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A metamodel-based shape optimization approach for shallow-buried blast-loaded flexible underbody targets

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ABSTRACT

Landmine detonation continues to be a serious threat to Army military vehicles in theater. One strategy to mitigate its effects is to use engineering design techniques to reshape the underbody of the hull. Previous works have shown that reshaping the hull's underbody can change the vehicle's response to blast loading. In the presented work, a metamodel-based shape optimization methodology is proposed for optimizing shallow-buried blast-loaded underbody structures. The shallow-buried blast load is simulated using an empirical model. Additional studies are conducted on target positions with respect to the blast load and load positioning and the effects of optimization parameters on the optimal solution. It is shown that target vertical position affects impulse response comparison, and for center-buried loads, the v-shaped underbody target produces a lower impulse than that of other shaped targets. Optimal solutions obtained using an adaptive domain reduction strategy produce more accurate solutions than a single iteration strategy. Based on the proposed optimization method, a unique v-like underbody shape is presented as the optimal underbody solution.

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1. Introduction

Anti-vehicle landmines continue to be a serious threat to Army military operations in theater. In fact, in previous conflicts on international soil, loss due to landmine detonation was as much as 70%. A major injury and kill mechanism that results from mine detonation is large gross vehicle movement. This type of movement can cause injury to an occupant's lower leg, spine, and head if the occupant is not restrained [1]. Strategies developed to mitigate these effects include increasing vehicle standoff (the distance from the bottom of the vehicle to the ground), which reduces impulse and local loading; adding retrofit kits or a sacrificial mass to the underbody of hulls; incorporating v-shaped and monocoque hulls; and sandbagging the floor of trucks to prevent occupant exposure to lethal fragments and increase the vehicle's weight [2].

The v-shaped hull design is commonly used today to protect armored military vehicles from improvised explosive devices (IEDs). Current examples of vehicles that have v-shaped crew compartments are the International MaxxPro, Casspir APC, and Cougar H. The MaxxPro also has an additional underbody plate to protect the drive train [3]. Experimental and numerical research has shown that a v-shaped target can reduce applied impulse from a charge by deflecting high-pressure gas and soil ejecta into the ambient. In addition, a portion of the applied pressure has a horizontal component that does not contribute to the vertical impulse transferred to the vehicle. This improves better protection because less load is applied to the vehicle [4].

In addition to v-shape targets, other shaped targets have been investigated [5–8]. Of particular interest is a work by Fox et al. [8], in which experimental and computational studies were conducted on the effect of shallow-buried blast location on shape target response. The results showed that downwardly convex and concave targets produce lower impulse than a flat plate for a given load. Reasons given for impulse reduction were increased distance between the explosive and target and a geometric shaping effect. Quarter loads generally produced larger target impulse than center loads.

Additional works [4,9–12] consider experimental and/or numerical analysis of various shaped targets. Chung Kim Yuen et al. [4] presented experimental and numerical results for v-shaped steel plates with different included angles subjected to localized air blast. Standoff was defined as the distance between the tip of the v and the closest face of the explosive. It was shown that for a fixed standoff and load size, if the v included angle is increased, then impulse and mid-point deflection are decreased. In addition, for a

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fixed-plate v angle and load size, if standoff is decreased, then impulse and mid-point deflection are increased. Barker et al. [12] conducted buried blast experiments and numerical analysis, using ConWep, on steel, hollow box, v-shaped targets of 10°, 20°, and 30°, with a top floor plate using centered and off-centered blast loads. Throughout the experiments, each target had the same standoff, which was defined as the distance from the spine of the v to the surface of the soil. Off-center shots were located midway between the spine of the v and the outermost edge of the target. The results showed that as target angle increased, target impulse decreased. It was suggested that this result was due to a geometric effect. It was also shown that for a charge size of 800 g, off-center shots produced a higher impulse.

In the works previously cited, target response was primarily compared by keeping the standoff constant. Again, standoff is defined as the distance from the ground, or charge, to the lowest point on the target. It was reported that v targets produced a lower impulse because of a standoff effect (i.e., underbody structure is farther away from the blast) or a geometric effect (i.e., the underbody vents blast ejecta). One inquiry of interest in this work is the performance of shaped underbodies with alternative methods of comparison. Would a v-shaped object outperform a flat-shaped object if standoff is defined from the ground to the top of the v instead of the spine? Experimental results from Anderson et al. [13] begin to answer this question. Anderson et al. conducted experiments on v-shaped targets where the centers of gravity of the targets were held constant. From Anderson's data, impulse comparisons could also be made between structures with the same distance from the ground to the structure's crown. Anderson's work is further discussed in Section 3, as it is used to validate the presented numerical model.

As already shown, targets of various shapes have been considered. These shapes were most likely determined by ad hoc techniques. While this approach may be useful in a down-selection process between a limited number of designs, it may not result in a superior structural shape for an objective of interest. Structural optimization techniques provide a mathematically based systemic approach to satisfy objectives of interest. In 2008, Gurumurthy [3] conducted 2D and 3D impulse analysis on air-blast-wave-loaded vehicle underbody shapes. Optimization was also conducted on a 2D elliptical underbody shape to reduce maximum impulse. Recently, a series of works that address shape optimization of rectangular panels for air blast load has been presented. Argod et al. [14,15] developed a nodal coordinate shape optimization methodology for solid panels that is defined by so-called velocity fields. The basis shape functions for the panels were the product of sine functions. The optimization technique of choice was the Differential Evolutionary algorithm, which is non-gradient-based. It was shown that a panel with a double bulge is ideal for minimizing local out-of-plane displacement and impulse. Jain et al. [16] presented an extension to Argod's work by considering additional nodal coordinate shape optimization methodologies and aluminum honeycomb sandwich panels under air blast load. Nayak et al. [17,18] focused primarily on the shape optimization of honeycomb sandwich structures and found that shape-optimized solid panels are better at reducing backface deformation, but shape-optimized honeycomb panels are more effective at reducing transmitted acceleration.

Although few examples of topology [19–21] or topography [22] optimization of blast-resistant structures exist in the literature, works of note were presented by Goetz et al. [19,20] of the University of Notre Dame. Goetz et al. used the Hybrid Cellar Automata (HCA) method to design a, CONWEP loaded, single material substructure to reduce the total energy that is transferred from the blast to the vehicle's interior. Optimization was conducted to maximize the strain energy absorbed by a coupled aluminum substructure. The optimized plate was composed of material where the blast load was highest but was removed along the boundary sides to increase energy absorption. In a second work, Goetz et al. [20] further showed that by modifying the HCA algorithm, convergence could be reached in both one and two material optimization (multi-material approach). By extension, Hofstetter et al. [21] used the Livermore Software Technology Corporation (LSTC) implementation of HCA to develop optimized one-material substructures for different objective functions.

The previously reviewed optimization based approaches to structural design implement air blast loading only. Shape and topology optimization of structures for buried blast loading have not been considered. One possible reason is that, until now, buried blast simulations have required ALE-based fluid structure interaction simulations, which require greater computational resources than ConWep for air blast loading. In this work, buried blast simulations will be conducted using a recently developed empirical model. This approach greatly reduces runtime and computational resources as it only requires Lagrangian elements. Validation of the developed empirical model will be conducted using published experimental data. Also, a geometric boundary shape optimization technique will be implemented in this work. The geometry that will be optimized is a curve. Once developed, the curve is extruded to form a surface that represents the underbody of target. The surface is meshed and connected to a top structure. The model is completed by applying boundary and loading conditions to the structure. This technique can be extended to surfaces that can be extruded into solids. Extruded shapes are ideal for vehicle surrogate structures due to enhanced manufacturability with respect to highly complex shapes, as suggested by Argod [14] and Jain [16].

The objective of this work is to present a metamodel-based shape optimization methodology for the design of underbody structures for targets subjected to shallow-buried blast loads. The objective of optimization is to minimize crew compartment impulse calculated using the finite element method. In the sections that follow, the optimization problem, target geometry and blast parameters are defined, and the presented empirical model is validated using experimental results. The proposed shape optimization methodology is also defined. Numerical results and discussion are presented for targets with various standoffs and for underbody shape optimization.

2. Model definition

In this section, the optimization problem, target geometry, and model components are defined and model validation is presented. The basic optimization problem that is solved is to determine the underbody shape that minimizes crew compartment vertical impulse. Crew compartment impulse is a local component of the target's global impulse.

The optimization problem is to minimize a variable-dependent cost function that is subject to constraints. In this work, the variables of the cost function are the coefficients of the Fourier series expansion that defines the underbody shape. This is further discussed in Section 4.1. The standard form of the optimization is as follows:

Find $\mathbf{a}$, $\mathbf{b}$.
minimize $F(\mathbf{a}, \mathbf{b})$
subject to

$$\begin{aligned} &S(\boldsymbol{x}, \mathbf{a}, \mathbf{b}) = 0 \\ &\mathbf{a}^L < \mathbf{a} < \mathbf{a}^U \\ &\mathbf{b}^L < \mathbf{b} < \mathbf{b}^U, \end{aligned} \tag{1}$$

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