A Review of Structural Part Modelling for Blast Simulations

Buğra Balaban, İlker Kurtoğlu

FNSS Savunma Sistemleri A. Ş.

1 Abstract

In this study, the effects of various element formulations and mesh sizes are investigated for buried charge simulations using the non-linear finite element code LS-DYNA®. Simulations are performed according to the real test conditions and the results are compared with the plate level mine blast experiments. Tests are carried out using a test setup which is designed and manufactured by FNSS. The blast simulations are examined using ALE method. Simulation model consists by ALE domain which includes soil, air and the explosive definitions and Lagrange domain for the bottom and side plates of the vehicle. The evaluated test plate is made of RHA steel. Simplified Johnson Cook material model is used and the parameters are determined by Split-Hopkinson Pressure Bar tests. Plates are modelled using shell, solid and thick shell elements with different element formulations. Consequently, the elastic and plastic deformation results, effective plastic strain distributions, pressure histories and the cpu times are compared. Furthermore, the advantage and disadvantages of the considered formulations and parameters are presented.

*KEYWORDS: Blast simulation, element formulations, solid elements, shell elements, thick shell elements, ALE, military vehicles

2 Introduction

Mine protection is a critical requirement for military vehicles. The vehicles should withstand the loads from the explosion and the secondary fragmentation. For this reason, plate level and full scale mine blast tests are performed for the evaluation of the vehicle survivability. Furthermore, computer simulations are commonly used and the accuracy of the simulations should be reasonable in order to have a successful final design. In case of blast loading; especially bottom plate has a great role for vehicle protection. During the hull design, bottom plate deformation behaviour is taken into account to determine the floor plate location. Since the blast protection is one of the most important design criterion, vehicle hull structures are made of high strength materials with relatively high thickness as compared to the commercial vehicles. Owing to these thick plates, using appropriate modelling techniques, element types and mesh sizes are important for acceptable simulation results. In this study different element types, are considered for the bottom plate and side plates of the military vehicle which are made of RHA steel. As a result, the total and permanent deformation results, effective plastic strain distributions, fluid-structure interaction (FSI) pressure histories and the cpu times are compared.

3 Buried Charge Tests

In order to evaluate the vehicle survivability capability against mine threats, plate level mine blast test are practically used and can give valuable results in the preliminary step of the full vehicle validation tests. General purpose is to evaluate different plate configurations against blast loads and global elastic and plastic deformations are measured for each plate configurations. Various configurations in terms of thickness and material of the bottom and side plate are tested. A deformation cone is designed and used in order to measure the total central displacement of the plates.

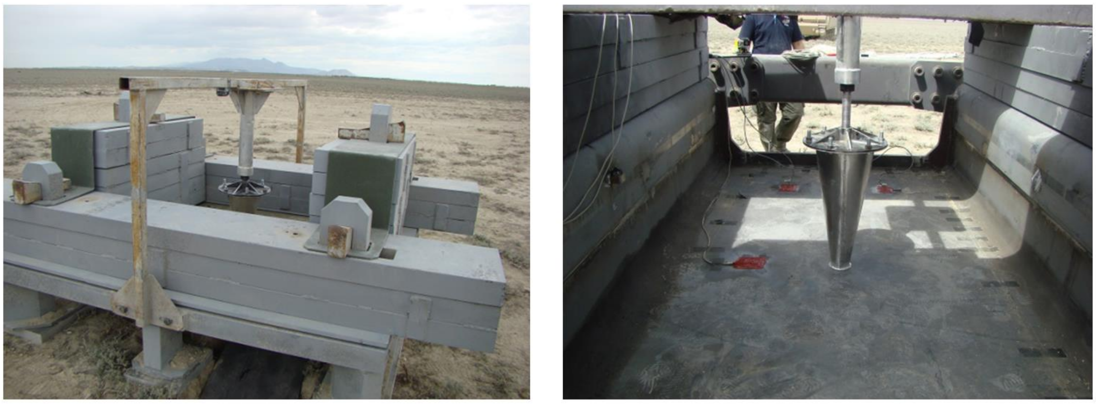

Fig.1: Test Setup

4 FE Models and Materials

Simulation model contains ALE domain which includes soil, air and the explosive definitions, lagrange domain for test setup and the tested plate configurations. Test setup is made of commercial steel and **`*MAT_PLASTIC_KINEMATIC`** material model is used. General steel material parameters are obtained from literature. Finite element model of the test setup is created with solid and shell elements which is compatible with real structure.

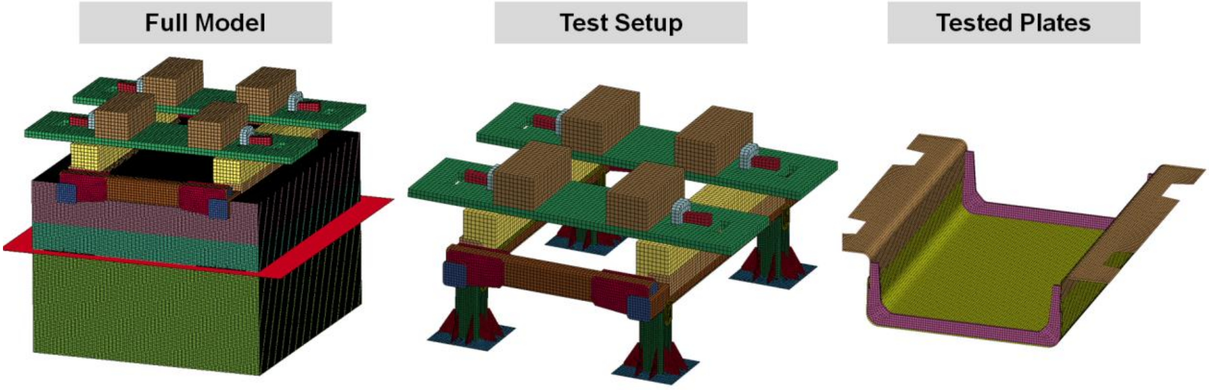

Fig.2: Full Model Mesh

4.1 ALE Domain

ALE domain consists by air domain, soil and explosive that shown in Figure 4. Air domain is divided into two parts, one of which is between the soil and the plate and the other one is the upside of the plate. Although single air domain is also applicable, this approach is selected to ensure more practical visualization and leakage optimization [1]. The air is modeled with **`*MAT_NULL`** and **`*EOS_LINEAR_POLYNOMIAL`** keywords. **`*MAT_SOIL_AND_FOAM_FAILURE`** is used for soil model. The equation of state parameters of air and the soil parameters which are determined by field tests are taken from [1]. The explosive material is modeled with **`*MAT_HIGH_EXPLOSIVE_BURN`**. **`*EOS_JWL`** equations of state with the parameters for TNT are taken from [2]. **`*INITIAL_VOLUME_FRACTION_GEOMETRY`** is used to fill into the ALE domain by soil, air and explosive. The fluid-structure interaction between the target plate and ALE model is carried out with **`*CONSTRAINED_LAGRANGE_IN_SOLID`** keyword and parameters are considered from previous studies which are optimized to eliminate leakage [1].

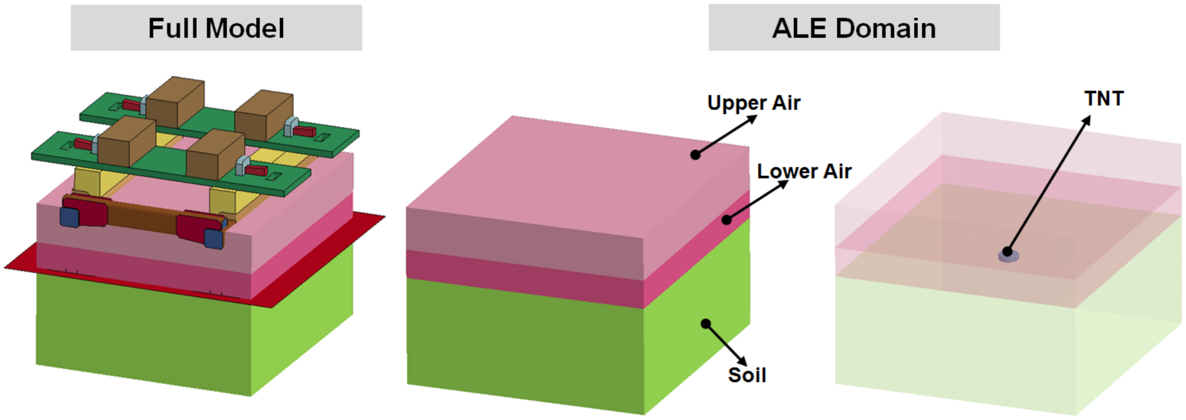

Fig.3: ALE Domain

4.2 Tested Plate

Test plate consists by bottom plate, side plates and side reinforcements made of RHA steel and modeled with **`*MAT_SIMPLIFIED_JOHNSON_COOK`**. Material parameters are determined by Split-Hopkinson Pressure Bar tests in Izmir Institute of Technology. Finite element models for plates are created with shell, solid and thick shell elements. Solid models are created with 1 and 2 element through thickness respectively. Different element formulations are utilized that shown in Table 1.

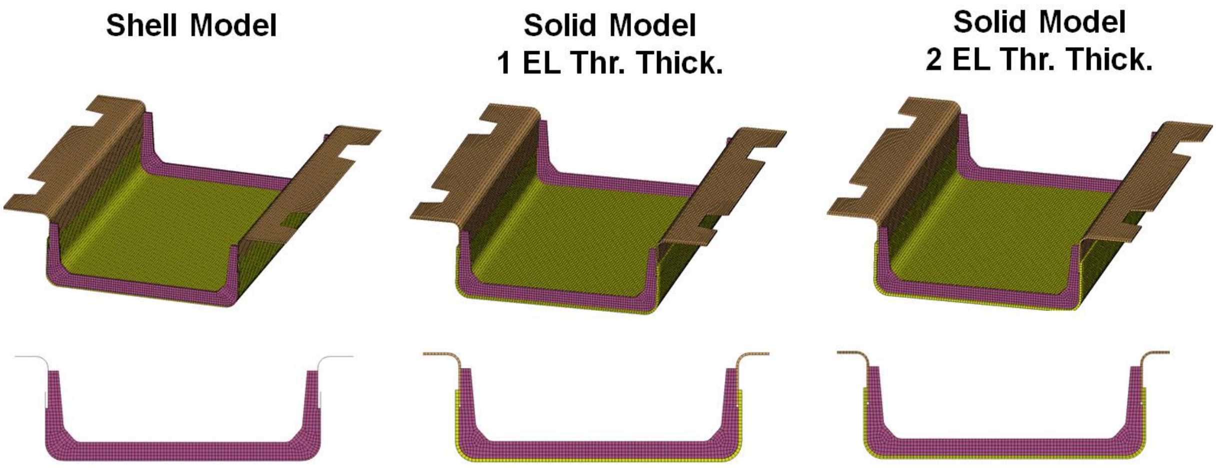

Fig.4: Shell and Solid Mesh Configurations

Model	Element Type	Element Formulation	Element Thru Thick.
SHL 1	SHELL	ELFORM 16	---
SHL 2	SHELL	ELFORM 26	---
SLD 1	SOLID	ELFORM 2	1
SLD 2	SOLID	ELFORM -1	1
SLD 3	SOLID	ELFORM 2	2
SLD 4	SOLID	ELFORM -1	2
TSH 1	TSHELL	ELFORM 2	1

Table 1: Mesh Configurations

As stated in Table 1, fully integrated shell formulation ELFORM16 and thickness stretch element formulation ELFORM 26 is considered. Gauss – integration (INTGRD=0 in **`*CONTROL_SHELL`**) with 5 integration point through thickness (NIP=5 **`*SECTION_SHELL`**) is used for shell models. Furthermore MAXINT=5 is defined in **`*DATABASE_EXTENT_BINARY`** keyword to get strain results at 5 integration points. Furthermore, fully integrated thick shell formulation ELFORM 2 is utilized which is 8 node shell with 2d stress state. As similar with shell formulations NIP=5 is considered.

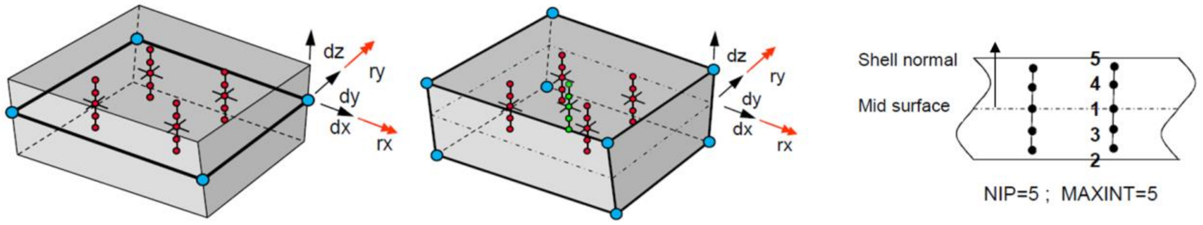

Fig.5: Shell, Tshell Integration Points[3,4]

Additionally, fully integrated S/R 8 node hexahedron solid formulation ELFORM2 and the extensive type ELFORM-1 are examined. As shown in Figure7, only 1 and 2 elements through thickness configurations are considered.

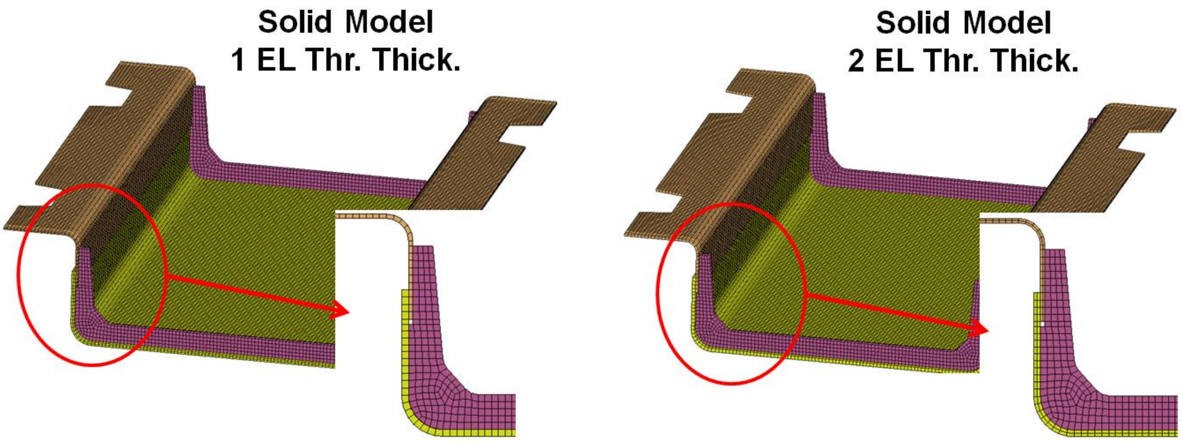

Fig.6: Solid Element Mesh

5 Simulation Results

All simulations are run at 20 cores. LS-DYNA® MPP 7.1.3 (SVN107967) solver and Intel® MPI is used. Totally 7 simulations are carried out with 5 element formulations. Simulations are performed in two steps. Firstly, simulations are solved 10,000 micro seconds with full model which includes ALE domain and all structures. Regarding the simulation results up to 10,000 micro seconds, it is concluded that forces from the fluid domain is close to zero. In this step pressure outputs, maximum displacement results, run times and effective plastic strain magnitudes are presented. In order to get more accurate permanent displacement results on bottom plate; in the second step, ALE domain and the fluid structure interaction are deleted with `*DELETE_PART` and `*DELETE_FSI` keywords respectively. The simulations are run up to 100,000 micro seconds to decrease the inertial effects. Permanent displacements on bottom plate are finally presented and compared with test results.

5.1 Pressure Results

Figure 8 illustrates the simulation stages up to 2100 micro seconds.

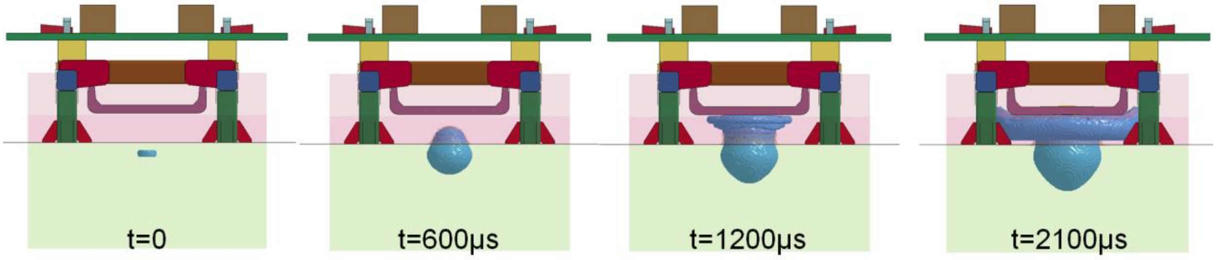

Fig.7: Simulation Stages

As shown in Figure 9 below, pressure history at bottom plate is presented. It is found that maximum pressure is obtained at time…. µs for all plates. Even the peak pressure magnitudes of solid mesh configurations are nearly 10% higher than shell models, thick shell mesh configuration has relatively high pressure history in comparison with both shell and solid models.

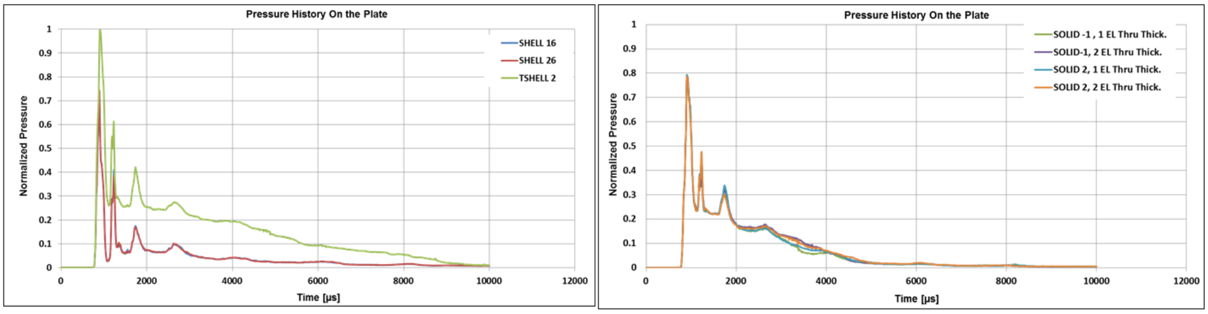

Fig.8: Pressure History on Bottom Plate

5.2 Displacement Results

Regarding the simulation results, maximum and permanent displacements are compared with experiments and % error levels are presented below.

Model	Element Type	Element Formulation	Element Thru Thick.	Maximum Displacement % Error	Permanent Displacement % Error
SHL 1	SHELL	ELFORM 16	---	5,8	11.9
SHL 2	SHELL	ELFORM 26	---	5,8	6.7
SLD 1	SOLID	ELFORM 2	1	9,9	23.1
SLD 2	SOLID	ELFORM -1	1	10.3	22.4
SLD 3	SOLID	ELFORM 2	2	1,8	4.5
SLD 4	SOLID	ELFORM -1	2	7,2	14.9
TSH 1	TSHELL	ELFORM 2	1	3.1	0.7

Table 2: Maximum and Permanent Displacement Comparison

It is obtained that SLD3 model has the lowest %error for maximum displacement results. In addition, TSH1 model is the best regarding the permanent deformations.
Figure 10 shows the displacement history for all mesh configurations up to 10,000 micro seconds. It is noticed that; SLD3 model reaches to maximum deformation stage earlier than the other mesh configurations.

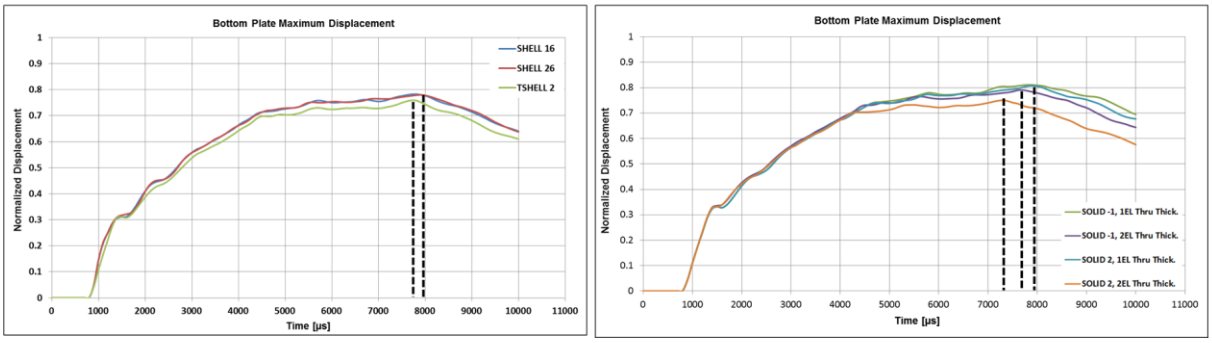

Fig.9: Bottom Plate Displacement History

Additionally, the deformations of bottom plate are compared for transverse and longitudinal directions at the time when the plate reaches its maximum displacement.

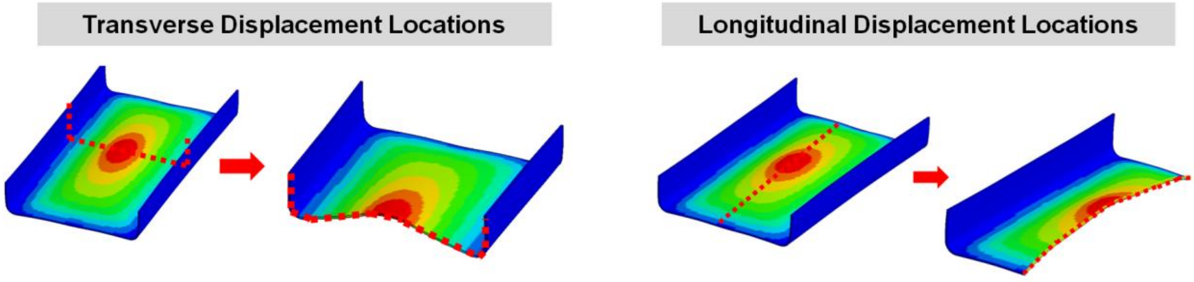

Fig.10: Transverse & Longitudinal Displacement Locations

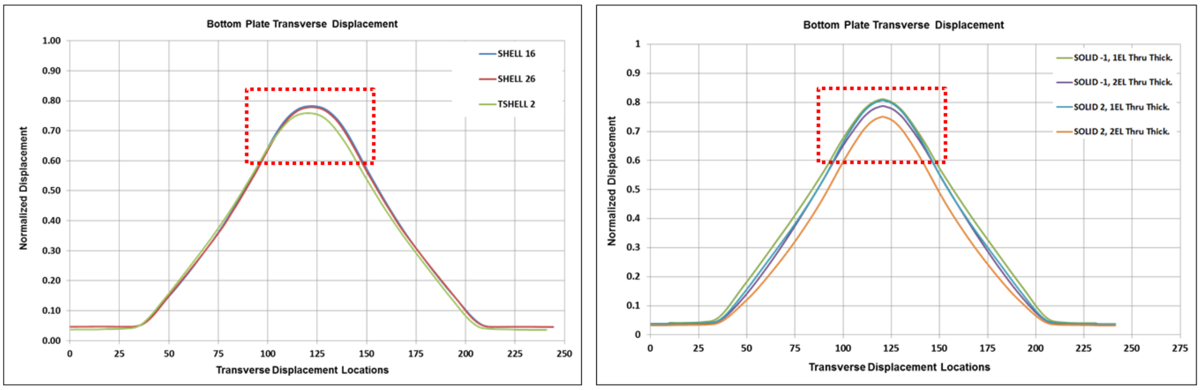

Fig.11: Bottom Plate Transverse Displacement Comparison

As illustrated at Figure 12 with the comparison of shell and thick shell elements, there is a small difference observed for transverse deformations.

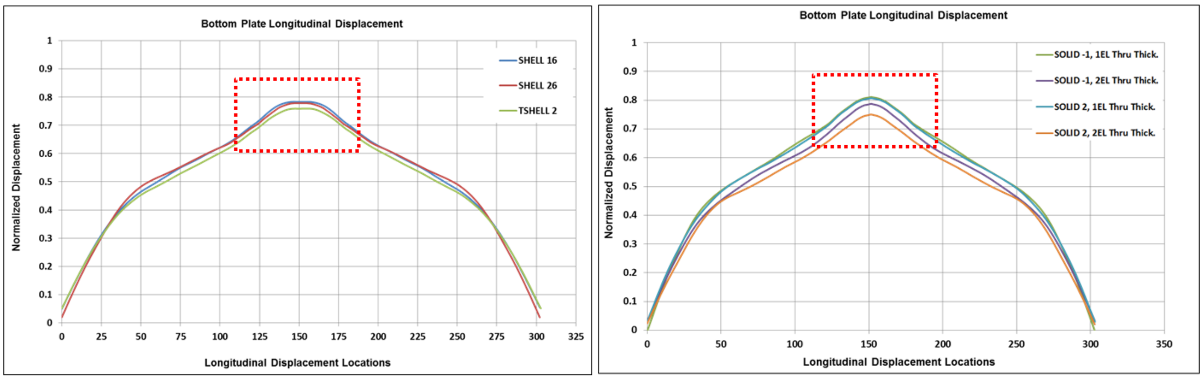

Fig.12: Bottom Plate Longitudinal Displacement Comparison

Figure 14 shows the deformation mode on the bottom plate. It can be seen that solid elements have ogival shape on top face, with the comparison of shell model.

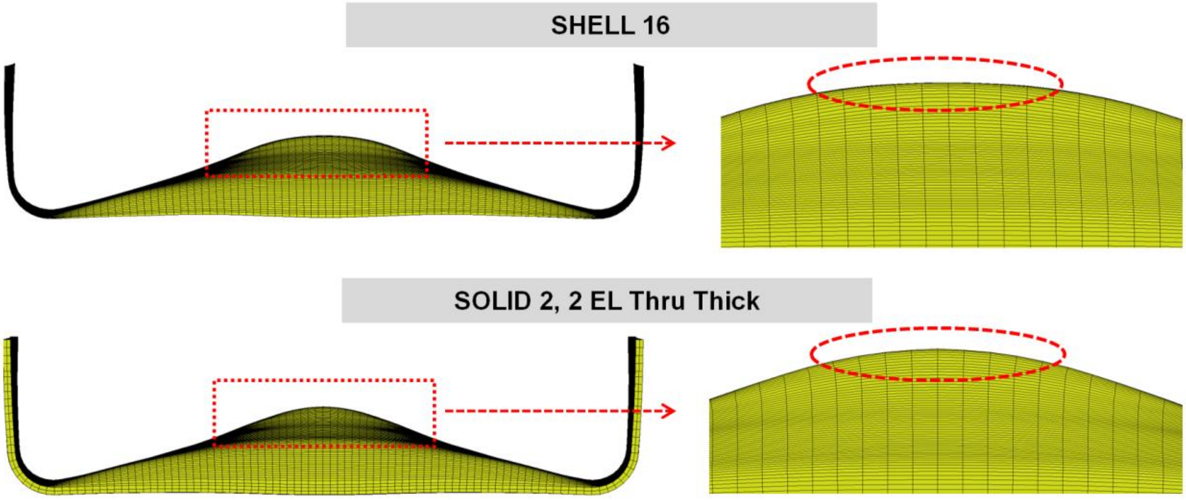

Fig.13: Maximum Deformation Shape of Bottom Plate

5.3 Run Time Comparison

Run times are compared in Table 4 and Figure 14 below.

Model	Element Type	Element Formulation	Element Thru Thick.	Run Time [s]
SHL 1	SHELL	ELFORM 16	---	32725
SHL 2	SHELL	ELFORM 26	---	33394
SLD 1	SOLID	ELFORM 2	1	38137
SLD 2	SOLID	ELFORM -1	1	37021
SLD 3	SOLID	ELFORM 2	2	40553
SLD 4	SOLID	ELFORM -1	2	50730
TSH 1	TSHELL	ELFORM 2	1	50130

Table 3: Run Time Comparison

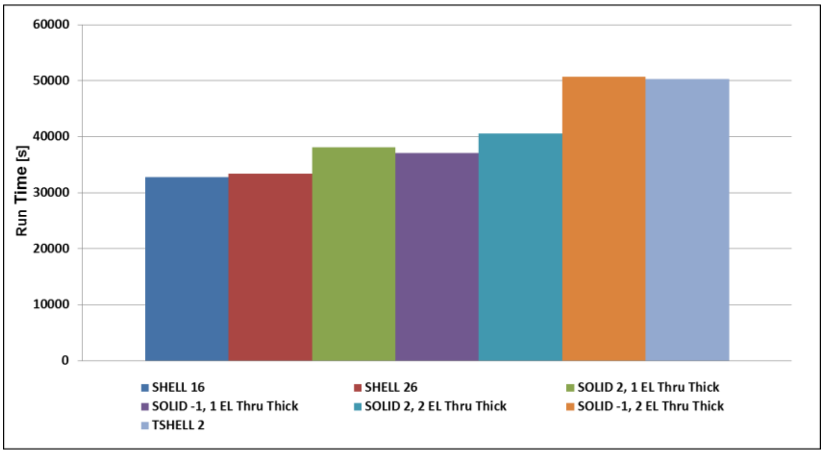

Fig.14: Run Time Comparison

In terms of run time SLD4 model is the most expensive mesh configuration in our case. Nevertheless there are slight differences between SLD4 and TSH1 models. Also, it is obtained that SLD1,SLD2 and SLD3 models have relatively similar run times and shell models are nearly 20% lower than solids.

5.4 Effective Plastic Strain Results

Effective plastic strain levels for all element configurations are presented below. Table 5 compares the maximum effective plastic strains at the center elements of the bottom plates where the maximum displacements are presented. For shell elements; maximum strains over 5 integration points and also average values of IP1 to IP 5 and average of IP1,IP4 and IP5 are calculated. For solid elements, similar with shell formulations, maximum strains over 8 integration points and also average values of IP1 to IP 8 are listed.

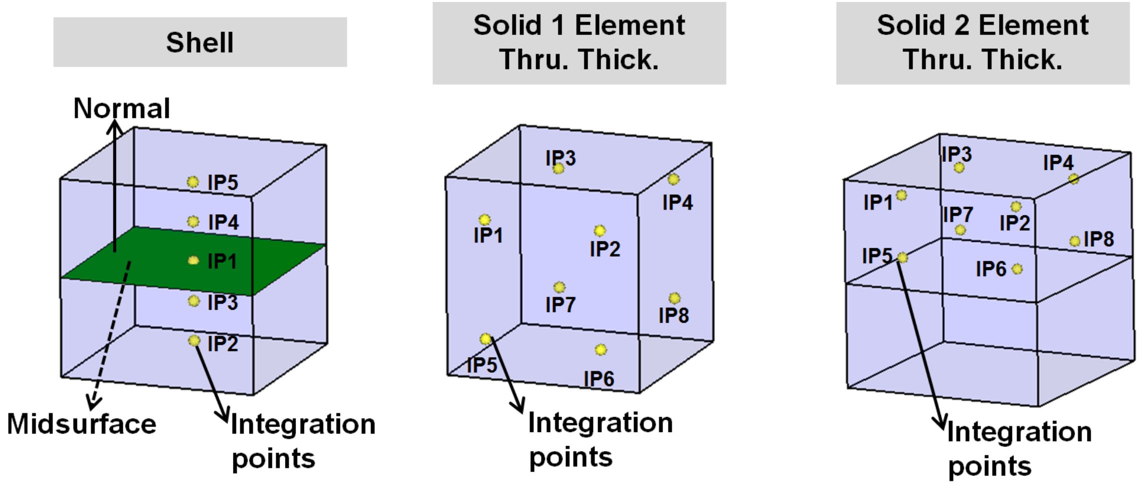

Fig.15: Shell and Solid Element Integration Points

Regarding the results, maximum effective plastic strain magnitues are calculated at upper integration points which are correspond to top face of the bottom plate. As shown in Table 5 maximum effective plastic strain levels of shell, tshell models (SHL1,SHL2, and TSH1) and solid models which have 2 elements through thickness (SLD3, SLD4) have similar results (Column A and D). Furthermore, with the comparison of average strain values of shell, tshell models (SHL1,SHL2, and TSH1) and solid configurations which have 1 elements through thickness (SLD1, SLD2) strain magnitudes are close each other (Column B and E). In addition, average strain magnitudes of SLD3 and SLD4 models are compatible with shell average strains of IP1,4,5 which are corresponded to upper side of the plate (Column C and E).

		A	**B**	**C**	**D**	**E**
Model		**Eff. Plas. Strain Shell Max.**	**Eff. Plas. Strain Shell Ave. [IP 1-5]**	**Eff. Plas. Strain Shell Ave. [IP 1,4,5]**	**Eff. Plas. Strain Solid Max.**	**Eff. Plas. Strain Solid Ave. [IP 1-8]**
SHL 1	**SHELL 16**	0.133	0.071	0.109	----	----
SHL 2	**SHELL 26**	0.124	0.064	0.103	----	----
TSH 1	**TSHELL 2**	0.126	0.063	0.085	----	----
SLD 1	**SOLID 2, 1 EL Thru. Thick.**	----	----	----	0.084	0.066
SLD 2	**SOLID -1, 1 EL Thru. Thick.**	----	----	----	0.085	0.066
SLD 3	**SOLID 2, 2 EL Thru. Thick.**	----	----	----	0.124	0.108
SLD 4	**SOLID -1, 2 EL Thru. Thick.**	----	----	----	0.117	0.104

Table 4: Effective Plastic Strain Comparison

Figure 16 illustrates the maximum effective plastic strain distributions of all mesh configurations which are calculated from the upper integration points. As shown in figure below, all models have different strain distribution. However, maximum strain magnitudes at center of the bottom plate have similar results especially for SHL1, SHL2, TSH1 SLD 3 and SLD4 models which are also presented at Table4.

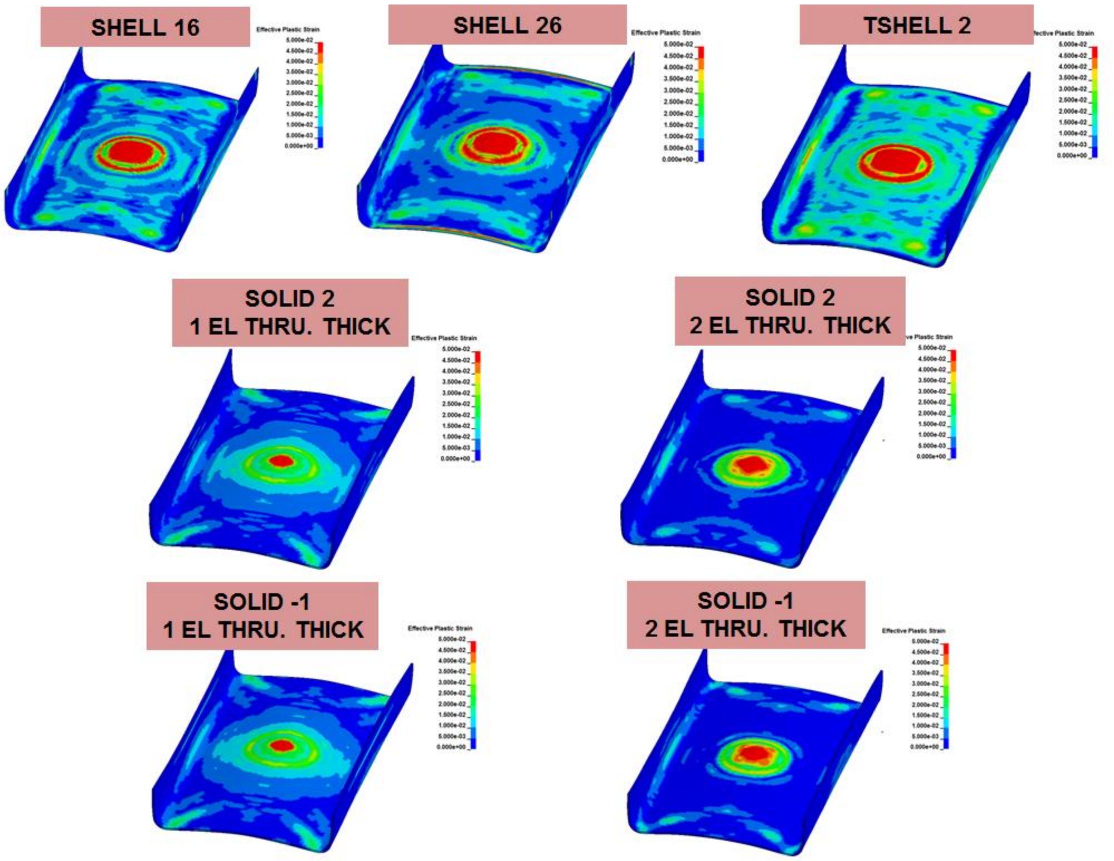

Fig.16: Effective Plastic Strain Distribution on Bottom Plate

6 Summary and Future Works

In this study different element formulations are considered for the bottom plate of a military vehicle in case of blast loading. Regarding the results, pressure history on bottom plate, maximum and permanent deformations, run time, deformation shapes and effective plastic strains are compared for all mesh configurations.

In terms of deformation results, thick shell ELFORM2 and solid ELFORM2 with 2 element through thickness configuration has the most compatible results with experiment. Moreover, thick shell ELFORM2 and solid ELFORM-1 with 2 element through thickness configuration are computationally expensive models. With the comparison of run time for solid ELFORM 2 and -1 configurations, SOLID -1 is 20% more expensive than SOLID 2. Similar conclusion is also stated in [3].

According to the pressure history results on bottom plate, it is found that tshell mesh configuration has relatively high pressure history in comparison with both shell and solid models. Pressure history outputs are calculated with the **`*DATABASE_FSI`** keyword. For shell and solid element configurations, bottom plate part id is selected for pressure output but for thick shell elements it doesn’t work and a segment set which defines the lower face of tshell elements and pressure output is calculated from defined segment set as STYPE. The difference can be caused by the STYPE definition and will be investigated at future work.

Finally, effective plastic strain distributions are presented and it is noticed that all configurations have different strain distributions on bottom plate. However maximum strain magnitudes at center of the bottom plate have similar results especially for SHL1, SHL2, TSH1, SLD 3 and SLD4 models. Since there is no strain measurements on bottom plate, simulation results couldn’t be compared with experiment.

As a result of the study, for the evaluation of the global deformation levels of bottom plate, shell ELFORM 26 has quite acceptable result and cost-effective run time. Moreover, if the local deformations are important, thick shell ELFORM 2 and solid ELFORM 2 with more than 2 element through thickness configurations should be used. As a future work, blast and impact tests will be carried out for bottom plates with similar thickness and in addition to elastic & plastic displacements, strains are also measured on tested plates and detailed comparison will be made with test and simulations.

7 Literature

[1] Kurtoğlu İ., An Assessment of ALE Mapping Technique for Buried Charge Simulations. 10th European LS-DYNA Conference, Würzburg, Germany, 2015.

[2] Dobratz B. M., Crawford P. C., LLNL Explosives Handbook – Properties of Chemical Explosives and Explosive Stimulants, Lawrence Livermore National Laboratory, California, USA, 1985.

[3] Stelzman U., Die große Elementbibliothek in LS-DYNA. ANSYS Conference & 28th CADFEM User’s Meeting , Aachen, Germany, 2010.

[4] Haufe A., Schweizerhof K., DuBois P., Properties & Limits: Review of Shell Element Formulations, LS-DYNA Developer Forum 2013, Filderstadt, Germany, 2013.

[5] LS-DYNA Keyword manual R7.1.

[6] Teng H.,Recent Advances on Higher Order 27-node Heahedral Element in LS-DYNA, 14th International LS-DYNA User’s Conference, Detroit, USA, 2016.