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Equidistant Truss Line Wave Generator (LWG)

by Dwight Hofstetter Jr, Justin Bays, Todd Brinkman, and Paul Duvall

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Equidistant Truss Line Wave Generator (LWG)

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14. ABSTRACT The US Army Combat Capabilities Development Command Army Research Laboratory researched and developed a line wave generator (LWG) to detonate three explosive masses reliably and simultaneously with the use of only one detonator. This report reflects the final “as-executed” experimental details and findings for experiments conducted to collect data on the effectiveness of various LWG designs with respect to delivering a detonating shock wave to separate explosive masses simultaneously. The optimal design would deliver individual shock fronts to each explosive mass simultaneously, use minimal explosive, and initiate reliably and repeatably. It was also necessary that the design be produced in-house, with limited tools, and be somewhat transportable. The LWG would need to be created on demand, transported, and potentially modified in the field in future uses. The explosive trains were placed on 1-inch-thick 6061 aluminum blocks and, when detonated, created a cavity in the aluminum that provided forensic evidence to the behavior of the detonation. High-speed video taken during the final experiment certified that the detonation front was delivered uniformly to each explosive mass.					
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1. Background and Objective

The US Army Combat Capabilities Development Command (DEVCOM) Army Research Laboratory (ARL) researched and developed a line wave generator (LWG) to detonate three explosive masses reliably and simultaneously with the use of only one detonator. This report reflects the final “as-executed” experimental details and findings for experiments conducted to collect data on the effectiveness of various LWG designs with respect to delivering a detonating shock wave to separate explosive masses simultaneously. The optimal design would deliver individual shock fronts to each explosive mass simultaneously, use minimal explosive, and initiate reliably and repeatably. It was also necessary that the design be produced in-house, with limited tools, and be somewhat transportable. The LWG would need to be created on demand, transported, and potentially modified in the field in future uses. The explosive trains were placed on 1-inch-thick 6061 aluminum blocks and, when detonated, created a cavity in the aluminum that provided forensic evidence to the behavior of the detonation. High-speed video taken during the final experiment certified that the detonation front was delivered uniformly to each explosive mass.

2. Overview

Three experiments investigating explosive LWG designs to detonate separate explosive masses simultaneously were conducted. Preliminary research was performed to explore previous LWG designs. Most LWG designs involve predetermined explosive path lengths to deliver the shock fronts at designated times. Morris et al. outline three LWG designs: circular sector, branching method, and perforated sheet.¹ Weckert et al. expanded on the perforated sheet design and explored explosive lenses where two different speed explosives were used to remove the curvature from the detonation wave and produce a straight-line wave.² A perforated sheet design was chosen based on its ease and repeatability of production. Through analyzing the experimental results of perforated sheet experiments, an LWG that used equidistant truss explosive pathways was devised.

It was decided to make the LWGs from 2-mm-thick rolls of RDX-based PRIMASHEET* 2000. Weckert stated that his design, which used an available hole template, was not suitable for use with 3-mm-thick PRIMASHEET 2000 explosive, likely due to critical diameter issues. Weckert declared the triangle side lengths to be 125 mm but did not provide secondary dimensions of his design. It was desired to expand on Weckert’s design; therefore, the necessary dimensions could be

*PRIMASHEET is a registered trademark of Ensign-Bickford Aerospace & Defense Company.

determined by uploading an image of the design into SolidWorks,³ scaling to the stated side lengths of the triangle, then sketching shapes on top of the image (see Fig. 1). Holes were found to be approximately 6.5 mm in diameter and spaced 2.75 mm between hole edges. Hole edges were also spaced 4.75 mm from the triangle edges. A spline was drawn from the point of detonation to the opposing edge, around holes cut in the PRIMASHEET to compare the middle explosive pathway to those on the outside. The total length of the spline was found to be approximately 124.57 mm, which was very close to the 125-mm triangle side lengths. This suggests that the detonation front would be arriving to the base edge at similar times whether traveling down the edges or through the middle of the LWG.

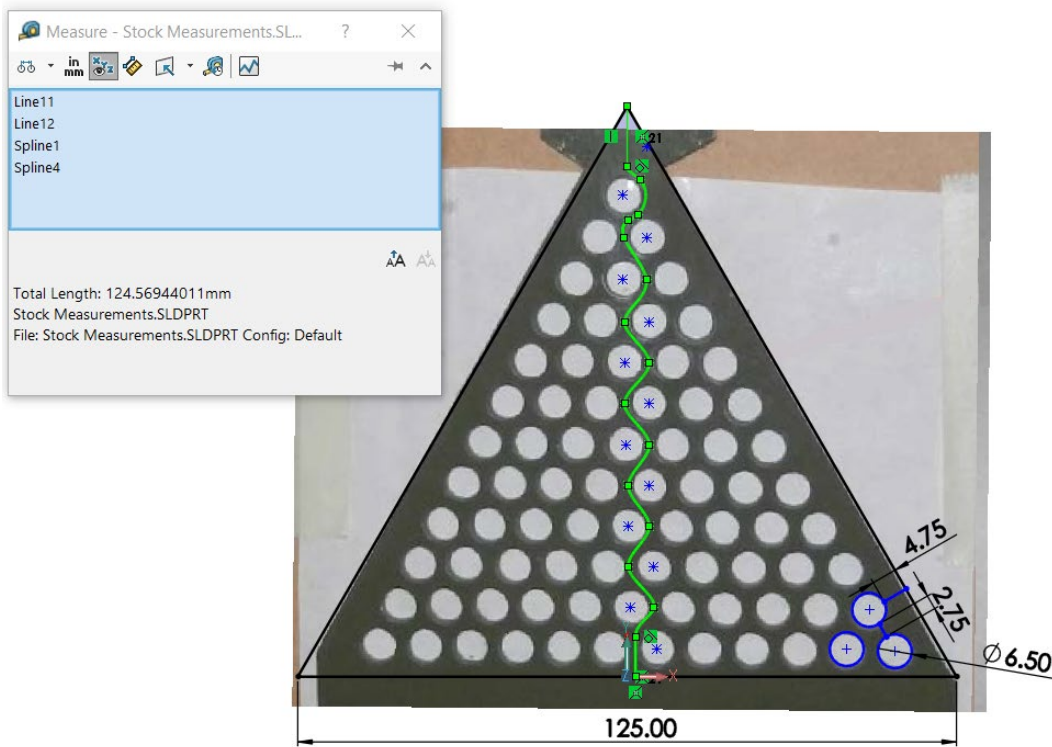


Fig. 1 Weckert perforated triangle reverse engineering

Preliminary experiments found that 2-mm-thick PRIMASHEET could be successfully detonated by inserting an RP-3 exploding bridge wire (EBW) detonator into a 2.5-g sphere of Detasheet pentaerythritol tetranitrate (PETN)-based explosive and placing it on a strip of PRIMASHEET at least 4 mm wide. PRIMASHEET with 2-mm thickness was desired to minimize the overall explosive mass. Although thinner than the PRIMASHEET Weckert used, it was believed that increasing width between perforations could provide the critical mass required to

fully detonate the PRIMASHEET. The perforated triangle design was modified to have 4-mm gaps between 8-mm holes (see Fig. 2).

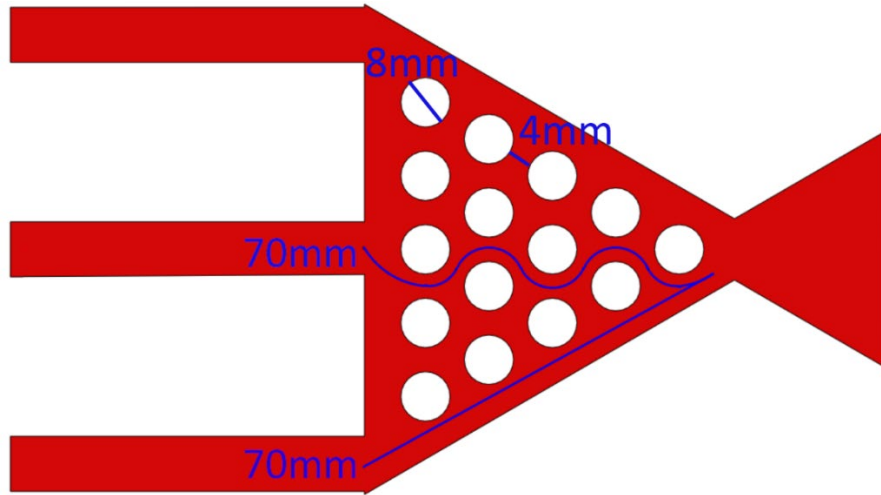


Fig. 2 DEVCOM ARL perforated triangle design

The leads going to explosive masses were parallel to each other and spaced 35 mm between centerlines. Explosive path lengths of 70 mm were chosen to stay within the maximum explosive weight limits of the experiment facility. The straight triangle edges and splines reaching the leads were set to 70 mm. The distance between the triangle sides and neighboring circle edges was 7 mm. A triangle was added to the detonation point with a 7-mm neck to ensure transfer of detonation energy to the LWG. The perforated triangle LWG had a volume of 4016 mm³.

Rather than placing a pattern on an explosive sheet and cutting the design with a knife, a punch was modeled in SolidWorks³ and additively manufactured on a Formlabs Form 3L with Clear Resin (see Fig. 3). Individual holes were punched with a hole punch also manufactured on the Form 3L. The hole punch was inserted through prepositioned holes in the larger punch. Slits in the rear of the main punch allowed explosive to be ejected by applying pressure from the rear. This was accomplished by using a dowel (or other long thin tool preferably with a blunt end). Compatibility tests were performed to ensure that the Clear Resin would not have a negative reaction with PRIMASHEET 2000.

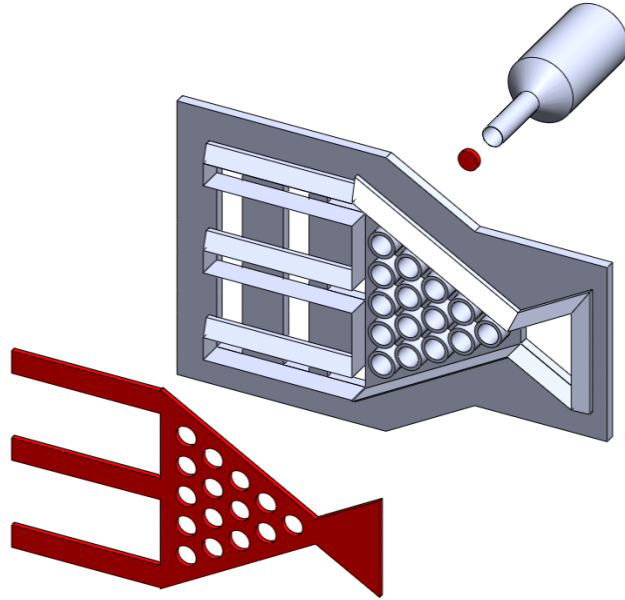


Fig. 3 Additively manufactured perforated triangle punch

It was later found that a 4-mm-wide, 2-mm-thick area of PRIMASHEET was not sufficient to reliably detonate—incomplete detonations were experienced several times. Additionally, producing the many punched holes was time consuming and the explosive was difficult to eject from the punch. To minimize the amount of explosive used and simplify production, different configurations of LWGs were investigated. Using serpentine paths was an option but the final layout did not produce a rigid design with the ability to be adjusted or moved and was not expected to be any easier to produce. A design that would use equidistant explosive path lengths cut in the form of a truss was settled on (see Fig. 4).

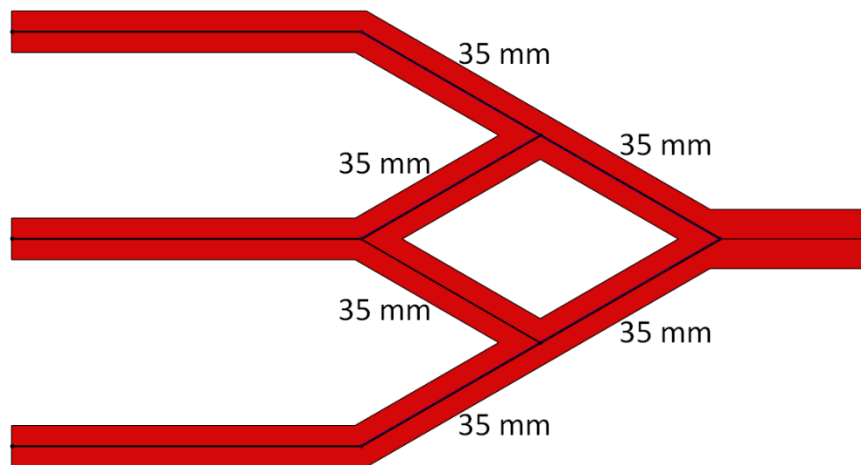


Fig. 4 DEVCOM ARL truss design

The truss shape would add rigidity to the form, which could be moved without stretching or reorienting the configuration. Explosive path widths were increased from 4 to 7 mm wide to guarantee full detonation. Individual truss lengths were set to 35 mm each with symmetric, gradual angles of separation. The angles of separation equaled $\pm 30^\circ$ from the horizon. A 10-mm-wide rectangle was added to the point of detonation to ensure transfer of detonation energy to the LWG. The truss LWG had a volume of 2811 mm³, which was approximately two-thirds of volume of the perforated triangle design.

A punch for the equidistant truss LWG was also additively manufactured on a Formlabs Form 3L (see Fig. 5). Since features were large a separate punch was not required to remove smaller features such as the holes in the previous punch. Slits in the rear of the punch allowed the explosive to be ejected by applying pressure from the rear. The explosive was also more easily ejected than with the perforated triangle design and overall, much quicker to produce.

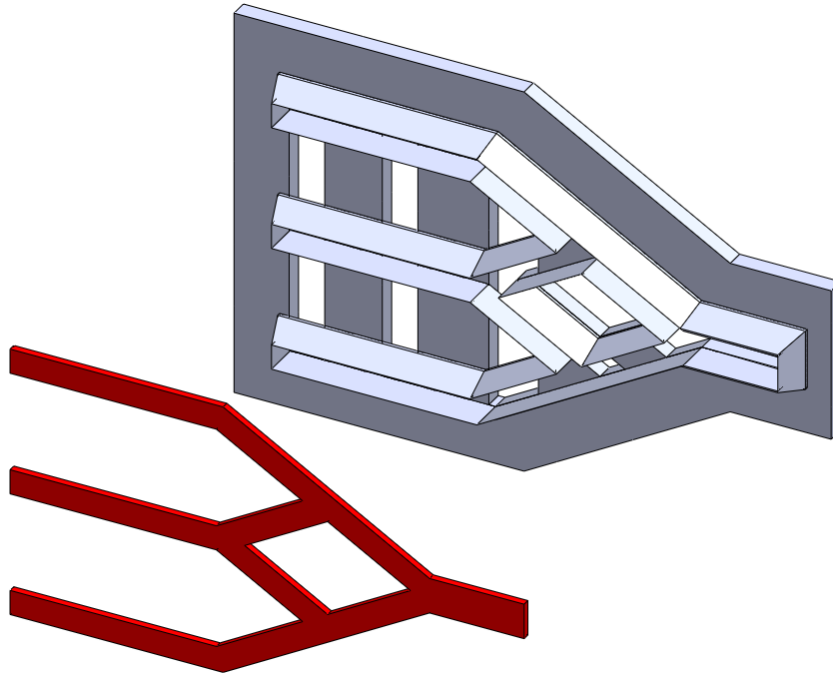


Fig. 5 Equidistant truss LWG punch

3. Experiments

Each experiment was executed at the same small-scale ballistic range at Aberdeen Proving Ground, Maryland. Each LWG was cut from the same 2-mm-thick roll of PRIMASHEET 2000 and placed on a 1-inch-thick plate of 6061 aluminum to serve as a witness panel. Overhead high-speed video with a frame rate of 500k fps was

implemented on the final experiment to track the detonation-wave propagation and confirm simultaneity to each lead.

The first experiment used a 2.5-g sphere of Detasheet PETN-based explosive with an RP-3 EBW detonator placed at the center of the tip of the perforated triangle LWG (see Fig. 6). The detonator was pushed into the Detasheet at an approximately 75° angle with respect to the aluminum. The first experiment incorporated 3-mm-wide leads branching from the LWG (not pictured).

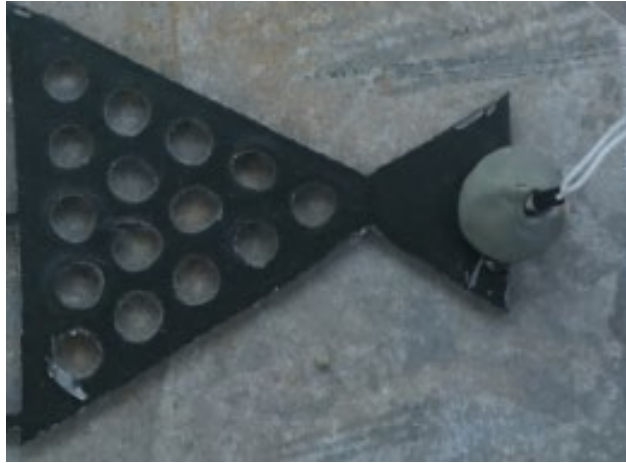


Fig. 6 Experiment 1 perforated triangle explosive with detonator and booster

The first perforated triangle did not fully detonate, leaving a partial cavity in the aluminum (see Fig. 7). The tip and sides of the perforated triangle closest to the detonator did detonate but the detonation did not follow the explosive between the holes in the perforation nor did it follow the vertical (base) triangle side.

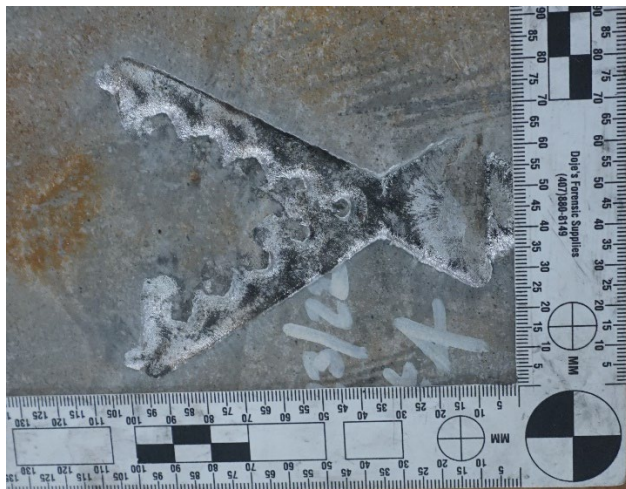


Fig. 7 Experiment 1 perforated triangle cavity

A 3-D scan of the aluminum plate surface showed additional detail and revealed that the cavity under the booster was approximately 4 mm deep (see Fig. 8). The cavity under the LWG that detonated was between 1.75 and 2.25 mm deep.

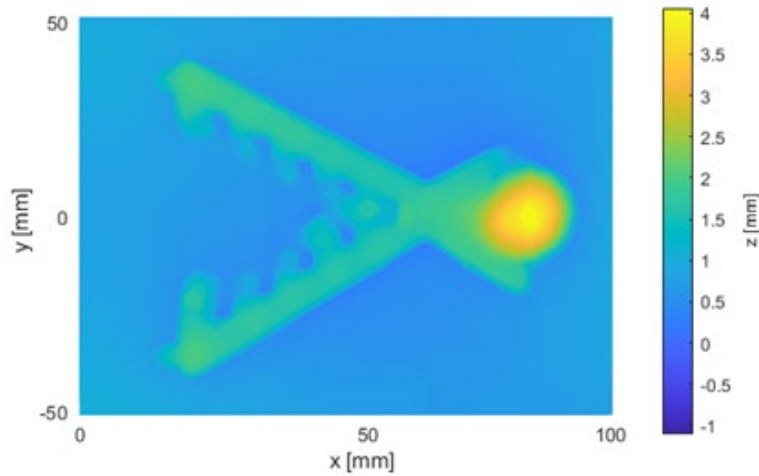


Fig. 8 Experiment 1 plate scan

The evidence from the scan suggested that once the RP-3 detonated the detonation front traveled radially from the point of detonation, detonating the Detasheet and propagating to the PRIMASHEET and down the sides of the LWG. The detonation did not successfully propagate around more than one hole in the perforated structure in the middle of the LWG. The hypothesized detonation path from the 3-D scan is annotated by arrows (see Fig. 9). The detonation terminated prematurely at the base of the LWG. The 3-mm leads coming off the LWG also did not detonate and showed very slight (a few millimeters) of detonation before the reaction stopped.

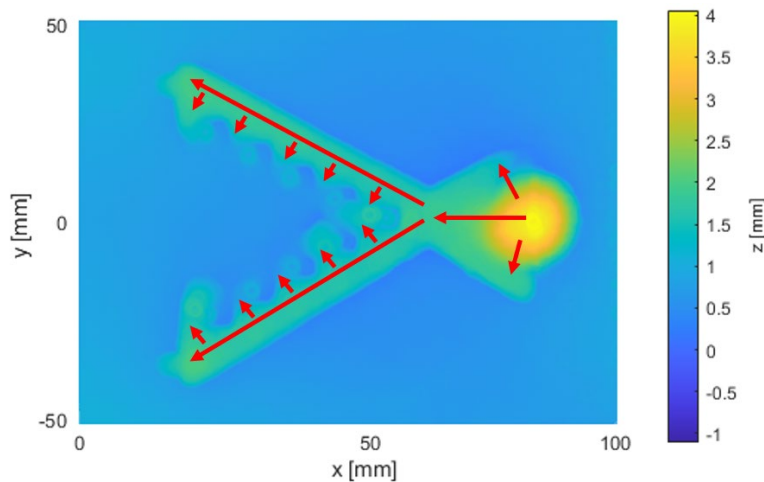


Fig. 9 Experiment 1 plate scan with hypothesized detonation path

The second experiment used a 2.5-g sphere of Detasheet explosive with an RP-3 detonator placed at the upper corner of the tip of the perforated triangle LWG (see Fig. 10). In this design the detonator was offset to examine the effects on the perforated area of the LWG. The leads from the LWG were also widened to 9 mm to ensure they would detonate if reached by the detonation front coming from the LWG. The detonator was pushed into the Detasheet at an approximately 75° angle with respect to the aluminum.

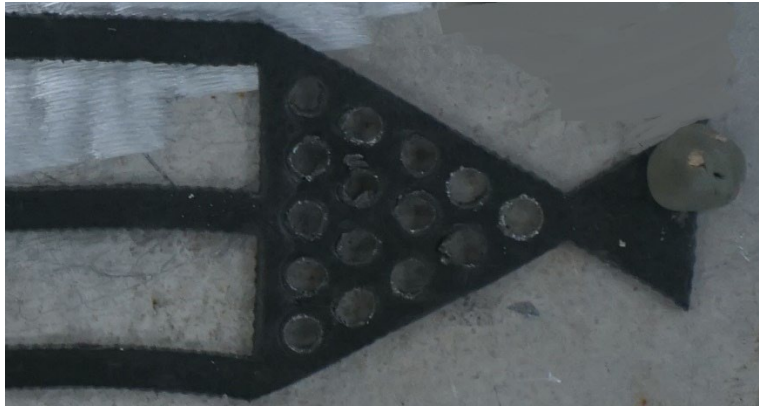


Fig. 10 Experiment 2 perforated triangle explosive with booster

The second perforated triangle fully detonated, leaving a full cavity in the aluminum (see Fig. 11).



Fig. 11 Experiment 2 perforated triangle cavity

A 3-D scan of the aluminum plate surface showed that the cavity under the booster was approximately 3.5 mm deep (see Fig. 12). The cavity under the LWG that detonated was between 1.5 and 2.5 mm deep. Deep yellow circles present in the

scan could have been caused by shadows or the orientation of the scanner while scanning the plate in a circular pattern.

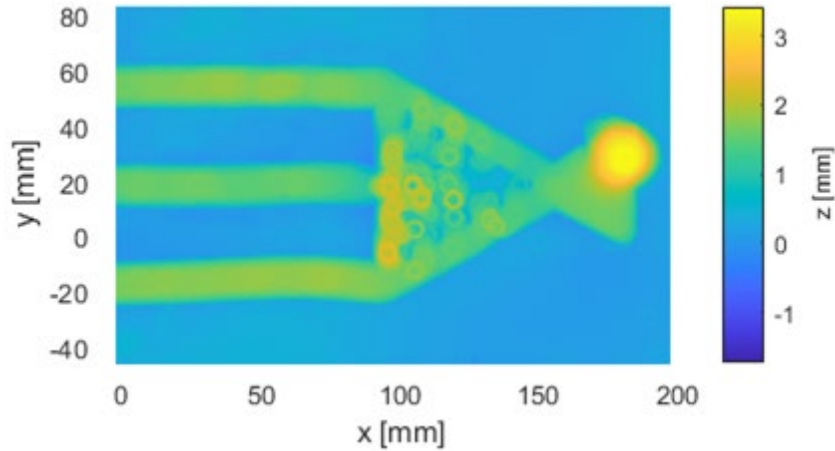


Fig. 12 Experiment 2 plate scan

The evidence from the scan suggested that once the RP-3 detonated, the detonation front traveled radially from the point of detonation, detonating the Detasheet and propagating through the PRIMASHEET. The lower side of the LWG was in a direct path to the point of detonation (no turns); therefore, the detonation front detonated the lower side first. The detonation front had to turn to detonate the upper side of the triangle slightly slowing it. Once again, the detonation front had difficulty propagating past the holes in the middle of the LWG. When the detonation front contacted the lead lines the resulting detonation (a two-times larger explosive width than the previous design) may have amplified the explosion and reflected energy back to the LWG. This may explain how the triangle side farthest from the point of detonation saw the deepest cavity in the aluminum. Once the detonation fronts from the top and bottom sides met along the third side, the energy detonated the middle lead and the remainder of the LWG. The hypothesized detonation path from the 3-D scan is annotated by arrows (see Fig. 13).

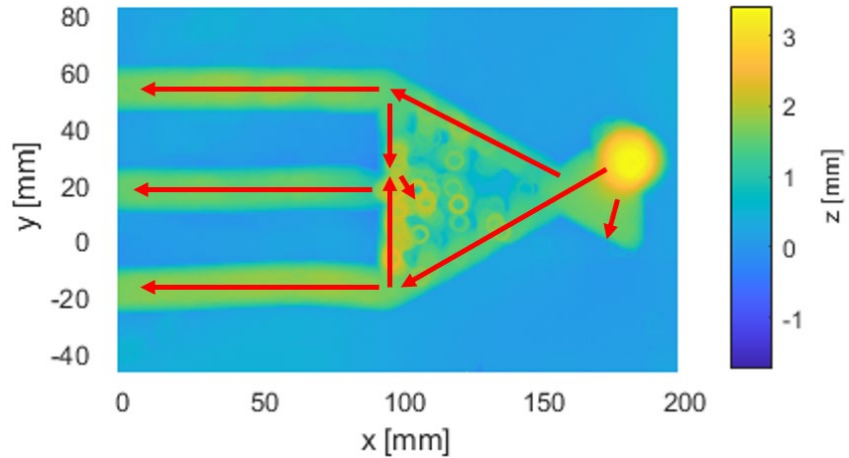


Fig. 13 Experiment 2 plate scan with hypothesized detonation path

The third experiment used a 2.5-g sphere of Detasheet explosive with an RP-3 detonator placed at the center of the tip of the equidistant truss LWG (see Fig. 14). The detonator was pushed into the Detasheet at an approximately 75° angle with respect to the aluminum. The width of the leads was 7 mm.

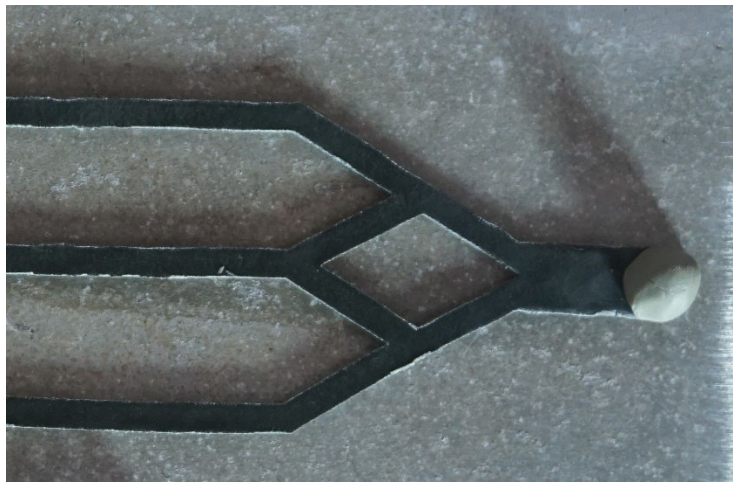


Fig. 14 Experiment 3 equidistant truss explosive with booster

Once initiated, the detonation front traveled along separate paths from the point of detonation to the leads at the same velocity as can be seen on the frames taken by the overhead high-speed camera (see Fig. 15). The detonation front almost makes a completely straight and vertical front as it simultaneously travels along the horizontal equally spaced paths.

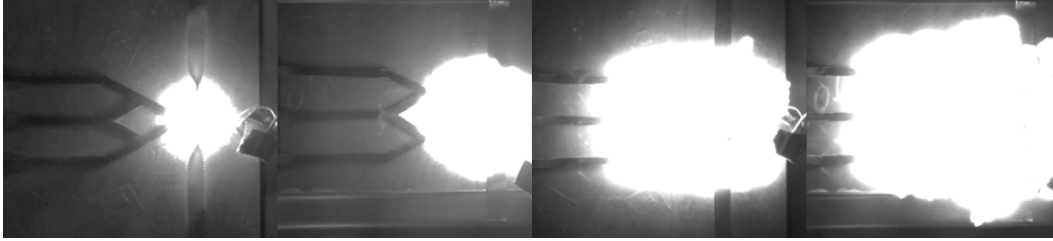


Fig. 15 Experiment 3 equidistant truss detonation front

The equidistance truss LWG fully detonated, leaving a full cavity in the aluminum (see Fig. 16).



Fig. 16 Experiment 3 equidistant truss cavity

A scan of the aluminum shows that the area under the booster saw a cavity of approximately 4.25 mm deep (see Fig. 17). The area covered by the LWG that detonated saw a cavity between 1.75 and 2.5 mm deep. The tip of the LWG that touches the middle lead appears to be slightly deeper caused by the convergence of the two truss segments. The equidistant truss LWG in experiment 3 and subsequent experiments had reliable detonation when detonated on rigid materials.

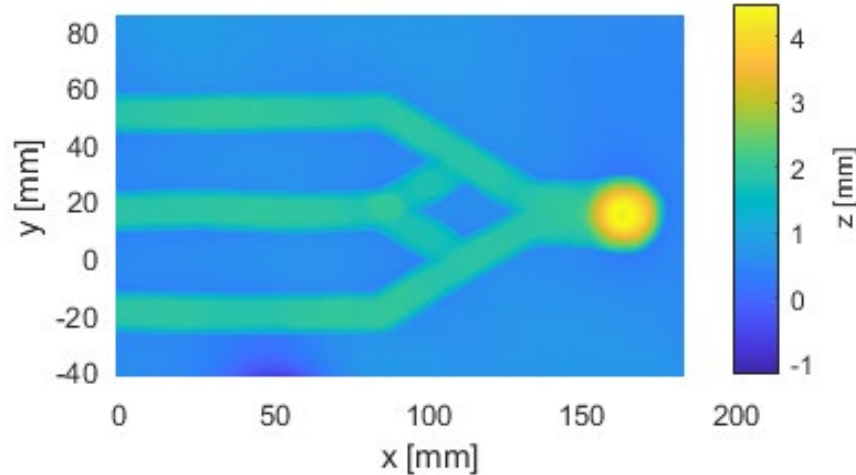


Fig. 17 Experiment 3 plate ScanBay

4. Conclusion

Repeatable simultaneous detonation of explosive masses can be executed with equidistant truss LWGs made of 2-mm-thick PRIMASHEET 2000. PRIMASHEET 2000 can be detonated with an RP-3 detonator if boosted with Detasheet or PETN-based explosive. Several LWG designs exist to create a straight-line detonation front. However, the type of explosive used can affect the reliability of each design. It was found that fully detonating a perforated triangle LWG made of PRIMASHEET 2000 with 4-mm gaps between perforations has a marginal success rate. The detonation front has difficulty both propagating around corners and traversing gaps 4 mm wide. Equidistant truss explosive path LWGs made with symmetric, gradual angles of separation and adequate width paths allow a detonation front to fully propagate. Overhead high-speed camera timing and witness panel scans confirmed that equidistant truss explosive path LWGs fully detonate. The equidistant truss explosive path LWG had a volume approximately two-thirds that of the perforated triangle design.

5. References

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List of Symbols, Abbreviations, and Acronyms

3-D	three-dimensional
ARL	Army Research Laboratory
DEVCOM	US Army Combat Capabilities Development Command
EBW	exploding bridge wire
LWG	line wave generator
PETN	pentaerythritol tetranitrate

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