Validation of Mine Blast Simulations with Field Tests

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Abstract

In this work, LS-DYNA® simulation results of mine blast of flat aluminum/steel plates and validation studies using mine blast tests are presented. The buried mine simulations are performed using ALE initial volume fraction and SPH methods. The high strain rate Johnson Cook material models of the plates are obtained through Split Hopkinson Pressure Bar tests, for both high strength steel and aluminum specimen. The soil parameters such as density and humidity ratio are determined by appropriate tests. Structural acceleration and strain data as well as blast pressures are measured during the field mine blast tests. A test setup is designed and manufactured in order to conduct the tests. This setup consists of dead weights for constraining the plate during the explosion. For measuring the plastic and total deformation of the plates, a novel method using thin walled aluminum cones are used. High speed and high bandwidth data acquisition systems are used to capture the highly dynamic behavior of the plates. Moreover, incident and reflected blast pressures from various distances are measured and compared with analytical methods, LS-DYNA simulations and bikini gage measurements. In this way, explosive and blast characteristics are verified. The correlation and similarity of simulation and test results for acceleration and deformation characteristics are presented. The results obtained by LS-DYNA simulations show very good agreement with results obtained in the field tests.

1 Introduction

Mine protection is a critical issue for the armored military land vehicles. The vehicle hull should withstand the loads that results from the blast pressure and secondary fragmentation. Testing and validating the protection level of a vehicle may not always be possible because of the high cost of mine tests. For this reason, a model verification procedure is developed in FNSS Savunma Sistemleri A.S. (FNSS) for the buried mine blast simulations, starting from a simple plate model and going up to the full vehicle. In this study, the first leg of this validation path, the plate simulations and verifications are explained and model verification test results are given. For the simulations, Arbitrary Lagrangian-Eulerian (ALE) method and Smoothed Particle Hydrodynamics (SPH) methods are used for aluminum plates and ALE method is used for steel plates. For the post processing of the simulation results and comparison with the test results, LS-PrePost®, software package is used.

2 Air Blast Tests

Before starting the validation of plate simulations, an air blast test validation is performed in order to make sure that the explosive parameters are consistent. A model is prepared for the air blast including the reflecting plates. The incident and reflected pressures are measured and compared with the analytical results as well as the test measurements. For the analytical approach, Brode method is used.

The model for the air blast is prepared as a symmetric model and two reflecting plates are modeled for the reflected pressure measurement. The soil and the explosive are modeled with INITIAL_VOLUME_FRACTION_GEOMETRY. The explosive is formed as a spherical charge. The mass of the explosive cannot be given due to the confidentiality.

The finite element model is shown along with the test setup in Figure 1 below.

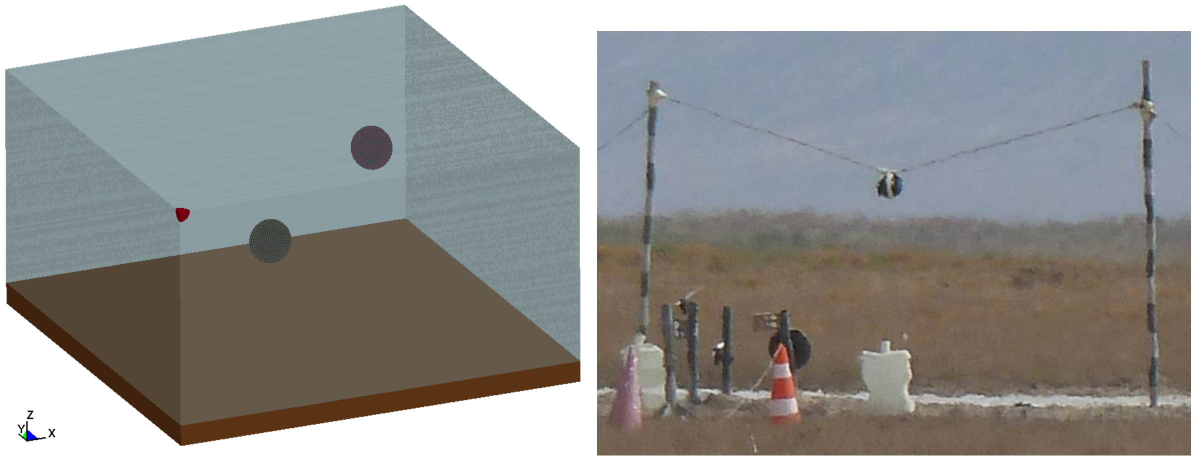

Figure 1. Air blast model and the test set up.

The comparisons of all results are shown in figure below with normalized values. Theoretical value of the incident pressure at 2.5 meters away from the explosive is taken as 1 and the other values are given with respect to the theoretical value.

Table 1. Air blast pressure data comparison.

	Theoretical	LS-DYNA	Test
Incident @2.5m	1	1.012	0,803
Reflected @2.5m	4.51	3.94	-
Incident @5m	0.21	0.41	0.45
Reflected @5m	0.57	0.71	0.79

As it can be seen from Table 1, LS-DYNA results are considerably consistent with the test data especially at 5 meters away from the explosive.

3 Test Plates and Materials

Simulation of two different plates is performed and verification tests are explained in this work. First plate is aluminum alloy with 25 mm thickness, and the second one is a high strength steel plate with 12 mm thickness. The type and amount of the explosive will not be given due to the restricted study conditions. For both plates, MAT_SIMPLIFIED_JOHNSON_COOK material model is used and Johnson-Cook material constants are found by conducting Split Hopkinson Pressure Bar Tests on the material examples. Temperature dependency of the Johnson-Cook model is not taken into account in the simulations. Normalized material flow curves are given in Figure 2 below.

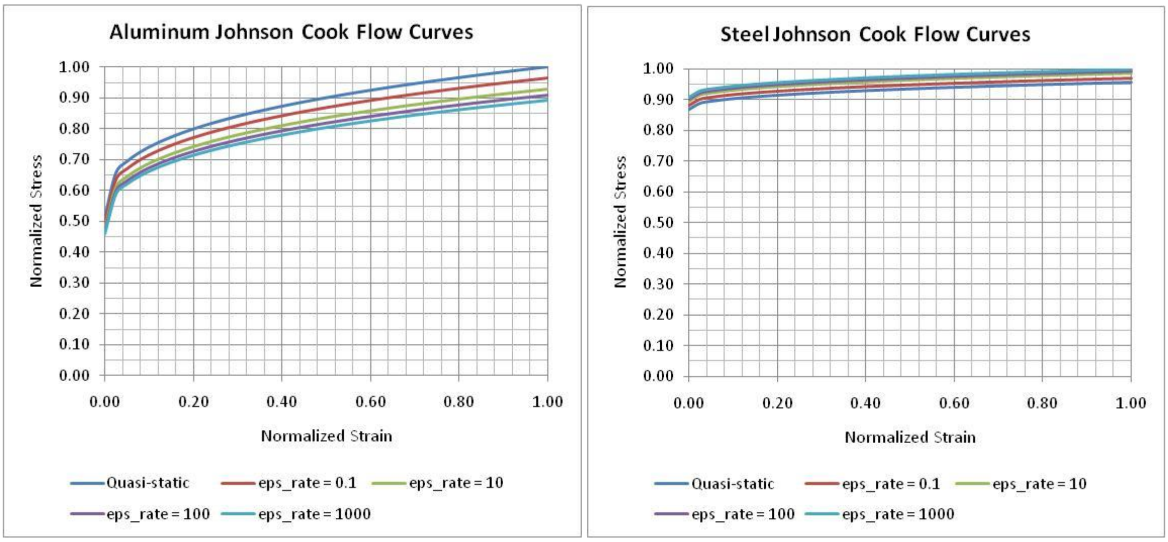

Figure 2. Material flow curves.

A deformation cone is designed and used in order to measure the total central displacement of the plates. This cone is manufactured from thin aluminum sheets in order not to affect the general stiffness of the system. *MAT_SIMPLIFIED_JOHNSON_COOK is used for modeling of the cones and the material parameters are found from the literature [2]. The cones are shown in Figure 3 below.

Figure 3. Deformation cone installation.

The test setup elements are modeled with *MAT_PLASTIC_KINEMATIC since they are not examined in detail. General steel material parameters are obtained from literature.

Air is modeled with *MAT_NULL along with the *EOS_LINEAR_POLYNOMIAL. The explosive is modeled with *MAT_HIGH_EXPLOSIVE_BURN and using *EOS_JWL. The physical properties and equation of state parameters of the explosive material are taken from literature [3].

4 Finite Element Model for Plate Simulations

The finite element model of the plates and test setup is shown in Figure 4 below.

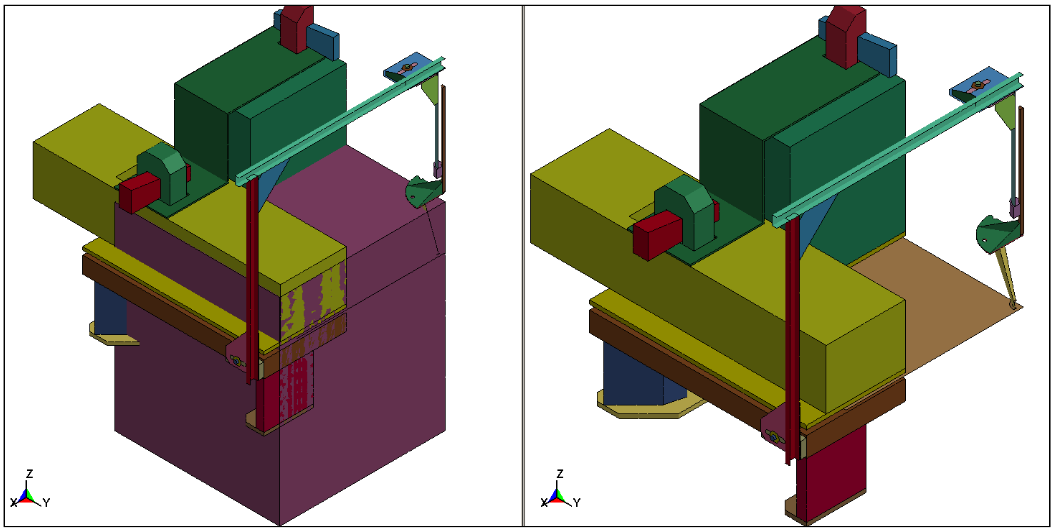

Figure 4. Finite element model of the test plates and setup.

In Figure 4, the left hand side is the total model with the ALE domain and the right hand side is the structural parts only. The soil, explosive and air is filled into the ALE domain by the LS-DYNA keyword *INITIAL_VOLUME_FRACTION_GEOMETRY. An interface is defined between the soil and the setup. Interaction between plate and ALE domain is performed by *CONSTRAINED_LAGRANGE_IN_SOLID keyword. Some parameter trials are performed in order to minimize the leakage problem.

The contacts between the test plate and setup weight are modeled with surface to surface type of contact. The contact between the deformation cone and the plate is modeled with automatic single surface contact because due to the buckling of the cone, the contact surface on the cone cannot be pre-determined exactly. Symmetry boundary conditions are used both for ALE and Lagrangian domains since the problem is symmetric. This process leads to shorter simulation times. Moreover, non-reflecting boundary conditions are used at the boundaries of the ALE domain where no symmetry boundary condition exists.

5 Simulation Results and Verification

5.1 Aluminum Plates

The simulation stages up to 3000 microseconds are shown in Figure 5 below.

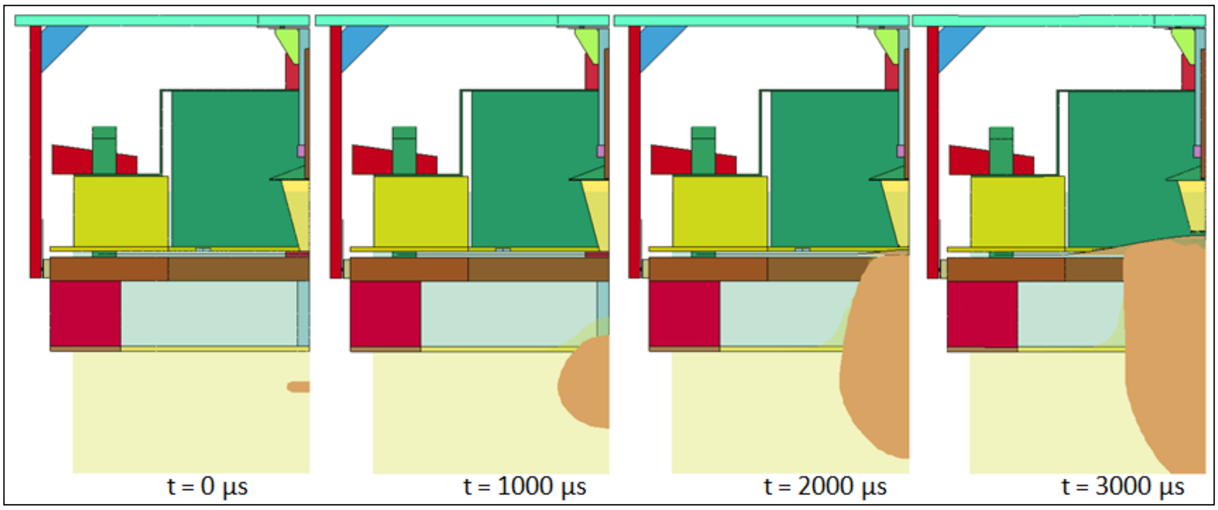

Figure 5. Simulation stages of aluminum plate.

Although the simulation stages are given up to 3000 microseconds in Figure 5, the simulation is performed up to 15000 microseconds. At the end of the simulation, the energy distribution is controlled first in order to make sure that the hourglass energy and the sliding interface energy is close to zero.

After checking the energy distribution, the average pressure on the plate is examined. The peak pressure is obtained around 3000 kPa. The pressure on the plate with respect to time is given in Figure 6.

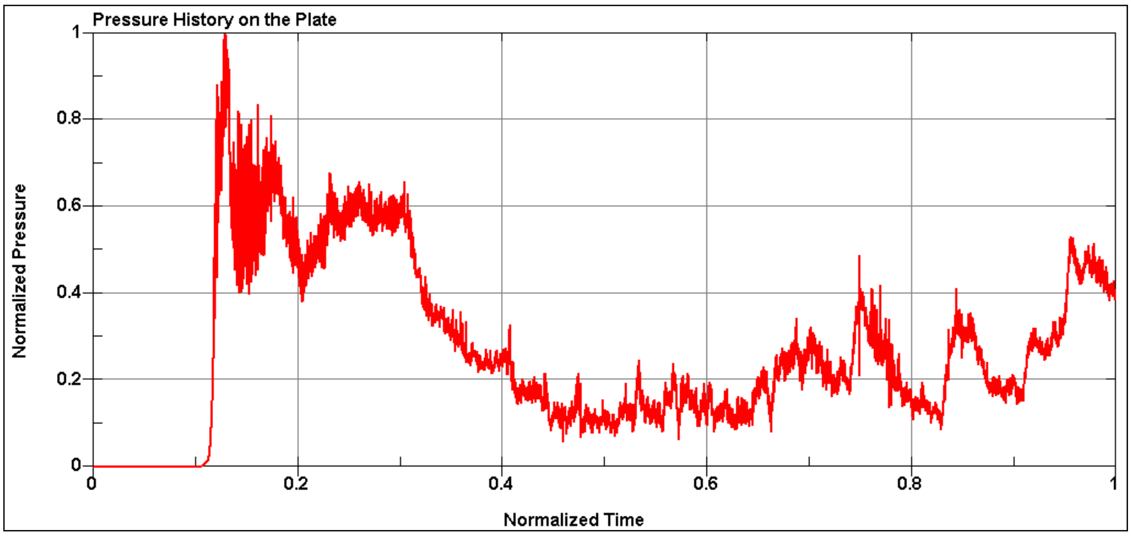

Figure 6. Pressure history on aluminum plate.

The total and plastic deformations of the plate are compared with the test results and a considerably reasonable agreement is obtained. The results are shown in Table 2, and the deformation of the plate and cone during the field test are shown in Figure 7 .

Table 2. Deformation results comparison for aluminum plate.

	Test	Simulation	Error (%)
Total Deformation (cm)	12.4	13.0	4.8
Plastic Deformation (cm)	11.5	11.7	1.7

Figure 7. Aluminum plate deformation with the cone.

After the deformation study, the accelerations are compared. The comparison is shown in Figure 8. The values are given as normalized acceleration due to the company restriction.

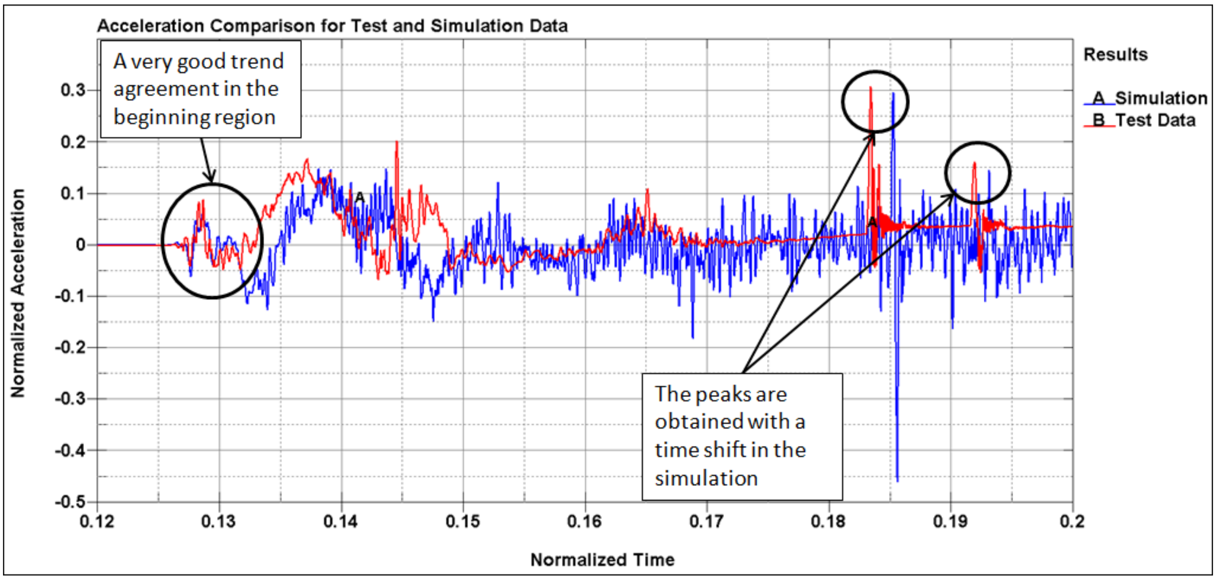

Figure 8. Acceleration comparison for aluminum plate

The trend of the acceleration is reasonably consistent with the test results. There are some shifts in the peaks which are encountered in most of the blast simulations. Strain data as well as the acceleration is compared with the test results. However, the strain measurements are taken for a very short time due to the high strain rate and the wire rupture. The comparison is shown in Figure 9.

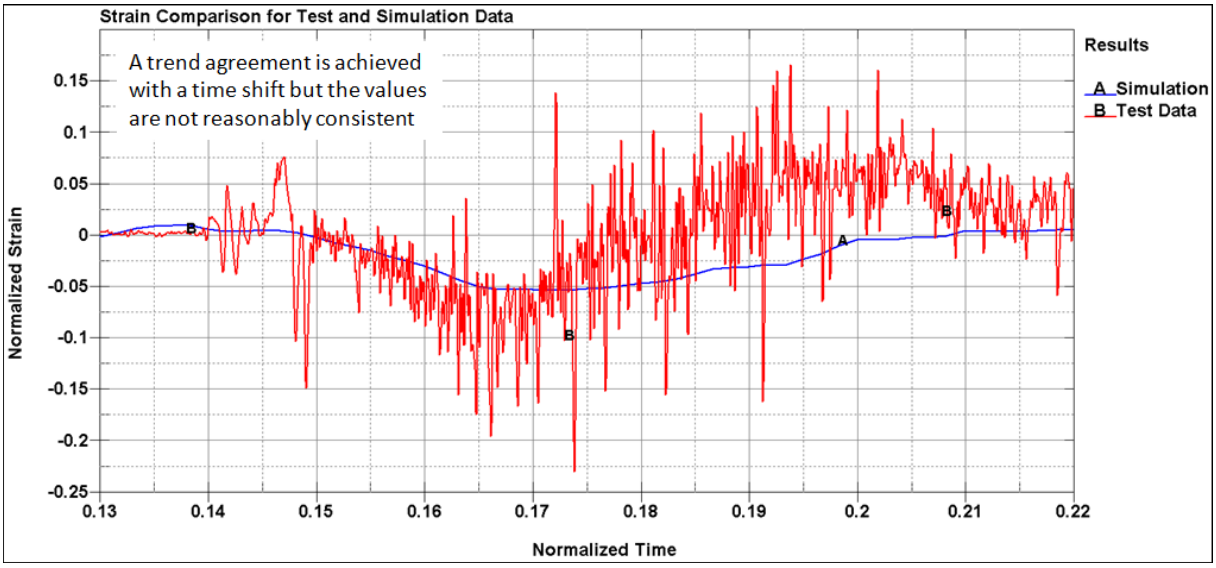

Figure 9. Strain comparison for aluminum plate.

The consistency achieved in the acceleration is not reached in the strain measurement case due to very short data duration and signal wire rupture.

5.2 Steel Plates

The simulation stages up to 3000 micro seconds are shown in Figure 10 below.

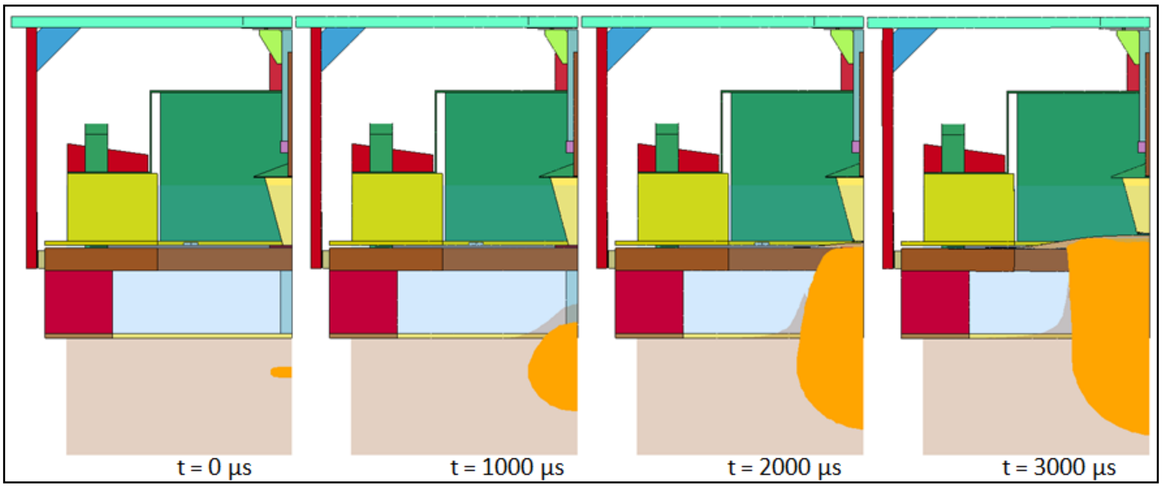

Figure 10. Simulation stages of steel plate.

The simulations are performed up to 30000 micro seconds for the steel plates since the behavior is more elastic than the aluminum plates. It takes longer time for the steel plate to become stable after the explosion.

The peak pressure on the plate is obtained around 3500 kPa. It is a little higher value than the aluminum plates since the distance of the steel plate is smaller due to the thickness. The average pressure on the plate with respect to time is given in Figure 11 below.

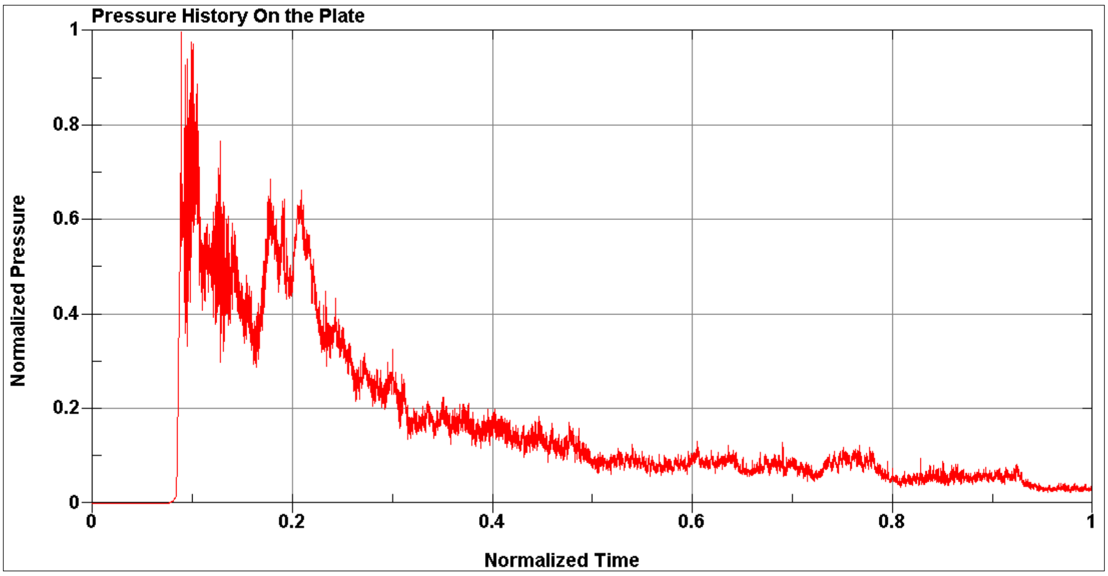

Figure 11. Pressure history on steel plate

The total and plastic deformations are compared with the test results and given in Table 3 and the deformation of the plate during the test is shown in Figure 12. The accuracy achieved in aluminum plate is not obtained with the steel plate from the point of total deformation; however, the results are still in the same order of magnitude. The studies are in progress to obtain a better coherence with the total deformation of the steel plate with the test results.

Table 3. Deformation results comparison for steel plate.

	Test	**Simulation**	**Error (%)**
Total Deformation (cm)	7.9	9.4	18.9
Plastic Deformation (cm)	5.2	5.3	1.9

Figure 12. Steel plate deformation with the cone

The accelerations and strains were measured for short time duration. Only the measured portions can be compared with simulation results. The normalized acceleration and strain results are shown in Figure 13 and Figure 14, respectively.

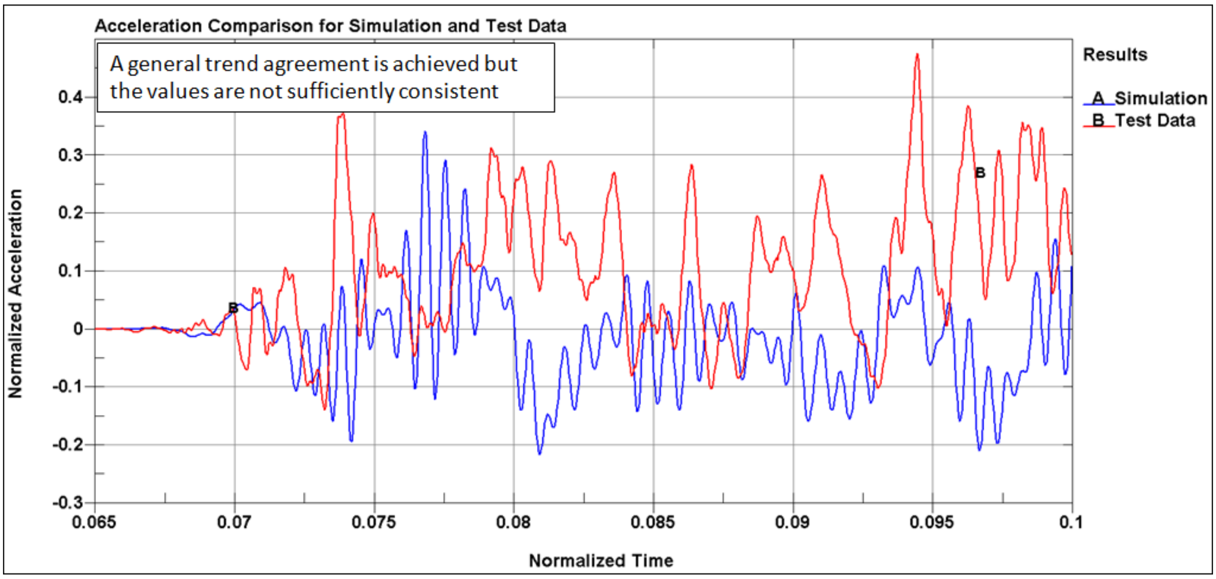

Figure 13. Z acceleration comparison for steel plate.

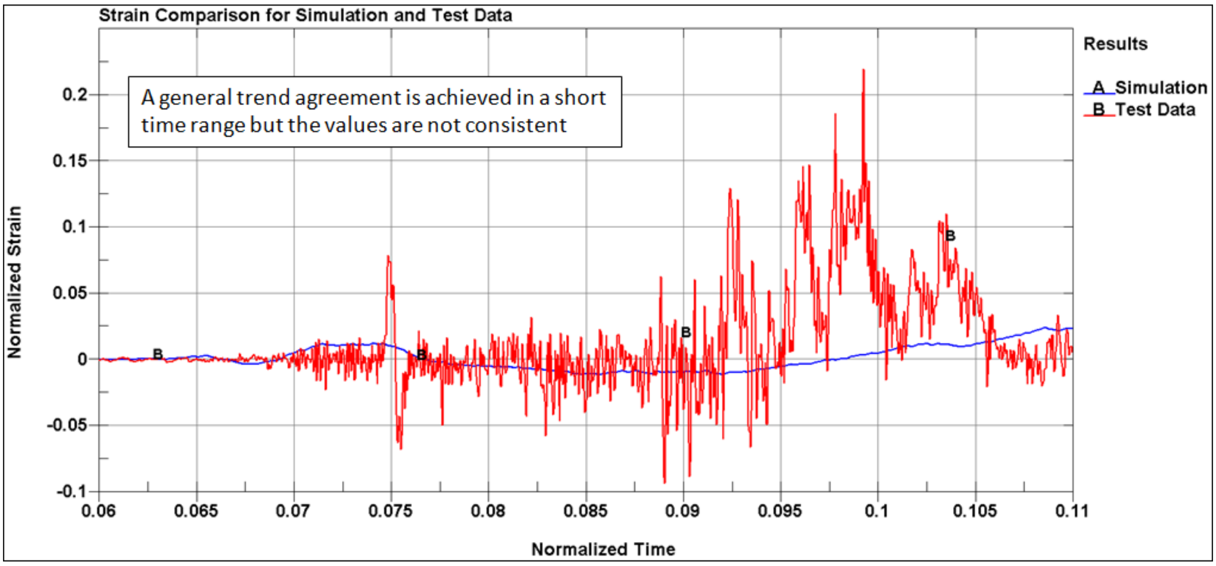

Figure 14. Strain comparison for steel plate.

Consistency between the simulation and test is not as good as the aluminum plate for steel plate from the points of acceleration and strain. However, good correlation is achieved in the displacement results.

6 ALE and SPH Comparison

Aluminum plates are simulated with SPH method as well as the ALE method. The SPH model has the same material properties and the same initial detonation point as the ALE model. The soil part of the system is not modeled fully with SPH nodes. Instead, the deformed part of the soil is modeled with SPH nodes and the rest is modeled with Lagrangian elements. The contact between the SPH particles and test plate is modeled with nodes the surface contact using SOFT=1. The bulk viscosity parameters are modified such that Q1=1.5 and Q2=1.0. By this way, physically more meaningful behavior is obtained for the soil particles. The simulation stages are compared with ALE method and shown in Figure 15 below.

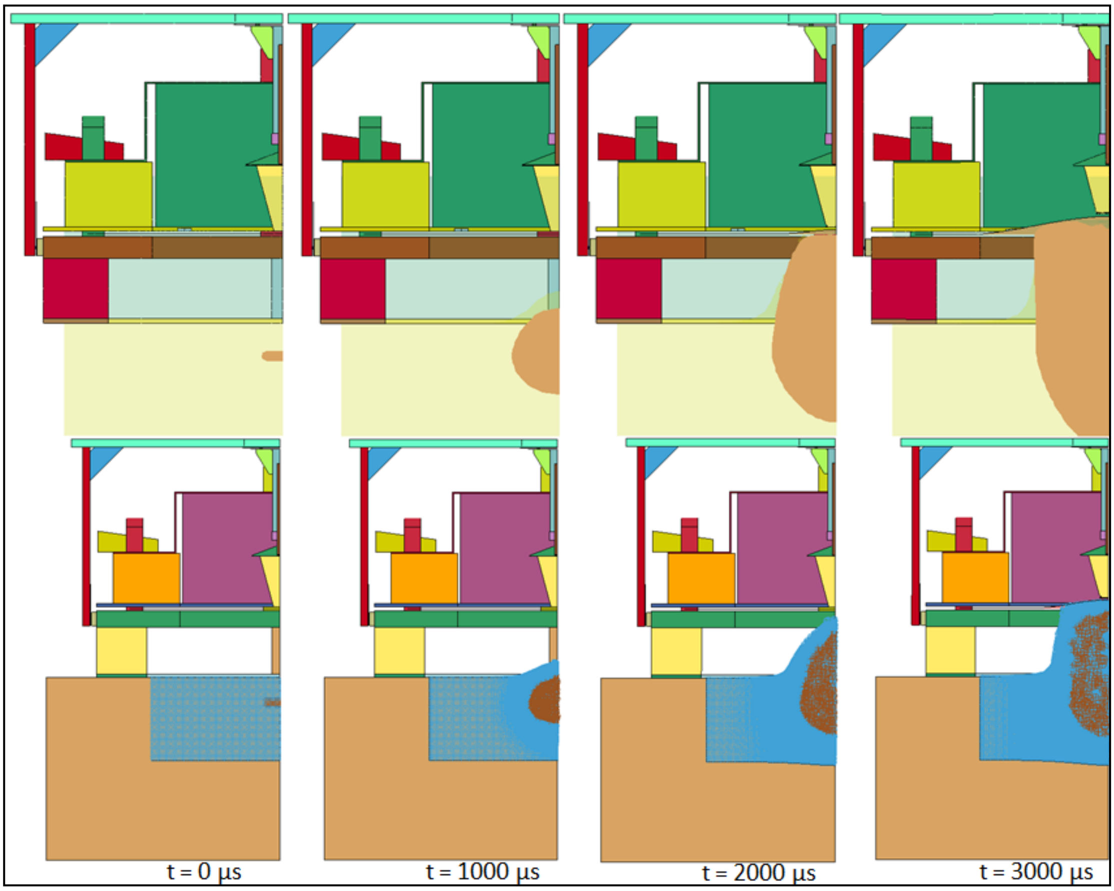

Figure 15. ALE and SPH comparison.

When the figures are examined in detail, it is observed that the SPH particles arrive at the plate with a small amount of latency as compared to ALE. Moreover, the Z-momentum on the test plate is estimated lower with the SPH method. The comparison is shown in Figure 16 below.

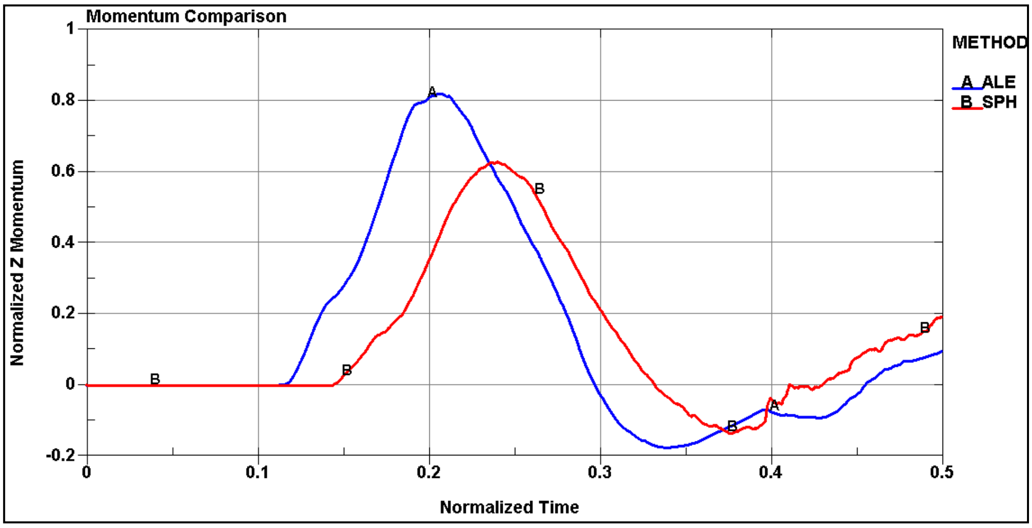

Figure 16. Z-Momentum of the plate.

Due to the lower momentum transfer, the displacements are measured also lower. The total deformation is measured as 10.6 cm.

7 Summary and Future Work

In this paper, the validation studies of buried mine explosion model prepared with ALE and SPH models are introduced. With ALE method, good agreement in displacement and acceleration with the test results is obtained especially for the aluminum plate. The parameter studies for steel plate are in progress.

The most challenging problem with the ALE method is the leakage. The parameters are optimized for *CONSTRAINED_LAGRANGE_IN_SOLID keyword and maximum momentum transfer is achieved, however, after the plate is extensively deformed, the ALE material starts to slide on the plate and leakage is then become inevitable. The studies on the leakage problem are in progress. At the end of the studies, it is desired to have a better coupling between ALE materials and the structure.

Another problem observed in the SPH model is that the arrival time of the pressure is higher than the ALE model. This is thought to be due to the artificial viscosity constants used in the model. A parameter study is in progress to find an appropriate set of constants to represent the soil and explosive behavior more accurately.

8 References

[1] "LS-DYNA Keyword User's Manual", Livermore Software Technology Corporation, Livermore, 2012.
[2] Fish, J et al., "AL-6061-T6 Elastomer Impact Simulations", 2005.
[3] TR-HFM-089, "Test Methodologies for Personal Protective Equipment against Anti-Personnel Mine Blast", NATO.