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US Army Research Laboratory

The Effect of Material and Side Walls on Hull Deflection during a Blast Event

by Danielle Abell
SURVICE Engineering Company
4695 Millennium Dr
Belcamp, MD 21017

under contract W911QX-16-D-0014

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14. ABSTRACT

Steel and aluminum have been used for different parts of military vehicles for many years. One component of particular interest to be made of aluminum rather than steel is the vehicle hull because the same level of protection could be achieved at a lighter weight. A rectangular surrogate vehicle finite element model was built to study the hull deflection when a steel or aluminum hull was present at various thicknesses and exposed to a blast loading event. The thickness of the side walls in the model was also studied to determine if it had an effect on the hull deflection. Based on the results and trends of the material and side wall studies conducted, a more robust surrogate finite element model could be built that more closely represented the weight and size of a standard military vehicle.

15. SUBJECT TERMS

blast, finite element analysis, FEA, LS-Dyna, ALE, steel, aluminum, deflection

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1. Introduction

Steel and aluminum are the main materials used in the design of military vehicles. Since World War II, rolled homogeneous armor (RHA) steel has been the primary material used to protect main armor components of heavy combat and recovery vehicles.[1] Improvements were made throughout the years to increase its hardness while maintaining its weldability and without increasing its brittle tendencies.[1] However, recent research has emphasized the use of aluminum for certain components to decrease weight, while still maintaining the same level of protection.

RHA steel has provided proven protection in military vehicles for years. It is known to be very durable and tough and is resistant to high velocity projectiles.[2] RHA steel has high tensile and yield strengths, which makes it an ideal metal for many applications. One of its greatest qualities is its formability. Steel can undergo plastic deformation and be cold worked into many different shapes, which can improve its properties.

Aluminum is a lighter metal due to its low density, which is about one-third that of steel. Despite its light weight, aluminum still has a high yield strength. Aluminum also does not become brittle like steel at low temperatures. Aluminum can be easily machined or formed using multiple techniques, and thus is useful for many applications. Aluminum is a high conductor of heat and electricity and has a great resistance to corrosion. When aluminum reacts with oxygen, a thin layer of oxide is created and provides corrosion protection.[3]

One of the main components currently of interest in this debate is the vehicle hull. The hull is the main component for protection of a vehicle and its occupants against an underbody blast threat. To provide the protection needed, the hull should be lightweight, durable, and tough. It should also be able to be formed into various shapes. Many factors, including available design space, must be taken into consideration to determine which metal is the best option for protection.

The use of modeling and simulation (M&S) will provide an understanding on what materials and thicknesses have the ability to be successful in protecting vehicles and its occupants. A surrogate vehicle in the shape of a rectangular box was built as a starting point to develop trends and a better understanding of how steel and aluminum relate in response to a blast event. This simple model allowed fast and inexpensive run times and quick turnarounds. It also provided the ability to compare multiple side wall thicknesses to determine if side wall thickness has an effect on the hull response. These results will lead to the capability to develop the most accurate but simple surrogate military vehicle and further M&S research into hull material and designs.

2. Purpose

The primary purpose of this research is to determine whether steel or aluminum is the better option in vehicle hull designs. As the analysis began, a second objective developed to determine if the thickness of side walls in the model affected the response of the vehicle hull when subjected to an underbody blast.

A baseline surrogate vehicle finite element model (FEM) of a simple rectangular structure was built to compare multiple aluminum and steel material models as well as various hull thicknesses. It was important to develop trends and an understanding of how the metals related to each other in terms of weight and blast equivalence. The hull must be strong enough to deflect energy from the charge, but light enough to maintain or increase mobility of the vehicle. Deflection of the hull was considered the primary metric for the comparison.

The thickness of the hull was also an important factor to be considered. Sway space between the hull and the floor is a critical factor in the design of a vehicle. This space is important to allow the hull to deflect without impacting the walk-on floor. If this impact were to occur, injury to the occupants' feet and legs may occur. The floor, in turn, cannot be made thicker or raised higher because the space between the floor and the ceiling is critical to accommodate the occupants and their equipment. A breach of the hull is also detrimental and must be avoided.

The side walls in the surrogate model were also studied to determine if changing the side wall thickness had an effect on the FEM. The initial baseline shell model was modified to solid elements with the same dimensions, and 2 thicknesses of the side walls were simulated for each surrogate model to determine if thickness had an effect on the hull response to a blast event. Hull deflection and nodal displacements were tracked for comparisons.

A more accurate and robust representation of a military vehicle can be built based on the findings regarding the material models, hull thicknesses, and side wall effect. This model can then be used to assess and determine the best material and shape of the hull to provide the optimal protection to the vehicle and its occupants.

3. Finite Element Models

The FEMs were generated using the HyperMesh 14.0 (Altair Engineering, Troy, MI) and LS-PrePost v3.2-x64 (Livermore Software Technology Company [LSTC], Livermore, CA).

3.1 Baseline Surrogate Model

The FEM was a simple rectangular structure used as a surrogate vehicle (Fig. 1). The structure was 6.5 m long, 2.5 m wide, and 2 m high. The top and sides of the structure were RHA steel. The thickness and material of the bottom varied, as part of the analysis. The model was made of shell elements.

Fig. 1 Surrogate model with shell elements

This model was simulated with RHA, aluminum 6061, and aluminum 5083 as the hull material. All material models used were Johnson-Cook (JC) due to its accuracy. Multiple hull thicknesses were run for each of the 3 materials. More thicknesses were run with aluminum 5083 to determine an accurate blast equivalence to RHA. The matrix of simulations including hull, which was the bottom surface, and full vehicle weight, can be found in Tables 1–3 for all 3 materials.

Table 1 Parameters of the simulations completed with RHA shell surrogate model

Hull material	Hull thickness (inch)	Vehicle weight (kg)	Hull weight (kg)
RHA	0.5	22456.299	1620.044
RHA	1	24076.342	3240.088
RHA	1.5	25696.386	4860.131
RHA	2	27316.43	6480.175
RHA	2.5	28936.474	8100.219

Table 2 Parameters of the simulations completed with aluminum 5083 shell surrogate model

Hull material	Hull thickness (inch)	Vehicle weight (kg)	Hull weight (kg)
Al 5083	0.5	21385.625	549.37
Al 5083	1	21934.995	1098.741
Al 5083	1.5	22484.366	1648.111
Al 5083	2	23033.736	2197.481
Al 5083	2.5	23583.106	2746.851
Al 5083	3	24132.476	3296.221
Al 5083	3.5	24681.847	3845.592
Al 5083	4	25231.217	4394.962
Al 5083	4.5	25780.587	4944.332

Table 3 Parameters of the simulations completed with aluminum 6061 shell surrogate model

Hull material	Hull thickness (inch)	Vehicle weight (kg)	Hull weight (kg)
Al 6061	1.5	22510.369	1674.114
Al 6061	2	23068.407	2232.152
Al 6061	3	24184.483	3348.228

The baseline surrogate shell model was also used to determine if the side wall thickness had an effect on hull deflection. The hull was kept constant at 1-inch-thick RHA, and the original thickness of the side walls was 2 inches. The side wall thickness was increased to 4 inches for comparisons. A 4-inch side wall will be overly stiff and could prevent bending in the walls and the floor. While this is an extreme case, it will be useful to understand how the hull is affected during a blast event. Table 4 shows the model properties used.

Table 4 Parameters used for sidewall research with shell surrogate model

Hull material	Hull thickness (inch)	Side wall thickness (inch)	Side wall material	Vehicle weight (kg)	Hull weight (kg)
RHA	1	2	RHA	24076.342	3240.088
RHA	1	4	RHA	38432.422	3240.088

3.2 Surrogate Vehicle with Solid Elements

The baseline surrogate vehicle was then modeled with solid elements. Solid elements are more computationally intensive than shell elements and will increase run times, but solid elements also provide more accurate bending of the side walls and hull. Three solid elements through the thickness was used to capture the bending of the plate. If a minimal difference is observed between the shell and solid models, then the shell model can be used for decreased run times. An isometric view of the model and a view without the front and back panels are in Fig. 2.

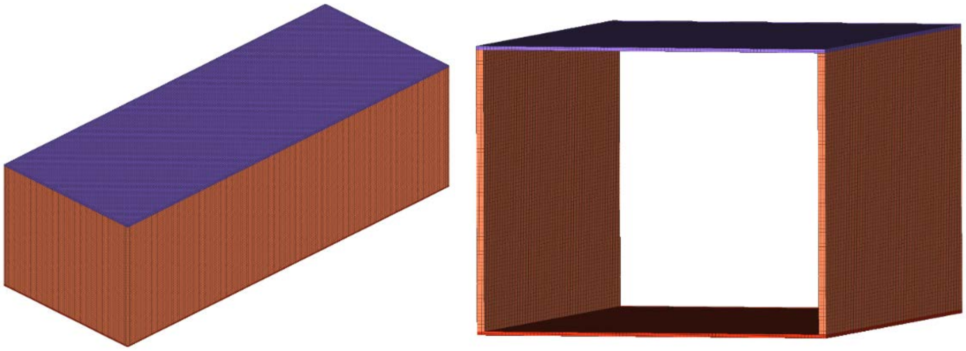

Fig. 2 Surrogate vehicle with solid elements

The hull remained 1-inch-thick RHA, and 2-inch and 4-inch side walls were used as in the shell model. The details of the simulations run using this solid model of the baseline surrogate vehicle are in Table 6.

Table 6 Parameters for solid surrogate model

Hull material	Hull thickness (inch)	Side wall thickness (inch)	side wall material	Vehicle weight (kg)	Hull weight (kg)
RHA	1	2	RHA	20265.548	3240.102
RHA	1	4	RHA	33786.841	3240.209

3.3 Arbitrary Lagrangian-Eulerian Mesh

Multi-material arbitrary Lagrangian-Eulerian (ALE) elements were used to model the large strains, extensive plastic flow, and the mixing of the detonation products, air, and soil. The surrogate vehicle was modeled with Lagrangian finite elements to achieve accuracy in the strength of materials and geometry of parts while maintaining the proper physics at the interfaces between parts. Energy was transferred from the soil and the detonation products to the surrogate vehicle via a penalty-based coupling methodology, which imposes a conservation of momentum at the interface between the threat represented in the ALE domain and the surrogate vehicle represented in the Lagrangian domain.

Figure 3 shows the ALE mesh used for all of the simulations. It was built in a cylindrical domain with a larger cylinder representing the air on top and a smaller cylinder on the bottom for the soil and charge. The air and soil domains were defined at the z = 0 plane. The upper cylinder has a diameter of 15 m, and the lower cylinder has a diameter of 6 m. The mesh was finer near the Lagrangian structures and biased radially and vertically as the mesh extended away from the surrogate vehicle. Element characteristic lengths ranged from 22 mm to 375 mm at the outermost edge of the domain. This allowed for a roughly 1:1 element length ratio between the Lagrangian and ALE meshes at the critical location of the blast event where the ALE mesh was finest.

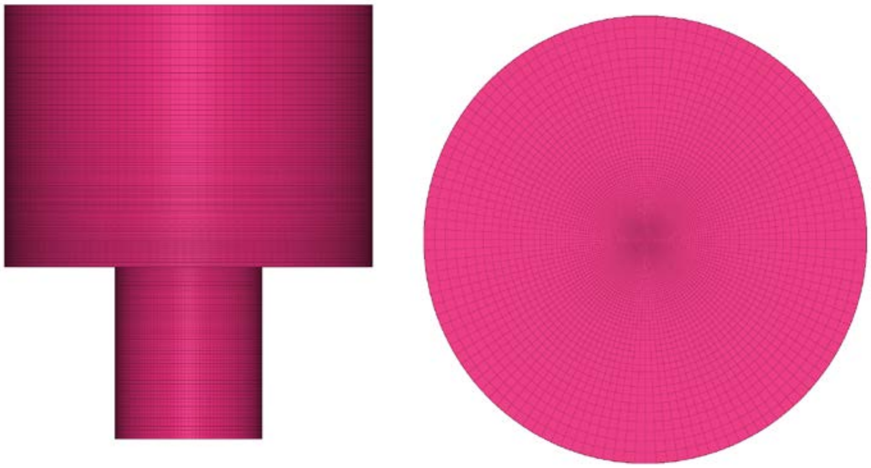

Fig. 3 ALE mesh

The setup for all of the simulations had a 0.0508-m depth of burial for the charge and a 0.5588-m standoff between the top of the soil and the bottom of the Lagrangian structure. Figure 4 depicts the setup of the ALE with the Lagrangian structure.

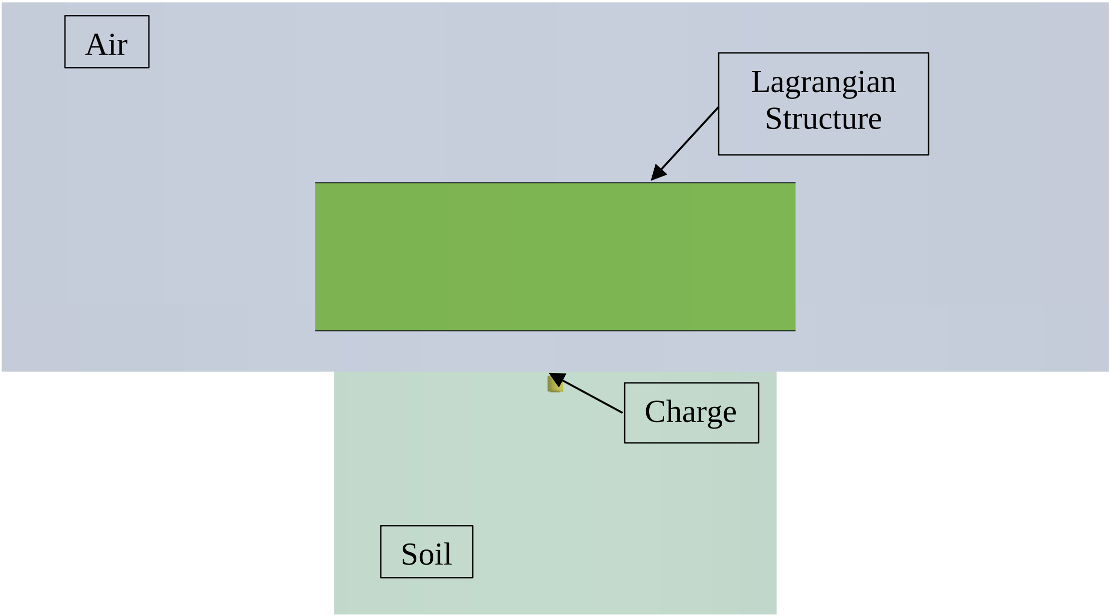

Fig. 4 ALE and Lagrangian setup

4. Results

The finite element analysis was completed using LSTC's LS-Dyna v8.0.0 on the US Army Research Laboratory Department of Defense Supercomputing Resource Center. All post-processing of the results was conducted using LS-PrePost v3.2-x64. The results included hull deflection values for each of the simulations run with the shell surrogate model with steel and aluminum hulls at varying thicknesses. Hull deflections and the displacement of the center node along the intersection of the side wall and the hull were collected for each of the simulations used to determine the effect of side wall thickness.

4.1 Steel versus Aluminum

The hull deflection values were determined by tracking the z coordinate of the center node of the hull. The initial location of the coordinate was subtracted from the peak location to determine the maximum deflection of the hull for each simulation. The hull deflection values for the simulations comparing different aluminum and steel material models can be seen in Tables 7–9. The values are shown in both meters and inches.

The gray-shaded boxes represent simulations where plastic deformation was present. Plastic deformation is permanent, nonrecoverable damage to the plate. A plate that already has permanent damage is more susceptible to further damage or even breach. The red-shaded box represents a hull breach, which is detrimental to the vehicle as well as the occupants. The baseline for comparisons was the 1-inch RHA hull. The 3-inch aluminum hulls are approximately equivalent in weight to the 1-inch RHA hull. The 3-inch aluminum hulls both deflected less than the 1-inch RHA hull. The blast equivalent to a 1-inch RHA hull was roughly a 2.25-inch aluminum hull based on the deflection seen in each hull.

Table 7 Deflection values for RHA hull at multiple thicknesses

Hull material	Hull thickness (inch)	Vehicle weight (kg)	Hull weight (kg)	Max deflection (m)	Max deflection (inch)
RHA	0.5	22456.299	1620.044	0.558	21.97
RHA	1	24076.342	3240.088	0.315	12.4
RHA	1.5	25696.386	4860.131	0.178	7
RHA	2	27316.43	6480.175	0.129	5.08
RHA	2.5	28936.474	8100.219	0.098	3.86

Table 8 Deflection values for aluminum 5083 hull at multiple thicknesses

Hull material	Hull thickness (inch)	Vehicle weight (kg)	Hull weight (kg)	Max deflection (m)	Max deflection (inch)
Al 5083	0.5	21385.625	549.37	1.1	43.31
Al 5083	1	21934.995	1098.741	0.723	28.46
Al 5083	1.5	22484.366	1648.111	0.518	20.4
Al 5083	2	23033.736	2197.481	0.371	14.6
Al 5083	2.5	23583.106	2746.851	0.278	10.94
Al 5083	3	24132.476	3296.221	0.21	8.27
Al 5083	3.5	24681.847	3845.592	0.169	6.65
Al 5083	4	25231.217	4394.962	0.14	5.51
Al 5083	4.5	25780.587	4944.332	0.112	4.41

Table 9 Deflection values for aluminum 6061 hull at multiple thicknesses

Hull material	Hull thickness (inch)	Vehicle weight (kg)	Hull weight (kg)	Max deflection (m)	Max deflection (inch)
Al 6061	1.5	22510.369	1674.114	0.511	20.1
Al 6061	2	23068.407	2232.152	0.37	14.57
Al 6061	3	24184.483	3348.228	0.199	7.83

4.2 Side Wall Effect

The hull deflection values for each simulation were recorded in the same way as described previously by tracking the center node of the hull. Table 10 shows the deflection values for all of the simulations comparing different side wall thicknesses using the shell and solid surrogate models.

Table 10 Deflection values for varying side wall thicknesses of baseline surrogate vehicle

Hull material	Hull thickness (inch)	Side wall thickness (inch)	Side wall material	Vehicle weight (kg)	Hull weight (kg)	Max hull deflection (m)	Max hull deflection (inch)	Element type
RHA	1	2	RHA	24076.342	3240.088	0.315	12.4	Shell
RHA	1	4	RHA	38432.422	3240.088	0.306	12	Shell
RHA	1	2	RHA	20265.548	3240.102	0.242	9.5	Solid
RHA	1	4	RHA	33786.841	3240.209	0.23	9.1	Solid

There was only a 0.4-inch difference between the simulations completed with a 2-inch and 4-inch side wall for both the shell and solid models. This minimal difference showed that the thickness of the side wall does not appear to have an effect on the hull deflection. There was about a 3-inch difference though between the shell and solid models for both the 2-inch and 4-inch side walls. This proved that the type of element does factor into how the hull was affected by the blast. This difference was due to the way the finite element code calculates the stress and bending in a hexahedral solid element compared to a quadrilateral shell element. Solid elements are more accurate than shell elements in terms of stresses and deformations.

The displacement of the center node along the intersection between the side wall and the hull was also tracked in the lateral and vertical directions. This was done by tracking the coordinates of the node in each direction. The displacement of the node was calculated by subtracting each location from the one previous to it. The global rigid body displacement then was subtracted from the nodal displacement to find the relative displacement of the node. The lateral and vertical nodal displacement versus time graphs for the shell and solid element surrogate models with 2-inch and 4-inch side walls are in Figs. 5 and 6.

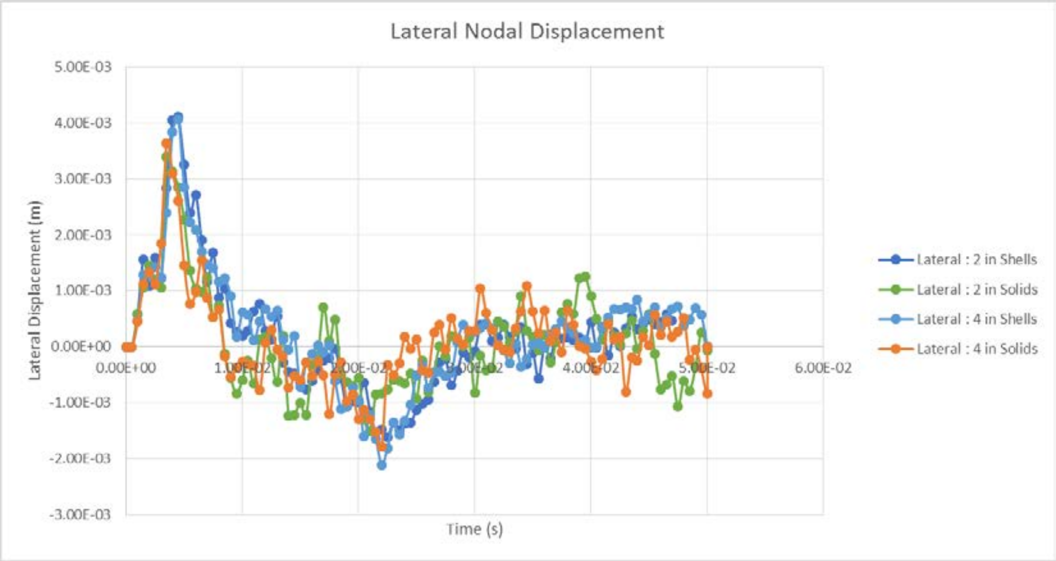

Fig. 5 Lateral nodal displacement for solid and shell surrogate models

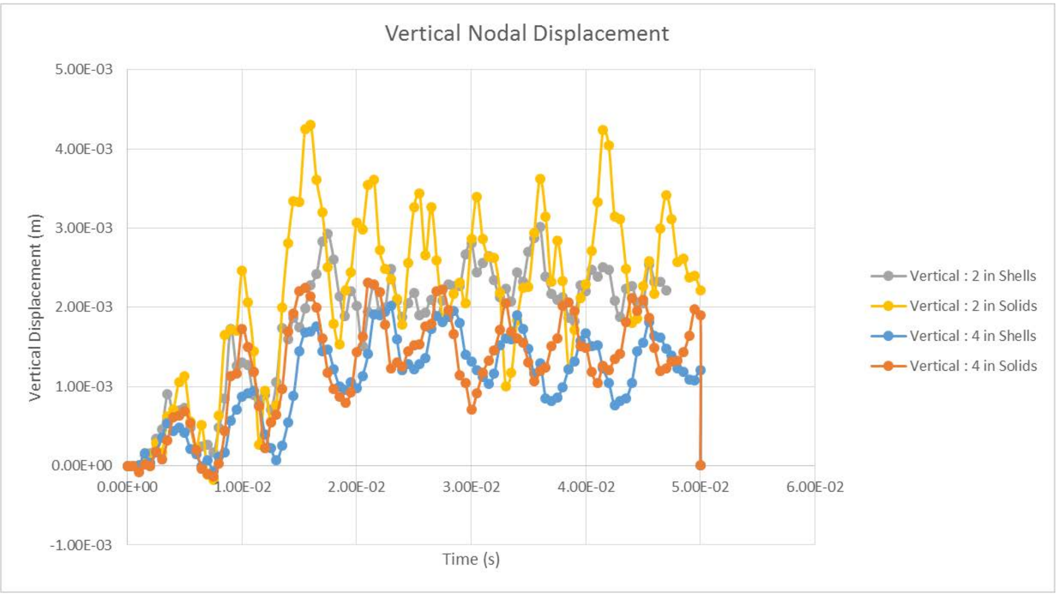

Fig. 6 Vertical nodal displacements for solid and shell surrogate models

The nodes from the 2 shell models track closely, as seen in the blue and teal colored traces. The nodes from the solid models track closely initially, as seen in the green and orange traces, but they diverge around 10 ms. This may be caused by the stiffness of the 4-inch walls affecting the nodal movement more than the 2-inch side wall. The shell models had higher peak lateral displacement values than the solid models. The differences between the shell and solid models may be due to the fact that a true intersection with the faces of the elements was modeled with the solid elements, whereas the intersection in the shell model was 2 edges of the side wall and hull.

The vertical nodal displacement did not track closely among all 4 cases. The models with a 4-inch side wall had lower displacement values than the models with 2-inch side walls for both the shell and solid models. These differences can be due to the different thicknesses and stiffness of the side walls. The weight difference of the side walls may also play a factor in the differences in vertical displacements.

5. Discussion

The baseline for this study was a 1-inch-thick RHA hull. Once this baseline was established, different aluminum models could be simulated at varying thicknesses, and the results could be compared. The trend in hull deflection decreased as the hull thickness increased. It was important to determine the blast equivalent and weight equivalent thickness of aluminum when compared to 1 inch of RHA based on the deflection of the hull. The RHA hull deflected approximately 12.4 inches; therefore, the blast equivalent of that was approximately a 2.25-inch-thick aluminum hull. A 2.25-inch-thick aluminum hull was approximately 500 kg less than the 1-inch-thick RHA hull. The weight of a 1-inch-thick RHA hull at the dimensions specified previously was 3240 kg, so the weight equivalent aluminum hull was 3 inches thick. The 3-inch aluminum hull deflected approximately 4 inches less than the 1-inch RHA hull.

Based on this data and the trends observed, aluminum appears to be a better option than steel, but the blast equivalent and the weight equivalent options are both thicker than the baseline 1-inch steel hull. This thickness decreases the sway space between the hull and the walk-on floor, which is critical to the protection of the occupants. The 3-inch aluminum hull will provide more protection than the 1-inch steel hull. The weight equivalent aluminum hull was 2 inches more in thickness than the 1-inch thick RHA hull, but the difference in deflection was 4 inches. This means that the aluminum hull thickness plus deflection was 2 inches less than the steel hull thickness plus its deflection. This is 2 inches more space between the hull and the floor at the maximum deflection for the aluminum hull as compared to the steel hull. Therefore, the weight equivalent aluminum hull allows for more sway space than the 1-inch steel hull.

The next step was to determine how simple of a model can be built that would effectively represent a standard military vehicle and its ability to protect against blast. It was necessary to determine if varying the thickness of the side walls would affect the hull deflection. The use of shell elements for the side walls would allow faster run times and a quicker turnaround. Both the shell and solid surrogate vehicles were run with 2-inch and 4-inch side walls. The deflection of the hull only decreased by 0.4 inches when the side wall thickness increased for both the shell and solid models. Thus, the thickness of the side wall had minimal effect on the hull deflection based on these results.

There was a difference, however, in hull deflection when comparing the shell model to the solid model at the same side wall thickness. The element type does have an effect on the hull deflection and must be considered when developing future models. Solid elements are more robust when analyzing the stresses and bending in a plate; therefore, solid elements may be required for this analysis despite the longer run times that result in using solid elements over shells.

The nodal displacement of the center node along the intersection was also compared to gain more understanding if using shell or solid elements have an effect on the model. The thickness of the side walls in the shell and solid surrogate vehicles had an effect on the lateral and vertical nodal displacements. The largest difference can be seen in the vertical displacement between the different thicknesses as well as the different element types. This could be the result of the increased stiffness with the 4-inch side wall, as well as the difference in intersection of the hull and side wall depending on the type of element used. Solid elements have a more realistic intersection with the connection being at the faces of the elements, while shell elements simply intersect at the nodes of the side wall and hull.

Based on these results, the thickness of the side wall does not appear to have an effect on the hull deflection, but it does have an effect on the lateral and vertical nodal displacements. The type of element used did have an effect on the hull deflection as well as the lateral and vertical nodal displacements. Thus, it can be determined that solid elements may be necessary despite the longer run times due to the discrepancies in hull deflection and nodal displacements.

6. Conclusion

RHA steel has been the primary material used for heavy combat and recovery vehicles since the 1950s, but aluminum may be an alternative material for the hull that could provide protection as well as decrease weight. A simple rectangular box was built with shell and solid elements for preliminary comparisons of the 2 materials and the effect of side wall thickness on the FEM. The hull was simulated using RHA, aluminum 6061, and aluminum 5083 at varying thicknesses. It was determined that a 1-inch RHA hull and a 2.25-inch aluminum hull are blast equivalent. A 3-inch aluminum hull was weight equivalent to a 1-inch RHA hull, but the aluminum hull deflected about 4 inches less. The side wall study showed that the thickness did not affect the hull deflection, but the type of element used to build the model did factor into the results. Despite the longer run times, solid elements may be required for future simulations.

Overall, this research yielded results that can be used to build a more robust, accurate representation of a standard military vehicle for further research. The trends in hull deflection from the steel and aluminum comparisons led to an understanding that aluminum may be a better option than steel. It also showed that side walls do affect the FEM and its response to a blast event. Further research on the effect that material and thickness have on varying hull shapes can lead to a more optimized hull and better protection for the vehicle and its occupants.

7. References

1. Prifti J, Castro M, Squillacioti R, Cellitti R. Improved rolled homogeneous armor (IRHA) steel through higher hardness. 1997 April. Report No.: ARL-TR-1347.
2. Cimpoeru SJ. The mechanical metallurgy of armour steels. Fishermans Bend, Victoria (Australia): Australian Department of Defence; Land Division, Defence Science & Technology Group; 2016 Oct. Report No.: DST-Group-TR-3305.
3. Davis JR. Alloying: understanding the basics. Materials Park (OH): ASM International; 2001. Aluminum and aluminum alloys; p. 351–416.

List of Symbols, Abbreviations, and Acronyms

ALE	arbitrary Lagrangian-Eulerian
FEM	finite element model
JC	Johnson-Cook
LSTC	Livermore Software Technology Company
M&S	modeling and simulation
RHA	rolled homogeneous armor

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