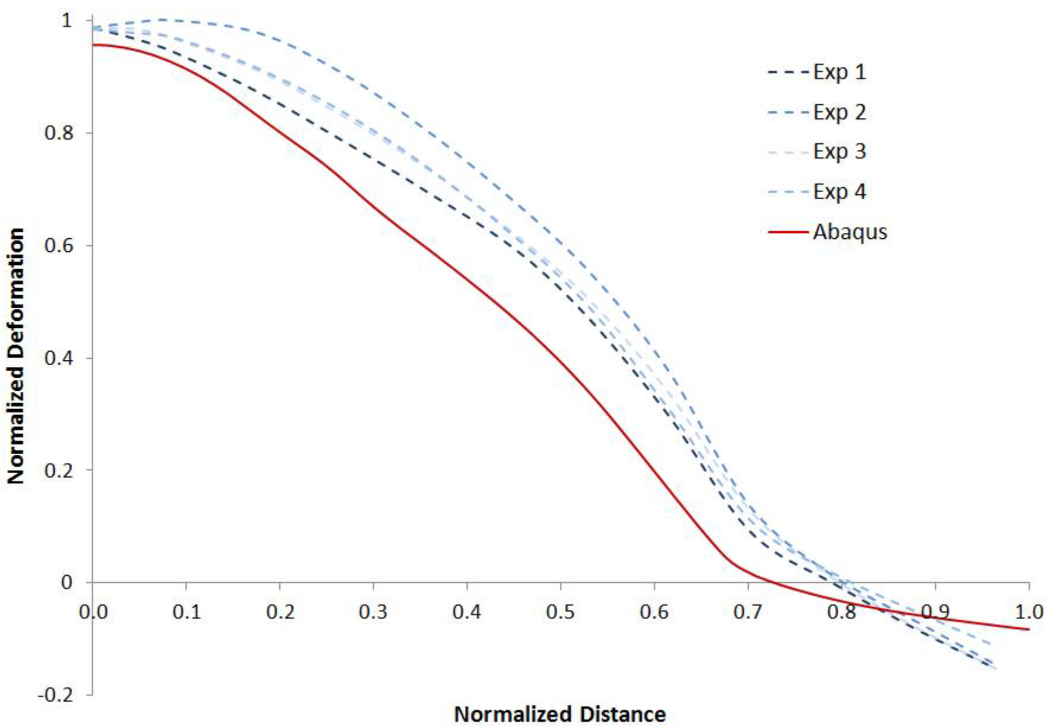


Figure 6. Comparison of the predicted deformation profile of the target plate with experimental results.

4.2 Comparison with Empirical Blast Models

There are several empirically-based blast models which have been used as engineering tools for blast prediction. These models can serve as a first-order approximation in understanding the effects of a blast event on a structure. However, since much of the underlying physics is simplified, calibration of these models is required when they are used for predicting complicated or novel blast events, ultimately limiting their use as predictive tools.

The CONWEP model consists of a set of blast loading functions that can be used to determine a pressure-time history for a particle at a specified distance from a blast event. These blast loading functions are empirically determined and so separate classes of functions are needed to describe dissimilar blast events. Implementation of blast functions describing the free air detonation of a spherical charge and the surface detonation of a hemispherical charge were incorporated into LS-DYNA as a type of boundary condition. Note that a similar feature is also available in Abaqus/Explicit. It is important to note that the CONWEP model was developed with the intention of predicting far-field blast events.

The U.S. Army TACOM Impulse model is an empirical relationship that predicts the impulse applied to a plate as a result of the detonation of a buried mine. Parameters incorporated into the relationship include the location of the mine relative to the target plate, the geometry and mass of the mine, the depth of burial of the mine, the geometry of the target plate, and the orientation of the target plate with respect to the mine. Application of this model allows one to predict the initial velocity field on the faces of a structure due to a blast event. A pre-processer was developed by DRDC – Valcartier which couples the predicted initial velocity field resulting from the U.S. Army TACOM Impulse model to an LS-DYNA input deck.

Previous work done by Williams *et al.*in which the CONWEP implementation into LS-DYNA and U.S. Army TACOM Impulse model were used to predict to the experiment described in this paper. The initial results of this analysis illustrate the limitations of using empirical blast models beyond their bounds of calibration. The LS-DYNA simulation under-predicted the maximum residual displacement of the target plate by 50% whereas the U.S. Army TACOM Impulse model over-predicted the maximum residual displacement of the target plate by 70%. This margin of error is in contrast to the Abaqus/Explicit simulation which under-predicted the maximum residual displacement by 3%. In order for the empirical blast models to produce results consistent with the experiment, the assumed mass of the charge in the CONWEP model was increased by a factor of 2.2. In the U.S. Army TACOM Impulse model, the predicted impulse was scaled by a factor of 0.66.

Modeling Approach	Error
Abaqus/Explicit Coupled Eulerian-Lagrangian	-2.7 %
LS-DYNA CONWEP Boundary condition	-48.0 %
LS-DYNA U.S. Army TACOM Impulse Model for initial conditions	72.8%

Figure 7. Modeling approach used and corresponding error in predicting the maximum residual deflection in the test plate.

4.3 A comment on the JWL equation of state

It is interesting to note that early into the simulation the JWL equation of state is outside of its calibrated bounds. Recall that JWL parameters are typically calibrated up to a volumetric expansion of eight times the initial volume. In Figures 4 and 5, the detonation products are colored black when they are outside of this range. Note that this occurs within the first fifty microseconds of the analysis. Despite this, the numerical results are within good agreement with the experiment. It is thought that the most significant physics associated with the detonation products occurs within this timeframe. This corresponds to the initial work imparted on the soil during the ejection process. Once the detonation products have undergone enough volumetric expansion to invalidate the JWL equation of state, they do little else that would affect the test structure.

5. Conclusions

The coupled Eulerian-Lagrangian (CEL) capability in Abaqus/Explicit successfully replicated the experimental deformation of a panel subjected to the detonation of a buried mine. This experiment is representative of the physical conditions present during an underbelly blast event on a light-armored vehicle. The results predicted by Abaqus/Explicit are a significant improvement over previous attempts that couple empirical blast models with finite element codes, since the predictive nature of empirical blast models are limited to the range of their respective calibration. The improvement of accuracy in this approach results from directly modeling the blast event (i.e. evolution of the detonation products) while simultaneously performing structural calculations for the structure of interest and any ambient mediums.

This particular study placed emphasis on assessing the feasibility of using Abaqus/Explicit – CEL to study underbelly blast events in a production-level environment. Factors such as model accuracy, the time required in producing the model, the time required to debug the model, and the computational requirements of the simulations are all important to consider. The initial model was developed and debugged within a two week period. Once this baseline model was established, a subsequent simulation could be completed in five hours. Presently, this type of modeling and simulation workflow is appropriate for engineering applications in the U.S. Army - ARDEC.

From an engineering standpoint, the deformation profile predicted by the analysis is adequate. However, there is a noticeable error that develops at points further from the center of the target plate. It is believed that the primary cause of this error is inaccurate treatment of the soil. Although the material model used to describe the soil has an accurate density, the assumed constituents of the soil are unlikely to be representative of the actual soil present during the experiment. The soil model used was a “best guess” in lieu of a more accurate model, which would have required material testing to establish. Therefore, it is not expected that the constitutive response of the soil was fully captured. Note that in the spirit of this case study, such a scenario is not uncommon in a production-level environment.

Due to the complex response of soil under high impulse loading and thermodynamic behavior of detonation products, perhaps the most significant source of modeling error lies in the constitutive treatment of these materials. Therefore, in simulating near-field blast events with Abaqus/Explicit-CEL, it is critical that representative material models are available for the problem under consideration. With the appropriate constitutive models, Abaqus/Explicit is a useful research and engineering tool in studying the effects of underbelly blast events. It is also suitable to be used in a production-level environment where modeling and simulation is expected to supplement the design process for complex products in an efficient and timely manner.

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