High Velocity Impact Response of High Strength Aluminum Using LS DYNA®

Güralp Başaran, Erkal Özbayramoğlu, Onur Bütün, Eren Öney, Ercan Gürses

FNSS Savunma Sistemleri A. S – Turkey, Oğulbey Mah. Kumludere Caddesi No: 11 06830 Gölbaşı Ankara + guralp.basaran@fnss.com.tr

Orta Doğu Teknik Üniversitesi, Üniversiteler Mahallesi, Dumlupınar Bulvarı No:106800 Çankaya Ankara+ ercan.gurses@metu.edu.tr

1 Abstract

Experimental and numerical studies were conducted to determine the impact response for high strength aluminum armor. A series of ballistic impact tests were carried out for the impact of a 20mm Fragment Simulating Projectile (FSP) with 25.4mm high strength aluminum armor plate at 960m/s impact velocity. This study deals with the measurement of ballistic limits of the deformable FSP against high strength aluminum armor material. The numerical models were developed using the explicit finite element code LS-DYNA®. All parts in the model are modeled with Modified Johnson-cook material model calibrated with performed tests in the company. Material properties are not shared due to confidential issues. A high-speed camera was used for calculation of projectile residual velocities and projectile output images. The numerical model was validated with live test results and a good agreement was achieved between experiments and numerical results. Parameter sensitivity analyses were performed to examine the effect of material model‘s parameters on the response.

2 Introduction

One of the most important subjects in defense industry is the ballistic protection. Numerical methods have been widely used for determination of the ballistic limit. Protection levels of armored vehicles generally depend on thickness of the armor, angel of incidence and nose shape of the projectile. The use of reliable numerical models has gained significant importance where the ballistic tests cannot be performed. In numerical simulations, there are many parameters which can lead to completely different results like element formulations, hourglass type, number of elements in the model, etc. This study contains both ballistic simulations and ballistic experiments to validate the numerical model.

3 LS-DYNA® Model

All numerical analyses were performed by explicit solver of LS-DYNA®. Analyses were done for 960m/s impact velocity only. A fragment simulating projectile was used.

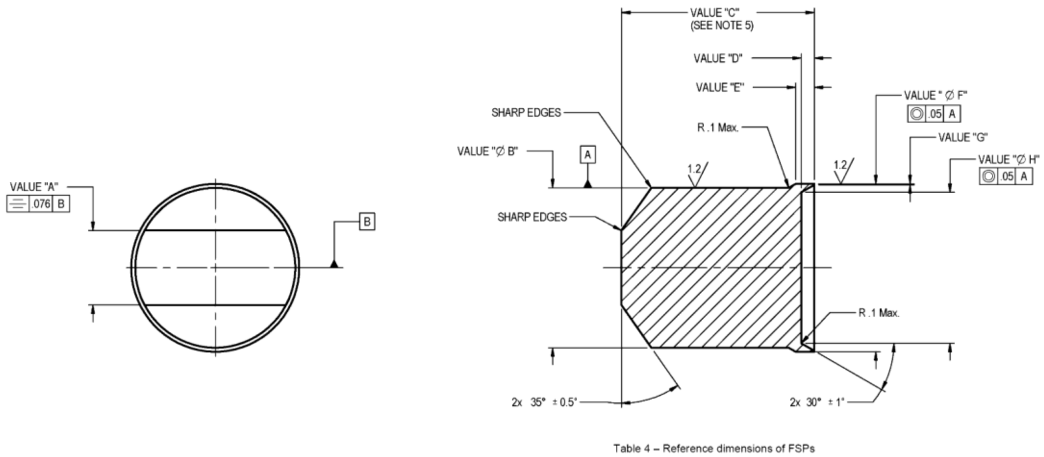

Fig.1: Fragment Simulating Projectile Representation [1]

Fragment Simulator	Weight(g)	A(mm)	ØB (mm)	C(mm)	D(mm)	E(mm)	ØF (mm)	G(mm)	ØH (mm)
12.7mm	13.4±0.13	5,69-0,4	12,57±0,05	15,24	1,15±0,05	1,47±0,05	12,75+0,08	0,13max	11,43±0,05
20mm	53,8±0,26	9,27-0,4	19,89±0,05	24	1,62±0,05	2,31±0,05	20,83+0,08	0,2max	18,80±0,12

Table 1: Dimension of 12.7mm and 20mm Fragment Simulating Projectile

FSP is a specific fragment simulator type based on a standardized cylindrical projectile with a chisel nose (see Fig. 1) which is available in a homologous size series. It is designed to be capable of gun firing to simplify armor testing. [1] A 20mm sized FSP is used at impact velocity of 960 m/s. The target plate is modelled as 300x500mm High Strength Aluminum Plate, see Fig. 2. The MPP LS-DYNA R10.1 solver is selected as solver version. Quarter, half and full model runs are performed, and correlations are made between all models in terms of the residual velocity value. Stiffness based LS-DYNA hourglass damping (`IHQ=6`) is used for all analyses and effect of type of hourglass formulation is examined. Eight node solid element formulation (`ELFORM=1`) with one integration point is used.

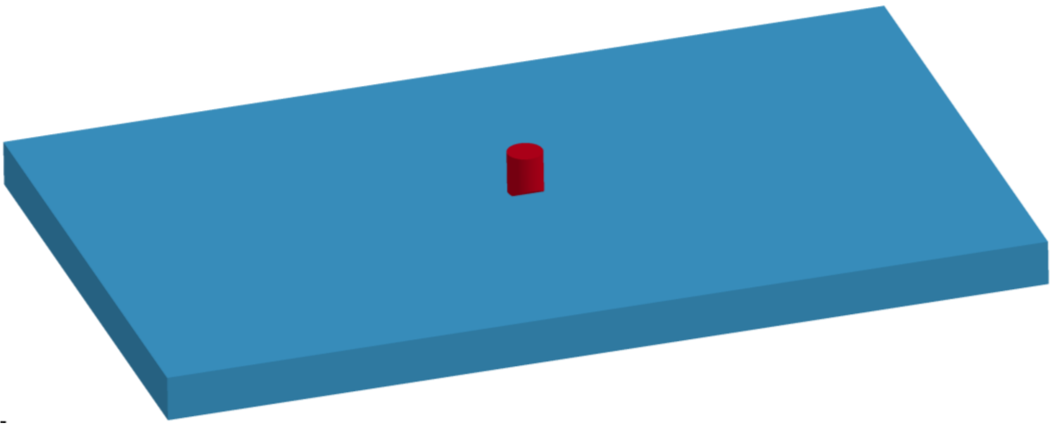

Fig.2: Target and FSP Representation

Impact analysis is performed for different mesh sizes of the impact region. The final element size of the impact region is 0.5x0.6mm with a hexahedral shape for quarter model. Furthermore, a mesh sensitivity analysis is performed only for target material to obtain a robust finite element model for all other cases. FSP mesh size is set same size with impact region for preventing non-physical penetration between the target and the FSP.
Element formulation `ELFORM=-1` is used for FSP and `*CONTACT_ERODING_SINGLE_SURFACE` with `SOFT=2` option is selected for the contact between target and bullet parts. The bucket sort searching algorithm is used at every cycle of the analysis to improve the accuracy. Analysis are finalized in 4 hours for quarter model with 20 cores MPP solution.

4 Material Model

The modified Johnson–Cook material model is used for all 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 [5]. Cockcroft-Latham failure model used in modified Johnson–Cook material model is a simpler failure model and does not need an equation of state input. Cockroft-Latham parameter is a failure criterion depending on stress and strain and it is defined as plastic work per unit volume as shown below.

$$D = \frac{1}{Wcr} \int_{0}^{\varepsilon_{eq}} \max(\sigma_1, 0) d\varepsilon_{p_{eq}}$$

σ_1 represents maximum principal stress and Wcr is the Cockroft-Latham failure parameter, which represents total plastic work. Failure of the element starts when value of *D=1* for `*MODIFIED_JOHNSON_COOK` model. In this study, high strength aluminum is modeled with Voce hardening option. Furthermore, the effects of the Cockroft-Latham parameter Wcr, the strain hardening parameter *n*, and the modified strain rate sensitivity constant *m* on residual velocity are examined. Due to company confidentiality, material properties could not be shared.

Parameter	Unit	Range
Strain hardening parameter n	-	$0.001 \leq n \leq 0.007$
Thermal Softening parameter m	-	$1 \leq m \leq 2$
Crictical Cockroft-Latham Parameter Wcr	GPa	$0.1 \leq Wcr \leq 0.2$

Table 2: Parameter setup for sensitivity analysis

Parameters Wcr, *n* and *m* are changed between the range as shown in Table 2 and their effects on the residual velocity are checked. For each analysis only one parameter is changed while other parameters are kept constant.

5 Experiment Setup

Ballistic tests are performed in ballistic laboratory with 20mm fragment simulating projectile at a 960m/s strike velocity. A view of ballistic laboratory is shown in Fig. 3. High strength aluminum plates of 25.4mm thickness are used in all tests. A high-speed camera is used to measure fragments exit velocity from the aluminum plate. Fragmentation and spall effects are observed with a 30.000fps high speed camera with a resolution of 256x176 pixels. The ballistic test setup is shown in Fig. 4.

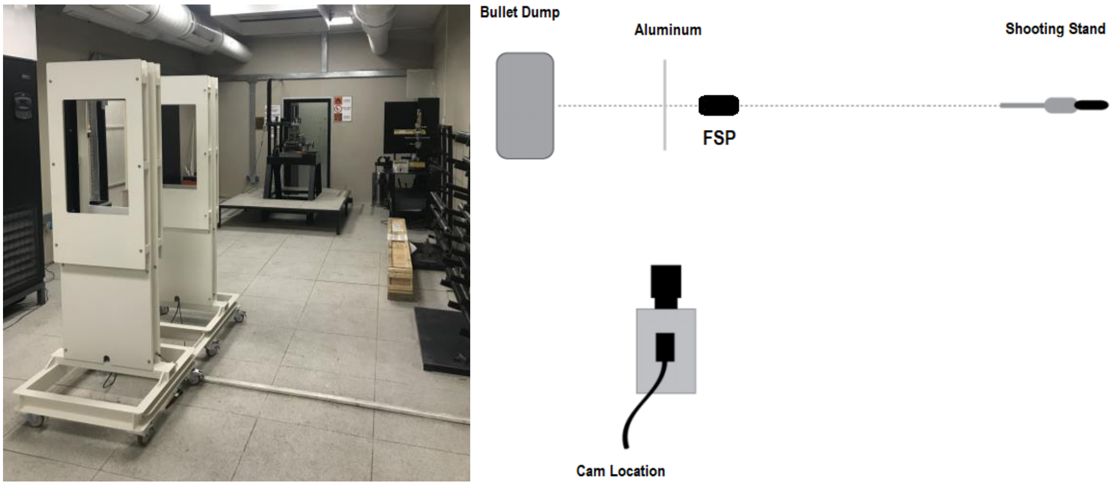

Fig.3: View of Ballistic Laboratory

Calibration of projectile speed is made before each shot and velocity of bullet is set around 960m/s with adjusting the amount of gunpowder. Three shots are performed for calibration of bullet speed and, ±10m/s variations of bullet speed are observed.

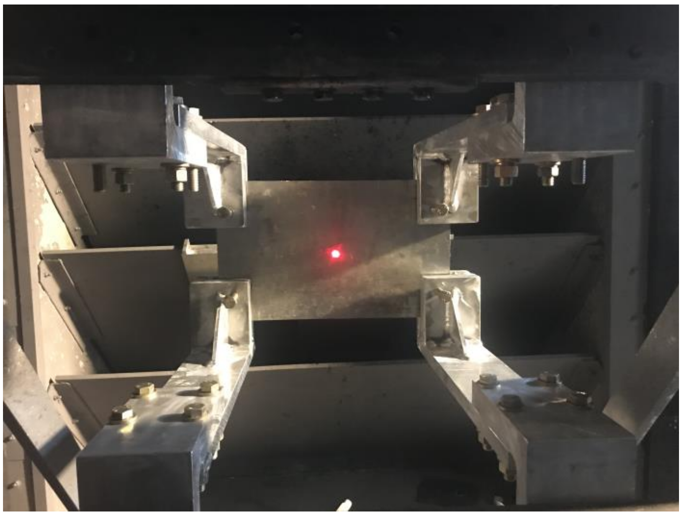

Fig.4: Ballistic Test Setup

Ballistic test results are shown in Fig4. Numerical analyses are conducted and compared with experiment results for the residual velocity values.

Test Number	Thickness of Plate(mm)	Strike Velocity(m/s)	Test Residual Velocity(m/s)
1	25.4	950	511
2	25.4	956	536
3	25.4	957	543

Table 3: Strike and Residual Velocities of Performed Tests

6 Analysis Results

6.1 Mesh Sensitivity Analysis

A mesh sensitivity study is performed for 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. As shown in Fig. 5 the residual velocity does not change much if there are 42 or more elements in the thickness direction.

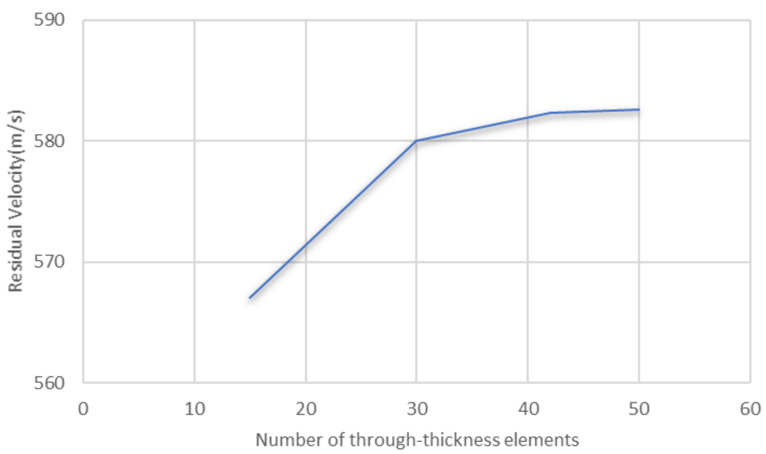

Fig.5: Mesh Sensitivity Analysis

Results show a good correlation with ballistic experiment for 25.4mm aluminum plate. Model number one gives stiffer results compared to other three models. All other three models give very close residual velocity values. Although the model two and three give similar residual velocity values, model three gives better crater shapes when compared to model two. Results of model three and model four are very similar in terms of the residual velocity and crater shapes. The size of the elements in the thickness direction is important in the event of tracing the material's behavior through the penetration process.

Model Number	**Number of Elements Through Thickness Direction**	**Residual Velocity[m/s]**
1	15	567
2	30	580
3	42	584
4	50	585
Experiment[Average]		530

Table 4: Residual Velocity Values

Larger elements may create an artificial eroding effect in the simulation and, therefore, lead to a larger crater size. According to residual velocity values, model three is founded as suitable numerical model for further simulations.

6.2 Hourglass Solutions

Furthermore, the hourglass and element type selection could affect the accuracy of simulations. The use of stiffness based hourglass algorithm yields best results from the energy ratio perspective, which must be close to 1. Standard hourglass damping formulation with a coefficient of 0.1 is compared with three forms of stiffness based hourglass algorithms exist in LSDYNA. A comparison is made for residual velocity values, and hourglass damping energy values.

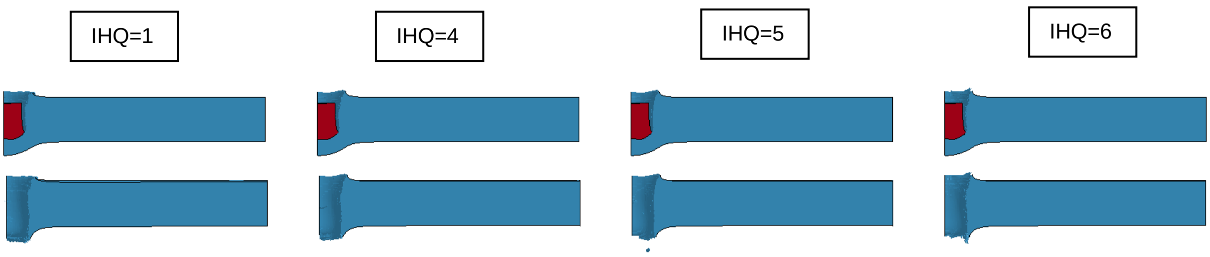

Fig.6: Deformed Shape Model for each Hourglass Formulation

Deformed shapes of each hourglass formulation are shown in Fig6. Damping values are set as constant value of 0.1 for each formulation. Depending on the hourglass formulation, differences are seen in crater shapes as shown in Fig. 6.

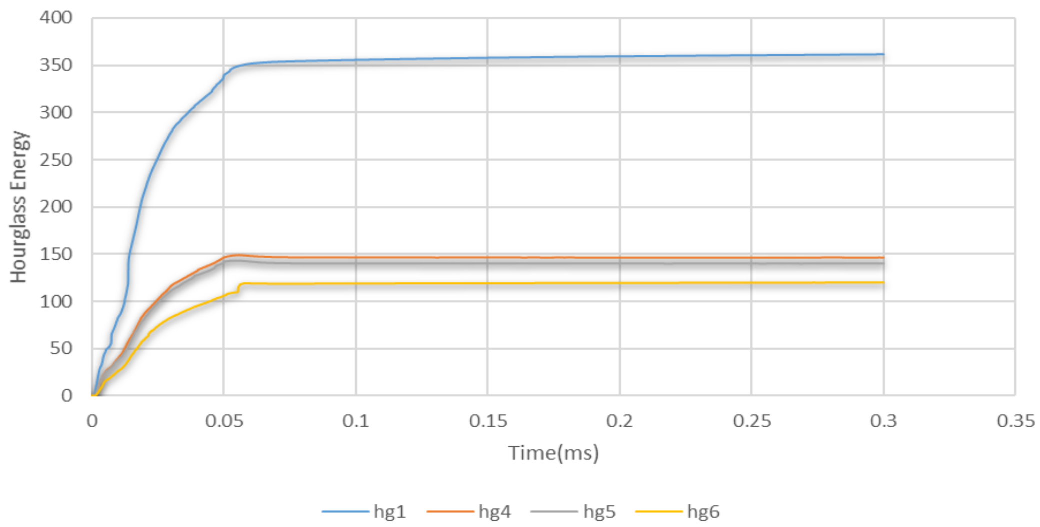

Fig.7: Hourglass Energy Comparison

Also, amount of hourglass damping energy is compared for each formulation. As can be seen in Fig 7 that IHQ=1 adds significantly more energy to the system rather than other damping formulations. IHQ=4 and IHQ=5 damping energy amounts are very similar. Type six IHQ=6 shows the best results among all hourglass formulations. In comparison to total energy of all models, the hourglass energy levels are very low. Similar residual velocity values are found for all hourglass damping formulations, see Table 6.

Hourglass Type	Damping Value	Residual Velocity[m/s]
1	0.1	580
4	0.1	582
5	0.1	584
6	0.1	584

Table 5: Table Hourglass formulations residual velocity comparison

6.3 Element Type Solutions

Four different element formulations (ELFORM=1, -1, -2 and 2) are used for a comparison study. The effect of element formulations on residual velocity results is studied.

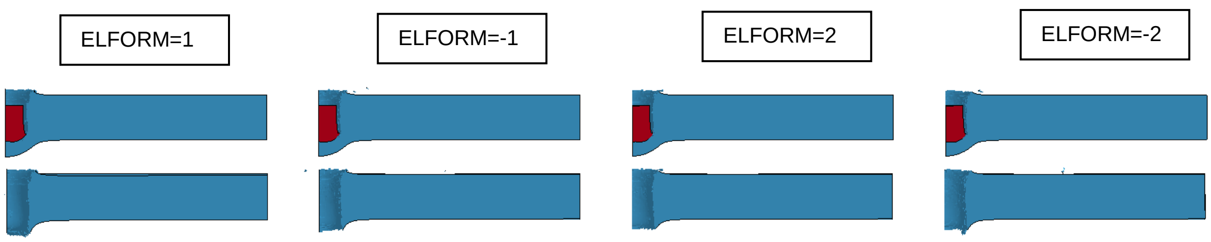

Fig.8: Deformed Shape of each element formulation

Deformed shapes of aluminum plates for different element types are shown in Fig8. As can be seen from the figure, different formulations give very similar crater shapes.

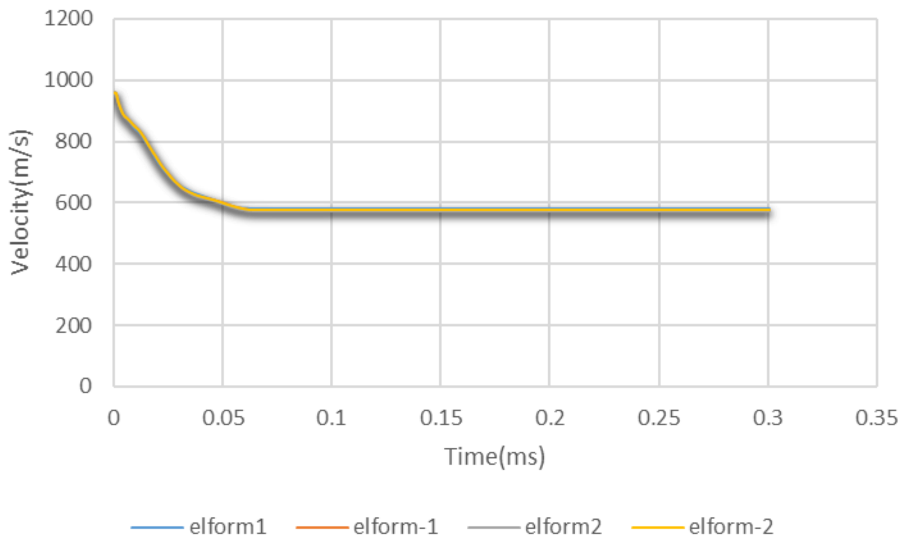

Fig.9: Different element formulation residual velocity results

Very similar residual velocity values are found for all element formulations, see Table 6. It can be seen from Fig. 9 and Table 6 fully integrated elements give slightly stiffer results in comparison to one-point integration formulation.

ELFORM	Residual Velocity[m/s]
1	584
-1	576
2	574
-2	577

Table 6: Residual Velocity Values for Each Element Formulations

7 Material Parameter Sensitivity Analysis

A, B, n, C, m and Wcr parameters are found from simple mechanical tests. In this study, strain rate parameters *n, m* and failure parameter Wcr are examined. For each parameter, analyses are performed and variation of residual velocity values are compared.

Parameter	Values	Residual Velocity(m/s)
Thermal Softening parameter (*m*)	1	577
	1.4	567
	1.75	567
	2	563

Table 7: Thermal softening Parameter effectiveness

Effect of thermal softening parameter *m* is shown in Table 7. An increase of one hundred percent of *m* changes the residual velocity by 2.4%.

Parameter	Values	Residual Velocity(m/s)
Strain Hardening Parameter (*n*)	0.001	577
	0.003	569
	0.004	565
	0.005	563

Table 8: Strain Hardening Parameter Effectiveness

Effect of strain hardening parameter *n* is shown in Table 8. An increase of five hundred percent of *n*, decreases the residual velocity by 2.4%.

Parameter	Values (GPa)	Residual Velocity(m/s)
Cockroft-Latham Parameter (Wcr)	0.1	601
	0.2	551

Table 9: Cockroft Latham Parameter effectiveness

Effect of Cockroft-Latham Wcr parameter is also studied. Doubling the Wcr parameter, decreases the residual velocity by 9% as shown in Table 9.

8 Test Results Comparison

A small thin casing is designed and put to plate side end for preventing flare effects at the start of impact. Projectile exit scene is shown in Fig. 10.

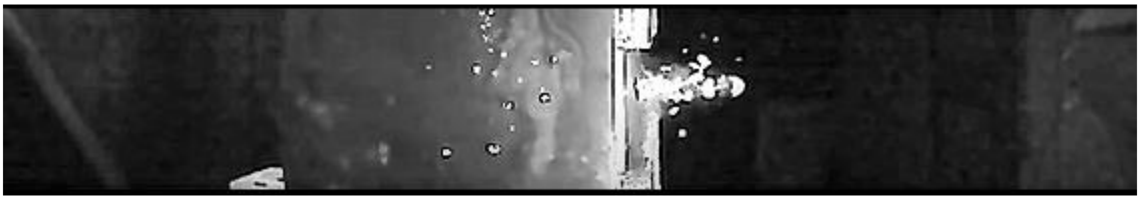

Fig.10: FSP exits scene from ballistic experiment

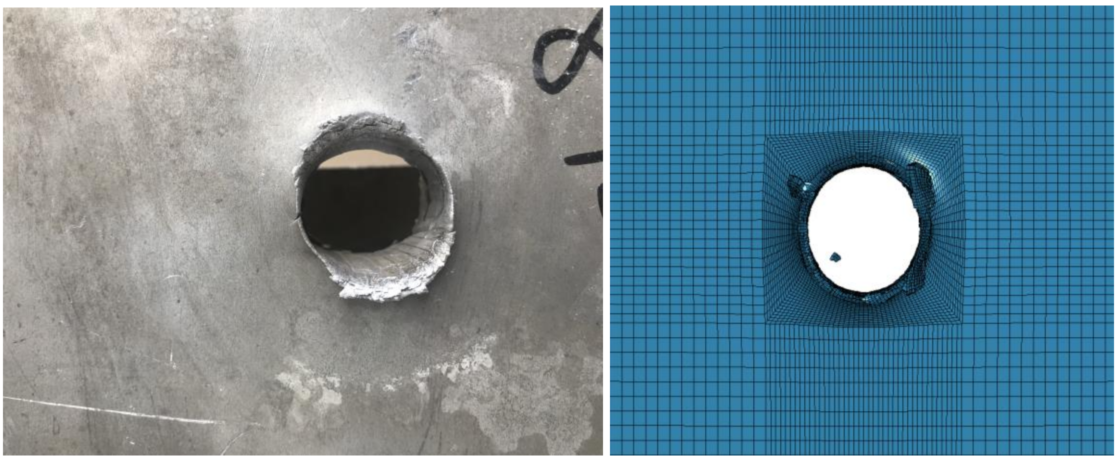

Fig.11: Experiment and Analysis Result Comparison

Deformed shape of plate after ballistic test and simulation results are shown in Fig. 11. A good correlation is seen in after impact crater shapes. Also, a comparison of residual velocity is made. Strike velocity values are measured by laser and high-speed camera pictures. A maximum difference of 6% is found between two measurements. On the other hand, numerical results differ with experiment by 10%.

9 Summary

Both experimental and numerical studied are conducted for impact of an FSP to 25.4mm high strength aluminum plate at an impact velocity of 960m/s. Experimentally, all enter/exit velocities of 20mm FSP are computed with high speed camera and result are compared with LS-DYNA simulations.

For numerical model validation study, mesh sensitivity, hourglass formulations and element formulations are examined. The effect of these parameters to the residual velocity values are evaluated.

In mesh sensitivity studies four types of mesh configurations are checked and minor changes are seen on residual velocity values. In terms of crater/deformed shape, model number three gives similar results with experiment. 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.

Additionally, hourglass formulations are investigated. In addition to standard hourglass damping formulation, three stiffness based hourglass formulations are checked. IHQ=6 gives the best results among all other hourglass damping formulations. Energy level of hourglass of formulation six is less than other formulations. Compared to total energy levels, the hourglass energy is relatively small in all formulations. Very similat results are observed among all hourglass formulations. Differences among all formulations are in %0.5-%1 range.

After the hourglass formulation study, different element formulations are examined. One integration point elements are compared with fully integrated elements. Fully integrated elements give stiffer results as expected, but residual velocity vales are very close with one-point integration element results.

Furthermore, a parameter sensitivity analysis is done for some parameters of the Modified Johnson-Cook model. Effects of Wcr, *m* and *n* on residual velocity are analyzed. Analyses are performed with different parameter values which are shown in Table 7, Table 8 and Table 9. Increasing the thermal softening parameter twice changes the residual velocity by 2.4%, whereas increasing the strain hardening parameter five times also changes residual velocity by 2.4%. Furthermore, effect of Wcr parameter examined. It is seen that when value of Wcr is doubled, the residual velocity changes by 10%. It is concluded that Wcr affects the residual velosity more significantly than the thermal softening and the strain rate parameter.

10 Literature

[1] NATO STANAG 4569, “Protection Levels for Occupants of Armoured Vehicles”

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[3] 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

[4] 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.

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