Numerical Study of High Velocity Impact Response of Vehicle Armor Combination Using LS DYNA®

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1 Abstract

The aim of this work is to perceive if the outcome from a ballistic impact can be predicted beforehand with the help of material testing and finite element simulations. Use of refined numerical simulation are gaining more importance especially in extreme load cases. A numerical investigation of the ballistic performance of monolithic, double layered metallic plates made of either steel or aluminium or combinations ,were impacted by a 7.62-mm APM2 projectile at a velocity of 820m/s. The numerical models were developed using the explicit finite element code LSDYNA®. The effect of different metallic parts- thickness on the residual velocity of APM2 projectiles is examined. Three configurations of plate arrangements with different total thicknesses were used. Both aluminium target and projectile have been modelled as deformable bodies with Modified Johnson-Cook material model based on input parameters from literature[1].The predicted values of residual velocities were compared with the literature and a good correlation was found between the two.

2 Introduction

The need for protection against projectiles has immense importance for defence industry. There are a large number of parameters which may influence the ballistic resistance of metallic plates such as material behavior, target thickness, angle of incidence, nose shape and size of projectile as well as target configuration. Combination of armour material have also significant effect on ballistic limit of armours. In this study a 7.62 mm armour-piercing projectile perforating into a thick Weldox700E and Al7075 amor combinations.Specific steel and aluminium models were selected following to the literature related to ballistics. Model set-up is based on the work[1].

3 LS-DYNA® Model

All the simulations were run in LS-DYNA® and all the analyses adopted the explicit finite element formulation. The energy ratio criterion was adopted to evaluate the acceptability of the simulations: the criterion requires that the total energy of the system should remain constant during the impact. Hence, the ratio between total energy, initial total energy and work of the external forces should remain as close as possible to one, acceptable within 5%.

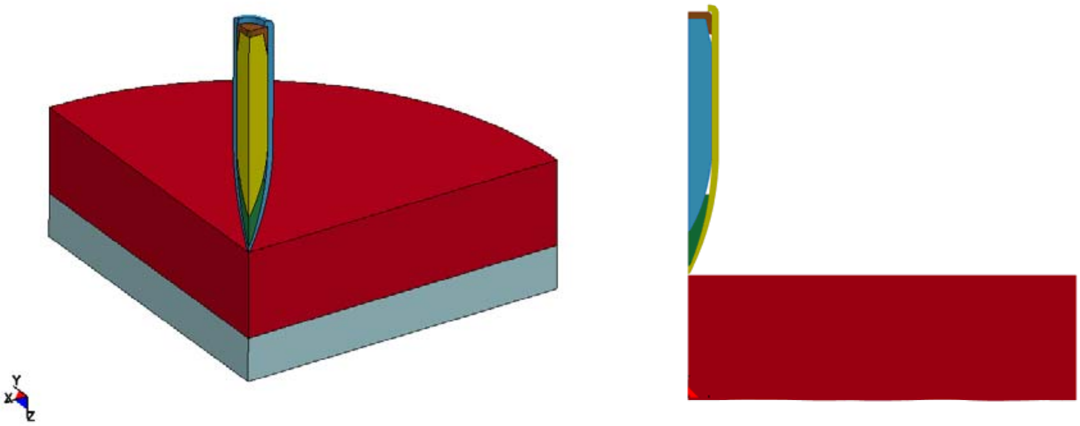

Fig.1: Quarter and Axisymmetric Model[1]

The LS-DYNA MPP LS-DYNA R7.1.3 solver is used an initial velocity of 820m/s is given to 7.62mm projectile with `*INITIAL_VELOCITY_NODE`. Only quarter of the model was to save computational expense of run time. Also, axissymetric model was analyzed a comparison is made between the quarter model and the axisymmetric model. Eight noded constant stress solid element(`ELFORM=1`) and Type 6 stiffness-based hourglass damping is used on hole model. Also, a comparison was made to see the effect of different hourglass formulations on residual velocities. The target was modelled as solid cylinder of radius 50mm.

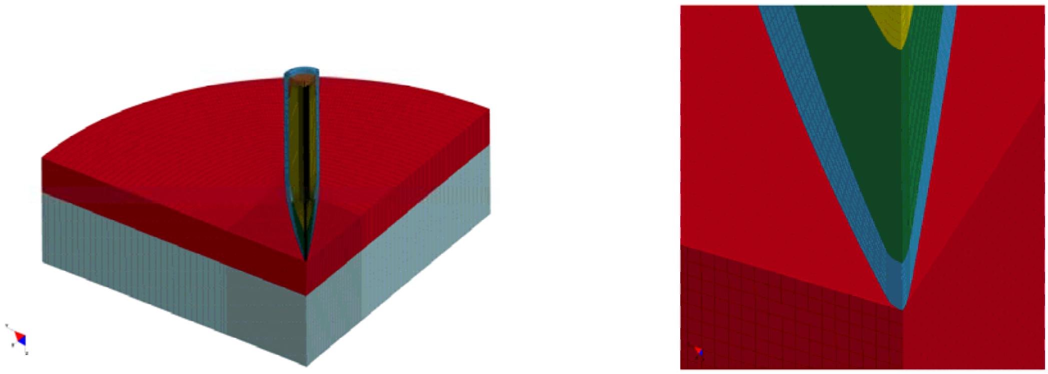

Fig.2: Finite Element Model of Target and Projectile[1]

The FEA mesh of impact region oft he target plate consists of 0.2x0.3mm hexahedron elements. Elements away from the impact region have larger size. A mesh sensitivity work has also been done for some different sizes. Different parts of the bullet (brass jacket, steel core, lead filler vs.) were modelled in detail for the analysis. For the axissymmetric case, 14604 axisymmetric elements were used with both area weighted(`ELFORM=14`) and volume weighted element(`ELFORM=15`) formulations.`*MAT_ADD_EROSION` option was specified as effective plastic strain failure at value of 2.0 for axisymmetric model.`*CONTACT_2D_AUTOMATIC_SINGLE_SURFACE` contact was used to define contacts between all parts.

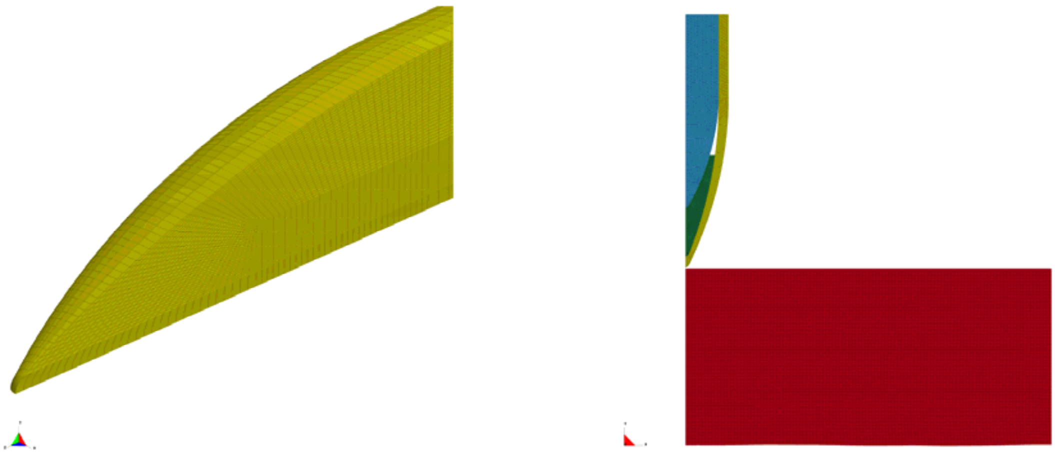

Fig.3: Mesh Model of Core and Axisymmetric Model

The mesh of the bullet consist 102681 hexahedron elements. Contact between penetrator and target plate was modelled with `*CONTACT_ERODING_SINGLE_SURFACE` with `SOFT=2` option. Bucket sort searching algorithm was used every cycle of the analysis to catch better contact surface results the between projectile and the target plate.The target plate was set as fixed at the boundary edges. Combinations were grouped into one layer multiple combinations double layered combinations. Also, the material selection was varied with combinations of double and triple versions of armor. The analysis was finalised in 4 hours for 16mm thick plate using 20 cores for 820m/s initial impact velocity. The CPU time increases when the thickness of the plate was set to 20mm and for the same machine configuration.

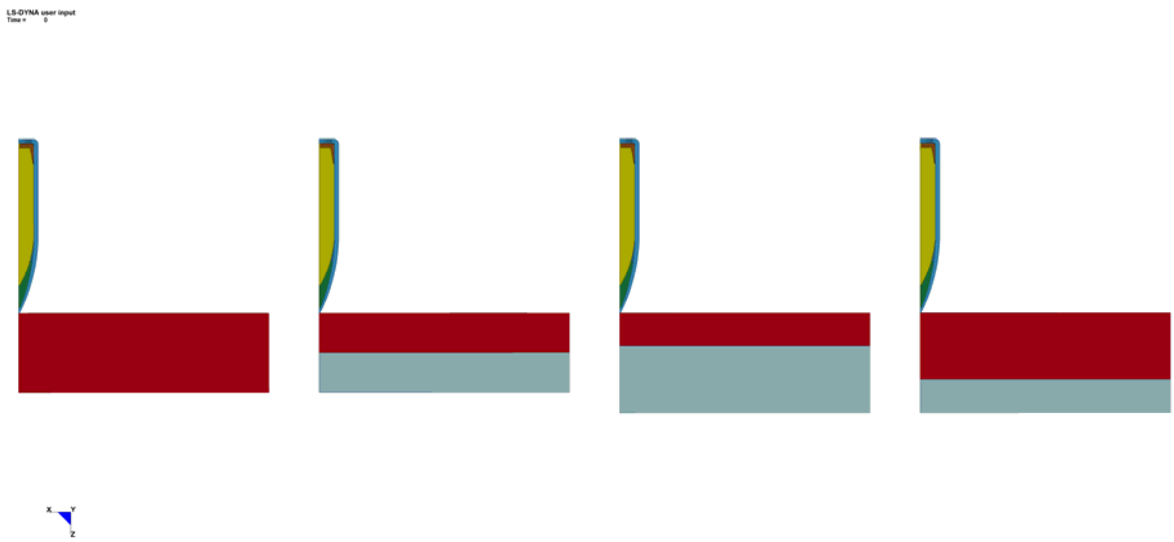

Fig.4: Armor Configrations

The ballistic performance of many different armor configurations were studied for an initial impact velocity 820m/s. The performance of the armor configration is based on the residual velocity oft he bullet. A numerical validation study was also done for quarter model of monolithic 16mm Weldox700E configration. Different hourglass formulations and different type of elements are used to determine its effectivenes on analysis results. Also, an axissymetric model was analyzed for monolithic 16mm Weldox700E case and compared with the quarter model solutions.

4 Material Model

The modified Johnson–Cook material model was used for all the materials. Comparing with type 15 classical Johnson-Cook Material model, the most important differences are in the strain rate dependence term and the failure criterion [2]. Cockroft-Latham failure model is simpler failure model and does not need to an equation of state input. The metallic combinations of the target, and the projectile hardened steel core, the brass and the lead part are all modelled with the Modified Johnson-Cook model. Material parameters were taken from literature and listed below[1].

Table 1: Table 1Material Properties[1]

Parameter	**Weldox700E**	**Steel Core**	**Lead Cap**	**Brass Jacket**	**Al7075-T651**
E (Young's Modulus) [GPa]	210	210	1	115	70
v (Poisson's ratio)	0.33	0.3	0.42	0.31	0.3
ρ (Density) (kg/m³)	7850	7850	10660	8520	2700
A (Yield strength) [MPa]	819	1200	24	206	520
B (Strain hardening parameter) [MPa]	308	50000	300	505	477
n (Strain hardening parameter)	0.64	1	1	0.42	0.52
$\dot{\varepsilon}_0$ (Strain rate) [1/s]	5e-4	5e-4	5e-4	5e-4	5e-4
C (Strain rate sensitivity parameter)	0.0098	0	0.1	0.01	0.001
Tr (Room Temperature) [K]	293	293	293	293	293
Tm (Melt Temperature) [K]	1800	1800	760	1189	893
m (Thermal softening parameter)	1	1	1	1	1.68
Cp (Specific heat capacity) [J/kg/K]	452	910	124	385	910
X (Taylor-Quinney coefficient)	0.9	0.9	0.9	0.9	0.9
α (Thermal expansion coefficient) [1/K]	1.2e-5	1.2e-5	2.9e-5	1.9e-5	2.3e-5
Wcr (Cockcroft-Latham parameter) [MPa]	1486	-	175	914	106

5 Model Results and Comparison

A mesh sensitivity study was done for a four different mesh sizes. The element size was changed through the thickness direction of target and residual velocity comparison was made for four different models.

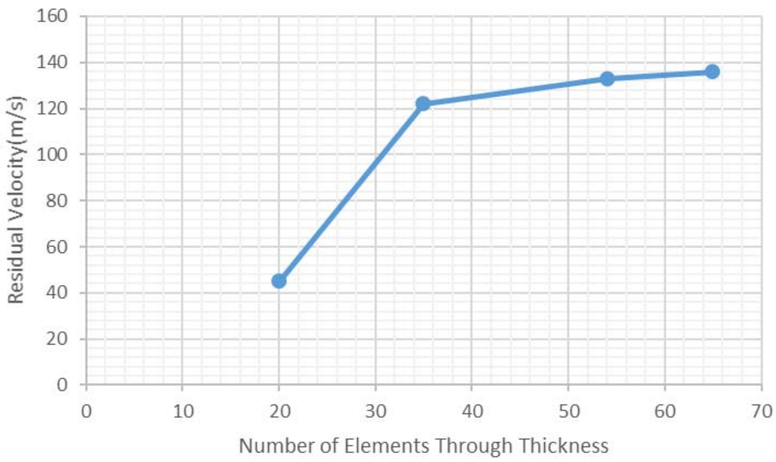

Fig.5: Mesh Sensitivity work

Results show good correlation of ballistic literature results[1]. Model number two was chosen to best fit to the ballistic literature results. The dimensions of the elements in the thickness direction are important in the event of tracing the material's behavior through the penetration process

Table 2: Residual Velocity Values for 16mm Weldox700E Model

Model Number	**Number of Elements Through Thickness Direction**	**Residual Velocity[m/s]**
1	65	137
2	54	133
3	35	122
4	20	45

Larger elements may create an artificial eroding effect in the simulation and, therefore, lead to a larger crater dimension in the results. Minor differences were seen between model-1 and model-2 for residual velocity values. According to residual velocity values, it would be sufficient to have 54 elements to obtain accurate results.

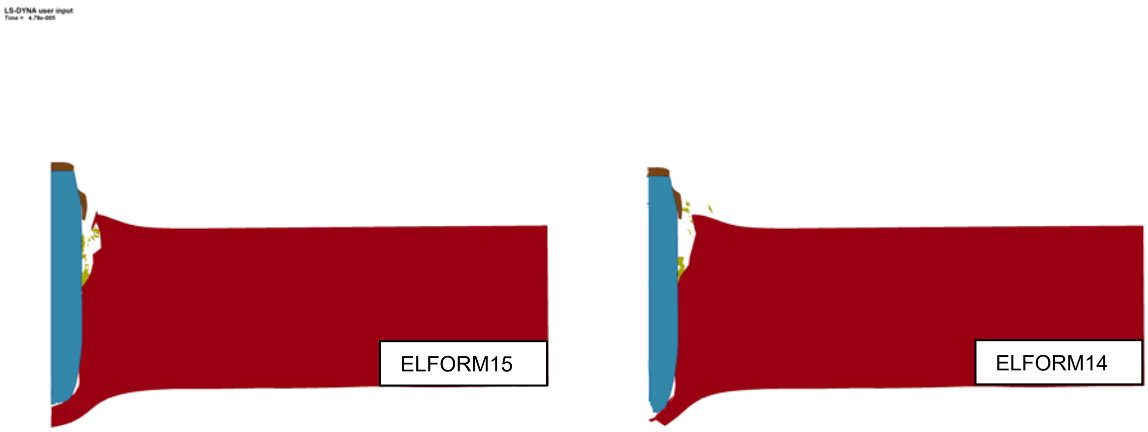

Fig.6: Residual Velocity Comparison between element formulations

Furthermore, the results of quarter 16mm Weldox700E model were compared with the axisymmetric solutions. There are two possible 2D axisymmetric solid elements: area weighted (type 14) and volume weighted (type 15).ELFORM=14 and ELFORM=15 axisymmetric element formulations were used for the simulations.

Table 3: Axisymmetric Model Residual Velocity Values

ELFORM	**Residual Velocity[m/s]**
14	257
15	185
Experiment [1]	133

ELFORM=15 is preferred for most impact applications [5]. High explosive applications work best with the area weighted approach, while for structural applications the volume weighted approach is recommended. Type 15 can lead to problems along the axis of symmetry if deformations are under very large. Often the symmetry condition is not obeyed, and the elements will kink along the axis.

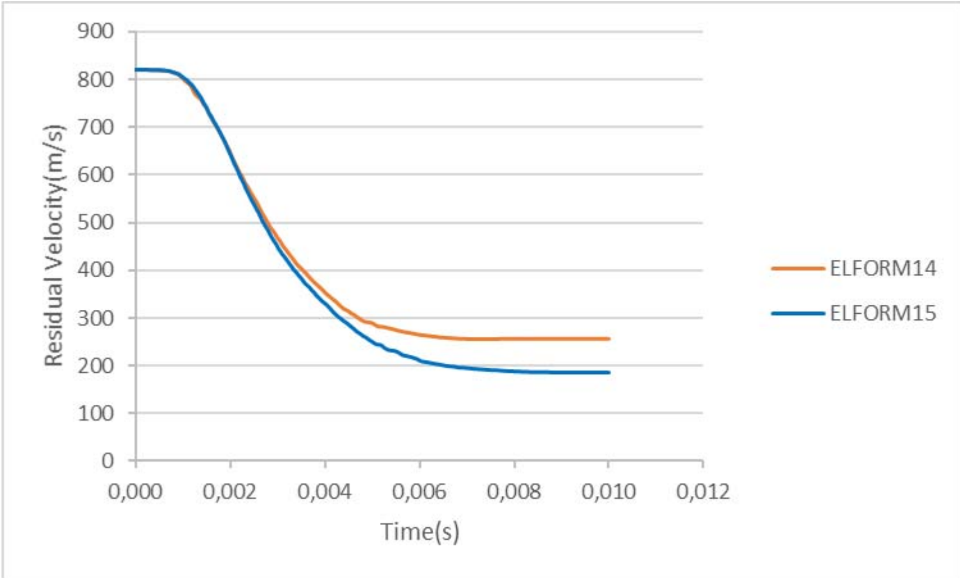

Fig.7: Deformed Shape Results Elform15 vs. Elform14

Residual velocity values are shown on Table 3. The axisymmetric model with ELFORM=15 gives results closer to the literature.The rotation of the bullet can be captured in quarter model setup while this isnot possible in the axisymmetric model. Therefore, so further analyses are done for a quarter model because of the accuracy of residual velocity and physical reality.

6 Hourglass Solutions and Element Type Solutions

In addition of element size choice of hourglass formulation and the element type could affect the accuracy of results as. Use of stiffness based hourglass algorithm yields best results from the energy ratio perspective, which must be close to 1. Three forms (TYPE:4,5 and 6) of stiffness based Hourglass algorithms exist in LSDYNA. In this study value of hourglass damping coefficient was kept constant and differences between IHQ types 4,5,6 are examined.

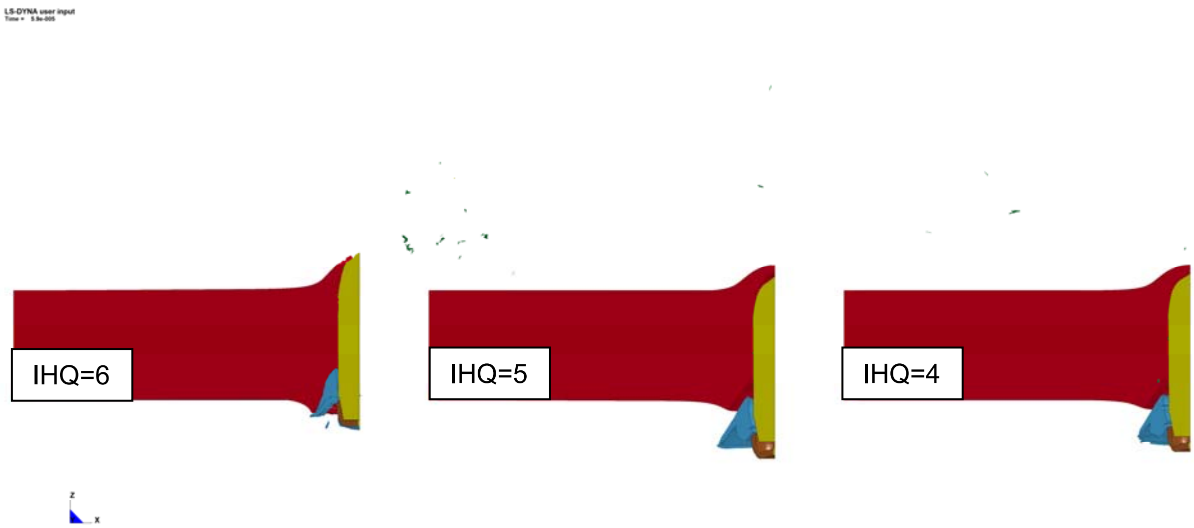

Fig.8: Deformed Shape Model for each Hourglass Formulation

Deformed shapes after the last time step is shown in the figure8. The damping value is set to a constant value of 0.13 for all hourglass formulations. The model with velocity results IHQ=6 formulation gives closest results to literature values with as shown in Table4.

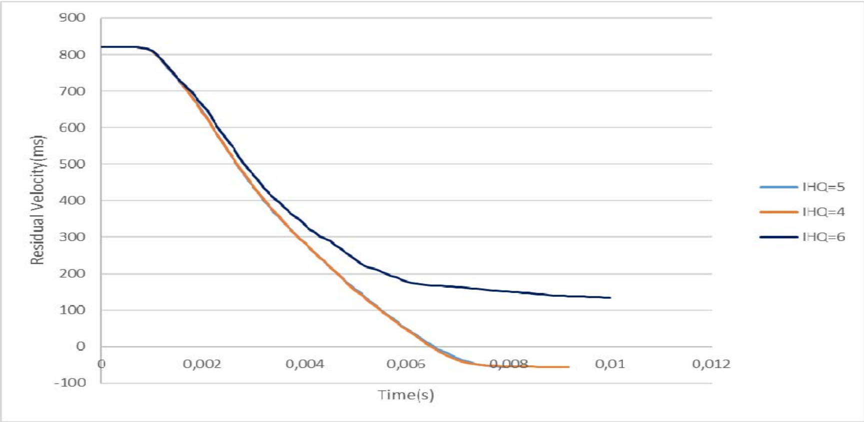

Fig.9: Residual velocity values for each type of Hourglass Formulation

Hourglass types 4 and 5 give stiffer results for a value of 0.13 for damping. It can be seen from figure9 that the residual velocity values decrease to 0 for IHQ=4 and 5 .

Table 4: Residual Veloctity Values

Hourglass Type	**Damping Value**	**Residual Velocity[m/s]**
4	0.13	0
5	0.13	0
6	0.13	133
Experiment	-	152

7 Element Formulation

Three different element formulations were used for a comprehensive study. For ELFORM=1, -1 and 2. The analysis results were investigated considering the element formulations effect on residual velocity.

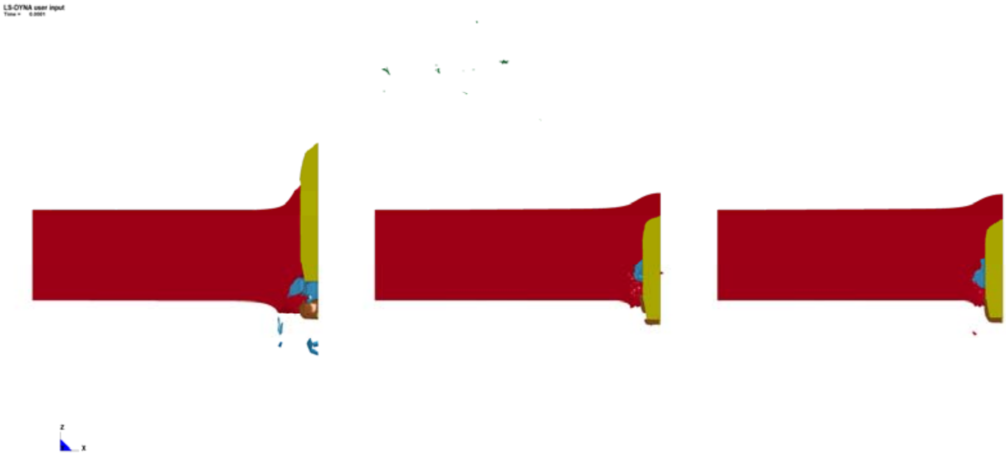

Fig.10: Residual Velocity Values for Different Element Formulations

The deformed shapes of 16mm Weldox700E armor for different element types are shown in figure10. As can be seen different formulations lead to significantly different deformed shapes.

Table 5: Residual Velocity Values for Each Element Formulations

ELFORM	Residual Velocity[m/s]
1	133
2	0
-1	0
Experiment	152

It is shown in Table 5 that ELFORM=1 formulations agrees best with the experiment results. Fully integrated formulations give stiffer results as seen from Table 5. The residual velocity goes to zero for other two formulations.

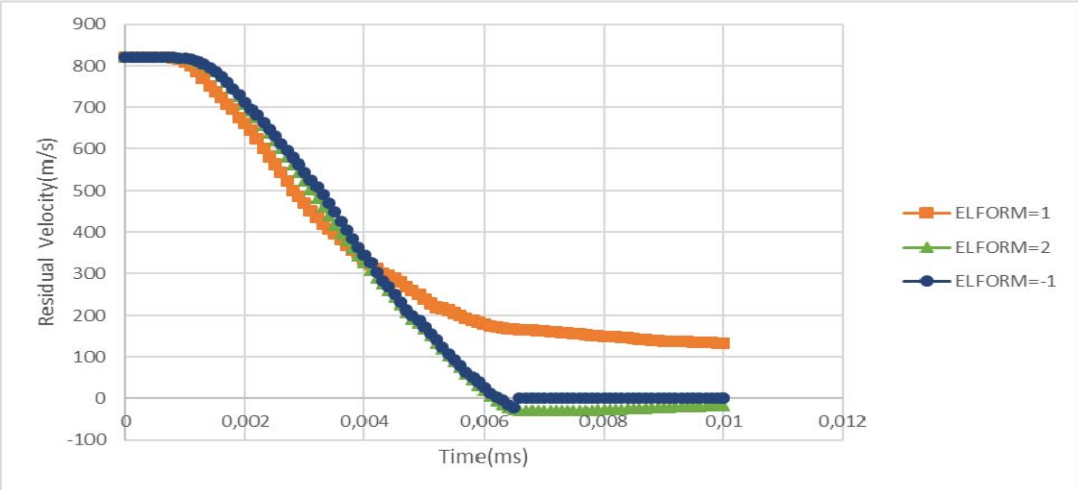

Fig.11: Residual Velocity vs. Time for Different Element Types

The formulation ELFORM=1 is selected for further analyses because of better agreements with literature [1].

8 Armor Configuration Analysis

Aluminum 7075 and Weldox700E have been studied as possible candidate materials for vehicle armor protection applications because of comparatively higher ductility and strength. Various multi-layered configurations, using single layered and double-layered mixed plates were studied.

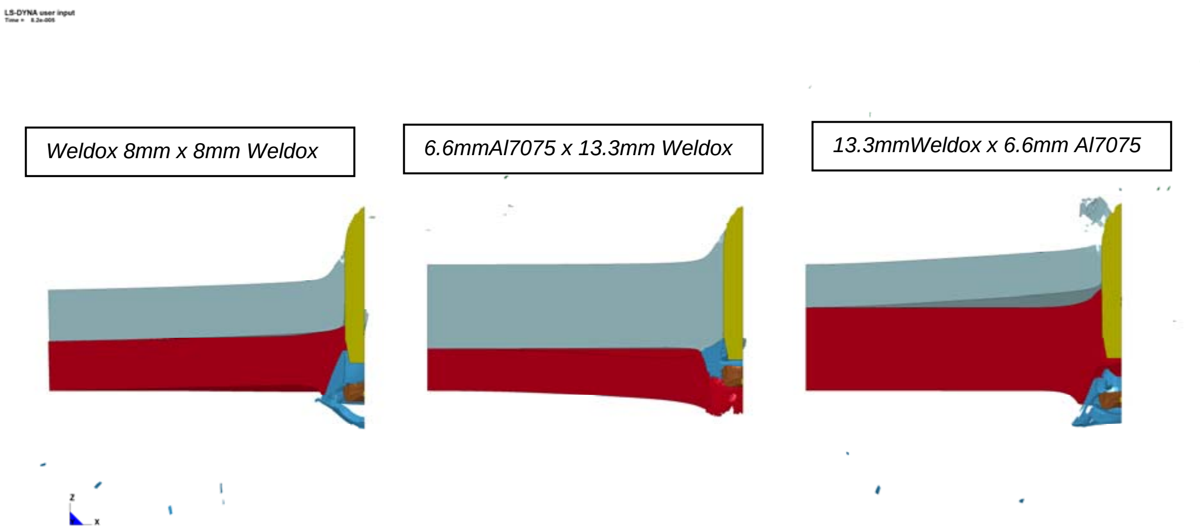

Fig.12: Deformed Shape of Armor Configurations

A double layered armor configurations and thicknesses of each armor material are shown in Figure 12. The first setup is based on double layered total 16mm thick Weldox700E material. In other two double layered configrations both aluminum and weldox materials are used .Also, a comparison of residual velocities with a single layered setup was made see Figure 13.

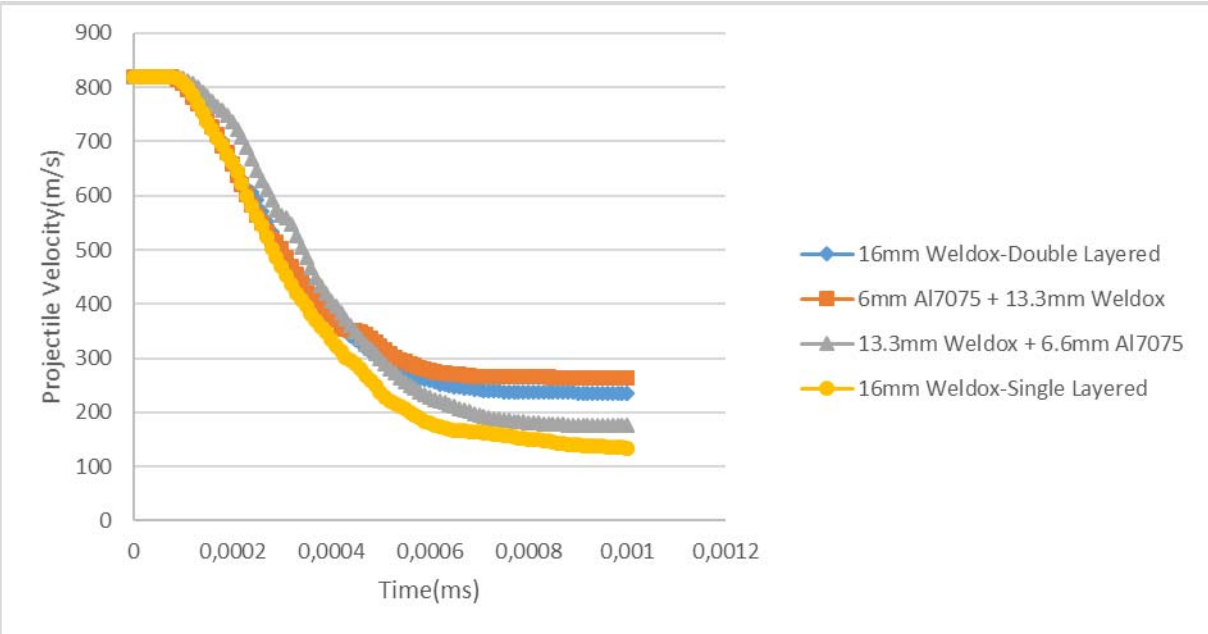

Fig.13: Residual Velocity Comparison of Armor Configurations

Lower projectile exit velocity for 16mm single layered weldox in comparison to double layered setup, can be due to explained from bending stiffness differences between two armor setups. The single layered weldox armor has a higher bending resistance than the double layered weldox configuration.

Table 6: Residual Velocity Values of each configuration

Model Number	Configration	Residual Velocity[m/s]
1	16mm Single Layered Weldox	133
2	16mm Double Layered Weldox	235
3	6.6mm Al7075 + 13.3mm Weldox	174
4	13.3mm Weldox + 6.6mm Al7075	262

The residual velocity is directly related with the back-plane failure characteristics of armor. Model 4 fails earlier than Model 3 because of brittle fracture of Al7075 in the second layer. Model 3 does not fail by ductile failure because this configuration has steel back support, which enhances its ballistic performance when compared with Model 4.

9 Summary

The impact resistance of the Weldox–Aluminium plate systems against full metal jacket projectiles (similar to NATO standard SS109) was numerically investigated. Validation studies were carried out using 2D axisymmetric and 3D Lagrange methods. Furthermore, different element formulations, hourglass formulations and mesh configurations were studied to determine their effects on residual velocity. Moreover, a comparison of single layered and double layered armor configuration was performed.

For numerical model validation study, 16mm single layered Weldox700E configuration was carried out. The mesh size of the target has a significant importance in for penetration analysis. It was shown that the element size in thickness direction of the target plate, directly affects the residual velocity values of the bullet within a high range off difference. It is observed that mesh sensitivity studies are inevitable for ballistic penetration studies. Also, a mesh size study can be done for the bullet as a future work within the scope of this study.

2D axisymmetric model is also analyzed for single layered weldox case. This part of study showed good agreement between literature and quarter model results. The performing axisymmetric case without ADD_EROSION option has some difficulties with the Cockroft Latham failure model option. Negative volume or very low time step values can be seen without defining any additional erosion criteria. For future analysis, adaptive meshing can be used to circumvent these difficulties while solving the axisymmetric model.

Hourglass formulations and element formulations were investigated. Results are checked to determine optimum model for the armor configuration analyses. Three stiffness based hourglass formulations are checked. At a constant 0.13 damping value Type 6 gives best results whereas type 4 and 5 gives over-stiff results. The hourglass damping type and value have extremely high important for the quality of the results. Iterative analyses have to be performed to determine the ballistic limits of armor in the case of lack of test data.

Effect of element formulations on results were also checked. One point and full integration element formulations were tested to examine the residual velocity values. The formulation with one point integration gave results agreeing better with the experiments.

Single layered and double layered Al7075 and Weldox700E armor configurations were analyzed. The single layered setup gives the best results with respect to its residual velocity value. Changing the armor to a double layered setup directly decreases the bending stiffness of the structure, so lower ballistic limit is possible increasing the number of layers in armor configurations. It is concluded that the single layered configuration showed the best result among all configurations. Weight-reduction and improvement of the ballistic performance of the structure are the design goals. Therefore, multi layered aluminum setups can be an option to reduce the weight with the same ballistic performance. Two different configurations were studied. It was observed front Al7075 back Weldox700E configuration is the best option for 20mm thick armor.

Further numerical study will be prepared with Dyneema® material which is widely used in armored vehicles. Due to its low density and ultra-high stiffness properties, armor combinations will be prepared with Dyneema® material and comparisons will be made with the metallic setups

10 Literature

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[1] E.A. Flores-Johnson*, M. Saleh, L. Edwards, Ballistic performance of multi-layered metallic plates impacted by a 7.62-mm APM2 projectile: International Journal of Impact Engineering 38 (2011) 1022e1032

[2] Dey S, Børvik T, Teng X, Wierzbicki T, Hopperstad OS. On the ballistic resistance of double-layered steel plates: an experimental and numerical investigation. Int J Solids Struct 2007;44:6701e23.

[3] Damith Mohotti, Tuan Ngo, Sudharshan N. Raman, Priyan Mendis Analytical and numerical investigation of polyurea layered aluminium plates subjected to high velocity projectile impact Materials and Design 82 (2015) 1–17

[4] B. Balaban, I. Kurtoğlu, An Investigation of AA7075-T651 Plate Perforation Using Different Projectile Nose Shapes 10th European LS-DYNA Conference 2015, Würzburg, Germany

[5] LS-DYNA Keyword User‘ s Manual, May 2014, Version R7.1, Livermore software Technology Corporation(LSTC)