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Procedure for Fast Ballistic Vulnerability Simulation of Armored Vehicles Supported by Finite Element Results and an Extensive Numerical Sensitivity Study of Key Parameters

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ABSTRACT

The presented work discusses how to make a V/L analysis of a vehicle based on an RHA equivalence. It is shown how the approach works using small examples and an impact of an M1 helmet. Further, different V/L analyses of the GAZ-2975 vehicle are displayed. Considered Response parameters are the VAA damage maps, Expected Protection Capability plot, and damage area fractions. Explicit Finite Element models are used to find the critical RHA equivalent armor thickness at normal impact. It is done with terminal ballistic models for three materials; RHA, Aluminum 5083-H116, and Armox 500T. The values found are used in a V/L analysis. A sensitivity study of eight relevant V/L design parameters is carried out on the driver side section of the GAZ-2975 vehicle with an EPC value as the response parameter.

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1. INTRODUCTION

To protect our warfighters under a ballistic attack, armored vehicles need to have a specific Protection Level for KE and artillery threats. This is the case for light armored vehicles as well as tanks, though the considered threats are different. A discussion of the procedure for evaluating the Protection Level can be found in [1,2], where it is mentioned that the acceptance criterion is a protection capability of 90%. Leniham *et al.* [3] provide a review of the integrity of vehicle armor under ballistic attack.

Experimental terminal ballistic testing is very costly [4], and the vehicle structure redesign in case of failure would add significantly to the development costs. Numerical tools that can estimate potential risk areas with low protections will reduce the costs and help to better protect the warfighters. The approach is widely used in place of experiments [5].

This work presents a tool that can show the vulnerable area for an armored vehicle. It is based on assumptions that the threat follows a straight path through the armor and expresses the protective performance based on an RHA equivalence. It is not a Finite Element Method but uses simplified material and geometric assumptions, making it possible to obtain a fast estimate for thousands of hits. The FE mesh defines the armor geometry, but the Response is independent of the mesh and the constitutive models. The tool needs the specific RHA equivalence of the different materials (RHA equivalence per unit armor thickness). It can be determined from ballistic experiments or detailed FE simulations, and, in general, it differs for each type of threat. A discussion of the experimental procedure is found in [6]. As an example of a vehicle, the GAZ-2975 Tigr is modeled. It is a Russian-produced all-terrain Infantry Mobility Vehicle.

2. Applied Method and Simple Examples

In this work, the Vulnerable Area Assessment algorithm implemented in the IMPETUS Afea Solver® is applied [7]. The parts in the model that are protected armor are specified, and for each of these, the material RHA equivalent per unit thickness is listed in tabular form. These values can be seen as material parameters for the ballistic performance, and it is the material ID that is referenced. Both the armor and the protective volume are meshed with finite elements, which need to be fine enough to capture the geometry.

Further, the protective volume must be specified. Shot angles are given by the horizontal (azimuth) and vertical (elevation) angles. These are specified as start and end locations, together with the number of frames representing a shot angle. For each frame, hit spots are used to define a ballistic threat. The threats follow a straight path through the armor, and based on this; damage evaluation can be done. It leads to damage maps visualizing the vehicle's ballistic performance and potential weaknesses. Figure 1 to the left shows an M1 combat helmet protecting an inside volume. The damage maps and the helmet are shown in the figure to the right. The vertical angle is specified to run from 0° to 45° with two frames. Horizontal angle is from 0° to 120° with four frames. It gives a total of eight damage maps.

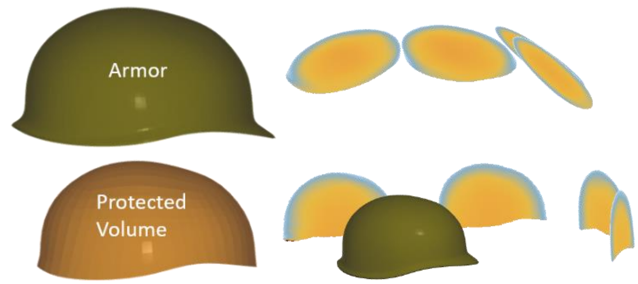

Figure 1: M1 combat helmet. Left: Helmet geometry protecting the inside volume. Right: The damage maps.

The threat path is computed with ray tracing, and the RHA equivalent is found along the path. Damage, D, is calculated according to:

$$D = \frac{RHA_c}{RHA_l} \quad (1)$$

Where RHA_c is the critical RHA equivalent armor thickness, and RHA_l is the local RHA equivalent armor thickness. If D is ≥ 1, then perforation of the armor is obtained for that fire direction.

The penetration depth of the threat can depend on the angle of the impact, which by default is taken into account by scaling the RHA_c with the cosine of the impact angle. A more detailed description can be provided by defining a curve to represent the scaling factor as a function of the impact angle. As mentioned, a table is provided, which makes it possible to set specific parameters for individual materials in the model. Except for specific RHA equivalence (always needed), optional inputs are reduction factors due to gaps, edge effects, heat effected zones (welding), etc. Gaps and edges can sometimes be around doors or other features of the vehicle. A few examples are shown to explain the output from the V/L analysis tool in the following sections. A threat with a certain penetration capacity is assumed and tested on a given structure. However, as an alternative to *RHAc*, one can provide a curve with penetration capacity versus velocity together with a specified impact velocity.

These will then lead to *RHAc*. The user can give the penetration capacity versus impact velocity, so it represents V50. This option is not used in the presented work but left for future studies.

2.1. Simple Single Armor Plate

To investigate the various outputs from the V/L analysis, consider the simple model shown in figure 2, where the dimensions can also be seen.

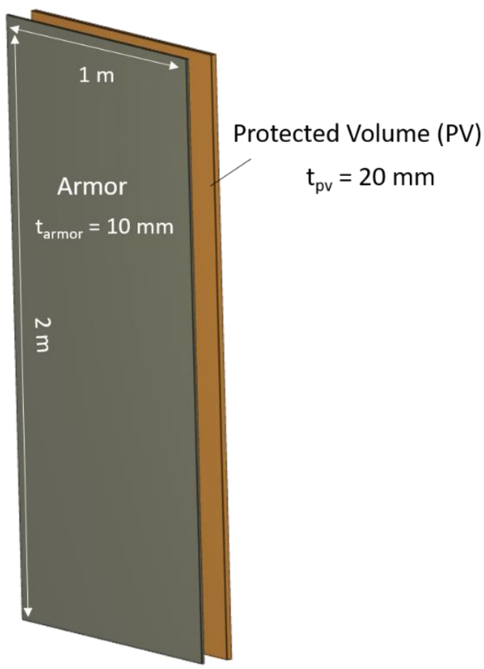

Figure 2: A simple plate set-up. An armor plate protects a target volume. Both have the same surface area.

As protection level for the armor, the RHA_c value is set to 5 mm, which means that the threat stops after 5 mm penetration into the armor since no scaling is done and a normal impact is modeled. Further, the specific RHA equivalence of the armor material RHA_l is set to 1. The azimuth start angle is 0°, and the end angle is 0°, and the number of frames is set to 1. An identical setting is used for the elevation points. This generates one frame in the normal direction of the armor plate, as seen in figure 3, which shows the damage map or the VAA value, which is the notation in the Post-Processing of the V/L analysis.

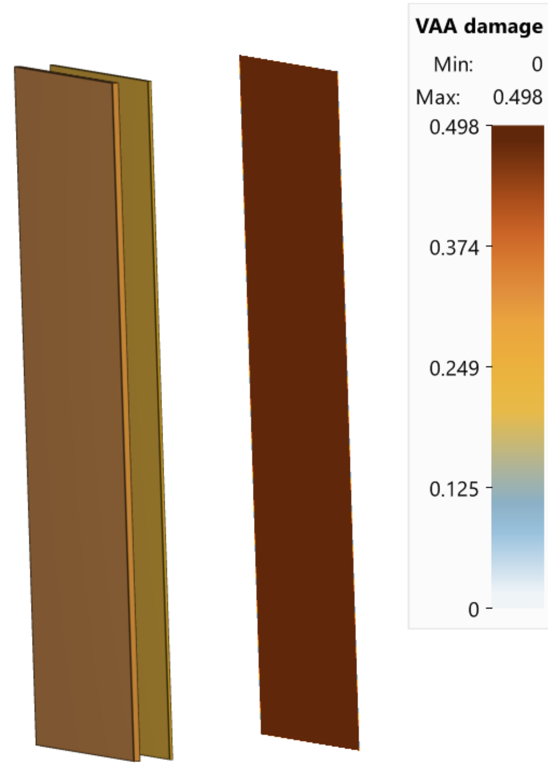

Figure 3: Damage map for the single armor plate model. Also shown are the armor and protected volume.

Figure 3 shows a VAA (Vulnerable Area Assessment) damage value of 0.498, which matches the calculation using equation (1). Recall that RHA_l is a value per unit thickness, and the thickness of the armor plate is 10 mm. This is seen as:

$$D = \frac{RHA_c}{RHA_l} \rightarrow D = \frac{5e{-}3\ m}{1 \cdot 10e{-}3\ m} = 0.5 \quad (2)$$

Another attribute that can be plotted is the RHA thickness, which is RHA_l multiplied by the armor thickness. Results for this simple case are plotted in figure 4, and a uniform value of 10.2 mm is shown.

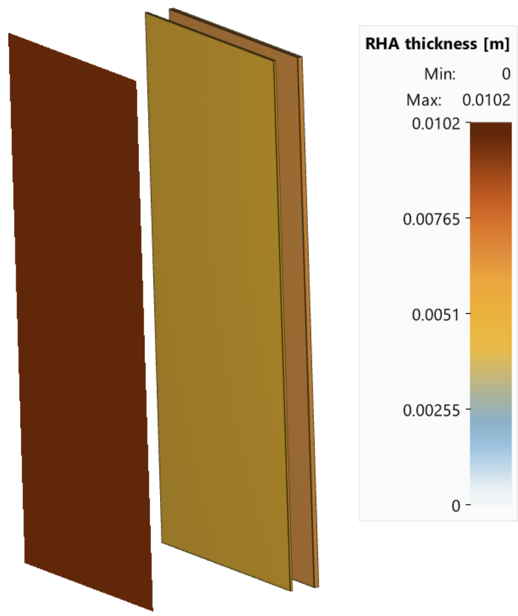

Figure 4: RHA thickness for the single armor plate model. The contour is plotted on the frame selected.

The value matches the expected value as RHA_l is defined per unit thickness leading to the calculation:

$$\begin{gathered} RHA\ thickness = RHA_l \cdot thickness \\ \downarrow \\ RHA\ thickness = 1 \cdot 10e - 3\ m \end{gathered} \tag{3}$$

The last attribute to consider is the RHA deficit which is how much armor needs to be added to obtain protection. Since there is no penetration, the values should be zero, which is confirmed in figure 5.

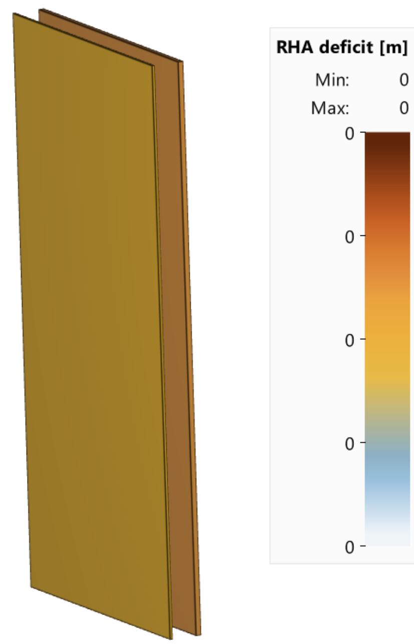

Figure 5: RHA deficit map for single armor plate.

A classic polar plot is the Expected Protection Capability plot, the EPC plot [8]. It shows the area fraction with a damage level below 100%. It means the area fraction that is not fully damaged. In this case, we have no damage, which means that 100% of the area is below full damage, leading to a value for the frame of 1 in the EPC plot, as seen in figure 6. It is the red circle in the figure. In a case with more frames, the EPC plot will be a curve, as will be seen later.

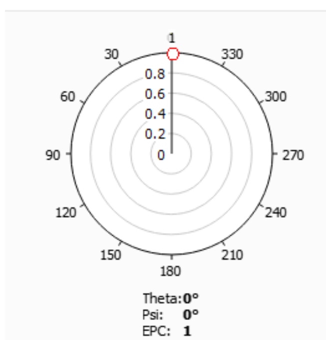

Figure 6: EPC plot for single armor plate. The red circle represents one frame.

In this simulation, there is 50% penetration since the thickness of the armor is 10 mm and RHA_c is set to 5 mm. Due to the set-up, it is the whole plate that is either damaged or not, one gets 100% or 0% for the Area Fraction above the value of the specified damage (RHA_c). Table 1 shows 100% (1) damaged area from the damage values 10-40%, then zero from 50% and upwards.

Area fraction above specified damage level:

10%	20%	30%	40%	50%	60%	70%	80%	90%	100%	110%	120%	130%	140%	150%	160%
1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0

Table 1: Area fraction above specified damage level.

2.2. Simple Two Piece Armor Plate

In the previous simple plate example, an armor plate was used. To investigate what would happen in a situation where the armor cannot provide protection, a model with two armor plates was developed. It is similar to the one armor plate model, except that the armor plate is now divided into two plates. RHA_c is still set to 5 mm, but RHA_l for one of the armor plates is now 0.5, leading to full damage for that plate. The set-up is displayed in figure 7.

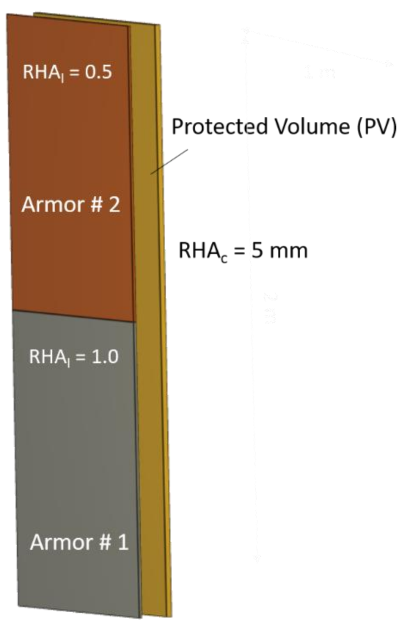

Figure 7: A simple two armor plate set-up.

In this case, half the area will now be fully damaged since the plates have the same dimensions. A contour plot of the VAA damage map is given in figure 8, where the difference between the two armor plates is clearly seen.

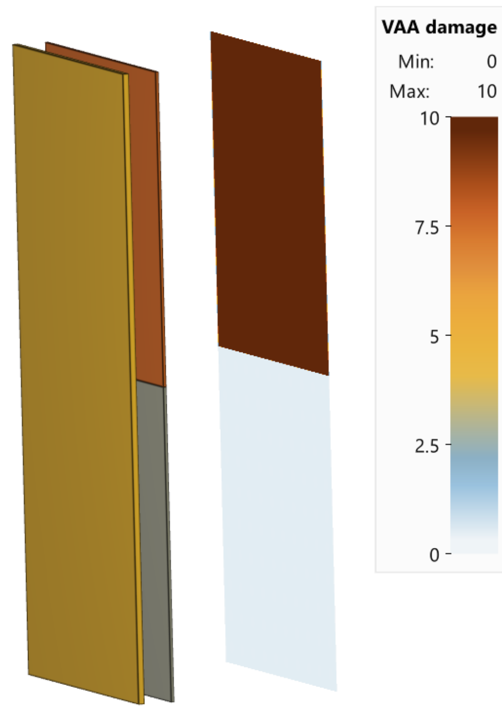

Figure 8: Damage map for the two armor plate model.

If the area fraction above a specific damage level is observed, then 50% is fully damaged since the table shows 0.5 beginning at the 50% damage level as seen in table 2.

Area fraction above specified damage level:

10%	20%	30%	40%	50%	60%	70%	80%	90%	100%	110%	120%	130%	140%	150%	160%
1	1	1	1	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5

Table 2: Area fraction above specified damage level, for example, with two identical sized armor plates but different values of RHA.

This behavior is also reflected in the EPC plot as shown in figure 9, where EPC is listed to be 0.5. The value is represented in the plot with a red circle.

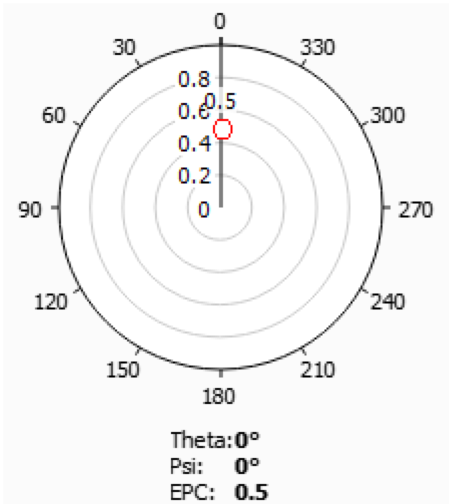

Figure 9: EPC plot for the two armor plate example. The red circle represents one frame.

2.3. Helmet with Curvatures

So far, only planar geometries have been shown, but this is not what one sees in reality. To have a more complex example, the previously shown M1 combat helmet is used. In total, 12 different azimuth angles are tested at 0° elevation. It is done every 30° from 0° to 360°. In figure 10, the EPC shows that each angle contributes to the polar plot. In this case, each shot angle gave an EPC value of 1. The figure also displays the VAA damage maps.

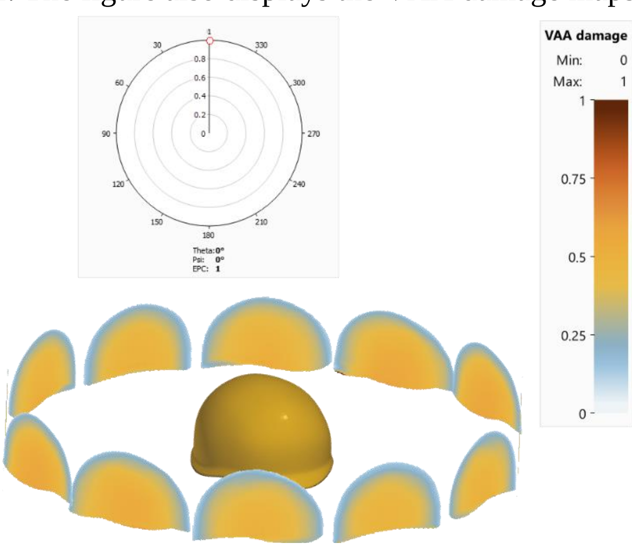

Figure 10: EPC plot and damage maps for every 30° shot angle. The model represents an M1 helmet.

No experimental data exists for this setup, but it shows that the method can handle more complex geometries, as in the case of a vehicle model.

3. Estimation of RHA Equivalent Values using Finite Element Models

As seen in the previous section, the RHA Equivalent value is an essential parameter necessary to judge the ballistic performance of an armored vehicle. It is preferable that these values are found for the armor by experimental testing. Unfortunately, this data is not always available, and it can be costly to perform these tests. Instead of guessing the values or extrapolating from one set of data representing one material to apply to a set of data for another material, one could carry out terminal ballistic Finite Element simulations. The idea is to find the limit thickness for a material impacted by a bullet and use that thickness value as the value for RHA_c in a V/L analysis of a vehicle. Three different materials were considered: RHA, Aluminum 5083-H116 and Armox 500T. All material parameters are taken from the integrated material library provided with the Finite Element solver. The Finite Element model is set up to reflect the specification listed in NATO STANAG 4569 Level 3 KE Protection [2]. It means that the bullet is a 7.62x54 B-32 API with a strike velocity of 854 m/s [1]. For all models, quarter symmetry is used with a 90° impact. The Finite Element Model is shown in figure 11. In finding the RHA_c for each of the three materials, only the thickness of the target plate is changed.

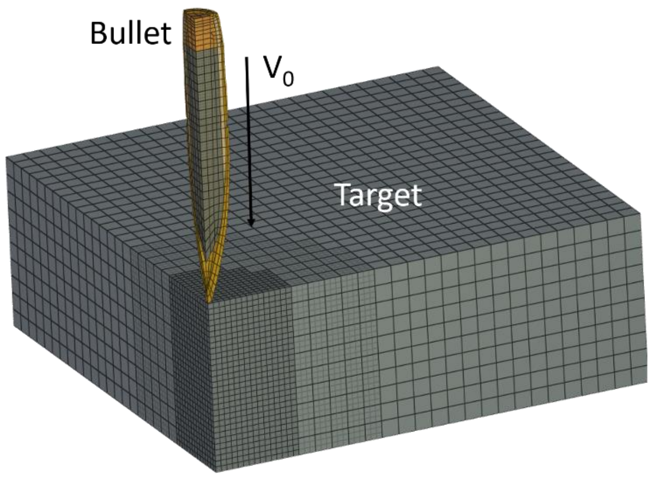

Figure 11: The Finite Element Model used to determine RHA_c. Different thicknesses are applied to find RHA_c.

The figure shows that cubic higher-order elements are applied, and a non-uniformed mesh is used, which is refined in the ballistic impact zone. In all cases, the same approach is used. The initial thickness is set to 5 mm, and if perforation occurs, then the next model will use a larger plate thickness. If the bullet is stopped, the thickness is scaled back. This continues until the limit thickness is obtained, where an accuracy of at least 1 mm is applied.

3.1. RHA

Material data is taken by specifying the RHA_R.F.Benck(1976)_38.1_DN_TP_ISO_YVM_SR_TS library in the Solver. According to the documentation, the material is based on the military standard MIL-DTL-12560 [10]. The yield strength is given by a combination of Voce and linear hardening. Damage is modeled with the Cockcroft-Latham damage model, and node splitting and element erosion are applied. Thermal softening and strain-rate sensitivity is also added to the model. Results for the 5 mm plate are seen in figure 12, where perforation is obtained.

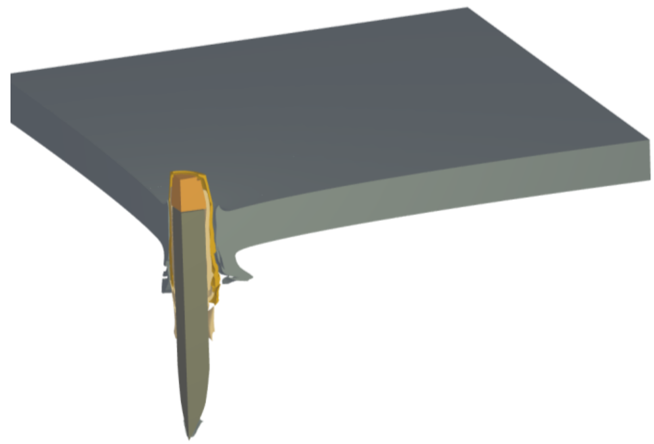

Figure 12: FE results of impact with 5 mm RHA plate.

A total of eight terminal ballistics test cases were performed. The penetration depth as a function of the plate thickness is shown in figure 13, where it is seen that the minimum plate thickness to stop the bullet is 25 mm. This is observed since the penetration is less than the plate thickness.

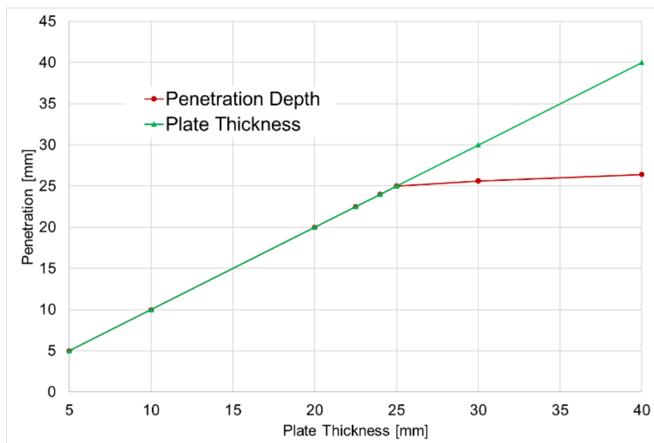

Figure 13: Results of terminal ballistic FE simulations of RHA material. The plate thickness required to avoid perforation is 25 mm.

With a 25 mm RHA plate, the 7.62x54 B-32 API bullet is stopped; however, it still penetrates through the backside of the target, as shown in figure 14.

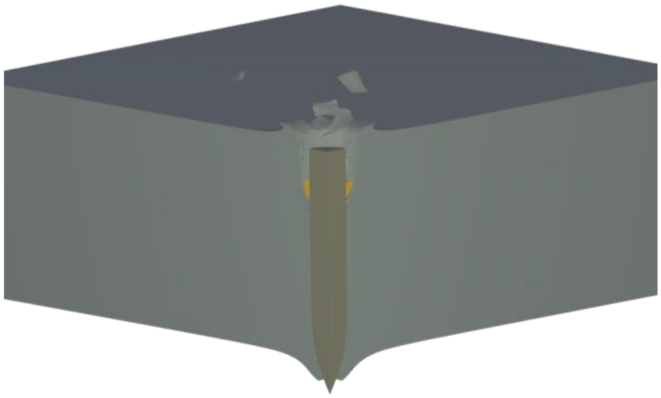

Figure 14: Final state of the RHA ballistic FE model. It is seen that the bullet penetrates the backside of the target.

One could consider selecting a higher value of the thickness, perhaps 25.5 mm, to be on the more conservative side. However, if one investigates the velocity history plot for the bullet's core part, it is seen that it is stable from just after 80 µsec, as shown in figure 15.

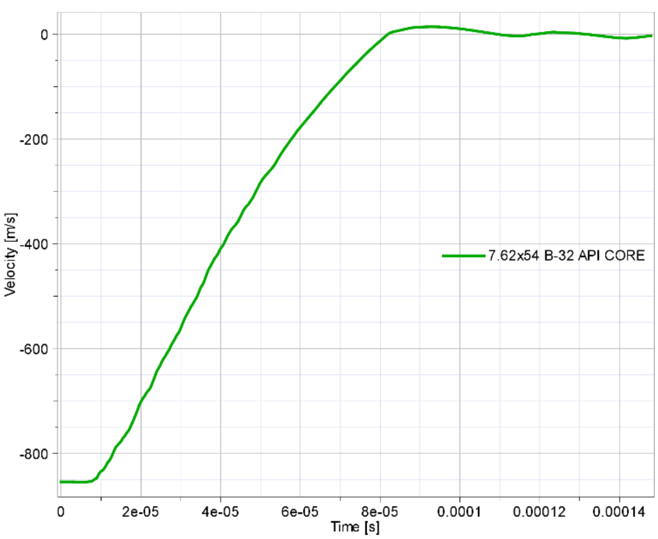

Figure 15: Velocity profile for the rigid core in the bullet.

3.2. Aluminum 5083-H116

Set-up for this FE model is the same as described in the previous section for calibration of the RHA material. In this case, the "Aluminium_AA5083-H116_T.Borvik(2008)_30_DN_TP_ISO_YVM_SR_TS in the Solver material library is used. According to the documentation, the material is mainly based on the work done at NTNU in Norway given by reference [11]. The yield strength is given by von Mises plasticity. Damage is modeled with the Cockcroft-Latham damage model, and node splitting and element erosion are applied. Thermal softening and strain-rate sensitivity is also added to the model. The first plate thickness for the target is given as 5 mm. In total, ten terminal ballistic simulations are carried out. The penetration depth as a function of the plate thickness is seen in figure 16, where it is seen that 62 mm plate thickness is required to avoid perforation.

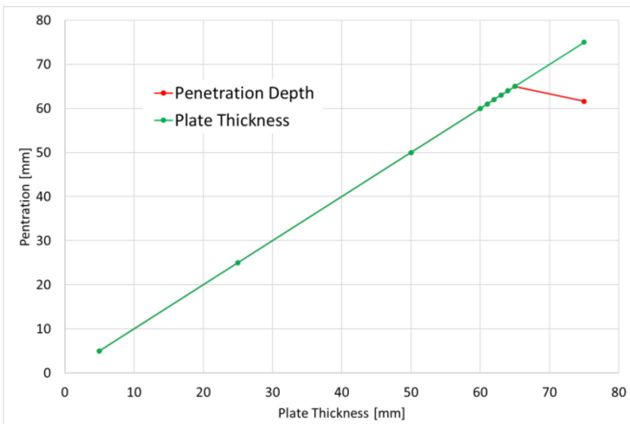

Figure 16: Results of terminal ballistic FE simulations of AL 5083-H116. The plate thickness required to avoid perforation is 62 mm.

As in the case of the RHA material, the projectile is also here penetrating the plate's backside but is stopped at 62 mm.

3.3. Armox 500T

The Armox 500T is modeled using Armox 500T_SSAB_M.Nilsson(2009)_DN_TP_ISO_YVM_SR_TS located in the material library. The calibration of this material is based on the work in [12]. The applied constitutive model is Johnson-Cook [13], and damage is done following the Cockcroft-Latham damage model, and node splitting and element erosion are applied. Thermal softening and strain-rate sensitivity is also added to the model. Nine terminal ballistic simulations were carried out applying the same technique as used in Sections 3.1 and 3.2. The minimum plate thickness to keep the bullet penetrating the armor was found to be 16 mm.

4. Vulnerability Simulation of Vehicle

Vulnerability Simulations are typically performed on a complete vehicle design. To see how the V/L analysis tool can be applied for this situation, the GAZ-2975 Tigr was modeled. It is a Russian-produced all-terrain Infantry Mobility Vehicle. The model was built based on publicly accessible CAD data, representing the vehicle's general geometry. Some of the more minor details have been removed since they are unnecessary for the Finite Element model or in a V/L model. The model consists of 63 different parts, including two protective volumes representing what needs to be protected in the V/L analysis. A finer mesh is applied in some areas since the model is also used in mine blast simulations. In the V/L analysis, no constitutive models are needed, so the materials are all specified as rigid. The vehicle is shown in figure 17, together with the protected volumes.

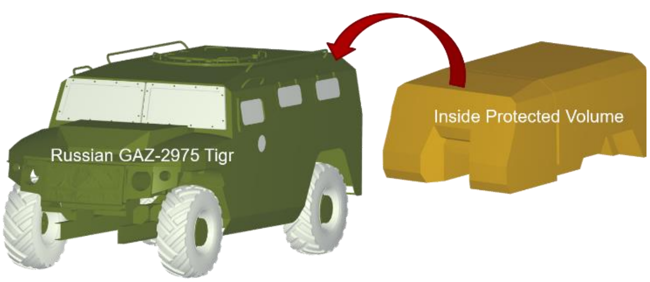

Figure 17: FE model of the GAZ-2975 Tigr vehicle together with the protective volume inside the vehicle.

A V/L analysis is done with azimuth angles from 0° to 360° with a frame defined for each 5°. This gives 72 frames. The vertical angles are 0°, 5°, and 10°. It results in a total of 216 evaluation areas (frames). In the first model, the same RHA_c value is used for all materials. The value is set to 25 mm, which was found in Section 3 as the RHA_c value for the RHA material. No scaling due to other features has been done in this initial model. The total number of trajectories is 45,111,384.

In figure 18, all the V/L analysis frames are shown, and it becomes apparent the need to investigate each frame individually.

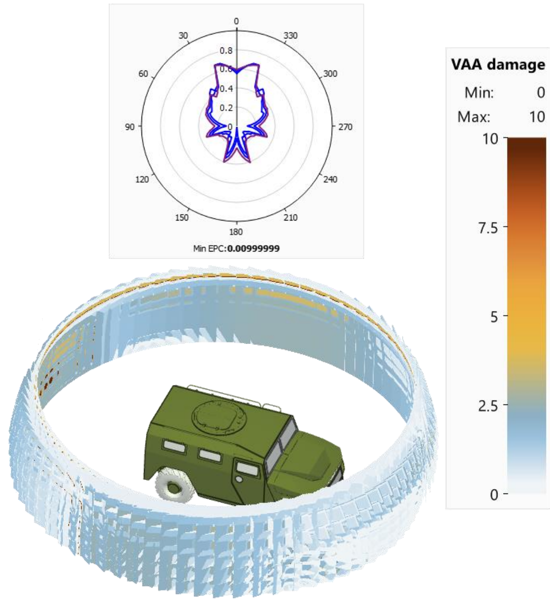

Figure 18: All 216 VAA damage maps displayed for the GAZ-2975 Tigr vehicle V/L analysis.

It is seen that a shot from 180° gives the most damage. The EPC plot can be displayed for each of the elevations, and these are shown in figure 19. It is observed that the rear end shot in the 0° vertical height is the least protected area of this vehicle. One has to remember that this is an educational example since the exact dimensions and protection armor details are not available. However, it clearly shows the features of the V/L analysis.

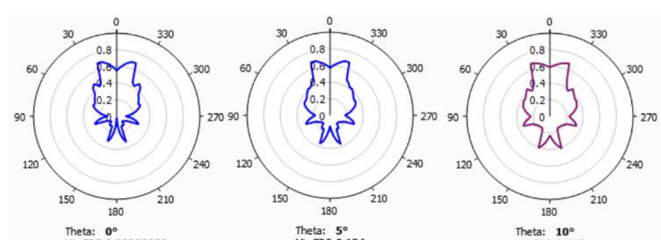

Figure 19: EPC plots for 0°, 5°, and 10° elevations. It is seen that the 0° shot from the rear end is the least protected.

The rear-end VAA damage map is plotted in figure 20. It is seen from the damage table that 99% of this area has over 100% damage.

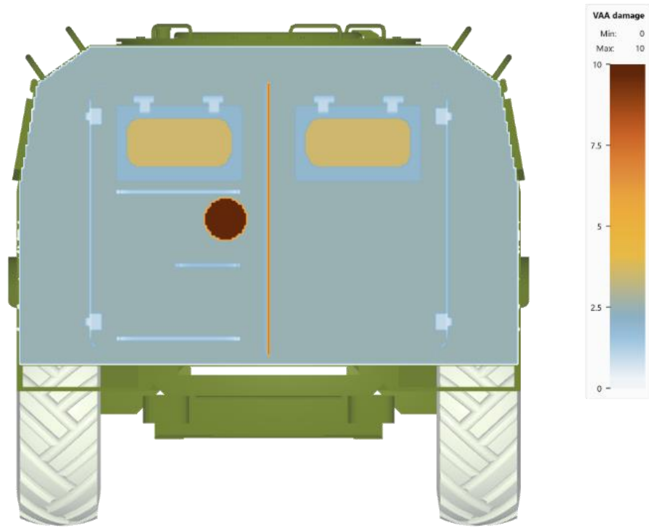

Figure 20: VAA damage map for 0° elevation and at a 180° azimuth angle.

The model ran to normal termination in around 7 hours on an NVIDIA RTX 8000 GPU.

In another V/L analysis, all the values of RHA_c found in Section 3 are applied. It was done for selected parts of the vehicle. In figure 21, the color-coding gives which part is modeled with which material. For example, RHA is used for parts in the bottom of the vehicle, Armox 500T is applied to sides and roof, and the rest use Aluminum 5083-H116.

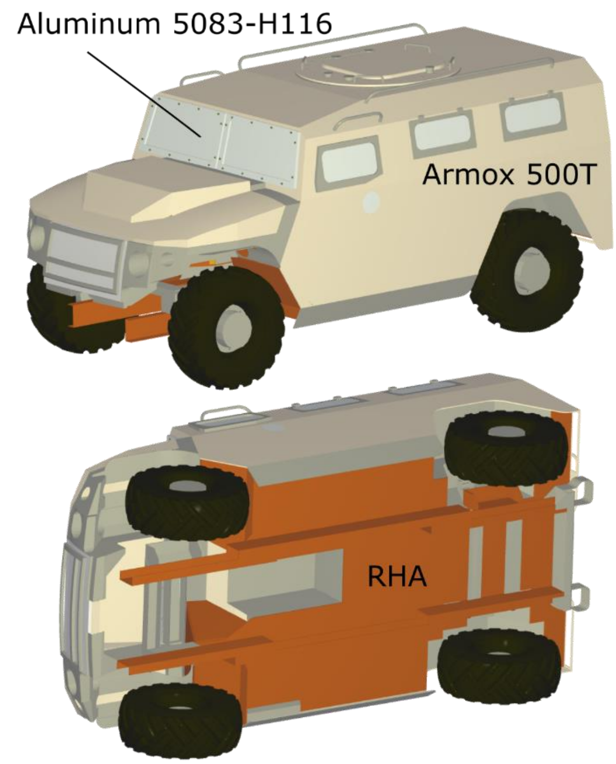

Figure 21: Three different materials are used for the GAZ-2975 Tigr vehicle V/L analysis. It is seen by the color which parts use which material definition.

For the three considered materials, the local RHA equivalent is given as input in a table. The specific RHA equivalence for RHA is always 1.0. We use the minimum plate thickness from the ballistic simulation in this work, which leads to RHA_l = 25/16 = 1.5625 for Armox 500T, and for AL 5083-H116, it is 25/62 = 0.4032. Since the weakest area was at the rear end it now has Armox 500T armor instead of the RHA material, it is expected that the protection level is increased. In addition, Armox 500T is applied to all sides, thus the EPC for each vertical angle is expected to have a higher value. The 216 VAA damage maps for this V/L case are plotted in figure 22.

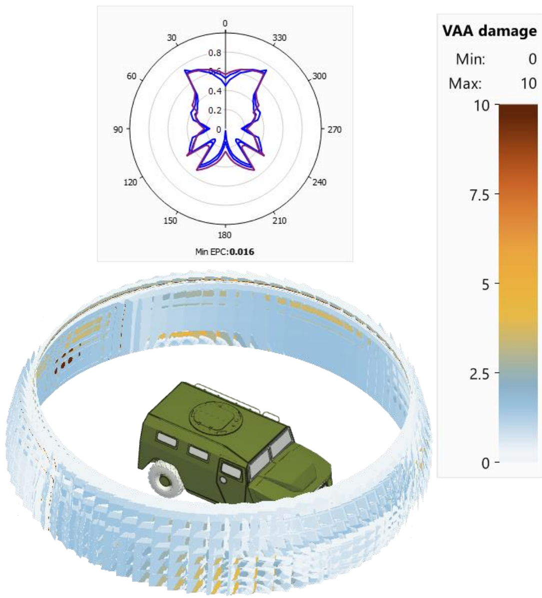

Figure 22: Displaying all 216 VAA damage maps. With three different materials, the VAA values are changed, and a better protection level is obtained.

The EPCs for the three different vertical angles are shown in figure 23, illustrating the increased protection of the protected volume. Notice that the overall minimum EPC value from the previous model is now increased from 0.009 to 0.016. This is seen in the EPC plot for 10° elevation.

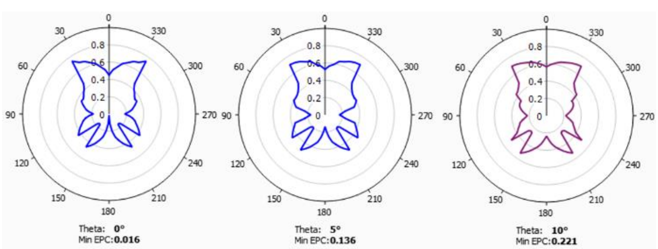

Figure 23: EPC plots for 0°, 5°, and 10° elevations. It is seen that the 0° protection now is increased.

5. Sensitivity Study on Vehicle Section

The different settings in the VAA algorithm can significantly change the response of the V/L analysis. Therefore, a user needs to be aware of the influence of the input to perform such an analysis. This knowledge can be obtained by performing a sensitivity study of the relevant parameters. Seven different design parameters were chosen for such a study, and they are listed in table 3. A scale factor due to damage from welding, the HAZ, can also be specified. However, the model presented does not have it specified, so this parameter was not investigated.

Parameter	Functionality
RHA_l	Material RHA
R_edge	Edge effect radius
sf_edge	Edge scale factor
sf_gap	Gap scale factor
tol	Error acceptance
Δhit	Hit spot grid size
caliber	Project caliber

Table 3: Design parameters in the sensitivity study.

At least five different simulations are performed per design parameter, and for each series, its functionality is explained as well. Again, the GAZ-2975 Tigr is used as an example. The chosen frame is at an azimuth angle of 90°, which is the driver's side, and it is done at a 10° elevation height. As the Response parameter, the EPC parameter is selected. A picture of the set-up is illustrated in figure 24. The Base Model to compare with is shown in Section 4, more specifically, the one using the same RHA_l for all parts. In that case, EPC=0.231 for the frame considered.

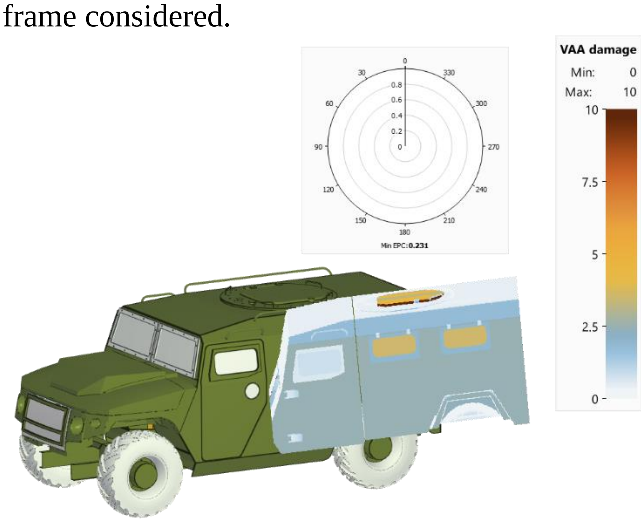

Figure 24: The GAZ-2975 Tigr vehicle with the frame used in the sensitivity study (Base Model).

The result for the EPC in the Base Model is compared with the specific frame in the full V/L model to make sure it gives the same result, which is the case. The computational time for the Base Model is around ½ hour, and the total number of trajectories is 208,849.

The RHA_l represents the specific RHA equivalence on the material level, and it is given in a reference table. RHA_l is the specific protective capacity of the material relative to RHA. Thus, this value is one for RHA. For other materials, this value is threat-dependent. The relative protective capacity of a material (compared to RHA) can differ depending on both projectile type, velocity, and impact angle. RHA_l is the most essential material input parameter in a vulnerable area assessment analysis. The higher the value, the less damage will occur, which would also increase the EPC value, as mentioned earlier. Ten different settings of RHA_l have been tested, as shown in table 4, where the results also are listed, agreeing with the expectation. The parameter has a massive impact on the EPC value.

RHA_l	EPC	%
0.1	0.011	95.2
0.2	0.032	86.1
0.3	0.042	81.8
0.4	0.057	75.3
0.5	0.165	28.6
0.6	0.169	26.8
0.7	0.193	16.5
0.8	0.200	13.4
0.9	0.229	0.9
1.0	**0.231**	n/a

Table 4: Applied values for RHA_l and EPC results. The bold value is the default value, which is used in the Base Model.

If the shotline hits on an edge, the impact on the vehicle is different than if it was on a flat surface. The *R_edge* and *sf_edge* parameters are used to describe the material's sensitivity to impacts near edges. The material is supposed to have its full protective capacity at distances from the edge larger than *R_edge*. It is a radius which means it has a unit that must correspond to the unit system used for the vehicle's FE mesh. Values are typically selected to be similar to the size of the threat. For the presented vehicle model, millimeter is used as the length unit. The *sf_edge* parameter is the remaining protective capacity if the projectile's center impacts right on the edge. There is an interpolation of the reduction scale factor from *sf_edge* at the edge to 1 at a distance *R_edge*.

Results and settings are seen in tables 5 and 6. It is chosen to change these parameters individually, so one series of tests is done with *R_edge* set to 3.963 mm, and variations are done for *sf_edge* and vice versa. The setting of *R_edge* is based on the radius of the 7.62x54 B-32 API projectile.

R_edge [mm]	EPC	%
0.01	0.232	0.4
0.1	0.232	0.4
1.0	0.237	2.6
3.963	0.241	4.3
5.	0.241	4.3
10.	0.241	4.3

Table 5: Applied values for *R_edge* and EPC results. In this case, *sf_edge* is set to 1.

sf_edge	EPC	%
1.0e-5	0.220	4.8
0.1	0.221	4.3
0.25	0.225	2.6
0.5	0.232	0.4
0.75	0.239	3.5

Table 6: Applied values for *sf_edge* and EPC results. In this case, *R_edge* is set to 3.963 mm.

There is an influence from these parameters with maximum differences to the baseline value between 4-5%.

sf_gap is a reduction scale factor for gaps in the armor. It can be a very narrow gap between two ceramic tiles. The gap may reduce the local protective capacity. Table 7 shows no influence from changing this parameter for the considered VAA frame.

sf_gap	EPC	%
0.01	0.231	-
0.1	0.231	-
0.25	0.231	-
0.5	0.231	-
0.75	0.231	-

Table 7: Applied values for *sf_gap* and EPC results.

The input parameter *tol* controls the largest acceptable numerical error in the calculations. Default is 1%, which means that the calculated RHA thickness can range from 9.9 to 10.1 mm for a 10 mm thick plate. Again for the selected frame, little influence is seen.

tol	EPC	%
0.01	**0.231**	**n/a**
0.05	0.231	-
0.1	0.231	-
0.25	0.230	0.4
0.5	0.230	0.4

Table 8: Applied values for *tol* and EPC results. The bold value is the default value, which is used in the Base Model.

Δhit is a discretization parameter, controlling the distance between the virtual shots. The default value is 0.2*RHA_c. Since RHA_c in the Base Model is 25, the value used for *Δhit* is 5. It should be noted that a smaller RHA_c gives a smaller distance, leading to increased computational time. Table 9 shows the results.

Δhit	EPC	%	#Trajectories
1	0.231	-	5,212,089
2	0.232	0.4	1,304,164
4	0.231	-	326,041
5	**0.231**	**n/a**	**208,849**
6	0.233	0.9	145,161
7	0.231	-	106,929
10	0.234	1.3	52,441

Table 9: Applied values for *Δhit* and EPC results.

The maximum difference to the Base Model is 1.3%, when ¼ of the number of trajectories is used. Note that the result is the same as the baseline for this frame, with over five million trajectories given.

caliber is the projectile diameter. This parameter is used to calculate if the projectile will be slowed down (or pass right through) gaps in the armor. The value for *caliber* is unit dependent and thus given in the units of the vehicle mesh. The below table shows no influence.

caliber [mm]	EPC	%
5.56	0.231	-
7.62	0.231	-
14.5	0.231	-
25.0	0.231	-
30.0	0.231	-

Table 10: Applied values for caliber and EPC results.

The sensitivity study clearly showed that RHA_l is the primary parameter influencing the vehicle's damage reaching a change in the protection of nearly 100%, compared to the Base Model. Some effects were seen from the input related to handling edge impact on the structure. However, a significant scaling was needed to obtain around 5% change in EPC value. No influence was seen from the parameters scaling protection level due to gaps in the structure. Very consistent EPC values were obtained for an extensive range of trajectories. In overall consideration, stable simulations were performed, and it is believed that variations in, e.g., settings of the gap parameters will have more significant effects for a different structure. An investigation of the side structure of the vehicle reveals the presence of flat panels with uniform thickness. Thickness variations and structures with ceramic tiles where gaps are seen would be expected to see more significant influence from changing the gap parameters. This is especially true when the EPS value is closer to 100%, which is typically the case for realistic structures. Then effects from gaps and edges become much more dominant.

6. Conclusion

A V/L analysis tool has been presented, and the various settings were explained. Two smaller armor plate examples together with an M1 helmet model are used to investigate the Response parameters. Around twenty-five different terminal ballistic Finite Element models were carried out to estimate the RHA Equivalent value for three common applied materials used in armored vehicle design. They are RHA, Aluminum 50083-H116, and Armox 500T. For these materials, the constitutive models were taken from the available calibrated libraries in the software package. Reliable Finite Element simulations can in this way substitute for any lack of experimental ballistic testing.

As an example of a vehicle, a model of the GAZ-2975 Tigr is developed. The vehicle model is not an official model from the manufacturer, nor are the material parameters applied. Thus, the results are for educational purposes only. Different V/L analyses are done for this vehicle to show the possible output options of the applied tool. It includes VAA damage maps and the Expected Protection Capability plot for a set-up with azimuth angles from 0° to 360° with a frame interval of 5°. The vertical angles are 0°, 5°, and 10°, leading to a total of 216 VAA damage maps. First, all parts are modeled with the obtained RHA Equivalent value for the RHA material, and the results are shown. The rear of the vehicle is found to be the less protected area of the vehicle. Next, all three materials investigated in the terminal ballistic simulations were applied. The main difference is to use Armox 500T for the sides of the vehicle. This increased the protection level as expected and seen in the EPC plots.

As shown by these two examples, the applied procedure described makes it possible to use a Finite Element model developed for e.g. FE buried mine blast simulations and directly perform a V/L analysis on this geometry instead of going via the CAD model. One must remember that the results are only for a 7.62x54 B-32 API bullet with a strike velocity of 854 m/s. It represents a Level 3 KE Protection in NATO STANAG 4569.

A frame representing shots in 90° azimuth angle and 10° elevation was used in a sensitivity study of eight design parameters. This leads to the characterization of the most influencing parameter, which is the specific RHA equivalence on the material level. It changed the results nearly 100% when looking at the EPC value for the chosen range of the design variables. The study also discovered that the vehicle model needs more details, including gaps and thickness variations, to see the effect from some of the available scaling parameters.

As a continuation of the presented work, it is planned to model the Russian Armata tank and use different threats such as shaped charges and explosively formed projectiles. In future work, it could be advantageous to investigate with Finite Element modeling how the limited armor thickness varies with the angle of impact. This would be similar to the findings of the RHA equivalent values, and it will make it possible to create a scaling curve that can be given as input for the V/L analysis. It is a hope that funding will be available for experimental work to verify the method for finding the RHA Equivalent values via Finite Element simulations.

7. Acknowledgment

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