Helping Keep Soldiers Safer with Realistic Simulation

Picatinny Arsenal uses Abaqus to analyze and improve strength of armor subjected to blast waves

The Objective Gunner Protection Kit mounted atop a combat vehicle.

When we talk of an Army and a mission, we usually think of soldiers in the field—patrolling through a combat zone in an armored vehicle, for instance. At the U.S. Armament Research, Development and Engineering Center (ARDEC) at Picatinny Arsenal in New Jersey, one critical mission behind the field operations is every bit as important: the analysis and testing of protective vehicle armor so that those soldiers return to base safely.

ARDEC's tradition of armament research at Picatinny stretches back a century. Due to the Center's expertise and vast amounts of accumulated physical data, it is occasionally tasked with proving out armor designs.

One such project was the structural assessment of an overhead cover add-on for the Objective Gunner Protection Kit (OGPK) used on the High-Mobility Multipurpose Wheeled Vehicle, or HMMWV. The OGPK, which received an Army Greatest Invention Award for 2007, is an integrated armor and ballistic glass cupola shield mounted on top of tactical and armored vehicles. It provides 360-degree protection from small arms fire and explosions while retaining visibility for the gunners. The mission for ARDEC was to ensure that the overhead cover provided effective protection during exposure to blast loading.

One of the best tools in their arsenal to accomplish this mission was finite element analysis (FEA) software, which they were already using extensively—but this time, engineers at Picatinny had a vision of how they could greatly increase the accuracy of their simulations and account for the effects of the shock interactions, including oblique blast waves on the OPGK due to reflections from the top of the HMMWV.

Achieving simulation accuracy

In the past, engineers at ARDEC had developed a standard process for structural analyses that involved using simplified blast parameters and manually applying pressure loads to a 3D model in Abaqus/Explicit to simulate a particular blast loading.

After weighing various simulation methods, the engineers at Picatinny decided to explore something new: conducting the blast load analysis using the fully Coupled Eulerian-Lagrangian (CEL) capability within Abaqus. The CEL capability enables the user to simulate a fluid or gas (the Eulerian domain) interacting with a structure (the Lagrangian domain). Here, the structure to undergo blast loading is surrounded by a volume of air. The blast wave that would exist at the inlet of the air domain is created through boundary conditions. The blast wave then propagates through the Eulerian domain and subsequently interacts with the Lagrangian structure located some distance from the inlet.

Pre-testing the analysis method

Before attempting a full-scale blast load analysis, the engineers at Picatinny validated the performance of the CEL method in Abaqus. They did this by verifying that the software could realistically model the reduction in strength of the shock wave as it propagated through the air (Eulerian domain) and that it could simulate normal and oblique reflections against the Lagrangian model accurately.

Simulating normal reflections: This was accomplished with a simple FEA one-dimensional (1D) domain CEL model of a "shock tube," much like the physical shock tubes used to study the behavior of gases under shock loading. A shock tube was used for the validation effort because the relevant analytical equations for the compressible flow are readily available. The shock tube consists of two chambers, one initially filled with gas under high pressure. The other was filled with room-temperature air at atmospheric pressure. The analysis is initiated in the state that would exist immediately after the burst diaphragm separating the two chambers ruptured. The expansion of the high-pressure gas into the low-pressure chamber creates a planar shock wave that propagates through the low-pressure chamber. Once the shock wave reaches the boundary at the end of the low-pressure chamber, a reflected wave is created. It is the pressure behind this normally reflected pressure wave that is compared against the theory to determine if the underlying code behind CEL is handling the compressible flow properly. Excellent correlation was observed between the shock tube model and the theory.

Spherical expansion: This validation test included a CEL domain representative of a 1D cut from a sphere (to account for spherical expansion). The Eulerian domain was assigned an air material at ambient temperature and pressure. At the narrow end (sphere center) of the domain, an explosive load is initiated and allowed to propagate through the domain. The load was defined using a velocity boundary condition with a triangular amplitude curve and a peak value equivalent to the initial particle velocity of the blast wave. As predicted by physical data, the shock wave decayed exponentially in strength, lengthened in duration and slowed down as distance increased from the source of the blast.

This simulation was also used for a mesh refinement study that was valuable for the final analysis model. When working with shock waves, the size of the mesh is quite important: a very fine mesh is needed to maximize the accuracy of the solution, though this increases the run time.

Simulating oblique reflections: From comparing the pressure decay of the 1D CEL model to data obtained empirically from exploding TNT, it was clear that accurately modeling the spherically expanding blast was an important factor in obtaining accurate results. In order to extend their methodology to a realistic problem it was therefore necessary to expand the validation of their modeling approach from 1D to 3D.

To accomplish this, the analysts modeled a 3D segment of a sphere for the Eulerian air domain with a Lagrangian modeled plate centered in it, tilted at a 45-degree angle. The blast wave used the same velocity boundary condition as the 1D CEL model and originated again from the inlet of the domain. This time, though, there were two results of analysis: peak reflected pressure at the surface of the plate, and incident overpressure in the air at the same distance from the inlet. The ratio of these pressures was compared to an empirical plot of reflected overpressure as a function of angle of incidence, and there was good correlation.

Now the engineers were ready to model and run a more detailed 3D CEL analysis.

CEL analysis

Structural parts of the analysis (the OGKP and a rigid part that represented the shape and angle of the HMMWV roof) were modeled with Lagrangian components. Most of the armor panels and brackets of the OGKP were meshed using SC8R 8-node continuum shell elements; the remainder of the brackets and the windows were meshed with C3D8R 8-node brick elements. Connector elements were used for all of the bolted joints to ensure that the structure was constrained properly and to enable monitoring of all the bolt forces. The mounting brackets of the HMMWV roof were modeled as elastic with linear strain hardening, while the armor panels were modeled using Johnson-Cook materials to capture plasticity and damage. For the baseline analysis, general contact was used to define the contact interactions between all of the armor panels and brackets.

The Eulerian domain represented the air around the structure that was the medium for the blast wave. The domain was modeled as a section of a sphere. To speed up the analysis while maintaining accuracy, a biased mesh was used in the Eulerian domain. In the region of interest near the Lagrangian structure the mesh consisted of 0.25" thick elements along the direction of initial blast wave propagation and coarser 1" thick elements everywhere else. This technique allowed for a reduced number of elements, even though the total was still relatively high at 2.6 million just for the Eulerian domain. The blast wave was defined using the same boundary conditions as described for the earlier simulations.

The Objective Gunner Protection Kit shown with an overhead cover add-on.

Realistic simulation guides future work

The simulated deflections on the armor panels were compared to previously conducted analyses that used simplified pressure loads on the surfaces exposed to the blast. Overall the comparison was favorable, with the CEL analysis providing more realistic results than previous analyses did.

Picatinny anticipates that CEL could be valuable in the design phase of new armor systems, since it provides an understanding of how a given armor system model responds to blast loading. This same analysis could be applied to any structure that might experience blast loading—for instance, an explosive test facility or buildings in a high-risk (combat) area.

One of the advantages of using the CEL approach is that Abaqus can execute all the shock interactions automatically, so that the analyst isn't required to calculate the angle of incidence for each surface interaction in order to find the correct reflected pressures on each oblique surface. (A new alternative to the manual technique can be found in SIMULIA's recent addition of ConWep to Abaqus, which can automatically calculate the correct distance and angles incidence in a blast model and assign the appropriate pressures.) Another important feature of CEL is that the Lagrangian structure can be easily reoriented within the Eulerian domain to analyze any angle of incidence that is required.

The ARDEC engineers concluded that the CEL approach for modeling blast loading shows great promise in its ability to provide valuable insight and realistic results. It also enables the analysis of very complex geometries that were previously impossible to solve accurately with more simplified methods. ARDEC intends to continue exploring Abaqus and CEL to thoroughly validate the new technique so that it may eventually be used to conduct predictive analyses.

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