The Role of Finite Element Analysis in the Development of a 60mm Sensor Mortar Projectile

Pasquale Carlucci, Pavol Stofko, and Mark Mellini

U.S. Army – RDECOM-ARDEC, Picatinny Arsenal, Picatinny NJ 07806

Abstract*: Reconnaissance projectiles are being developed by the U.S. military with increasing frequency to facilitate a variety of emerging needs. One of those needs includes long range deployment of these projectiles, while maintaining the survivability of electronic sensors and other components. To help fill this need, a completely new remotely deployable 60mm sensor mortar projectile was designed and developed by ARDEC. Through the use of finite element analysis (FEA), the design cycle was drastically reduced to the point where first article prototypes successfully survived live fire testing at Yuma Proving Ground. FEA was used to ensure the survivability of the round under gun launch and blow-by overpressure conditions before any testing was conducted. This paper will give an overview of the design, and the key role that FEA played in developing a successful design at a reduced development cost and short project schedule.*

Keywords*: Assembly Deformation, Bending, Connectors, Constitutive Model, Plasticity, Dynamics, Elasticity, Experimental Verification, Geomechanics, Heat Transfer, Gun Launch, Impact, Mechanisms, Bearing, Multi-Body Dynamics, Projectile, Soils, Soil-Structure Interaction.*

1. Introduction

The miniaturization of electronics and sensors has allowed their usage in gun launched projectiles for over a decade. As technology continues to progress, it has allowed for more capability to be added to projectile designs. Though the main challenge for integrating modern technology into projectiles is not packaging or size constraints, but survivability and reliability in the very harsh gun launch environment. The typical gun launch event duration is 3 ms – 20 ms and peak accelerations can exceed 20,000 Gs depending on the specific system. Reconnaissance projectiles represent a special subset in current projectile development, and include additional design challenges. In addition to surviving the gun launch environment, they also are subject to delivery and impact loads which can be of the same order of magnitude as gun launch. Specialized sensors, optics and the electronics necessary for accomplishing the desired surveillance tasks must also survive these additional delivery and impact loads.

To determine the viability of current sensor and optics technologies for reconnaissance projectile applications, a research and development testbed projectile was proposed. Experimental results from the testbed prototype were required to inform current technology decisions and an aggressive schedule of two years was required. Too meet this schedule, first article prototypes of the testbed design needed to function successfully in the actual gun launch environment. A 60mm mortar projectile was selected, and the design was approached from a clean slate. Finite Element Analysis (FEA) was integral for this design to be successful and to meet the required schedule.

All the FEA calculations completed for this development effort were completed using Abaqus/Explicit and Abaqus/Standard. FEA model setup and results post processing were completed using Abaqus/CAE.

2. Projectile Mechanical Design

While the design was approached from a clean slate, there were several constraints and requirements for the projectile. The exterior envelope and total mass needed to match that of an existing 60mm mortar projectile, this would allow use of existing propelling charge and tail boom designs. Except for the propelling charge, the mortar could not contain any energetic material (expelling charge, explosive, etc.) to accomplish any deployment functions. Most importantly, there was a given mass and volume required for the desired sensors, electronics and battery payload to survive gun launch and impact loads.

2.1 Determining a need for a parachute

Since the projectile shape, total mass and propelling charge were known; the ballistic flight path and impact velocity could be computed. While the design needs to survive impact loads, it also needs to not bury itself on impact with soft ground (e.g.sand). Determining the allowable impact velocity, and impact mass (in the cases of parachute deployment or shedding parts post gun launch) would be the basis of the design. Abaqus/Explicit CEL was used to conduct the soft-sand impact analyses for the various configurations. Figure 1 shows the geometry and nomenclature used for the 60mm mortar projectile.

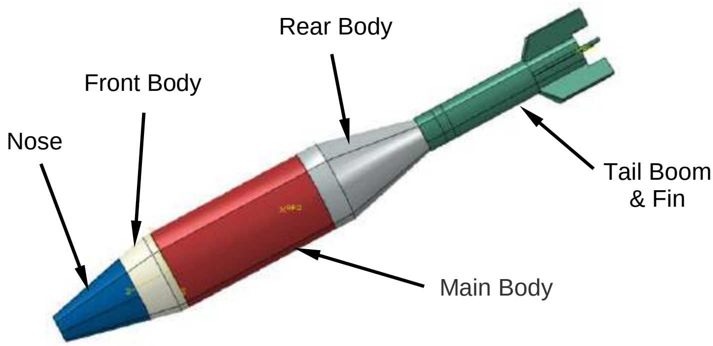

Figure 1. 60mm Mortar Projectile Geometry and Nomenclature.

Four impact cases were considered for the Abaqus/Explicit CEL analyses. Case 1 is the full projectile mass and envelope at the ballistic impact velocity of 120 m/s; Case 2 assumes the rear body and tail boom are ejected prior to impact but no parachute nor drag device is used resulting in an impact velocity of 100 m/s; Case 3 is the same as case 2 except a parachute is used to drag the projectile to an impact velocity of 8 m/s; Case 4 assumes a small cartridge/capsule (which is the sensor package) is deployed with a parachute for an impact velocity of 5 m/s. All the cases assumed a zero angle of obliquity to the impact surface which would be considered a worst case for burial. Figure 2 shows the Abaqus/Explicit CEL model setup and mesh density used for the Eulerian domain.

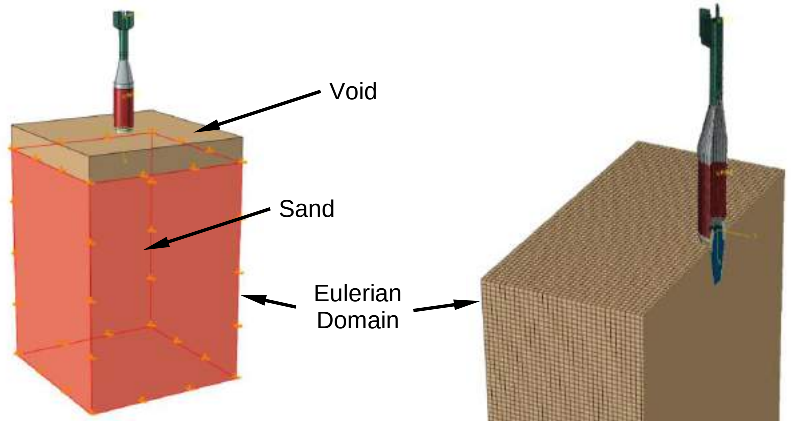

Figure 2. Abaqus/Explicit CEL Model Setup.

The sand/soil material was modeled using an experimentally measured parameter fit for the Drucker-Prager strength model using cap plasticity for a sandy-clay with ~10% moisture content. The projectile was modeled using a Lagrange mesh. Figure 3 shows the analysis results for the impact with predicted burial depths of ~550mm, ~430mm, ~45mm, and ~5mm for Cases 1 thru 4 respectively.

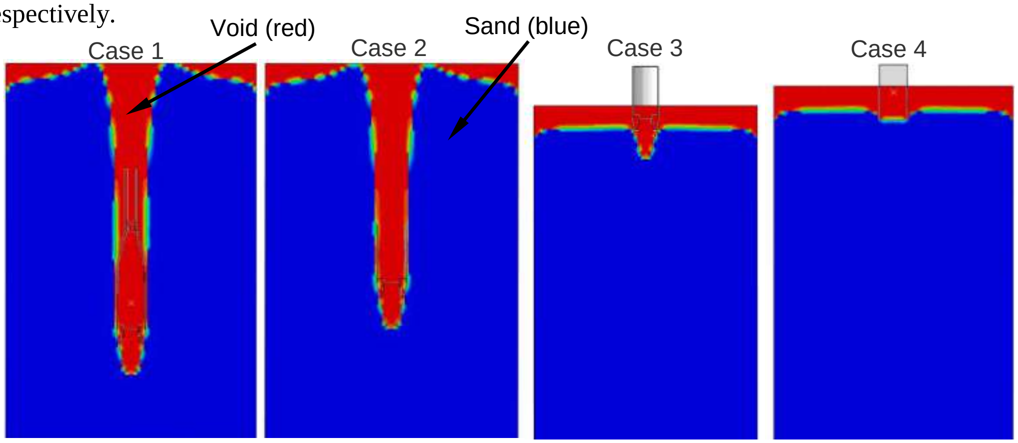

Figure 3. Abaqus/Explicit CEL Soil Impact Model Results.

It is important to note that for soil properties there is a fairly high degree of variability that can be expected; with strengths strongly dependent on moisture content, particle size distribution, and soil constituents (Stewart 2013, Brown 2007). The intent of these analyses was to capture a worst-case burial that could be used to guide the design. With that in mind, it was clear that a parachute was necessary to drag the projectile down to a sufficiently low velocity to prevent burial. Noting the very low impact velocity of ~8 m/s, surviving the impact loads becomes much less of a concern as they are significantly less than launch loads.

2.2 Deployment mechanism and parachute bearing design

Once it became clear that a parachute was necessary, the detailed mechanical design could begin. The mechanism needed to accomplish a few discrete operations after gun launch: 1) expel/separate the rear body and tail boom, 2) deploy a parachute to drag down the projectile, 3) after impact expel/separate the parachute, 4) deploy a set of legs to stand the projectile upright (necessary to accomplish sensor tasks). While it would have been significantly easier to accomplish some or all of these tasks using expulsion charges, the design requirements precluded these methods.

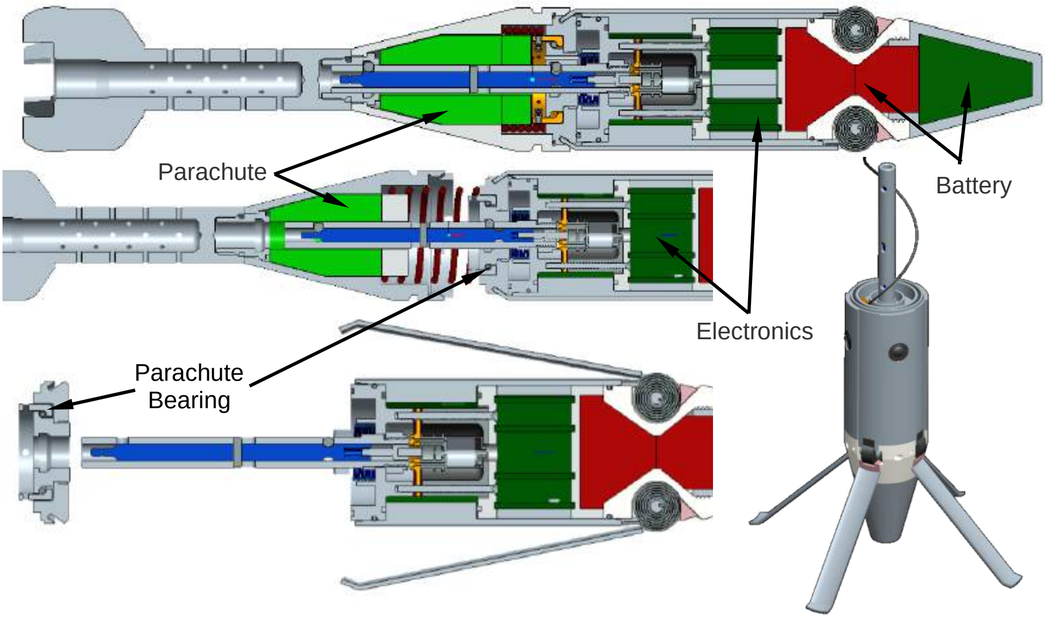

Figure 4. 60mm Mortar Projectile Mechanism Design and Function.

Starting with a mechanical design concept capable of fulfilling all the required functions, FEA analyses for gun launch survivability were completed concurrently with detailed design. Once the model was setup the Explicit solver was well suited to multiple iterations, allowing exploration of several parallel mechanical designs. This approach allowed for a rapid convergence on a final design that was feasible and robust. For gun launch loads the peak acceleration approached 10,000 Gs and the muzzle exit velocity was ~260 m/s. Through the many FEA analysis iterations conducted, survivability of the parachute tether bearing was consistently a concern. Note that this bearing is critical to the function as it allows relative spin between the projectile and parachute during descent to prevent cord tangling and parachute failure. The bearing needed to support both radial and thrust loads (in one direction only), and there was limited space claim allowed for feasible mechanical design. Given these constraints there were no suitable commercial bearings readily available, and FEA analysis was used to design a custom bearing by directly using surfaces of the native parts. Figure 5 shows Mises stress contours for a snapshot of time during gun launch for the projectile mechanism and custom bearing.

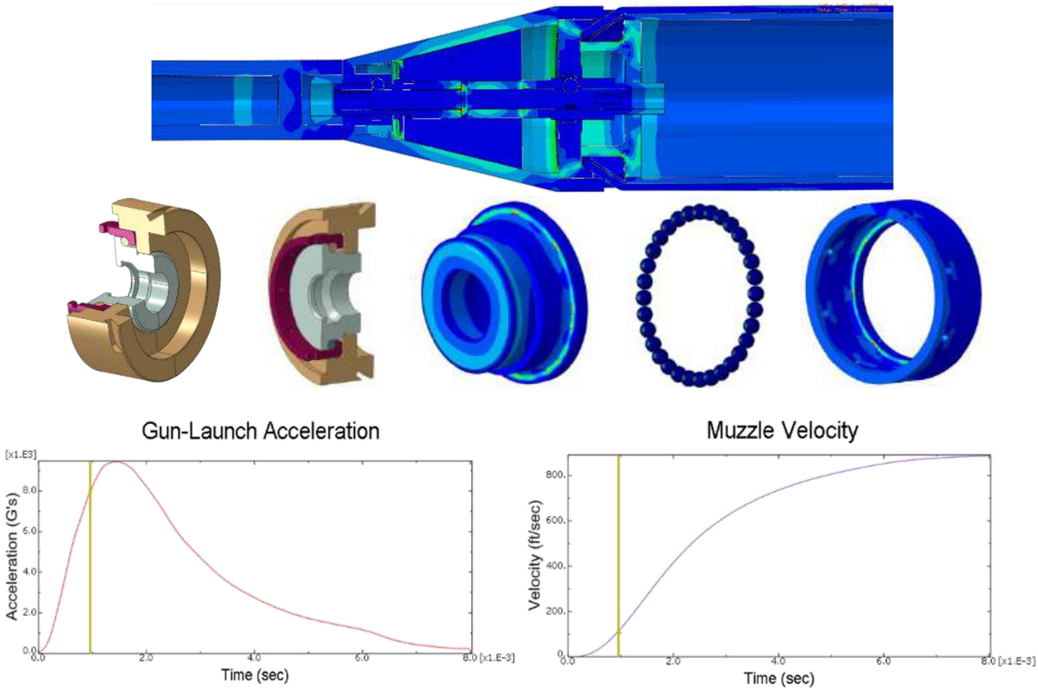

Figure 5. Gun Launch Load and Mises Contours – Mechanism and Bearing.

In addition to the fully deformable FEA analyses used to assess gun launch survivability, extensive use was made of connectors and kinematic type analyses using rigid body constraints. These analyses were used to confirm correct mechanism function and proper sizing of springs and detents. While the main advantage was greatly reduced computational expense, the ability to use the FEA model already developed for gun launch saved a great deal of time.

2.3 Electronics gun launch survivability and heat dissipation

With the mechanical design complete and a defined space claim for the battery, the balance of the available volume could be used for mounting the electronics (see figure 4). The initially considered circuit board layout was customary for this configuration, with the plane of the board perpendicular to the axis of the projectile. This was the preferred electrical layout since it resulted in a stack of circular boards of identical outline allowing for direct board to board connections. Through Abaqus/Explicit gun launch analyses, it quickly became apparent that survivability was not possible with this arrangement. Even considering the conventional practice of potting all the circuit boards in epoxy was not sufficient to survive the gun launch loads. The primary cause of "failure" were large deflections of the boards in the projectile's axial direction which would result in broken components and solder leads. Instead, the plane of the circuit boards were rotated to be aligned with the projectile axis. While this complicated the board layout to some degrees due to the need of several rectangular boards of different sizes, the result was a feasible and robust support for the boards that required no epoxy potting for survivability. This was especially desirable for this research and development test bed since it would allow for recovery of electronics after experimental testing. Figure 6 shows a Mises contour for the circuit boards and supporting structure.

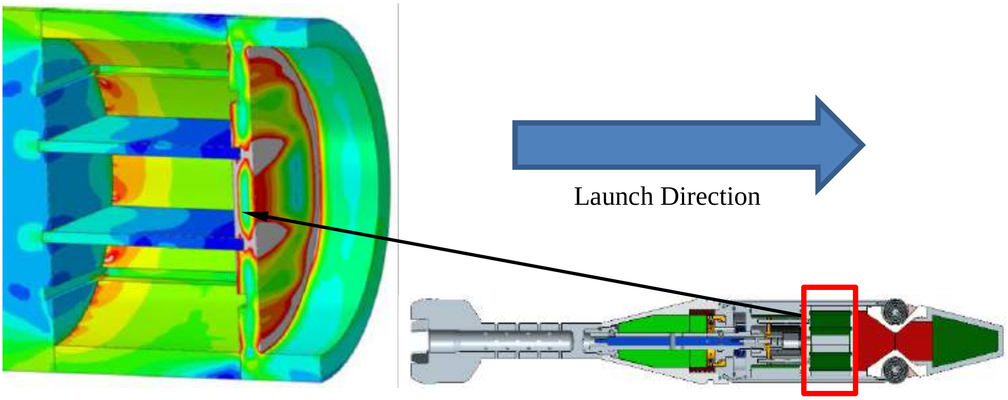

Figure 6. Gun Launch Mises Contour – Electronics and Circuit Boards.

One additional consideration for the electronics was dissipation of waste heat. While most of the components would maintain an adequate temperature with passive cooling in the current configuration, one power amplifier in particular was of concern due to its large waste heat output. A series of heat transfer analyses were completed to find a suitable solution to dissipating the waste heat to the exterior of the projectile and to the ambient environment. Working to our advantage was the aluminum construction of the projectile main body, which served as an excellent heat conduit from the interior to the environment. The ambient design temperature is 60°C (140°F), with ambient natural convection on the projectile surface. Figure 7 shows temperature contours for the heat transfer analysis of the selected arrangement.

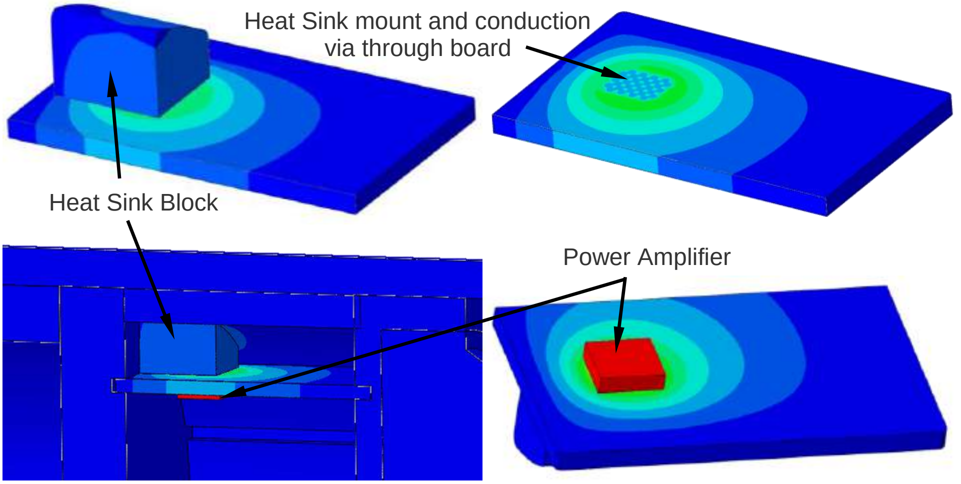

Figure 7. Heat Transfer Temperature Contours – Electronics and Circuit Boards.

The use of a solid copper heat sink block mounted between the circuit board and projectile body was satisfactory for dissipating the required heat load. For the given ambient design condition the maximum power amplifier temperature was ~75°C which was below the maximum allowable temperature of 85°C. For this arrangement the projectile surface temperature reaches ~69°C.

3. Experimental Testing

Fabrication of hardware began immediately after the design was finalized. A very limited amount of experimental testing was conducted during the design process due to the short schedule. Even this testing was constrained to readily available methods and representative hardware. The live fire testing eventually conducted at Yuma Proving Ground (YPG) was effectively the first tests the newly developed mortar system would undergo. Since the projectile was designed to deploy a parachute during flight and land "softly", recovery of all the test projectiles was expected. This would allow a post-mortem inspection of the projectiles, assuming they functioned properly.

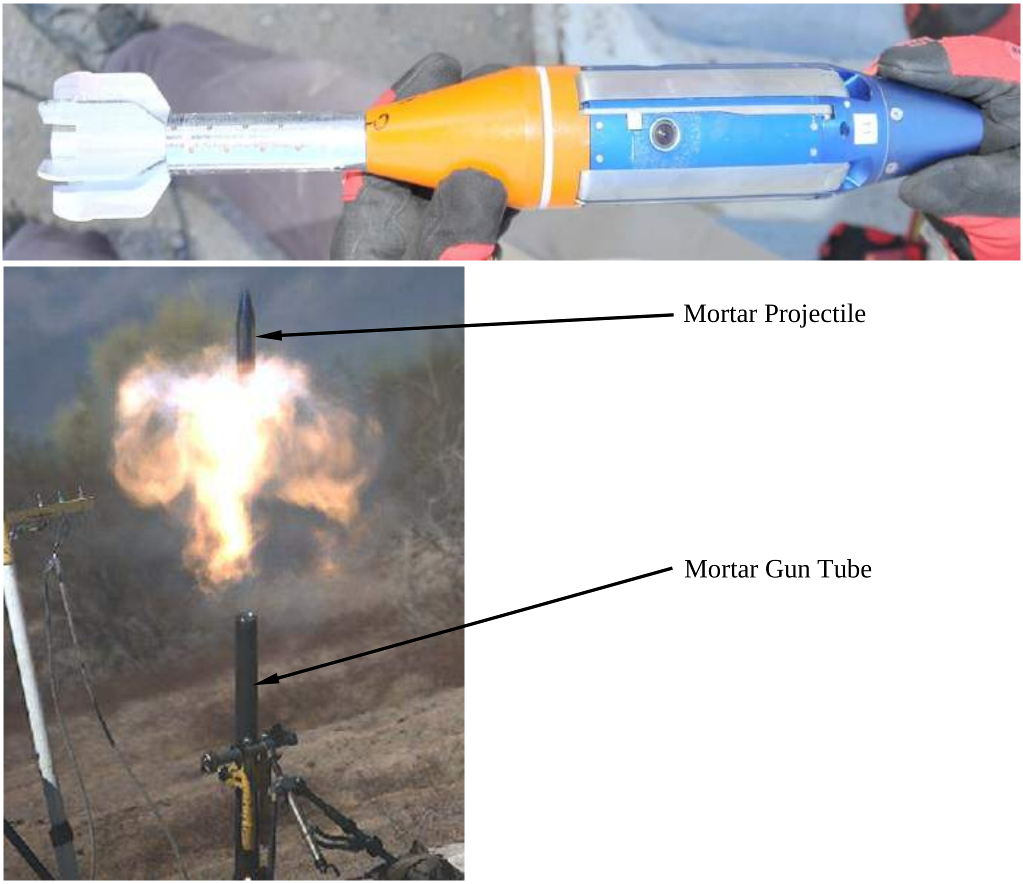

Figure 8. Fully Assembled Mortar Projectile and Muzzle Exit Images.

Figure 8 shows the an image of a fully assembled mortar projectile ready for testing, as well as a still image of the projectile at muzzle exit. Figure 9 shows a series of still images of: (1) mortar projectile in flight; (2) in flight with parachute deployed; (3) at ground impact; (4) parachute ejected and mortar projectile fully upright; (5) mortar projectile which did not deploy parachute and became buried.

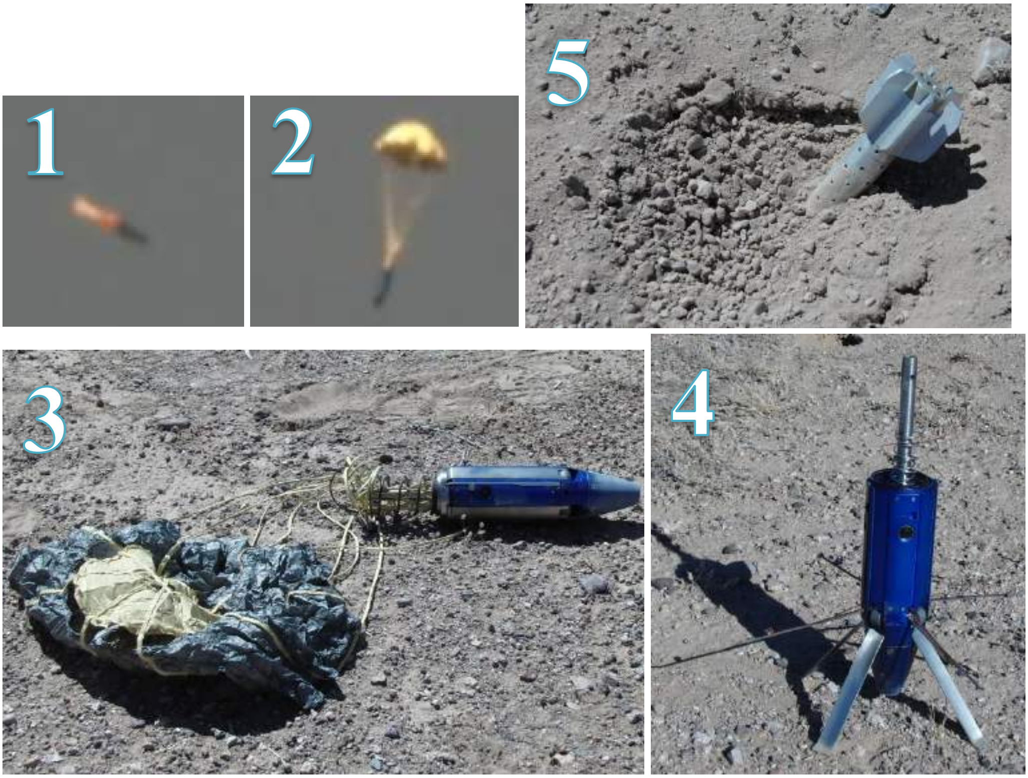

Figure 9. Still Images of Mortar Projectile – Experimental Testing.

A test firing was considered successful if the mortar projectile survived gun launched and performed all of its mechanical functions as depicted in figure 9. With a few exceptions, the projectiles performed their functions as expected. Picture 5 in figure 9 shows one of these exceptions which failed to deploy its parachute, impacted the ground and buried itself. One other projectile also failed to deploy its parachute but became buried ~250mm below the surface (picture not shown). The failures to deploy were traced back to timing issues, and the post-mortem revealed that the mechanism survived the gun launch and deployment loads in all cases. The two buried test projectiles provided qualitative validation of the Abaqus/Explicit CEL model and experimental justification for including a parachute in the design.

4. Conclusion

For the given design and schedule constraints, a research and development testbed projectile was designed and successfully tested. First article prototypes of the testbed design were demonstrated to function successfully in the actual gun launch environment. Finite Element Analysis (FEA) was integral for this design to be successful and made it possible to avoid the conventional design-test-design-test development cycle which is still common today in projectile design. The authors' goal is to demonstrate the value of using FEA at design inception in reducing schedule and cost in projectile development. Total cost savings for this effort were estimated at $250k - $300k, while at least one year of development time was saved as compared to the iterative design-test approach. Completing this development effort within the required two year window would not have been possible without the use of FEA to guide design decisions, and the development effort would have not been approved at its outset without confidence in the ability to deliver a working prototype within the required schedule.

5. References

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