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by Jacqueline Finch, Austen Deppe, Christopher Cummins, Steven Segletes, Jeffrey Lloyd, and Aaron Freidenberg

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**14. ABSTRACT**

The objective of this study was to use finite element simulations to design new underbody armor truss structures for buried blast mitigation. A selected, small-scale structure was fabricated using additively manufactured Ti-6Al-4V and subjected to an equivalently small-scale buried blast test. Boundary conditions generated by the Moment Impulse Numerical Evaluation (MINE) code suite were applied within LS-DYNA and used to analyze the structural response of the candidate truss structure subjected to buried blast loading. Simulation results were compared to data from the experimentally fabricated and tested structure, giving close agreement between measured and predicted behavior. Overall, the chosen structure was shown to reduce the peak deflection by 55% when compared with the performance of a flat, monolithic Ti-6Al-4V plate of equivalent areal density.

**15. SUBJECT TERMS**

buried blast, modeling and simulation, LS-DYNA, scaled experiments, Moment Impulse Numerical Evaluation, MINE

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## 1. Introduction

Today's combat vehicle platforms commonly use flat, monolithic aluminum or steel underbody armor plates. One commonly used material, rolled homogeneous armor, consists of a solid, rolled steel plate that is considered marginally effective at mitigating the effects of a buried improvised explosive device. Additional weight from add-on armor improves vehicle protection but has a negative impact on vehicle performance.[1] While monolithic plate armor performs moderately well under blast scenarios, sandwich designs where a structure with free space is clamped between two solid plates generally outperform equivalent areal density monolithic plates for the majority of blast scenarios.[2,3] In this work, the response of a novel Ti-6Al-4V structure that consists of a truss-like core, sandwiched between two plates, was investigated under loading from a buried blast. Ti-6Al-4V was chosen due to its high strength-to-weight ratio and its common use in additive manufacturing. The truss structure was chosen based on research that demonstrated the effectiveness of pyramidal structures in blast mitigation.[3–5]

Since the truss is thicker than a monolithic plate of the same material and areal density, the total dynamic space claim should be taken as the sum of the truss depth and the peak dynamic deflection resulting from the blast. A physical gap between the armor and the floor that supports the occupants of the vehicle must be present to accommodate this deflection (Fig. 1). Success for the design will be determined by its ability to minimize the dynamic space claim.

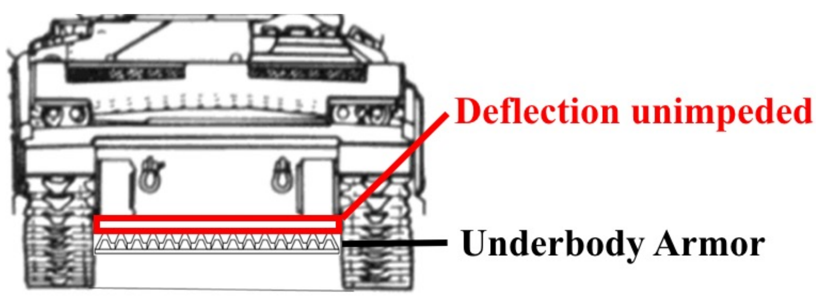


**Fig. 1 Illustration of a military vehicle with underbody armor. The underbody armor is designed to deflect into the region enclosed in red to protect the occupants inside the vehicle.**

Analysis via a finite-element (FE) simulation was performed, which included a simplified treatment of the boundary conditions and material behavior. The material model was an elastic, perfectly plastic model that possessed a 1-GPa yield strength. Average properties of Ti-6Al-4V were used including density, Young's Modulus, and Poisson's ratio. The Momentum-Impulse Numerical Evaluation (MINE) code suite[6] and the Offline Reconstruction of the Blast on Target (ORBIT) 2-D-to-3-D interface[7] were used to generate boundary conditions, which were applied within LS-DYNA[8] to conduct FE simulations of candidate designs in response to a buried charge. One truss design was fabricated via powder bed fusion in Ti-6Al-4V at subscale, bolted along two sides to a ballast mast, and subjected to loading from a buried explosive charge that was scaled accordingly. The truss design was shown to reduce peak deflection by 55% when compared with an equivalent weight Ti-6Al-4V monolithic plate, and close agreement was observed between the FE and experimental results. This work demonstrated that FE analysis, additive manufacturing, and direct experimentation can be used to design and assess the performance of small-scale structures intended to mitigate defeat during a buried blast event.

## 2. Truss Design Using FE Simulations

First, the pressure–time history as a function of the angle and radius from buried explosive is determined using the MINE program.[6] The model is configured using 2-D spherical coordinates (polar angle and radius) where all radial equations are solved analytically for the radial incompressible flow and the polar-angle equations are solved using discretization. ORBIT takes the output from MINE and then applies it to a 3-D geometry by creating a load curve for each element exposed to the blast during the simulation in LS-DYNA.[7,8]

MINE requires 40 inputs to solve for pressure–time history as a function of the polar angle and radius for a given buried charge. The explosive is assumed to detonate instantaneously. The resulting blast wave propagates outward in a hemispherical manner imparting momentum to the soil, which ultimately impacts the target. The deeper a charge is buried the more significant the effects are created by the impulse.[6] It is estimated that the Detasheet C explosive used in the experimental portion of this work releases 5% less mechanical energy per unit mass than TNT. Additionally, the detonator is estimated to release 1% of the total mechanical energy.

MINE stores the blast field for the program ORBIT to subsequently generate the pressure–time histories to each target geometry element defined by *NODE, *ELEMENT, and *SEGMENT_SET in the LS-DYNA input file. ORBIT outputs a pressure–time history for each segment on the blast face of the model in the input file using keywords *DEFINE_CURVE and *LOAD_SEGMENT.[7] The load curve and boundary conditions are then copied into the input file and the FE analysis run on a Department of Defense high-performance computer.

With MINE providing loading conditions, the performance of various iterations for equilateral truss designs was quantified using FE simulations, as shown in Fig. 2. Parameters that were varied include the overall truss depth, number of truss bays, number of total trusses (varied from 2 to 68), and thicknesses of the truss bars. Ultimately, truss Design 5 was chosen, which consists of nine trusses (each with 15 bays) of depth 11.6 mm, each connected to each other by small stringer beams, for a total areal density 2.83 g/cm$^2$.

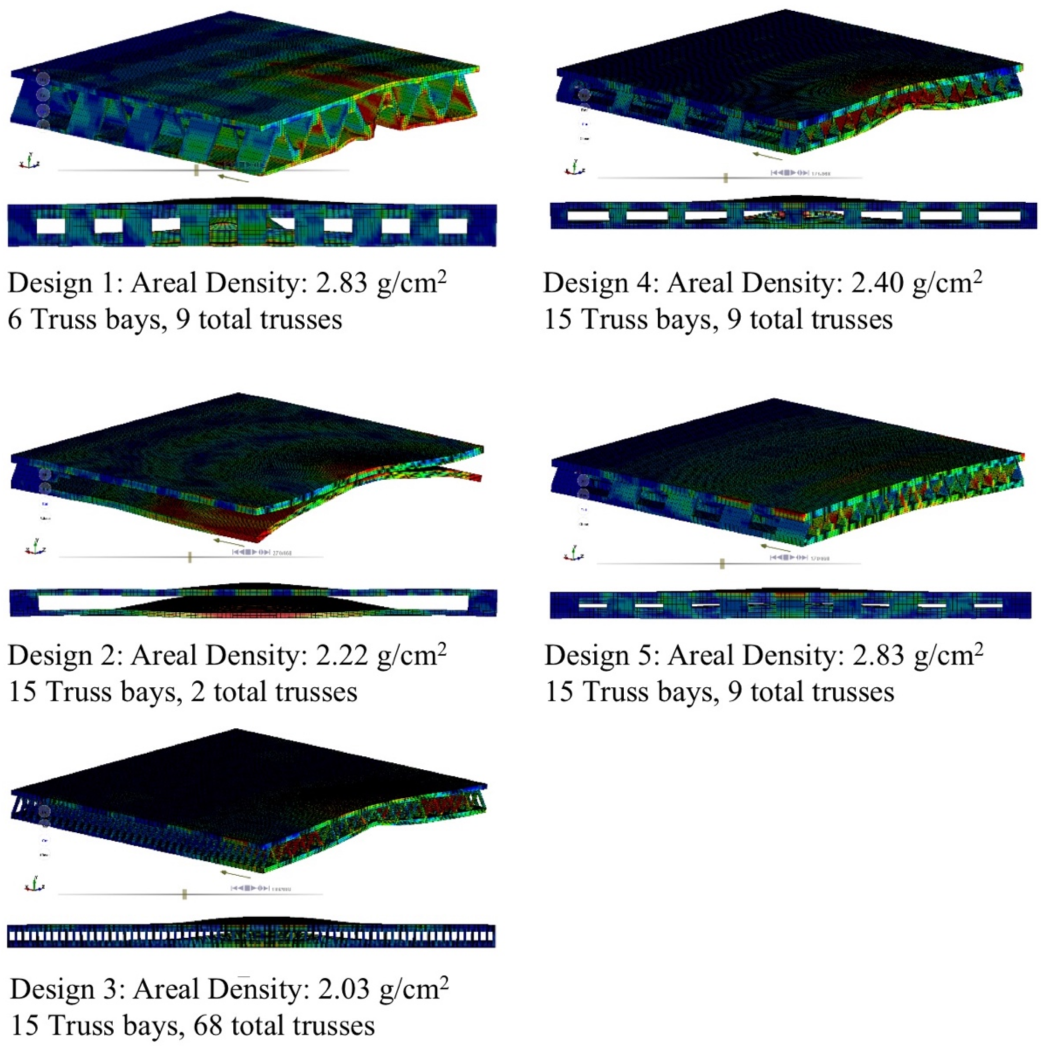


**Fig. 2 An isometric section cut and side view of the various equilateral trusses considered at peak deflection during FE simulations. The warmer colors indicate a greater stress concentration.**

## 3. Buried Blast Experiment and Results

The solid geometry of Design 5 was built in SolidWorks and then manufactured via powder bed fusion 3-D metal printing. The printed specimen is shown in Fig. 3.

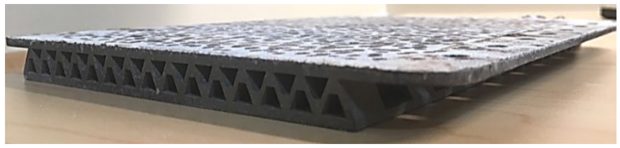

**Fig. 3** **Isometric view of the 3-D printed specimen in Ti-6Al-4V via powder bed fusion**

It was experimentally tested at the US Army Combat Capabilities Development Command Army Research Laboratory's small-scale buried blast facility located in Aberdeen, Maryland, which is shown in Fig. 4 and described in detail in Cummins et al. (2018).[9] The structure was mounted to the ballast mass by seven #4-40 socket head cap screws along the length of each side as shown in Fig. 4. The standoff, measured from the surface of the soil to the lowest point of the specimen, was 2.44 m.

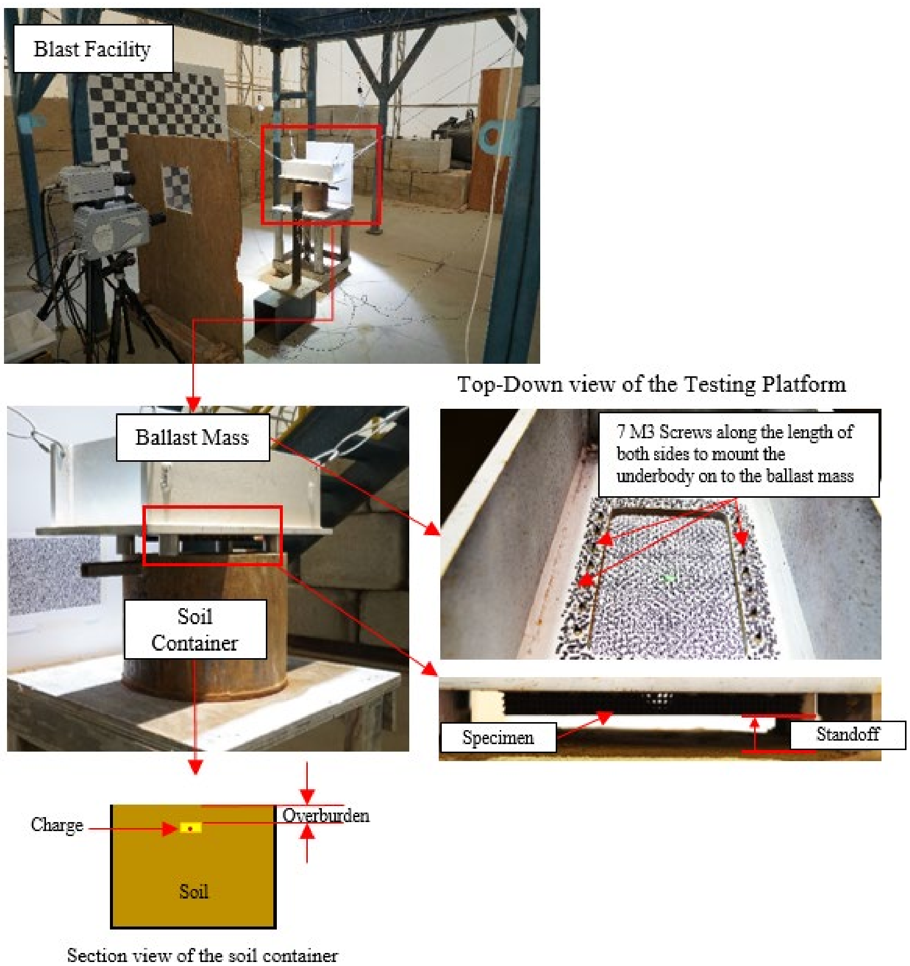


**Fig. 4** **Experimental setup inside the small-scale buried blast facility and associated terminology**

A gram-scale explosive charge was emplaced in an engineered soil bed that was compacted to a roadbed representative state. The charge configuration and emplacement conditions matched a previous study carried out at the same facility.[9] High-speed cameras operating at rates of over 200,000 frames per second recorded the top and side views of the specimen during the blast, enabling the method of digital image correlation (DIC) to capture dynamic displacement measurements. DIC uses two of the high-speed cameras to measure the deflection of the randomized dots painted on the top plate, producing a deflection versus time plot (Fig. 5).

**Fig. 5 Screen capture from one of the high-speed cameras recording the experiment**

In addition to the printed structure, four monolithic plates of varying areal density were subjected to identical blast environment parameters, creating a baseline data set for comparison.[9] The deflection of the truss design is compared to its mass equivalent Ti-6Al-4V plate as shown in Fig. 6. The ratio of the mass equivalent plate deflection to the truss deflection is termed the mass efficiency ratio, and is a useful metric for armor performance. In this case, the truss outperforms its mass equivalent plate by a factor of 2.2. However, the space claim of the truss exceeds the mass equivalent plate, since the thickness of the truss is much greater than the flat plate.

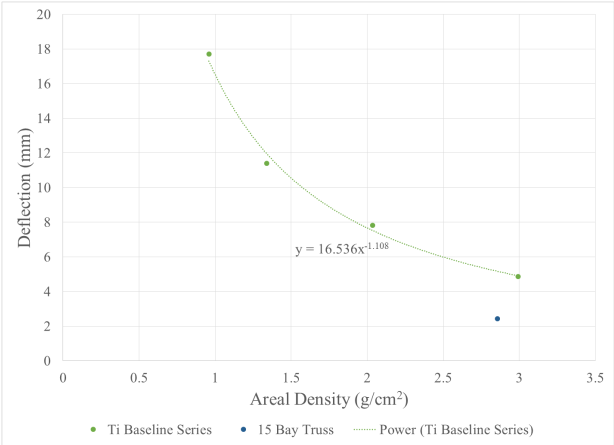


**Fig. 6 Deflection of the experimental specimen (Design 5) compared to a mass equivalent Ti-6Al-4V plate**

## 4. FE Model of Plates and Chosen Prototype

Simulations of the four monolithic plates as well as the sandwich truss structure were performed using LS-DYNA. All plates are Ti-6Al-4V, with the lightest having an areal density of 0.952 g/cm$^2$ and the heaviest 2.99 g/cm$^2$. The sandwich truss structure has a total areal density of 2.83 g/cm$^2$. All simulations use the same material properties and boundary conditions. Sensitivity studies were performed on the models to ensure a proper balance of computational cost and mesh discretization.

The plate models consist of 106,000 reduced-integration hexahedral elements, while the truss model consists of 630,000 elements. In the test setup, the plate is affixed to the ballast mast on two edges, using seven bolts per edge. To approximate these constraints without modeling the bolts explicitly, boundary conditions were placed through the depth of the plate at these seven locations (Fig. 7). All three degrees-of-freedom are constrained for these nodes.

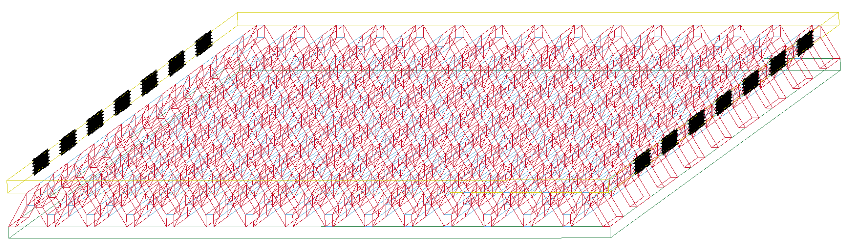

**Fig. 7 Wireframe view of the truss structure with clamped boundary conditions highlighted in black**

The deflection–time history of the LS-DYNA simulation of the truss is plotted against the experimental result in Fig. 8. While the time of peak deflection appears to be correctly predicted by the simulation (to the accuracy the DIC sampling rate permits), the magnitude of the peak deflection is overestimated by the simulation. Of the simulations of the four plates, two of them overpredicted the peak deflection, while two of them underpredicted it. The peak deflections for all five simulations are plotted against the experimental results, as a function of areal density, in Fig. 9, and overall the simulations appear to reproduce salient features of the experimental results.

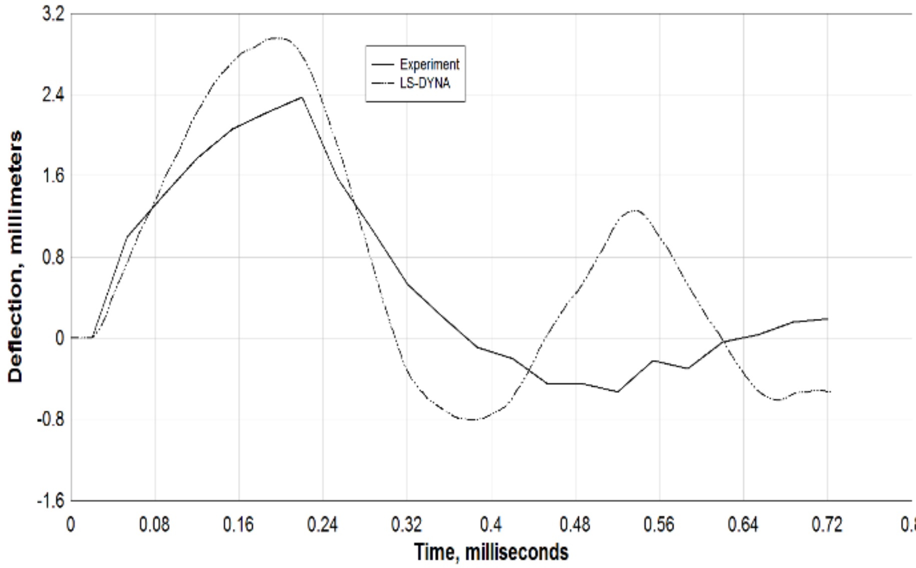


**Fig. 8 Deflection–time history of the specimen during the explosion compared with LS-DYNA simulations**

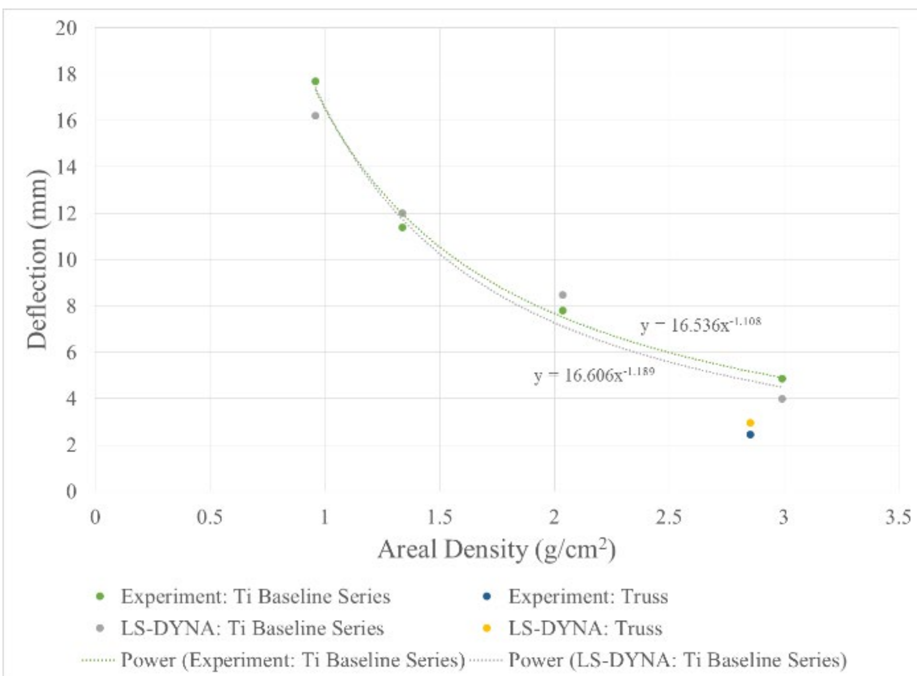


**Fig. 9 Peak deflection for the five simulations plotted against the experimental results, as a function of areal density**

## 5. Conclusion

The MINE/LS-DYNA interface to conduct a simulation of a new underbody armor truss structure in comparison to a scaled blast test on a Ti-6Al-4V additively manufactured specimen showed close agreement. The results indicate that FE/computer-aided design modeling can be combined with additive manufacturing and scaled blast testing to rapidly assess the performance of structures intended to mitigate defeat due to buried blast. Improved boundary conditions and material models that capture strain rate sensitivity and material failure may improve predictive capability. To conclude, the prototype proved to be an effective improvement over a traditionally configured monolithic Ti-6Al-4V plate armor system. It reduced the peak displacement by 55% compared with an equivalent areal density flat plate of Ti-6Al-4V plate. Due to the thickness of the design, its dynamic space claim did not exceed that of a flat plate. Therefore, if plate thickness is a critical design feature for end use, then a flat plate should be used instead of the structure. However, if weight is the most important design parameter and thickness is of secondary importance, the truss structure produced in this work outperforms the flat plate.

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## List of Symbols, Abbreviations, and Acronyms

| | |
|---|---|
| 2-D | two-dimensional |
| 3-D | three-dimensional |
| DIC | digital image correlation |
| FE | finite element |
| MINE | Momentum-Impulse Numerical Evaluation |
| ORBIT | Offline Reconstruction of the Blast on Target |
| TNT | 2,4,6-trinitrotoluene |

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