Making Army Helmets Tougher and Safer with Realistic Simulation

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The U.S. Army helmet is an iconic piece of military equipment. The storied steel M1, first introduced in 1942 during WWII, served not only as head protection but as a seat, wash-basin, and soup bowl. It was standard issue to U.S. soldiers for the next four decades. As materials, ergonomic design, and ballistics protection evolved, the M1 was finally replaced by the 29-layer Kevlar PASGT (personnel armor system for ground troops) helmet in 1985, which in turn gave way to the lighter Kevlar/Twaron ACH (advanced combat helmet) design in 2003 (Fig. 1). Helmet liners progressed too, from compressed paper fibers, plastic, and rayon in the early days, to more sophisticated suspension-webbing systems with chin straps constructed from stronger synthetics such as nylon.

Fig. 1 —*U.S. Army's advanced combat helmet (ACH). Courtesy U.S. Army.*

Preventing head injury is even more critical today with the development of advanced body armor, which is used routinely by most U.S. troops: body armor decreased the number of fatalities from explosions, but as a result, survivors are experiencing an increase in nonfatal traumatic brain injuries (TBI). According to the Defense and Veterans Brain Injury Center (DVBIC), established in 1992, more than 150,000 U.S. military personnel have been medically diagnosed with TBI since 2001. Some experts believe that at least 30% of all troops who have spent four months in combat in Iraq or Afghanistan have been exposed to potential brain-injuring explosions.

TBI can be caused by land mines, mortar rounds, rocket-propelled grenades, suicide bombs, and most frequently, improvised explosive devices (IEDs), all of which generate a shock wave that travels 1600 ft/s. The vast majority of brain injuries, ranging in severity from concussions to penetration injuries, are classified as mild to moderate (89%) and come with accompanying physical, cognitive, emotional, and behavioral symptoms. In past conflicts, TBI was labeled shell shock and battle fatigue and has even been linked to post-traumatic stress disorder (PTSD). Today, TBI is the signature wound of soldiers returning from combat. To address this reality, the military launched a program to develop a liner for the ACH that will reduce the frequency and severity of these debilitating injuries.

The challenges of helmet liner design

Since the 1970s, there has been no shortage of ideas about how to construct helmet liner systems. Countless patents and designs have emerged using air- and fluid-filled chambers. But designs are primarily been sports related—for bike, ski, hockey, football, and horseback riding—and the protection systems focused on protecting against impact (striking an object) rather than blast (from a shock wave).

There is also been no shortage of hypotheses about what materials would be most effective at blast attenuation. Mechanical properties are the major contributor to the behavior of shock waves at material interfaces: acoustic impedance mismatches determine what portion of a wave is reflected and transmitted. Layered composites, cellular materials, expanded polystyrene, vinyl nitrate foams, and glycerin have all been suggested as candidates, while material properties such as porosity, density, and heat capacity have been proposed as factors contributing to blast mitigation.

Simulating liner materials and helmet-head contact during blasts

Dr. Laurence Young's research on helmet and liner systems at MIT in the Man-Vehicle Laboratory started out with sporting applications. The focus shifted in 2007 when his lab was awarded a three-year contract from the Office for Naval Research (ONR) to work on improvements for the ACH liner design. Finite element analysis (FEA) technology was identified as the primary tool for evaluating potential design solutions.

The MIT team comprised graduate students Andrew Vechart and Rahul Goel. For this reason, according to Vechart, "We needed an FEA solution that had a short learning curve and was well-supported and documented." There were several other important requirements as well. "The software needed to handle the nonlinear complexity of the contact between the helmet, head, and air," says Vechart. "And it also had to be good at simulating the

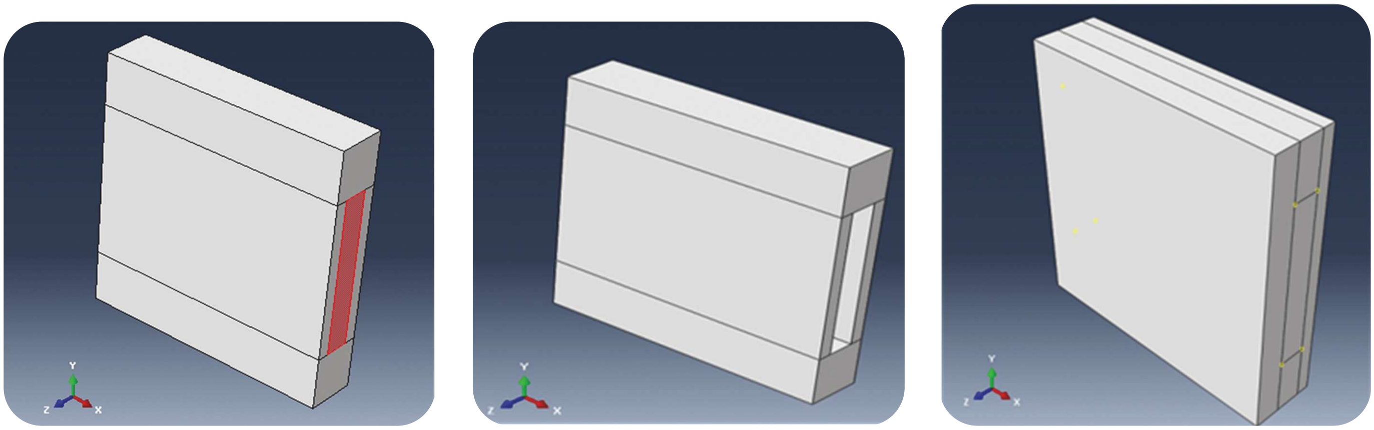


Fig. 2 — *Simulation of a simplified flat-plate model tested the effectiveness of both solid and liquid filler materials for the helmet liner, with the blast force coming from the left in the z-direction. The solid filler materials (foam, glass beads, and aerogel) were modeled in red (left). CEL analysis was used to simulate fluid filler materials (water and glycerin): the Lagrangian frame of reference for the solid portion of the model (center); the Eulerian frame of reference for the fluid filler portion (right). Solutions were computed to two milliseconds after detonation when transmitted pressure values had stabilized.*

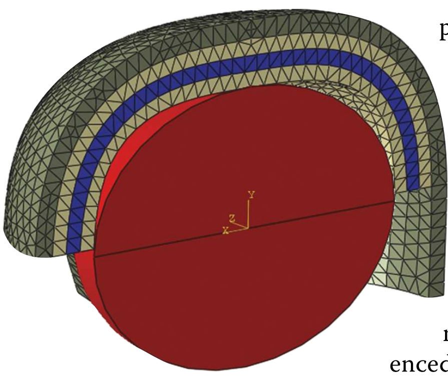
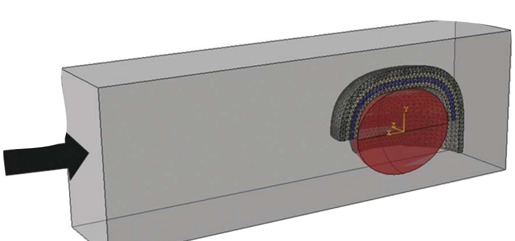


Fig. 3 — *Helmet and head models are simplified to decrease computational complexity of benchmarking helmet-liner filler materials.*

physics of the blast wave moving through air." Other design challenges included comfort, fit, and feel. The team chose Abaqus from SIMULIA, the Dassault Systèmes brand for realistic simulation, for its ability to meet these requirements; it is frequently referenced in the literature for its blast modeling and analysis capabilities.

"Simulating a blast event provides important, realistic data without the risk of involving test subjects," says Vechart. "It also eliminates the need for special facilities and permissions required to handle explosives."

To evaluate effectiveness of different filler materials during a blast event, the team first analyzed a simplified liner model: a flat sandwich-plate manufactured from high energy-absorbing vinyl nitrile foam. A cavity in the plate was used to hold the different fillers including fluids (water and glycerin) and solids (foam, glass beads, and aerogel) as shown in Fig. 2. Results from these tests were compared against the benchmark case of a solid piece of foam with no cavity. The team used the CONWEP air blast capability in Abaqus to reduce computation times by eliminating consideration of the blast media (air) from the analysis. They then used the coupled eulerian-lagrangian (CEL) feature in Abaqus to analyze the realistic behavior of fluid filler materials.



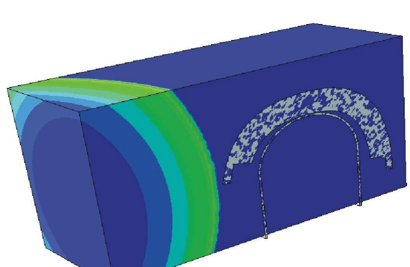


Fig. 4 — *Simulation of the helmet-head model with the incoming air blast direction (represented by the arrow) calculated peak transmitted overpressure, pressure gradient, positive pressure pulse, and pressure histories (rise time and duration) as the air blast pushes the helmet onto the head.*

A simplified helmet-liner model was created and coupled with a simplified surrogate head model (Fig. 3). CEL simulation effectively replicated the relatively complex fluid-structure interaction (FSI) of the air blast—high blast levels, short time spans, compressibility effects, and some nonlinearity (Fig. 4).

For both analyses, Abaqus was used for the entire process: from modeling the geometry, to running the nonlinear and multiphysics simulation, to post-processing the results. Solutions were computed up to two milliseconds after detonation with peak transmitted pressure being of primary interest.

Benchmarking results and future simulations

To validate simulation results against physical experiments, collaborators at Purdue University's Zucrow Laboratory used a shock tube to create a controlled explosion equivalent to the one used in the simulation and an approximation of a typical IED explosion (50 lb of TNT at a distance of 20 ft). The simulated blast had peak overpressures strong enough to cause TBI (50 psi) but not strong enough to be fatal; at 100 psi, there is a 1% chance of fatality (Fig. 5).

According to Young, the project was recursive, going from experiment to model to experiment, with each being refined based on input from the other. "The FEA model is an effective tool to plan and critique each series of experiments," says Young.

For the solid foam liner, there was reasonable agreement between simulation and test results for peak loading pressures and rise time as the shock wave impacted the liner, as well as for transmitted pressure on the back-side of the model (Fig. 6). Comparing transmitted pressures for a variety of solid and fluid filler materials, the analyses indicated that glass beads, water, and glycerin had the lowest peak pressures; with glass beads having a value 80% less than solid foam. These results (in partial agreement with the experiments) also indicated that the rise time and pressure gradient for glass beads, glycerin, and water demonstrated the best characteristics for blast attenuation (Fig. 7).

"For validation we used a relatively simple model," says Vechart. "In the future, we would like to create numerical models and use actual helmet and liner-channel geometries coupled with a realistic head model based on CT or MRI scan data." By using simulation, Vechart believes the engineering community will not only come up with a better liner and a more protective helmet, but the medical community will develop a deeper understanding of how to diagnose and treat traumatic brain injuries. ❍

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Fig. 5 — *Shock tube and advanced combat helmet (ACH) at Purdue University Zucrow's Laboratory. The pressures measured during the physical tests were compared to simulation results to benchmark the FEA models.*

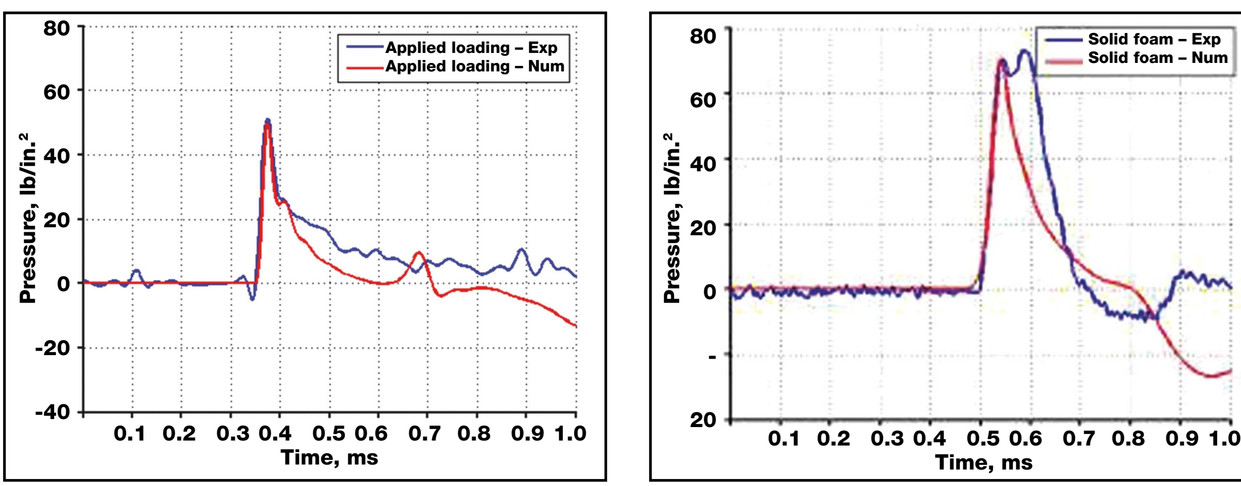

Fig. 6 — *Comparison of experimental and simulated loading pressure on the front face of the simplified liner model (left); and comparison of experimental and simulated transmitted pressure on the back side of the liner model (right).*

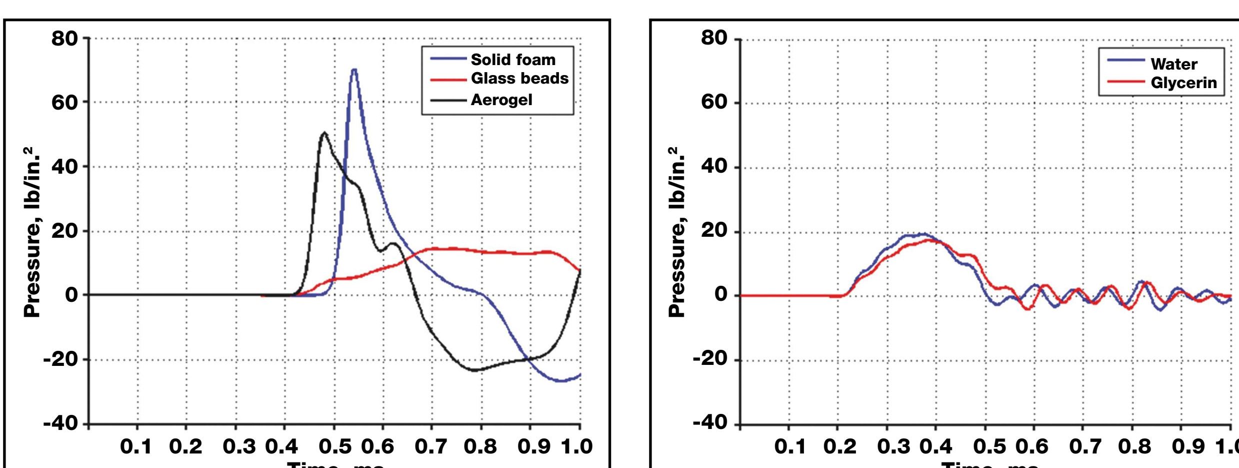

Fig. 7 — *Comparison of experimental and simulated transmitted pressure for solid and liquid helmet-liner filler materials: foam, glass beads, and aerogel (left) and water and glycerin (right).*