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US Army Research Laboratory

Reusable Rapid Prototyped Blunt-Impact Simulator

by Douglas A Petrick

NOTICES

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Weapons and Materials Research Directorate, ARL

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14. ABSTRACT

Advancements in component fabrication using rapid prototyping (RP) have recently begun to revolutionize the field of projectile development. RP components have been successfully used in wind tunnel mock-ups, internal electronics packaging, and sabot applications, to name a few. The ability to produce highly detailed geometry in very short manufacturing lead times, often less than 24 h, is being used in the early stages of projectile development to accelerate schedules and save costs. The US Army Research Laboratory (ARL) Guidance Technologies Branch recently used RP technology to create a custom reusable projectile for air-cannon-launched impact research. Several projectile configurations with varying frontal impact area geometries were manufactured using selective laser sintering RP technology. These projectiles were launched with a compressed air cannon developed by ARL's Survivability/Lethality Analysis Directorate and Weapons and Materials Research Directorate for the behind helmet blunt trauma research initiative. The projectiles contained a commercial-off-the-shelf onboard recorder in conjunction with a 3-axis accelerometer to measure impact forces between the projectile and target. The projectiles were subsequently recovered, and the recorded impact data were downloaded via an embedded connector interface for analysis. The objective of this report is to inform the audience of a novel use of RP technology to fabricate projectiles for a nonclassical gun experimental application.

15. SUBJECT TERMS

rapid prototype, additive manufacturing, reusable projectile, 3-axis accelerometer, compressed air cannon, soft launch, helmet back-face deformation

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1. Introduction

Rapid prototyping (RP) is the term most commonly used to describe additive manufacturing technologies. An additive manufacturing technology is any manufacturing process that fabricates a part by adding one layer of material at a time, one on top of the other, to produce detailed 3-D geometries directly from 3-D computer-aided design (CAD) models. The additive manufacturing process generally uses a computer-controlled deposition/curing process to create the individual layers, eventually culminating in a 3-D reproduction of an input CAD geometry. Some processes produce finished, fully cured parts, and others produce parts that must be cured as an additional process. This differs from conventional machining, which can be thought of as subtractive manufacturing. Conventional machining creates a part by cutting away material from a piece of solid stock material such as a rod or a block. Conventional machining can be combined with computer-aided manufacturing (CAM) software to produce highly complex geometries directly from CAD models.

There are advantages and disadvantages to each process that must be considered each time a designer wishes to take his/her design to the manufacturing stage. Even with the advancements in CAM software for conventional machining, the initial setup process requires a substantial amount of time and effort by the designer and machinist each and every time a part is manufactured. Generally, RP technologies are relatively easy to set up and operate. There is less interaction required between the designer and the person operating the machine, which is typically the biggest time saver and error reducer when comparing the 2 manufacturing methods. For the purpose of this experiment, an RP manufacturing technology was chosen by the designer based on these principles. This allowed for highly accurate parts to be manufactured with the ability to quickly incorporate design changes, as the experiment was in its early stages, producing various types of geometries that were evaluated before a final experimental model was chosen.

There are a variety of different additive fabrication processes in use today, including stereolithography, selective laser sintering (SLS), direct metal SLS, and fused deposition modeling, to name a few. Each of these technologies can create parts from a variety of different materials. However, in comparison, conventional machining can be applied to a much larger variety of metallic materials that, to date, RP technologies are not capable of producing.

The initial parameters of this experiment pointed toward RP technologies as a viable option. The experiment required a lightweight and robust material that could survive several blunt impacts before being discarded. An SLS technology was selected and the material chosen was a glass-filled polyamide material that had adequate impact resistance and durability. This selection was based on the previous experience of the US Army Research Laboratory's (ARL's) Guidance Technologies Branch (GTB) in the design and fabrication of sabots for nontraditional shaped projectile geometries used in smoothbore-gun-launched applications.[1,2] SLS technology uses a bed of powdered material that is introduced to a laser. The laser is controlled by a computer to sinter the particles of powdered material to form the aforementioned layers of material one on top of the other until the entire geometry emerges fully cured.

As part of their behind helmet blunt trauma (BHBT) research initiative, the Warfighter Survivability Branch(WSB) of ARL's Survivability/Lethality Analysis Directorate (SLAD) was commissioned to design and build a projectile that could be used to record impact data between itself and a variety of target materials. The projectile needed to provide stable, repetitive flight for a set distance between a compressed air cannon, developed by SLAD in collaboration with the Weapons and Materials Research Directorate's Flight Sciences Branch, and a target. Experimental results needed to be recorded with high-speed photography and by data collection onboard the projectile using a commercial-off-the-shelf (COTS) onboard recorder (OBR). As part of the experiment, a specific frontal geometry was needed that could produce the correct amount of force on a desired impact area. Varying frontal geometries were developed to be evaluated during the first phase of the experiment. Of these geometries, 2 specific frontal radii of curvature (RoCs) were chosen for use in Phase 2 of the experiment. Phase 2 consisted of taking the selected frontal geometries and adapting them to a projectile that contained a COTS OBR and power supply with an external interface for data download and power recharging. Leveraging specific expertise in creating internal gun-hardened electronics for a variety of high-g applications, GTB developed an internal electronics package containing a COTS OBR that could be custom fit into the projectile geometry chosen from Phase 1 with a few modifications.[3–6] The final product was a robust self-contained projectile that could be reused over multiple firing events, providing many valuable impact data points to the customer.

1.1 Experiment Description and Results: Phase 1

The objective of Phase 1 was to create a blunt simulator projectile with the frontal impact geometry derived from WSB's preliminary experimental results in BHBT research. The concept behind selecting the geometry was to launch an instrumented projectile that would simulate the impact caused by the deformed helmet after defeating a ballistic threat. A schematic for the design concept of the blunt-impact simulator is shown in Fig. 1.

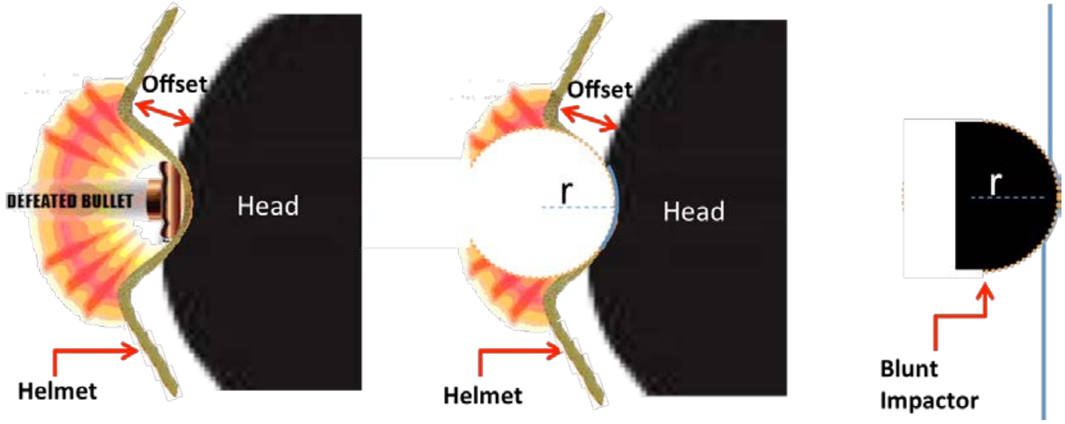
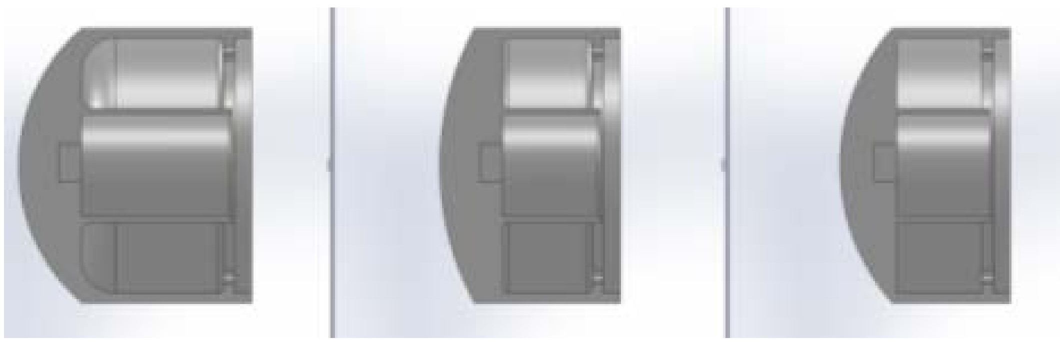


Fig. 1 Development of radius of curvature (ROC) for blunt impactor

Based on internal helmet surface deformations recorded using digital image correlation (DIC) from empty helmets against various ballistic threats at different velocities, 3 RoCs were chosen to be evaluated, as shown in Fig. 2. These geometries were selected to represent the deformation of the helmets when the greatest kinetic energy and momentum occurred.



50-mm RoC 80-mm RoC 110-mm RoC

Fig. 2 Three evaluated RoCs

The clay Peepsite headform, shown in Fig. 3, can be used to measure impact geometries. Figures 4 and 5 show examples of impacts produced and digitized using the portable 3-D coordinate measuring system FAROArm (FARO, Lake Mary, Florida) to determine impact geometries and volume. Figure 4 shows the imprint on the headform created by helmet back-face deformation by a 9-mm bullet shot, and Fig. 5 shows the imprint from an 80-mm RoC blunt-impact simulator.

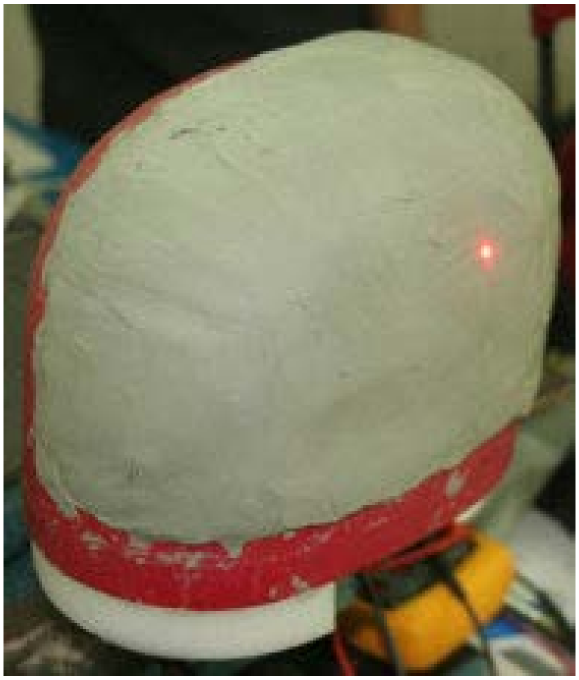


Fig. 3 Peepsite headform used to assess impact conditions from helmet back-face deformation and blunt-impact simulator

Fig. 4 Imprint of 9-mm bullet

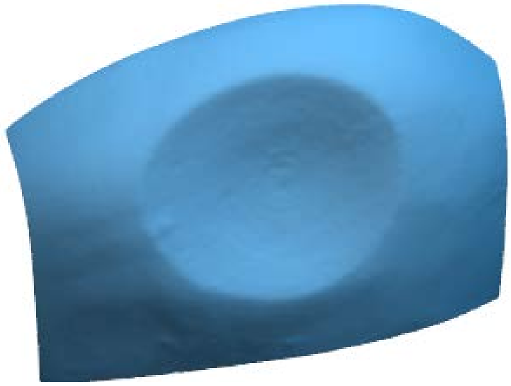


Fig. 5 Imprint of 80-mm RoC blunt-impact simulator

A variety of blunt-impact simulator configurations was evaluated with each RoC before a suitable design could be implemented for progression into Phase 2 of the experiment. During these initial tests with the experimental range setup shown in Fig. 6, the projectile is launched using a compressed air cannon, and after muzzle exit it travels approximately 5 m through the air before impacting the target. From these tests, it became readily apparent that in addition to the helmet back-face geometries, another key performance capability of the simulator had to be considered. It was extremely important to maintain projectile stability during flight to produce consistent impact profiles on the designated target material.

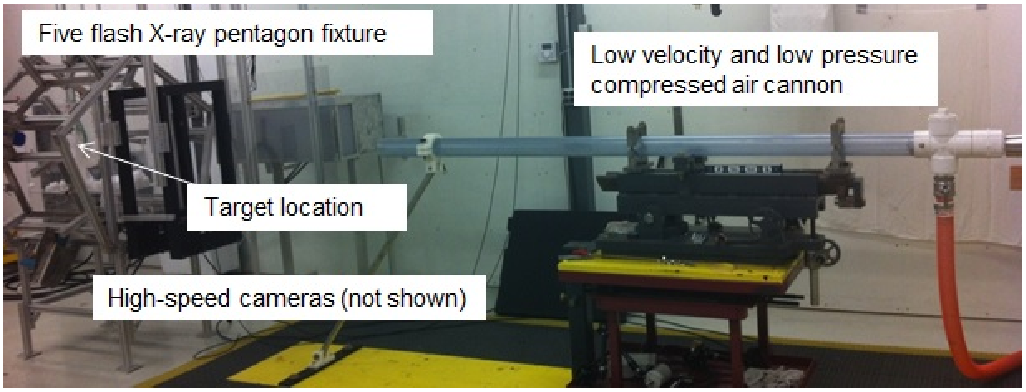


Fig. 6 Compressed air cannon experimental setup

WSB was actively refining projectile requirements during this initial phase of the experiment. Comparisons were made of the projectile impacts and data collected from previous experiments using a 9-mm bullet and helmet on both the Peepsite headform and the ballistic load sensing headform (BLSH; Biokinetics, Ottawa, Ontario, Canada), shown in Fig. 7. Mass, velocity, geometry, and momentum from these existing back-face deformation studies were used to optimize the projectiles. Projectile mass was dictated by frontal area and material strength requirements, plus predicted mass of future instrumentation. The ability to rapidly produce prototypes to be used to adjust certain portions of the geometry was key in being able to meet these customer requirements in a timely manner consistent with their aggressive project schedule. As experiment parameters were refined, the projectile geometry was able to be updated and prototypes were produced, usually within one or 2 working days.

Fig. 7 Ballistic load sensing headform

Within 6 iterations, an optimized projectile configuration emerged that met these requirements, provided a stable, repetitive flight, and withstood over 20 projectile launches and impact events (Fig. 8). The final projectile design consisted of 3 separate parts: a threaded can portion (capable of containing future OBR electronics), a threaded blunt face (with each RoC being interchangeable with any can), and an obturator portion (slip-on foam doughnut). WSB then repeated previous experiments performed with a 9-mm bullet and a helmet using this projectile with selected RoCs on both Peepsite and BLSH targets.

Design Iteration	Material	Mass (g)	Target Velocity (ft/s)	Strength	Flight
1	GF PA	120	135-195	Support braces broke	Unstable
2	GF PA	118	135-195	Back fin broke after impact	Unstable
3	GF PA	123	135-195	Did not break	Stable
4	GF PA	97	167-216	Face broke on impact	Stable
5	GF PA	102	158-211	Back fins broke after impact	Stable
6	GF PA with foam	95	170-219	Did not break	Stable

Material Legend: GF PA: Glass-filled Polyamide

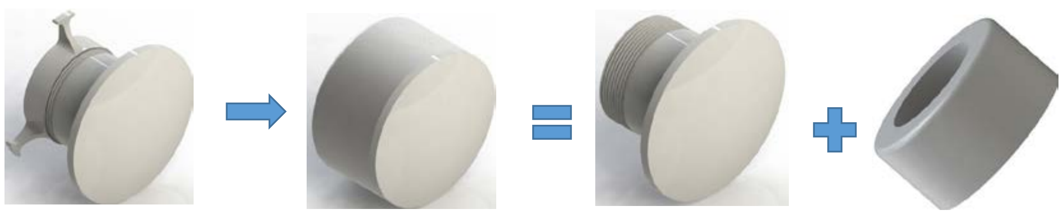


Fig. 8 Projectile design iterations

1.2 Experimental Description and Results: Phase 2

The objective of Phase 2 of the experiment was to instrument the projectile geometry and 2 RoCs chosen in Phase 1 of the experiment with a COTS OBR modified to operate off of a rechargeable power supply and fit inside the available blunt-impact simulator volume determined in Phase 1. The OBR was also modified to interface with an embedded connector for data download, OBR configuration, and charging applications (Fig. 9). These instrumented blunt-impact simulators were used to measure and record impact data that were later compared with existing data from helmet back-face deformation impacts on instrumented headforms. These new data were subsequently analyzed by WSB to verify accurate reproduction of impact characteristics caused by 9-mm projectile impacts with helmeted head surrogates.

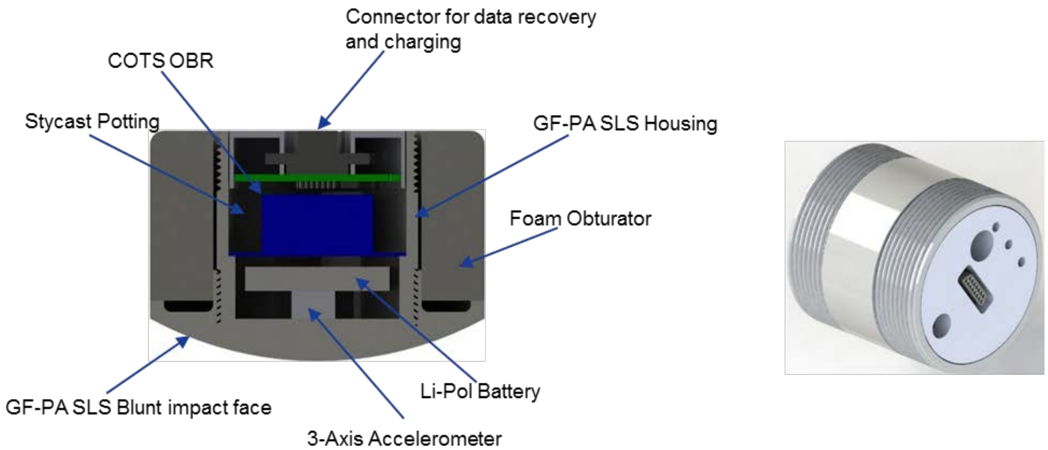


Fig. 9 Instrumented blunt-impact simulator

Two threaded can sections were instrumented with OBR components including rechargeable power supplies, interface connectors, and a 3-axis accelerometer.[4] Each instrumented can was capable of adapting to a screw-on blunt-face geometry of either a 50- or 80-mm RoC. To date, 84 impacts have been performed using one of the 2 instrumented cans using interchangeable and replaceable blunt-face geometries. Figure 10 shows an example of plotted 3-axis accelerometer data downloaded from the projectile after an impact with a target. In all 84 impact cases, similar data were recovered, proving the functional reliability of the OBR, which in turn met the primary objective of the Phase 2 projectile design. Figure 11 shows a comparison of a subset of measured projectile velocities with varying initial air cannon pressures taken from the OBR with velocity measurements taken from a high-speed camera and a laser beam interruption setup along the firing line.

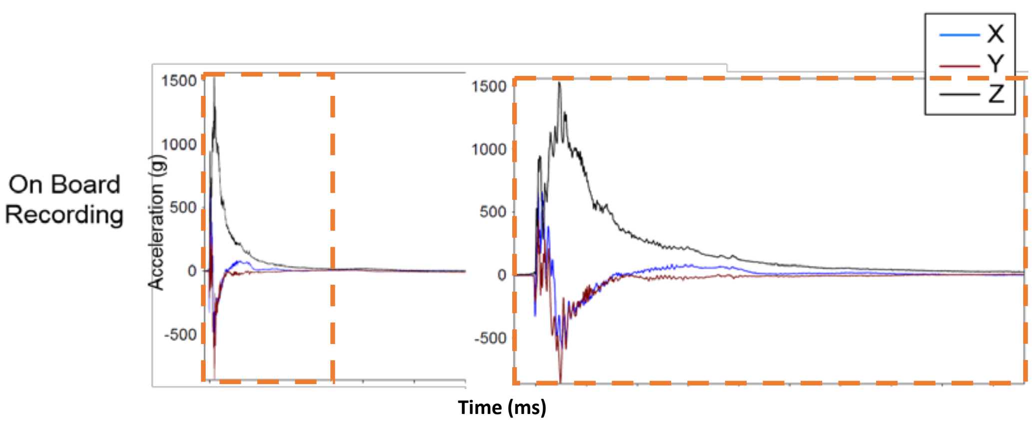


Fig. 10 Acceleration (g's) vs. time (milliseconds)

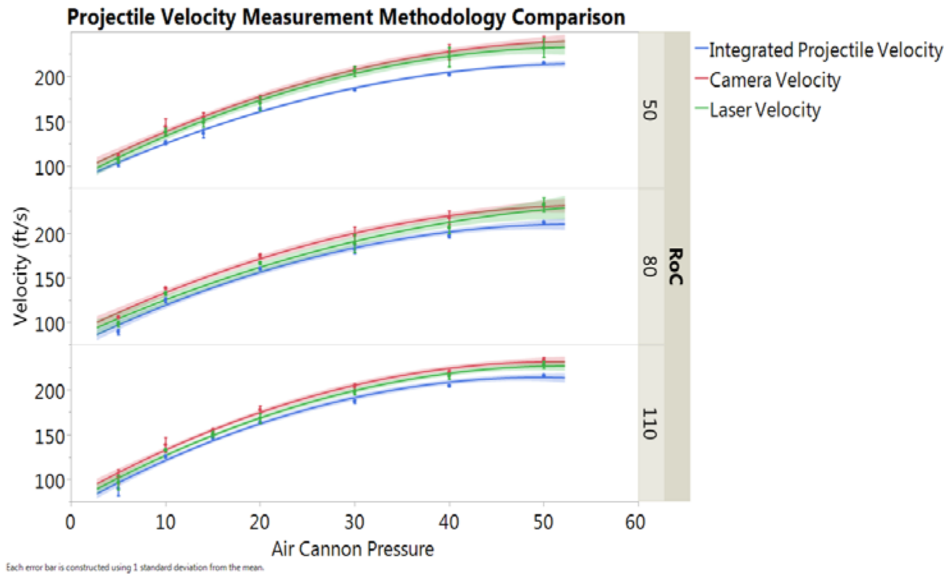


Fig. 11 Measured velocity (feet per second) vs. air cannon pressure (pounds per square inch)

The OBR blunt-impact simulator measures a higher force with a faster response time than the load-sensing biokinetic headform target that was used in previous 9-mm helmeted tests. This is due to the protective rubber cover on the load cells in the headform that dampens the impact before it is picked up by the sensors. Data taken from an OBR blunt-impact simulator's impact with a biokinetic headform target exemplify this phenomenon, as shown in Fig. 12.

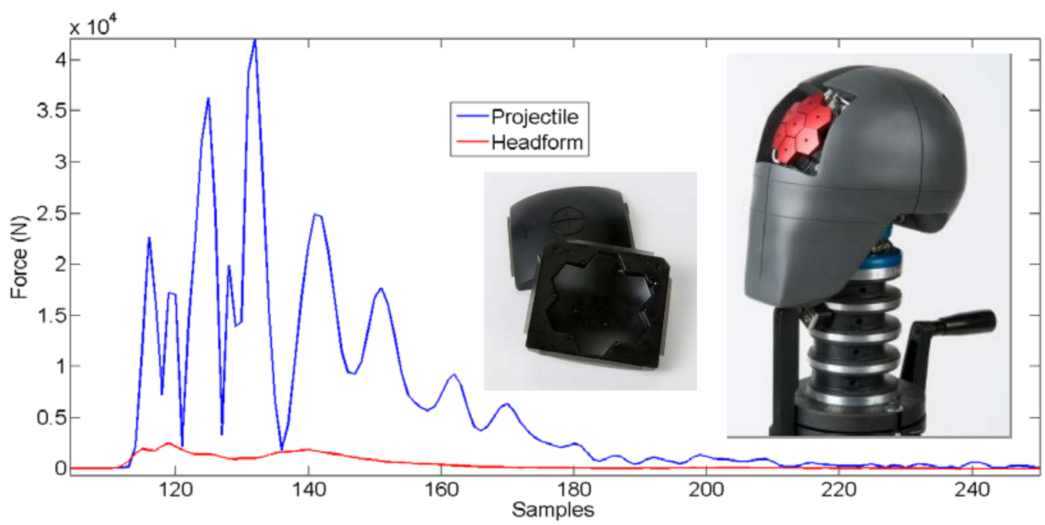


Fig. 12 Blunt-impact simulator impact with biokinetic headform experiment

The OBR blunt-impact simulator is better suited to measure and understand the impact loads imparted to the head from a ballistic-blunt event than the existing methodologies using an instrumented ballistic load sensing headform.

2. Conclusion

The use of SLS RP technology made it possible to quickly adapt to changes in projectile requirements in the initial phases of experimentation. This led to a robust 2-piece design capable of adapting to all RoCs that were of interest in this study. This projectile design, when produced in glass-filled polyamide material, was proven to have adequate impact resistance to survive multiple experiments. Costly and time-consuming dynamic finite element analysis was avoided by the ability to quickly and cost effectively produce test items. Two instrumented OBR blunt-impact simulator projectiles were produced for testing in Phase 2 of the experiment. Repeated re-use demonstrated robustness, making production of additional test articles unnecessary and saving significant time and manufacturing cost. Glass-filled polyamide SLS manufactured parts are suitable for future projectile geometries involved in soft-launched recoverable applications. They may also be appropriate for use in other areas of nontypical gun-launched research.

In the field of RP technology, newer materials and processes are continuously being developed. These new materials and processes will continue to prove useful for these types of applications as well as for any application where project requirements are constantly being driven by time and money as limiting factors. The time from concept to working prototype during Phase 1 projectile development was on the order of a few weeks instead of the months it would have taken to prototype and pursue a conventionally manufactured solution.

3. Future Work

In the third phase of this experiment, OBR blunt-impact simulators will be used to create impacts representative of helmet back-face deformation on postmortem human heads, as shown in Fig. 13. These tests will provide the most data for understanding the injury mechanisms that contribute to BHBT events to date.[7] Helmet designers will be able to use this research's data to make changes in helmet composition and geometry to better protect the warfighter.

	Low Radius of Curvature		High Radius of Curvature	
	Side	Front	Side	Front
High Velocity	5	5	5	5
Moderate Velocity	5	5	5	5
Low Velocity	5	5	5	5

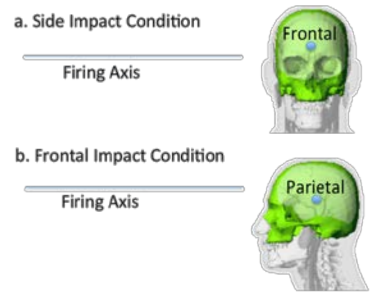


Fig. 13 Phase 3 postmortem human head experimental layout

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List of Symbols, Abbreviations, and Acronyms

ARL	US Army Research Laboratory
BHBT	behind helmet blunt trauma
BLSH	ballistic load sensing headform
CAD	computer-aided design
CAM	computer-aided manufacturing
COTS	commercial off the shelf
DIC	digital image correlation
GTB	Guidance Technologies Branch
OBR	onboard recorder
RoC	radius of curvature
RoCs	radii of curvature
RP	rapid prototype
SLS	selective laser sintering
WSB	Warfighter Survivability Branch

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