Shaking Things Up for the Nation's Defense

A supersonic sled test showcases an efficient approach for developing complex conventional weapons for supersonic aerospace systems.

A team of Lawrence Livermore engineers and scientists, in partnership with the U.S. Air Force Research Laboratory, helped design and develop an advanced warhead for the U.S. Air Force Space and Missile Systems Center for high-speed applications. The five-year warhead development effort, which reflected the contributions of dozens of Livermore researchers, culminated in a highly successful sled test in which the warhead was propelled down straight rails by rocket motors. The test assessed how this warhead, shrouded and protected by a Livermore-designed carbon-epoxy aeroshell, responded to simulated flight conditions. Conducted on October 23, 2013, at Holloman Air Force Base in New Mexico, the tests achieved speeds of greater than Mach 3.

By mimicking a weapon in flight, the sled test demonstrated how well the warhead performed at speeds similar to those anticipated in an operational system. It also provided data for determining the material strength of the carbon-epoxy aeroshell and how the device responds to aeroheating and ablation (loss of material from the high temperatures generated by the test).

The test results demonstrated the effectiveness of using advanced computational and manufacturing technologies to efficiently develop complex conventional munitions for the Department of Defense. Livermore researchers used high-performance computer simulations as part of the design process, allowing for a shorter, more efficient, and significantly less expensive testing phase that culminated in the sled test. This approach improves on legacy aerospace industry practices, which often involved expensive and time-consuming tests of prototype designs and candidate materials.

Artist renderings depict a supersonic conventional weapon as it (above) emerges from its rocket nose cone and (top) reenters Earth's atmosphere on its way to target. (Courtesy of Defense Advanced Research Projects Agency.)

The effort to design and develop the warhead and its protective aeroshell also showcased the Laboratory's long-standing ability to integrate specialists from different disciplines. Experts in high explosives, aerodynamics, thermal mechanics, materials science, systems engineering, and supercomputing simulation quickly formed an interdisciplinary team to meet the Air Force goals. "We leveraged expertise in critical engineering disciplines as well as computational and experimental resources," says Livermore engineer David Hare, project manager for the sled test. The Laboratory team served as the project's technical lead and had overall responsibility for the sled test.

Aeroshell Collaboration

Lawrence Livermore has conducted research in carbon composite materials for more than two decades. These compounds

The sled test track at Holloman Air Force Base is 16 kilometers (10 miles) long.

are made by combining two or more materials to produce specific characteristics, such as lighter weight, added strength, and resistance to extreme temperatures. Livermore weapons engineers and scientists have developed two warheads with composite casings. The first was a variant of the Air Force small-diameter bomb, called the Focused Lethality Munition. This weapon replaced a bomb's typical steel casing with a lightweight carbon composite to reduce collateral damage (unintended harm to property or people).

Laboratory researchers developed a second low-collateral-damage carbon composite bomb known as BLU-129/B for the U.S. Air Force, completing the work in record time. Introducing a new munition into the field can take up to 6 years, says engineer Kip Hamilton, who managed the BLU-129/B project and served as Livermore project manager for the new warhead effort. The first BLU prototype was produced in 9 months and the warhead was fielded only 18 months after the design effort began. (See *S&TR*, March 2013, pp. 4–9.)

Weapons engineer Mitch Moffet had previously worked with Applied Aerospace Structures Corporation (AASC) in Stockton, California, a leading provider of lightweight aerospace components. "For the sled test, we had a tighter budget and a much shorter time to produce an aeroshell than for BLU-129/B," he says. The engineering team recognized that a fielded weapon would presumably feature a carbon composite aeroshell so it could survive high flight temperatures for up to an hour or more. But the sled test would last less than 10 seconds. In response, the Laboratory worked closely with AASC to produce a one-off aeroshell made of carbon epoxy (plastic reinforced with carbon fibers) to significantly reduce manufacturing time and costs.

Moffet says, "We looked at tooling costs, material availability, and processing costs and selected a manufacturing technology from among four options." The Livermore team designed the aeroshell and material specifications with input from AASC. "It was an incredible challenge for AASC," adds Moffet. "We could never have done the sled test without them. We optimized the design virtually and built a few parts to validate our design. We essentially took an idea; designed, built, and tested it; and shipped it to Holloman in less than a year."

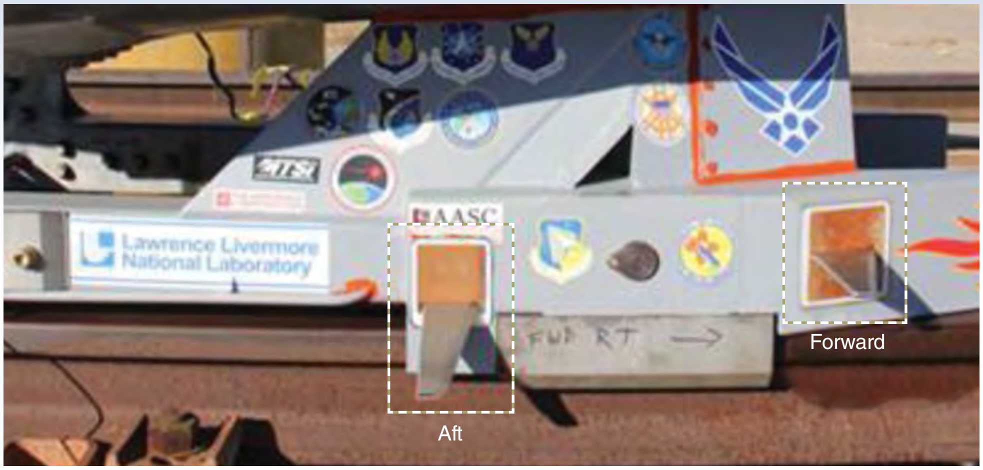
Engineer Michael King, who served as chief scientist for the sled test, says, "We were concerned about heat transfer to the warhead and ablation of the carbon fiber material. Our models showed that carbon epoxy would work."

An extensive material testing and characterization program was instituted to evaluate the material and ensure it could meet the structural, aerodynamic, and heat requirements for the sled test. Static material tests were performed to examine tensile and compression strength, interlaminate shear and tension, density, bearing strength, thermal conduction, and heat capacity. The results from those experiments and the simulations gave the engineering team confidence that carbon epoxy's structural and thermal properties would be more than sufficient for the 10-second sled test.

Simulating Extreme Shaking

The Laboratory's high-performance computing capabilities helped the engineering team optimize the mechanical and thermal properties of the carbon epoxy aeroshell. Computing codes simulated the aeroshell responding to the sled's

© Vibe Images - Fotolia.com



The sled test used four knifeblades, two forward and two aft on the forebody sled carrying the warhead. When these 0.5-meter-long steel blades cut through electrified mesh screens (called screenboxes) near the end of each rail, they completed an electrical circuit that triggered onboard warhead detonators.

extreme shaking and high-temperature environment, assessing material behavior up to warhead detonation. The simulations revealed the aerodynamic loadings and vibrations, stresses, and strains on the test object and sled; heating of the aeroshell; response of the knifeblades comprising part of the warhead detonation system; and the behavior at supersonic speeds of such features as the telemetry antennas.

The numerical analyses required extensive calculations with massively parallel computational fluid dynamics (CFD) codes. A core competency of Livermore's Engineering Directorate, CFD is used to analyze fluid flow such as the onrush of air as it swirls past the speeding sled and the test object secured to it. Results from these simulations were handed off to specialists who were responsible for the structural integrity and thermal performance of the conventional warhead and aeroshell during the test.

Computational engineer Ian Darnell says the advanced simulations were critical to ensuring the weapon would survive more than the anticipated Mach 3 speeds. As part of that work, material and structural engineering specialists used both materials codes and finite-element codes to study the response of the speeding test object to the extreme conditions. "During a sled test, weapon components experience more severe vibrations than they would experience in flight," says Darnell, who served as lead structural analyst. "It's a very rough ride down the track, so we needed to calculate the stresses on the sled from violent shaking."

NIKE3D's Two Million Elements

Darnell worked with the mechanical deformation code NIKE3D, originally developed by Livermore to address engineering problems involving dynamic deformations such as the response of bridges to large earthquakes. Employed in the automotive, aerospace, manufacturing, and defense industries, this finite-element code reveals how components break or deform. Finite-element codes solve problems by stepping them forward in time. In this approach, a solid object is divided into an assemblage of simple elements for which the computer calculates structural behavior. Visually, the collection of elements resembles a wire mesh.

With NIKE3D, Darnell constructed a high-fidelity model with two million elements that together represented the test object secured to the sled as it traveled at greater than Mach 3. "We modeled everything down to individual bolts and screws and even the threads on critical bolts," he says. The simulations depicted the sudden jolts of high initial acceleration as the first and second stages of solid propellant rocket motors ignite and push the test object to maximum speed. However, the most extreme jostling occurred after the sled had attained maximum speed, just before the warhead detonated. The maximum shaking seen in the simulation guided the engineers to reinforce several places on the sled with additional bracing.

Darnell notes that the simulations were informed by Livermore's extensive tests on carbon epoxy. The validated codes were important because composites respond to vibration and heat much differently than metal does.

In particular, the simulations focused on the knifeblades—the 0.5-meter-long steel blades jutting out from the side of the sled. Knifeblades are designed to cut through mesh screens (called screenboxes) mounted near the end of each rail and trigger the onboard warhead detonators. Because strong aerodynamic forces could cause the thin knifeblades to deflect and miss the screenboxes, the Livermore team used CFD to determine the aerodynamic loads the knifeblades would likely experience. Those loads were then transferred into a NIKE3D

An arena test at the Laboratory's Site 300 used an aeroshell fashioned from commercial carbon composite panels. This experiment validated warhead performance prior to the sled test.

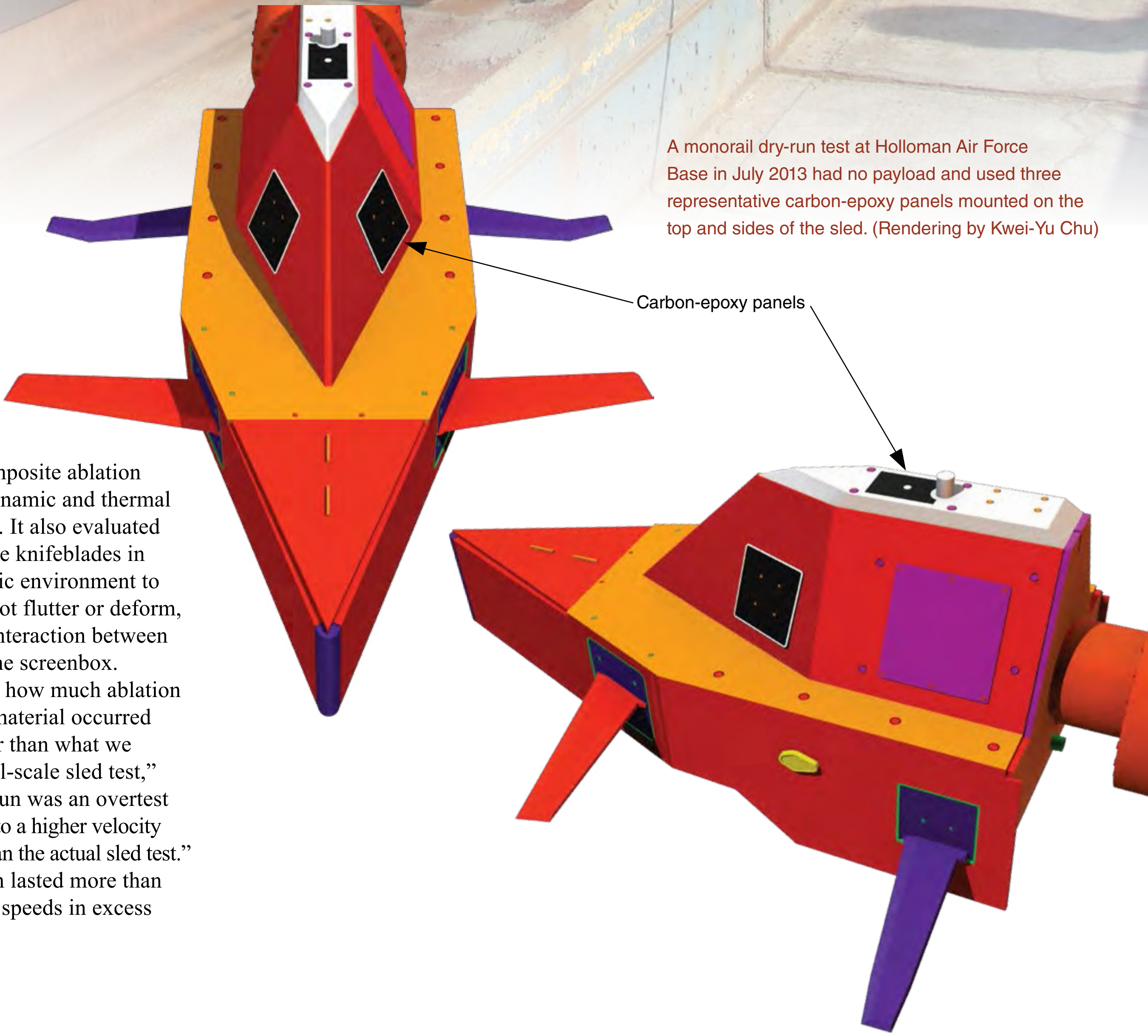
structural finite-element model that included every bolt, nut, and plate making up the knifeblades and the associated components.

Many Tests Set Stage for Sled Test

The design, development, and engineering effort to develop the warhead and later the aeroshell involved several preliminary experiments. Shaker tests were performed at Site 300, an experimental test site about 24 kilometers southeast of the Laboratory's main site. The Site 300 experiments focused on how well components could withstand violent shaking. One shaker test subjected the warhead to severe heat, shock, and vibration. A second one examined the firing initiation system that the sled test would use to detonate the warhead. The shaken initiation system was then detonated at Livermore's High Explosives Applications Facility in a heavily instrumented experiment conducted in a firing tank. "This test gave us additional confidence that the sled test would be successful," says Hare.

To validate warhead performance, the team conducted so-called arena tests, in which the warhead was placed on a pedestal, connected to diagnostic instruments, and detonated. An arena test at Site 300 using an aeroshell made with commercial carbon composite panels provided engineers with performance data. A test with no aeroshell was also conducted at Eglin Air Force Base in Florida. High-speed cameras showed minimal performance differences between the two tests, which increased confidence in the success of the impending sled test.

As a final verification of material robustness, a dry run was conducted at Holloman Air Force Base in July 2013. The dry run was a monorail test, in which a smaller sled ran on only one rail to save costs. The test was conducted with no warhead but with three Livermore–AASC representative carbon-epoxy panels mounted on the top and sides of the sled. The monorail test measured



A monorail dry-run test at Holloman Air Force Base in July 2013 had no payload and used three representative carbon-epoxy panels mounted on the top and sides of the sled. (Rendering by Kwei-Yu Chu)

the carbon-epoxy composite ablation resulting from aerodynamic and thermal effects at high speeds. It also evaluated the performance of the knifeblades in a realistic aerodynamic environment to ensure that they did not flutter or deform, and it examined the interaction between the knifeblades and the screenbox.

"We wanted to see how much ablation of the carbon epoxy material occurred at speeds even greater than what we anticipated for the full-scale sled test," says Hare. "The dry run was an overtest because it accelerated to a higher velocity and longer duration than the actual sled test."

The dry run, which lasted more than 60 seconds, achieved speeds in excess

Rocket sleds have been used for decades to simulate a flight environment for missiles, ejection seats, aircraft shapes, and the effects of high speeds on humans. (Courtesy of Holloman Air Force Base.)

of Mach 3.9. The ablation effects were thus harsher than those the sled test event would likely produce. However, all three panels exhibited minimal ablation, as anticipated. The knifeblade and screenbox functioned flawlessly. With 100 percent data return, the engineering team, together with Holloman Air Force Base personnel, began to prepare for the dual-rail sled test.

A Sled Propelled by Rockets

Rocket sleds have been used for decades to simulate a flight environment for missiles, ejection seats, aircraft shapes, and even the effects of high speeds on humans. In a rocket sled test, a platform (sled) slides along two rails on steel pads called slippers that curve around the rails to prevent the sled from flying off the track. “A sled test is really an overtest of flight conditions, but it is critical to see how a weapon performs at speed,” says Hare. “The system goes through a highly dynamic environment. Components want to break apart going down the track. It’s vastly cheaper than a flight test over water, which requires clearing vessels from a corridor in the ocean.” King adds that a sled test allows researchers to observe much more than they can see in a test flight. “We can watch the system being launched and traveling down the rails,” he says.

The Holloman High Speed Test Track is similar in appearance to a railroad track. Although the track measures 16 kilometers long, the sled test required only the last 4.8 kilometers for the 10-second run. The sled train consisted of three individual sleds—all pushed into contact with each other at the launch point. At the front, the nonpropulsive forebody sled carried the aeroshell and inside that, the warhead. The warhead’s case was fabricated at Livermore and shipped empty to the High Explosive Research and Development facilities at Eglin Air Force Base, where it was loaded with high explosive. It was then transported to Holloman Air Force Base for integration with the aeroshell.

Two pusher stages propelled the forebody sled, which held the test object (the aeroshell, warhead, and detonation system) and consisted of two strut arms and bulkhead. In the first stage, four Nike rocket motors fired manually at the launch point provided the initial thrust for the entire train. The second-stage pusher sled was loaded with two Super Terrier rocket motors that were fired by screenboxes. The forebody sled knifeblades successfully contacted the track-side screenboxes, sending a signal to the detonation system. This signal caused the warhead to detonate at the intended location near the end of the rails and impact various targets.

Diagnostics, some of which were designed by Livermore engineers, were deployed at the end of track and aboard the sled train. Ten channels of FM (frequency modulation) data were telemetered from the sled and collected by ground stations. Test data included acceleration, temperature, and structural loads. Doppler radar and breakwire position data measured the sled velocity. Photographic images were recorded by 44 fixed cameras and 3 tracking cameras that followed the train from start to warhead detonation.

“The sled test was an unequivocal success,” says Hare. All test objectives were met, all systems performed as planned, all diagnostics and targets captured data as designed, and the data were consistent with predictive simulations. The forebody sled achieved a maximum speed of greater than Mach 3. The Livermore-designed carbon-epoxy aeroshell survived the shock, vibration, and heat until detonation.

The forebody sled was propelled by two pusher stages. (top) In the first stage, four Nike rocket motors provided the initial thrust. (bottom) The second stage was loaded with two Super Terrier rocket motors.

Livermore engineer Susan Hurd called the test a significant technology advancement. "The successful execution of this high-speed sled test of a warhead was a necessary step in the progression to an operational capability," she says. "Now that we've demonstrated that the warhead functions in a flight-representative environment, we're one important step closer to that goal." Hurd adds that although high-performance computer modeling and simulation had been performed as well as small-scale and static tests, "in order to assess its performance in flight conditions, you have to do the dynamic test—you have to do the sled test."

King notes that the test object behaved as the models predicted. "Our failure models, which were pivotal to the successful sled test, are overly conservative," he says. "As a result, the sled test was a little overdesigned."

"The sled test was the pinnacle for the program," says Hamilton. "We started with small-scale tests that proved the materials. Then we went to full scale with static, arena, and shaker tests to demonstrate to ourselves that the weapon was rugged enough for flight and for being transported."

A Departure from the Norm

According to Hare, the sled test "showcased what Livermore has to offer in designing and performing the system engineering of new types of aerospace systems." He notes that legacy development processes often involved hundreds of tests, many of them repeated to assess small design changes. These repeated cycles of prototype testing can be time-consuming and expensive.

"We can now do a handful of small-scale tests, then an arena test, crunch the data, perform detailed simulations, and tell with confidence how a weapon will perform," says Hare. "We save money and deliver the weapon more quickly. And we gain greater technical understanding than were obtained from traditional programs."

He adds that Livermore engineers involved in designing advanced weapons systems for the Air Force continue to leverage expertise gained from using high-performance computers to determine likely behavior of materials and designs under extreme conditions. In addition, says Hare, the data gained from the sled test will be applicable to future warhead configurations.

The successful sled test and warhead development effort have been particularly satisfying to engineer Bob Addis, who was the project's principal investigator from 2005 to 2013, when he became a deputy program director for Defense in the Laboratory's Strategic Development Office. Addis says the effort demonstrated a Livermore core capability: advanced simulation expertise coupled to powerful computers. "We showed an extremely strong correlation between the results of our physics and engineering codes and results from our arena, structural, environmental, and sled tests," he explains. "This is groundbreaking work, and I believe it reflects the future approach to designing new conventional weapon systems."

Addis also notes that the team effort strengthened existing partnerships between the Laboratory's weapons engineers and the Air Force. From sled tests to design and development efforts, Livermore engineers are shaking up weapons research and helping lead the way to new capabilities.

—Arnie Heller

Key Words: aeroshell, carbon epoxy, focused lethality munition, knifeblades, Nike rocket, NIKE3D code, supersonic sled test.