Novel Approach to Conducting Blast Load Analyses Using Abaqus/Explicit-CEL

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Abstract: A new method is introduced for conducting blast load analyses using the new Coupled-Eulerian-Lagrangian (CEL) capability of Abaqus/Explicit. In the past, either a 1-D blast code or tabular data was used to determine a pressure vs. time curve that would be applied to the exterior surfaces that were assumed to interact with the blast wave. These pressure curves were generated using knowledge of the amount/type of explosive and line-of-sight distance away from the explosion. While this method remains valid, with increasingly complex structural geometry, oblique surfaces, and with corners facing the blast, the amount of overhead required to analytically determine the necessary pressure loading for each of the various surfaces becomes exhaustive. This new approach involves surrounding the structure with a body of air (Eulerian), imparting a blast (pressure) wave as a boundary condition into the body of air, and then having it propagate into the Lagrangian structure. The Lagrangian structure can be positioned arbitrarily within the Eulerian domain to achieve any angle of incidence that is desired. This new method negates the need to determine reflected pressures for oblique surfaces a priori. This approach remains to be validated against test data (impulse-momentum traps) but thus far the results look promising.

Keywords: CEL, Coupled Analysis, Explosive, Shock

1. Introduction

A significant amount of energy is contained within a blast wave. Considerable damage can occur should it impact a structure. However, it is difficult to assess the loading experienced by the structure because of the large number of variables at play: cased explosive versus uncased, effects of afterburning, angle of incidence with respect to incoming shock, nearby geometry/barriers interacting with the shock, possible mach reflection due to air burst, etc, etc.

During the design phase of new armor systems, for example, it is valuable to understand how the armor system will respond to blast loading even if only in an approximate sense. This procedure can be extended to any structure that may experience blast loading, be it explosive test facility or buildings in high risk areas**.** What follows is first an overview on the characteristics of explosive shock waves, then a discussion of some of the historical modeling techniques and how these models provide the inputs to a new analysis technique.

2. Characteristics of Explosive Shock Waves

When explosive materials detonate, they release large amounts of energy very quickly. This rapid release of energy creates a shock wave that travels into the surrounding atmosphere. The idealized form of a blast wave (Figure 1) can be thought of as a pressure pulse with a sharp discontinuous rise in pressure across the shock front, up to the peak overpressure, P_S. There is then an exponential decay in pressure. The period of positive pressure is known as the positive phase duration.

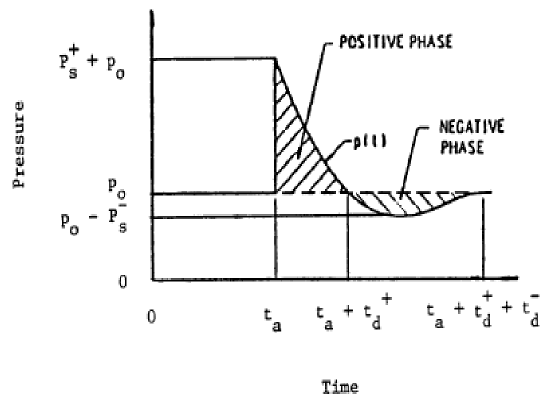

Figure 1. Ideal blast wave (DOE/TIC-11268, 1981).

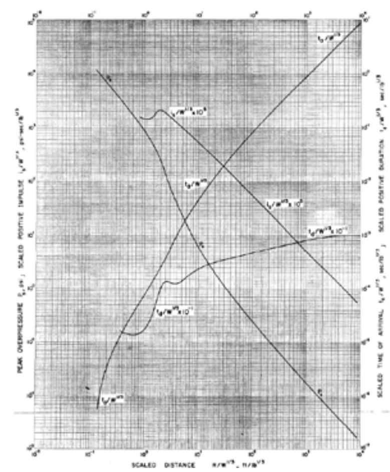

Figure 2. Blast parameters as a function of scaled distance – from TNT air blast data (DOE/TIC-11268, 1981).

Due to inertial effects, the volume of air accelerated by the shock wave tends to over-expand and the result is that a partial vacuum is formed. This is known as the negative phase. The negative phase is typically much longer in duration and lower in amplitude than the positive phase. Little data exists for that regime and it is often neglected. The area under the curve for the positive phase is known as the specific impulse. Of particular interest in subsequent blast loading calculations are the peak overpressure, positive phase duration, and specific impulse.

Armed with a knowledge of the explosive weight and the distance from the explosive to the structure, using cube-root scaling one can calculate the scaled distance (in units $ft/lb^{1/3}$) for a particular blast loading scenario (TM 5-1300, 1990). Using charts like the one shown in Figure 2, the blast parameters (peak over pressure, positive impulse, and positive phase duration) can be determined for a particular scaled distance. Figure 2 was generated from TNT air blast data for bare, spherical charges at sea level.

Blast waves behave much like sound waves. When the blast wave collides with a surface, a reflected wave is formed. The reflected overpressure can be much larger than the incident overpressure. For very strong shocks, where the ideal gas approximation is no longer valid, the predicted upper limit for reflected overpressure is much as 20 times the incident overpressure (AMCP 706-181, 1974)! Also, it is important to note that the reflected pressure varies with the angle of incidence of the shock with respect to the boundary surface. This can be seen in Figure 3 for a number of different shock strengths. This is important because it means that the objects surrounding a structure can create reflected waves that increase the loading seen by the structure. Additionally, there can be reinforcement in the corner geometries where multiple reflected waves can interact.

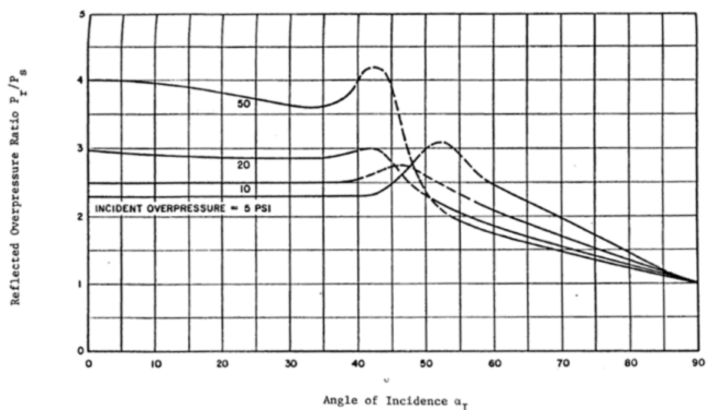

Figure 3. Effect of the angle of incidence on the reflected pressure ratio (DOE/TIC-11268, 1981).

3. Modeling Techniques, Past and Present

3.1 Past

Historically, the structural system would be reduced to a single degree of freedom (SDOF) model and the simplified pressure loading (derived from Figure 2 or 3 or equivalent) applied as the forcing function in order to determine the dynamic structural response. These SDOF systems were well validated and worked nicely for large relatively simple structures. The accuracy of these models breaks down for complex structures with many oblique surfaces. Refer to TM 5-1300 (1990) for more information regarding SDOF models.

3.2 Present

Slightly higher fidelity could be gained by using the same simplified input as for the SDOF model, but instead applying them in a modern structural finite element analysis code. The full 3D geometry can be modeled, realistic boundary conditions defined, and the (blast) pressure loading applied to the structure. Again, the simplicity of this modeling technique breaks down when the structure has complicated geometry and oblique surfaces and the applied loading can be time consuming to predict analytically.

The next step up in fidelity would be a one-way coupling of a computational fluid dynamics (CFD) code with a structural analysis code. The CFD code would be used to predict how the blast wave interacts with the structure. However, in this case the structure only serves as a boundary condition for the CFD model – it cannot deform. In the CFD analysis, the pressure on the surface of the structure is tracked. Then in the structural analysis code, those pressures are mapped into the analysis from the CFD output. This one-way coupling between the two codes will be very accurate, so long as the deformation of the structure has little impact on how the shock waves interact with the structure. Otherwise, the deformation will affect the load that gets applied, but the one-way coupling will not account for this and the result will not be representative of reality.

It is the opinion of the authors that, given the current modeling capabilities, the most *efficient* technique would be to use the simplified blast parameters and apply those as pressure loads to a 3D model of the system in a structural finite element analysis code. As simple as the model may be to set up, the fidelity of the solution will be largely dependent on the experience and judgment of the analyst responsible for translating a particular load case into the correct pressure loads. As much of the existing data is for spherical TNT air blasts – it requires care to manipulate that data for other scenarios (for instance a ground burst of a cylindrical projectile filled with Comp-B explosive at 6500ft elevation– i.e. not TNT, not spherical, not free air, not uncased, and not at sea level).

Recently Abaqus implemented the ConWep model. This model essentially automates the task of determining the pressure loads to apply to surfaces. Based on user input regarding the location of the blast, ConWep automatically calculates the correct distance and angles of incidence and assigns pressures accordingly. This should alleviate much of the burden of setting up the problem manually. There are some limitations on the use of ConWep but that discussion is beyond the scope of this present work. At the time when this technique was being used, ConWep had not yet been implemented within Abaqus.

For these types of blast loading analyses, setting criteria for material failure remains problematic. Very good material models are necessary and even then choosing the damage initiation criteria requires a good deal of experience to do correctly. Also, the material models should be calibrated for the strain rates to be encountered in the analysis. As should be the case with all models, before the analysis is used as a predictive model, it needs to be well validated against testing.

4. Fully-coupled Eulerian-Lagrangian blast load analysis using Abaqus/Explicit-CEL

4.1 Overview

The goal is to create a fully-coupled model which can handle the blast wave propagation through air, the blast wave interaction with the structure, and the associated structural response of the system. While it would be ideal to model everything from the ground up, starting with the initiation of the explosive material, followed subsequently by the detonation and creation of an outwardly propagating shock wave that eventually impacts our structure, that capability does not exist yet. One major simplification that will be used here is to cut out the first few steps and fill in the blanks with the extensive TNT air blast data that has already been collected.

4.2 Assumptions

There are some conveniences to be had if the blast loading problem is simplified by only considering far field air blast loading. Here, far field is used to mean the region outside of the fireball (product gases). There are two benefits to this. The interaction with the product gases can be neglected. The farther the structure is from the fireball, the less significant the effect due to leftover hydrocarbons reacting with oxygen in the air to create an afterburning effect. Nearby the explosive, afterburning acts to increase the overall duration of the positive phase and thus increases the impulse applied to any structure in close proximity. This far field simplification also means the shock wave can be considered spherical in shape; that is, one can ignore any non-uniformity in the blast wave due to initial non-spherical explosive geometry.

Other assumptions are to neglect any additional loading from fragmentation, blast occurs at sea level, and the charge was uncased and not in contact with the ground. Many of these issues could be incorporated fairly easily – it would mean more legwork on the part of the analyst to scale the inputs accordingly.

4.3 Method Description

Let's begin with the supposition that the explosive has already detonated and created a shock wave that is spherically diverging from the source of the explosion. That removes quite a lot of the complication of the reality of the situation. Assuming we know what explosive was used and in what quantity, the method of TNT-equivalence can be used to map the actual explosive energy to the TNT standard (TM 5-1300, 1990; Cooper 1996). There is a sizable collection of data for spherical charges of TNT being detonated in free air.

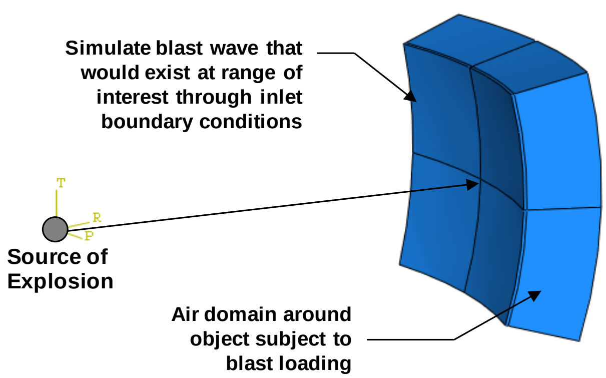

Figure 4. Pictorial representation of new analysis technique.

In the model, the Lagrangian structure of interest will be surrounded by a volume of air modeled using Eulerian elements. Some distance away, there will be a point that corresponds to the theoretical location of the explosive. The intent is to create a shock wave at the inlet of the air domain (through boundary conditions) that is equivalent to the incident blast wave that would actually exist at that distance away from the explosive once detonated. This would now be the starting point for the analysis and it obviates the need to model the actual detonation of the explosive.

The same model inputs are required for this model as would be for the simplified SDOF structural model – the blast parameters such as incident overpressure, specific impulse, positive phase duration, and exponential decay coefficient. This requires detailed knowledge of the load case: type, amount & shape of explosive, distance away from blast, air or ground burst, cased or uncased, elevation, etc. It is up to the user to translate these criteria into meaningful blast parameters. Alternatively, a simpler approach may be to use ConWep to define the pressure load at the inlet. Whatever approach is used, the important thing is that the analyst should understand what load he/she is applying and why he is applying it.

It is worth mentioning, the most important blast parameter to model correctly for short duration pressure pulses is the specific impulse. If the correct specific impulse is applied to the structure over short time durations, the actual shape and duration of the pressure loading are not of the highest importance. For longer duration pulses (relative to the period of the structure), the magnitude of the pressure is the more important parameter. When the duration of the loading is on the same order as the period of the structure, both magnitude and duration are important (Duffey, 2009)

4.4 Validation Case Studies

One of the motivations of this new modeling technique is that the software would handle all of the shock interactions without user involvement. This would negate the need for the analyst to calculate angle of incidences for each surface interaction in order to find the correct reflected pressures on oblique surfaces. Also, to examine a different orientation of the structure relative to the blast, the Lagrangian structure can simply be reoriented within the Eulerian domain to achieve any angle of incidence that is required.

Before a full scale blast load analysis was attempted, it seemed prudent to validate and gain confidence in this new analysis capability found in Abaqus/CEL. It was necessary to verify that the code would handle both normal and oblique reflections accurately. Also important is that the strength of the shock wave attenuates as it propagates through the air domain. In reality, this occurs both because of the spherical divergence and effects such as shock heating of the surrounding air.

This necessary validation was achieved through two small scale problems, each testing a different aspect of the code which would be required in the full scale blast model. These tests included 1D wave propagation through a spherical domain and oblique shock reflection with Eulerian-Lagrangian interaction.

4.4.1 Validation Test #1 – Spherical expansion and mesh refinement study

4.4.1.1 Motivations

As discussed in the paper by P. Carlucci (2010), a shock tube was modeled in order to evaluate the compressible flow implementation within Abaqus/CEL. Temperature, pressure, and density in the region behind both the incident and reflected shock fronts were compared against theory and the results were virtually identical (under 0.25% error). However, there are some important differences between the characteristics of the shock wave created in the shock tube and that of a blast wave. In the shock tube, the shock front is fully supported by the high pressure gas that continues to expand throughout the event. In actuality, the blast wave is a much more transient pressure pulse with a set amount of energy. Its amplitude should decay as a function of distance only. For that reason, it was important to test how a pressure pulse would propagate through the air domain, specifically to see if the expected exponential decay was captured correctly.

4.4.1.2 1D Model Description

To do that, a simple test case was set up. The causes for the attenuation in peak pressure of the shock are well documented – the shock wave should have an exponential decay in strength, lengthen in duration and slow down. The primary reason is the spherically expanding nature of the wave. In order to capture the effects of that expansion, a representative cut of a sphere was used for the 1d domain (see Figure 5). The air material was defined to be at standard ambient temperature and pressure and modeled using the ideal-gas equation of state with typical values assigned for specific heat (C_v) and dynamic viscosity (μ).

The model was set up using spherical symmetry. Zero displacement boundary conditions on the Eulerian mesh were used to restrict flow normal to the walls but allow tangential flow. The loading was implemented using a velocity boundary condition with a triangular amplitude curve and a peak value equivalent to the initial particle velocity of the desired wave. This produced a triangular pressure pulse of the correct magnitude and duration. Using the velocity boundary condition proved to be more stable than directly specifying the pressure loading on the inlet surface.

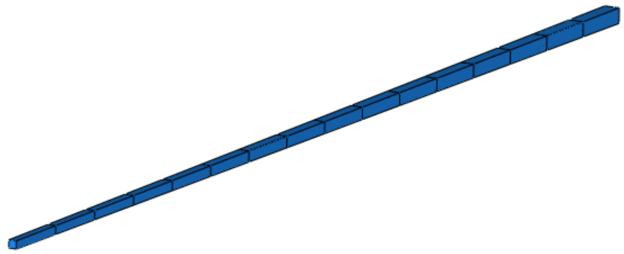

Figure 5. 1D domain incorporating spherical expansion.

A mesh refinement study was completed using this model. When working with shock waves, the size of the mesh is quite important. Trying to model a physical discontinuity using discrete elements is problematic. A very fine mesh is necessary in order to minimize the amount of lost information. If the elements are too large, it will be evident because the peak of the triangular waveform will begin to round over and the rise time will elongate. This makes it unfeasible to model shock propagation through extremely large volumes of air using this method because the mesh density requirements for the air domain quickly exceed computational limits. Figure 6 shows some of the results of the mesh refinement study. From a qualitative standpoint, it is clear that the larger elements do not handle the sharp discontinuity of the shock nearly as well as the smaller elements.

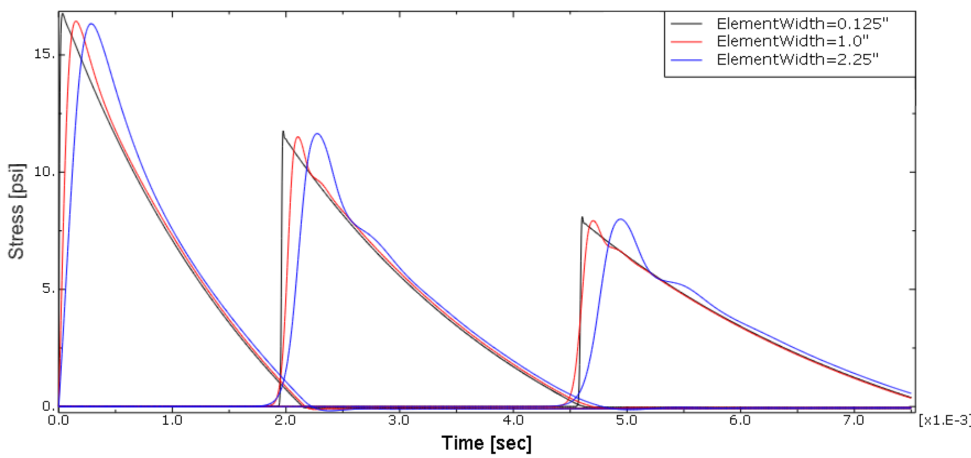

Figure 6. Results of mesh refinement study for elements widths of 0.125", 1.0", and 2.25" in the direction of wave propagation.

4.4.1.3 Results

In comparing the pressure decay of the 1D CEL model to that of the empirical TNT data (see Figure 7), it should be evident that the spherically expanding domain was the dominant factor in capturing the correct response. There is a reasonable explanation why the two curves are not identical. Given the same initial conditions, the shock wave in the CEL model decays slower because there are some loss paths not taken into consideration.

While Abaqus/CEL includes the full implementation of the Navier-Stokes equations, it does not include turbulence effects. With a viscosity specified in the material model used for air, it results in the laminar flow assumption. In free stream flow, it is equivalent to inviscid compressible flow (using the ideal gas equation of state). Energy dissipation due to turbulence and viscous effects are not captured. In addition, since the cell size used in this analysis was relatively large, in comparison to boundary layer size, viscous boundary layer effects are not captured. This may account for the discrepancy between the two curves.

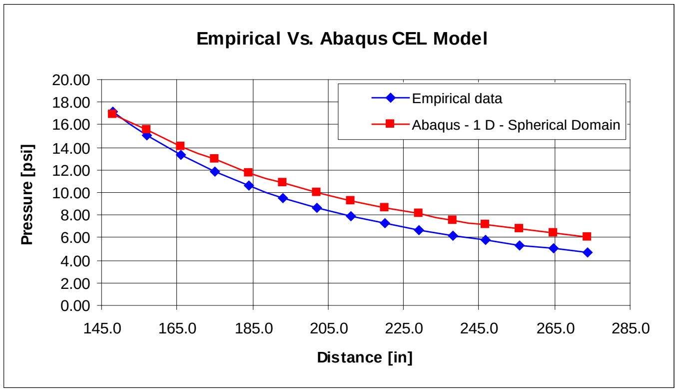

Figure 7. Comparison of results for shock strength decay between 1D spherical expansion model and empirical data.

4.4.2 Validation Test #2 – Oblique Reflection

Now that it has reasonably been established that a transient pressure (blast) wave can be reproduced accurately in CEL, it was necessary to examine oblique reflection off a Lagrangian surface placed within the Eulerian domain. The same type of domain was used as for the 1D case. It was scaled up large enough in order to fit a 12"x12" plate (Figure 8). The plate was placed in the center of the Eulerian air domain and tilted at a 45 degree angle relative to the flow. The bottom front edge of the plate was encastred. General contact was used to define the interaction between the Eulerian and Lagrangian components. For this case, the same velocity boundary condition was used to create the blast wave at the inlet of the Eulerian domain.

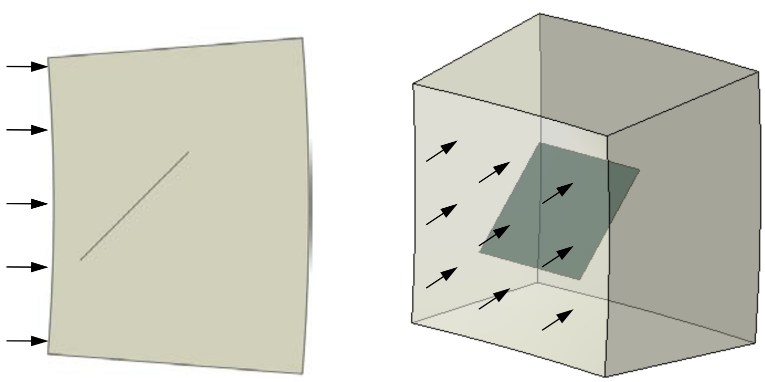

Figure 8. Oblique reflection model.

As can be seen in Figure 9, the peak reflected pressure at the surface of the angled plate was measured as well as the incident overpressure at the same distance from the inlet. The ratio of those pressures was compared against the empirical plot of reflected overpressure as a function of angle of incidence and there was good correlation.

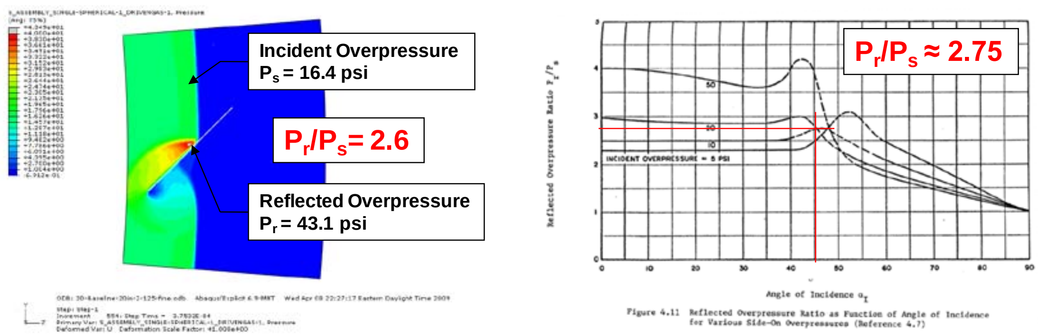

Figure 9. Comparison of results between oblique reflection model in Abaqus/CEL model and empirical data.

4.5 Full scale model of Overhead Cover Kit

4.5.1 Overview

One area where this method finds application is in modeling the structural response of add-on armor kits subjected to blast loading. A case study where this method was used was in the analysis of the Overhead Cover add-on kit for the Objective Gunner Protection Kit for the HMMWV (Figure 10). A roadside bomb/IED is now a typical threat faced by these vehicles. The goal with this analysis is to subject the armor kit to the worst case blast loading it is expected to see during combat and evaluate the structural integrity of the components.

By performing the analysis when the add-on kits are still in development, it allows for the designers to quickly evaluate different design iterations (or completely different designs) and make improvements up front that will strengthen the structure so it may survive blast loading. This analysis can also be used to determine how many load cycles the structure can survive before failures are to be expected. Also, by modeling the blast propagating through the air, one of the results of this analysis can be to predict the overpressure that would be experienced by the gunner should he be manning the turret at the time of the blast. This information could be utilized to conduct a survivability analysis.

Presented here is a scenario where ConWep would be insufficient for defining the loading experienced by the structure. Depending upon the orientation of the vehicle relative to the blast loading, the vehicle's shape can actually enhance the blast wave. In this case, if there was an elevated explosive charge that detonated near the rear of the vehicle, the blast wave would first reflect off the slanted roof at the rear of the vehicle before impacting the armor panels. As a result, the lower portion of the side armor panels would experience a much higher loading than the ConWep program would tend to predict.

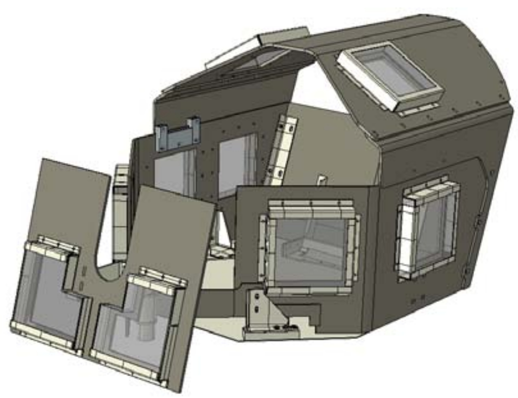

Figure 10. Gunner protection kit.

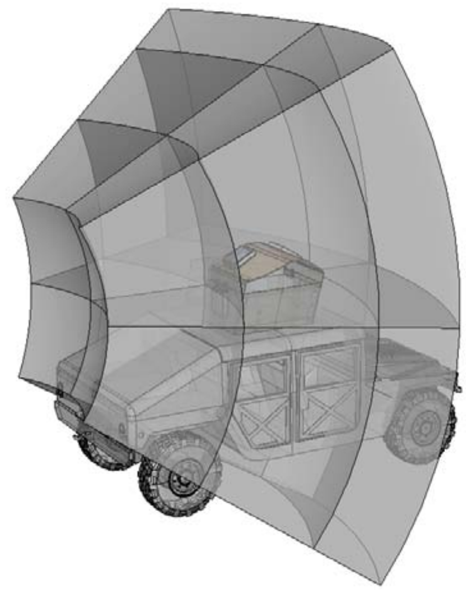

Figure 11. Full scale blast load model of gunner protection kit mounted on HMMWV.

4.5.2 Description of Lagrangian components

This analysis was performed using Abaqus/Explicit 6.8EF-1. All of the parts were provided in Pro/Engineer format. The majority of the armor panels and brackets were meshed using SC8R 8-node continuum shell elements. The remainder of the brackets and the windows were meshed using C3D8R 8-node brick elements. Connectors were used to model all of the bolted joints. This was for two reasons. First, it assured that the structure was constrained properly and second, it enabled the monitoring of all the bolt forces within the structure.

Though a HMMWV is shown, it was modeled as a display body. However a rigid part representative of the shape of the roof was used in place of the vehicle. The mounting brackets were modeled as elastic with linear strain hardening while the armor panels were modeled using Johnson-Cook plasticity and damage. Due to the sensitive nature of the information, the material properties and parameters for these components are not provided in this paper.

In the baseline analysis, general contact was used to define the contact interactions between all of the armor panels and brackets. To be conservative, the contact was modeled as frictionless. Later, when implementing the coupled Eulerian-Lagrangian analysis it became necessary to specify surface-to-surface interactions individually in order to cut down on the computational overhead. Due to the size of the Eulerian domain, there was some initial difficulty in getting the problem to run.

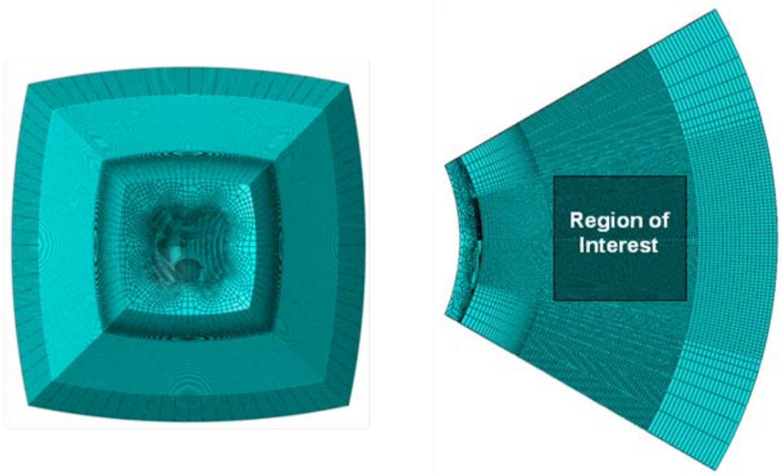

Figure 12. Mesh used for Eulerian air domain – 2.6 million elements total.

4.5.3 Description of Eulerian mesh

For the Eulerian domain, spherical symmetry was again used. As mentioned previously for the 1D test case, at the inlet a velocity boundary condition with triangular amplitude curve was used. The peak value was equivalent to the initial particle velocity of the blast wave and this resulted in a triangular pressure pulse of the correct magnitude. The Eulerian domain was sized so that any waves reflected off the structure would not have time to reach the boundary and get reflected back into the structure (spurious result) during the time period of interest. Type EC3D8R linear reduced integration bricks with default hourglass control were used for the Eulerian elements.

Due to the size of the domain, it was necessary to use a graded mesh. Elements were sized such that in the region of interest (Figure 12) they were 0.25” (6.35mm) in thickness along the direction of initial wave propagation. This size element was selected as a result of the mesh refinement study conducted for the 1D test case and because of the need to resolve contact between the Eulerian and Lagrangian elements (thin armor panels).

It was observed that when 1.0” thick elements were used inline ahead of the 0.25” elements there would be an initial elongation in rise time and rounding of the peak as the wave traveled through the larger elements. But when the wave entered the 0.25” elements it would “shock-up” and the rise time would shorten and the peak would sharpen up. Accordingly, this was evidence that using a graded mesh in the direction of shock travel was a reasonable method to reduce overall mesh size which wouldn’t detract from the accuracy of the solution.

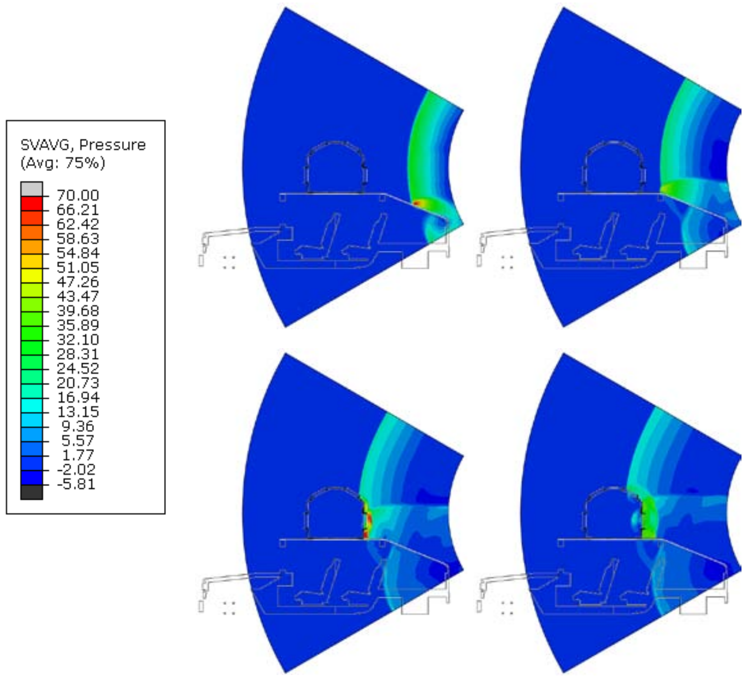

Figure 13. Contour plot of the blast overpressure (in units psi) at various time increments.

4.5.4 Qualitative Observations

The observed deflections for the armor panels were compared to previously conducted analyses which used simplified pressure loads on the surfaces exposed to the blast. Overall the comparison was favorable. Much additional insight was gained from seeing the shock interactions around the armor panels.

4.5.5 Issues and Limitations

It may be necessary to break the analysis down into two parts, the loading phase and the response phase. The shock wave will impart the impulsive loading to the structure much quicker than the structure will fully respond to it (speaking in regards to this geometry only). The duration of the blast wave is on the order of a few milliseconds. The time to peak deflection in the structure is on the order of tens of milliseconds. But in order to view the final deformed shape or run subsequent load cases after the structure has come to rest, that would take on the order of hundreds of milliseconds to seconds. As it doesn't make much sense to maintain the Eulerian mesh (and all of its 2.6 million elements), once the blast wave is no longer interacting with the structure the analysis should be stopped. A separate restart analysis can be used to import the Lagrangian structure from the previous analysis and allow it to equilibrate in a much more computationally efficient manner.

When setting up this analysis the first time, it was necessary to reduce the number of Lagrange surfaces in the contact definition with the Eulerian domain. Too many and the job would simply not run. It has yet to be determined whether this was actually a contact issue or a problem with the high performance cluster the job was submitted on. This will be investigated further.

Because of the high number of elements required for the Eulerian domain, this type of analysis has long run times even when using 32 processors. This makes it a rather expensive analysis to run. Visualizing the results (and post-processing in general) is also somewhat problematic due to the large size of the output database. This is again due to the high number of elements in the analysis.

4.5.6 Present Work

There is one final validation test the authors would like to conduct. That is with regards to the Eulerian/Lagrangian interface. It is not yet clear whether the correct impulse is being transferred into the Lagrangian structure across that interface. It would be desirable to use this fully-coupled Eulerian-Lagrangian approach to model an impulse-momentum trap and compare against empirical data. Short of conducting actual instrumented blast testing on the armor kits in question, that should be sufficient for validating the model.

5. Summary

A new method has been introduced for conducting blast load analyses using the new Coupled-Eulerian-Lagrangian (CEL) capability of Abaqus/Explicit. This new approach involves surrounding the structure with a body of air (Eulerian), imparting a pressure wave as a boundary condition into the body of air, and then having it propagate into the Lagrangian structure. The Lagrangian structure can be positioned arbitrarily within the Eulerian domain to achieve any angle of incidence that is desired.

Despite being in the early stages of validation/verification, the CEL approach for far field blast loading shows great promise in its ability to provide valuable insight. It also enables the analysis of very complex geometries that would otherwise be impossible to handle with the previously mentioned simplified methods. The time invested in this validation effort provided the confidence necessary to move forward with additional test cases. The intent is to continue pushing this capability so that eventually it may be used to conduct predictive analyses.

6. Acknowledgements

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