Defence Science Journal, Vol. 65, No. 6, November 2015, pp. 477-482, DOI : 10.14429/dsj.65.8594

Finite Element and Experimental Analyses of an Armoured Vehicle Subjected to Landmine Blast

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ABSTRACT

Landmines severely threaten the armoured vehicles. The principal objective is to present a methodology for blast simulations of vehicles subjected to landmine explosions. First, free field blast experiment of 2 kg TNT charge in a steel pot is carried out to validate the blast parameters used in the numerical simulation. Overpressure-time history collected in the free field blast experiment is compared to the numerical simulation results. Numerical simulations are performed in LS-DYNA hydrocode that employs Arbitrary Lagrangian Eulerian formulation enabling a fully coupled interaction between the blast wave, the detonation gases, and the vehicle. Second, the full-scale field test of an armoured vehicle exposed to 6 kg of TNT charge in a steel pot underneath the rear end of the vehicle is conducted. Maximum dynamic deformations measured inside the vehicle are compared to the results calculated in the numerical simulation. Results show that the numerical simulation is in good agreement with the full-scale field test.

Keywords: Landmine blast, full-scale blast test, numerical simulation, shock wave, mine resistant armoured vehicle, LS-DYNA

NOMENCLATURE

p	Pressure
V	Relative volume
E_0	Initial internal energy per volume
D	Detonation velocity
P_{CJ}	Chapman-Jouguet detonation pressure
ρ_0	Initial density
ρ	Current density
γ	Specific heat ratio
mm	Millimetre
kg	Kilogram

1. INTRODUCTION

Many countries have suffered numerous casualties as the direct result of asymmetric threats. A large majority of casualties resulted from landmine explosions, which drastically affect armoured vehicles and their occupants.

Landmines are frequently used to neutralise the combat vehicles and their mannequins in modern warfare. Anti-mine protection systems that mitigate blast loading effects help to reduce the vulnerability of vehicle and improve the survivability of the occupants during landmine blast. In traditional approach, development of anti-mine protection systems necessitate successive full-scaled blast experiments in order to prove their functionality in decreasing blast loading effects on vehicle. Full-scale field tests of armoured vehicles exposed to landmine blast are costly and time consuming and it might not ensure an optimised design. In addition, a variety of field conditions make each blast test difficult to perform. On the other hand, numerical simulations provide a faster alternative to measure the vehicle performance under blast loads.

The limited numbers of studies investing mine resistance of vehicles in the literature are found. Grujicic[1], *et al*. carried out a numerical simulation in order to investigate the kinematic response of an F800 truck subjected to landmine blast under the front right wheel. The study focused on associating behaviour of gaseous products and air domain with structural components such as soil and vehicle body using the ALE formulation. The authors concluded that the moisture content of sand highly affects kinematic response of vehicle and blast momentum transferred to the vehicle. Larsen[2], *et al.* examined both computational analysis and field test of a mine resistant armoured vehicle M113 exposed to 5.56 kg of C4 plastic explosive underneath the hull of the body. In the computational model, they utilised the ALE approach to interact structural components with gaseous domain. The authors observed that the floor plate fails both in the numerical model and in the experiment. Erdik[3], *et al*. investigated the blast loading effects of a landmine detonated in a steel pit underneath the V-shaped hull on an armoured vehicle using the ALE formulation. The authors pointed out that the computational results were in agreement with the blast experiment. An intriguing study was examined by Yuen[4], *et al*. They examined the effect of angle on dissipating blast wave for various V-shaped hulls to be used in a future combat vehicle. They found out that smaller angles deflect more energy than larger angles for V-shaped hull. The

Received 20 March 2015, revised 09 October 2015, online published 10 November 2015

correlation between numerical simulation and the experimental measurements was promising for the displacement – time history.

In this study, free field blast experiment of a 2 kg of TNT charge in a steel pot is carried out in order to validate the blast parameters used in computational analysis of free field. The incident pressures measured in free field blast experiment and calculated in numerical simulation as well as computational results of reflected and incident pressures are presented. Fluid structure interaction (FSI) 'control parameters' calibrated for the blast simulation of armoured vehicle are discussed in Section 3.2. The full-scale blast testing and numerical simulation of an armoured vehicle exposed to 6 kg of TNT charge in a steel pot conducted. Finally, experimental results measured in the full-scale blast test are compared with the results of blast simulation and a conclusion is drawn.

2. FREE FIELD BLAST EXPERIMENT

NATO AEP-55[5] describes the experimental field conditions for determining the resistance level of logistic and light armoured vehicles exposed to grenade and blast mine threats defined by NATO STANAG 4569[6]. Landmine might be placed either beneath the saturated sandy gravel or in a steel pot according to the same standard. In this study, TNT charge is placed in the steel pot buried on the ground in order not to take uncertainties stemming from soil properties into consideration.

Free field blast test is performed for the validation of blast parameters of numerical simulation. Blast testing setup involves the TNT charge, the steel pot, and the blast pressure probes. 2 kg of cylindrical TNT charge is placed in the steel pot, which is manufactured of 42CrMo4 alloy. Figure 1 demonstrates the dimensions of the steel pot and the TNT charge. Two blast pressure pencil probes are attached onto separate steel rods to measure incident overpressure during explosion. The rods with the height of 1000 mm are located at a distance of 1700 mm from the centre of the steel pot. Illustration of the test setup is shown in Fig. 2.

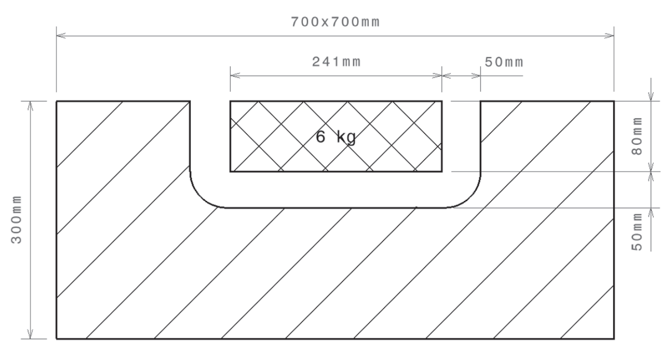

Figure 1. Dimensions of steel pot.

3. NUMERICAL SIMULATION OF FREE FIELD BLAST EXPERIMENT

Incident pressure obtained by free field blast experiment is used to calibrate the parameters in the numerical simulation. Once blast parameters are calibrated in free field blast simulation, full-scale blast simulation of armoured vehicle can be carried out through these parameters.

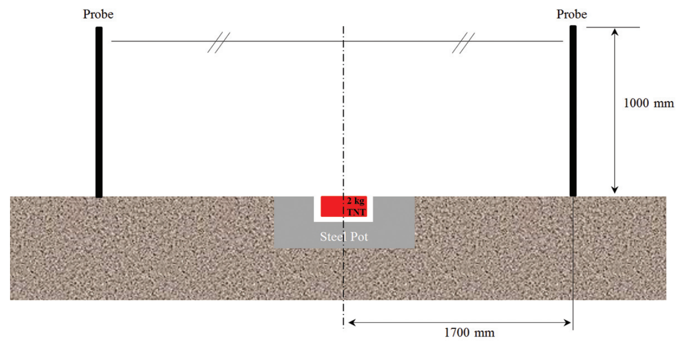

Figure 2. Schematic drawing of test set-up.

Numerical simulations are performed using LS-DYNA hydrocode V971 R6.1.0 on an HPC cluster system having 36 CPUs and 216 GB RAM at OTOKAR Otomotiv ve Savunma Sanayi A.S. The Arbitrary Lagrangian Eulerian technique (ALE) available in LS-DYNA hydrocode is used to simulate blast wave propagation and couple blast loading with the target. The ALE technique[7] is a combined Lagrangian and Eulerian computing method allowing for the application of the Navier-Stokes fluid dynamics equations for the blast wave propagation. The coupling algorithm provides the interaction of the blast wave with the target structure.

3.1 Free Field Blast Modelling Details

Numerical model consists of the surrounding air, high explosive, steel pot, and a target. The surrounding air and high explosive are defined as Eulerian mesh, while the steel pot and the target are selected as Lagrangian mesh. A point fixed in space is selected as a sensor and single quadratic shell element is defined as the target in order to compute the incident and reflected overpressures, respectively. The target is assumed to be single rigid reflecting surface while steel pot is specified as mild steel and they are immersed in the surrounding air that shares common nodes with high explosive. The materials of the surrounding air and the high explosive are specified as multi-material. TNT is selected as high explosive and modelled with hexahedral solid elements. Material model of the TNT is defined using MAT_HIGH_EXPLOSIVE_BURN with the Jones-Wilkins-Lee (JWL) equation of state (EOS). MAT_NULL is used for the material of the surrounding air, which is modelled in a cubic topology, with the linear polynomial equation of state.

3.2 Control Parameters

Critical control parameters used in the Fluid Structure Interaction (FSI) calculations of computational analysis are discussed in this section. The ALE formulation is specified as a continuum treatment in the CONTROL_ALE card with the Van Leer method using a second order monotonic half-index-shift technique. This advection algorithm allows the calculation to provide a good accuracy with coarser mesh resolutions than the calculation using first order accurate algorithm.

Number of cycles between advection steps is selected as one. CONSTRAINED_LAGRANGE_IN_SOLID card is used to couple the surrounding air and high explosive to the vehicle. Penalty coupling for shell and solid elements is exploited as the coupling type with 2 interface points for the Eulerian elements. No specific leakage control parameter is included in the FSI calculations. However, it is addressed special attention to the ratio between Eulerian and Lagrangian element lengths to prevent leakage between Eulerian and Lagrangian meshes. Namely, the element length ratio for both Eulerian and Lagrangian type of elements are roughly set to '1' at FSI coupling regions in order to produce proper contact forces.

3.3 Equations of State of Surrounding Air and High Explosive

The physical properties of the surrounding air and the high explosive are defined using equations of state which are constitutive equations describing mathematical relationships between state functions associated with temperature, pressure, volume, or energy. The JWL empirical equation of state (EOS_JWL)[8] for explosive products is widely used in mine explosion calculations to define the pressure as a function of relative volume V and initial internal energy per volume E_0 as given in Eqn 1.

$$p = A\left[1-\frac{W}{R_1V}\right]e^{-R_1V} + B\left[1-\frac{W}{R_2V}\right]e^{-R_2V} + \frac{WE_0}{V} \qquad (1)$$

A and B are the parameters of pressure,whileR_1, R_2, and W are constants. The parameters of JWL equation of state for the TNT high explosive material provided by Dobratz and Crawford[9] are presented in Table 1.

Table 1. JWL equation of state parameters for TNT

ρ_0 (kg/m^3)	D (m/s)	P_{CJ} (GPa)	E_0/V (GPa)	A (GPa)	B (GPa)	R_1	R_2	W
1630	6930	21.0	7.0	371.213	3.231	4.15	0.95	0.30

The detonation velocity is given by D, P_{CJ} is the Chapman-Jouguet detonation pressure and ρ_0 is the initial density. The detonation process is performed by using the programmed burn option available in the LS-DYNA hydrocode.

The linear polynomial equation of state (EOS_LINEAR_POLYNOMIAL)[10] is used for the surrounding air domain to express the constitutive relation between pressure, initial volume, and energy as seen in Eqn 2.

$$p = C_0 + C_1\mu + C_2\mu^2 + C_3\mu^3 + (C_4 + C_5\mu + C_6\mu^2)E \qquad (2)$$

Here C_0, C_1, C_2, C_3, C_4, C_5, and C_6 are coefficients. The variable μ depending on the relative volume $V$is given in Eqn 3.

$$\mu = \frac{1}{V} - 1 \qquad (3)$$

In expanded elements, the coefficients of variable μ^2 are set to zero; hence the coefficients C_2 and C_6 in Eqn 4 are zero.

$$C_2 = C_6 = 0 \qquad (4)$$

The linear polynomial equation of state can be used to model gas with the gamma law equation of state by setting the coefficients C_0, C_1, C_3 to zero in Eqn 5 and then C_4 and C_5 are obtained in Eqn 6.

$$C_0 = C_1 = C_2 = C_3 = C_6 = 0 \qquad (5)$$

$$C_4 = C_5 = \gamma - 1 \qquad (6)$$

Gamma, γ is the ratio of specific heat. The pressure is finally obtained in Eqn 7.

$$p = (\gamma - 1)\frac{\rho}{\rho_0}E \qquad (7)$$

The initial and current densities of air are represented by ρ_0 and ρ, respectively and the internal energy per unit volume is given by E.

4. RESULTS OF BLAST EXPERIMENT AND NUMERICAL SIMULATION

Figure 3 shows the incident overpressure- times histories collected from blast pressure probes and calculated in numerical simulation. It is worth noting that although two identical probes measure overpressure at the same distance to the explosive, a minor distinction is observed in pressure-time profiles. Small angle deviations from the vertical positions of the poles while sticking them in the ground may bring about the difference between probes. It also appears a slight gap of arrival times between experimental measurements and numerical calculation. The delay in time of arrival of numerical simulation presumably results from the mesh resolution of the surrounding air.

The reflected and incident overpressures calculated in the numerical simulation are represented in Fig. 4. It can be seen from the graph that the maximum reflected overpressure is roughly 20 times larger than the maximum incident overpressure.

5. FULL-SCALE BLAST EXPERIMENT

A full-scale blast experiment is carried out on an armoured vehicle subjected to landmine explosion so as to compare experimental measurements with the blast simulation results by measuring dynamic deformations on specific locations inside the vehicle. The setup for the

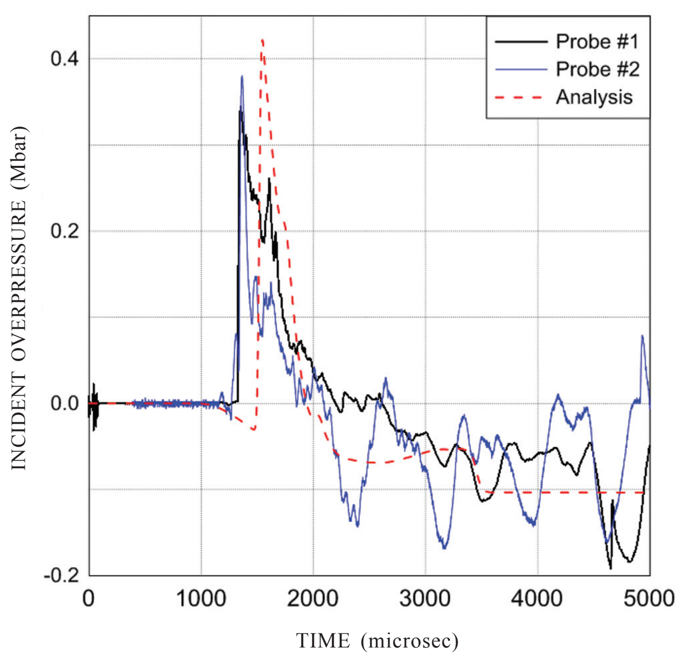

Figure 3. Incident overpressure-time histories of experiment and analysis.

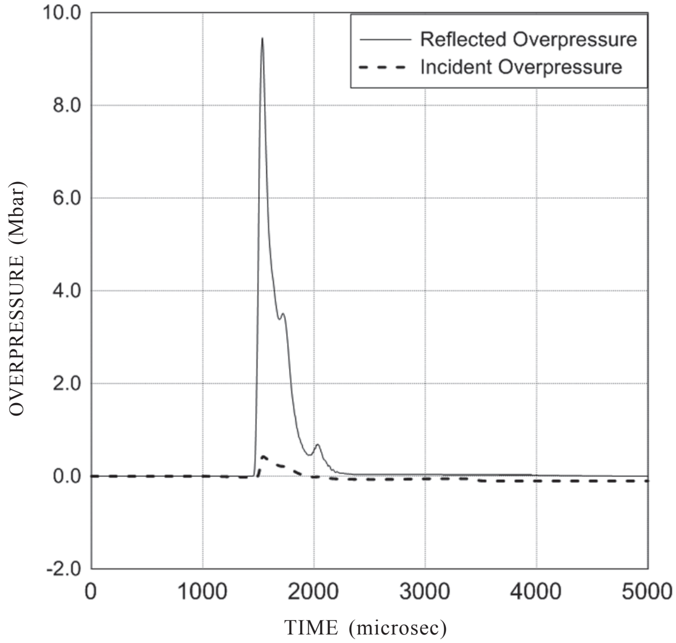

Figure 4. Reflected and incident overpressures.

experiment is as shown in Fig. 5. An explosive charge of 6 kg of TNT is encased in a steel pot buried in the ground. The position of the steel pot is opted as the centre of the rear end of the vehicle, with the intent that the hull be totally exposed to the landmine and any components of vehicle subsystem, which is capable of energy absorption during explosion, does not obstruct the blast waves through the vehicle. The vehicle includes hull structure, doors, glasses, and subsystems such as axes, shafts, transmission box, and suspension. It stands on the two supporting frame representing the wheels.

To measure maximum dynamic displacements around the pedestrian plate and the sidewalls inside the vehicle body, crushable tubes are used. The tubes are made of lead and provide precise measurement of displacements due to the mechanical properties of the lead. Fig. 6 shows the positions of the displacement tubes, which are symmetrically mounted at ten different locations to the framework inside the vehicle.

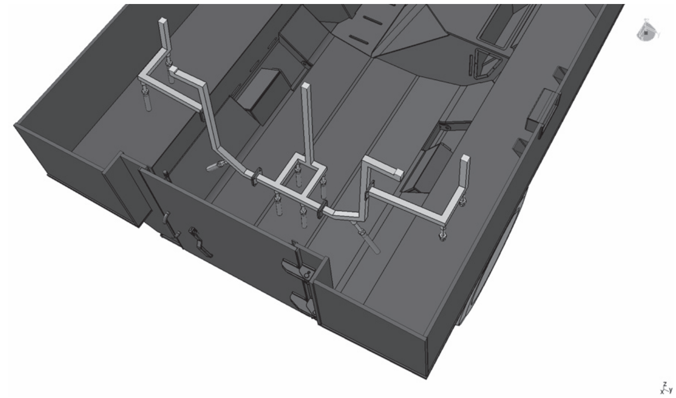

Figure 6. Displacement tubes (Top view).

6. NUMERICAL SIMULATION OF THE FULL-SCALE BLAST EXPERIMENT

The computational domain includes the finite elements models of the surrounding air, the high explosive, the steel pot, and the armoured vehicle. Figure 7 demonstrates the isometric view of the computational model. The surrounding air and the high explosive are modelled as Eulerian mesh and the mesh for the armoured vehicle and the steel pot are modelled as Lagrangian mesh. The modelling explanation involving fluid structure interaction coupling parameters can be found in Section 3.1. Penalty formulation is opted for the contact definition between Lagrangian elements. Components of transmission, axes, suspension, and steering system, as well as the steel pot are modelled with hexahedral solid elements and assumed to be made of mild steel. MAT_ELASTIC_KINEMATIC is selected as the material model of the mild steel, of which mechanical properties are presented in Table 2. Bolts are modelled using beam element formulation with a failure criterion. Welding is described with one-dimensional rigid elements. The vehicle hull is modelled using the Belytscho-Tsay shell element

Table 2. Material properties of mild steel

Density (kg/m^3)	Elastic modulus (GPa)	Poisson Ratio	Yield Strength (GPa)
7860	210	0.30	0.355

Figure 5. Experimental setup.

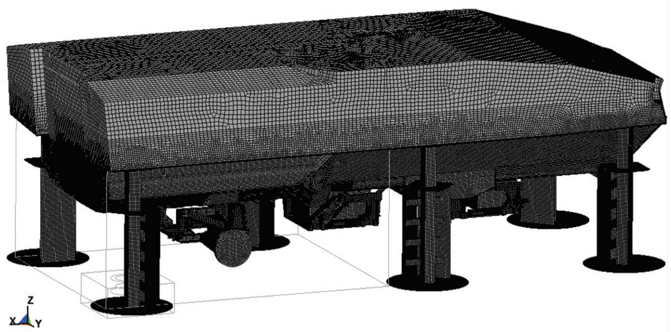

Figure 7. Computational domain of full-scale blast testing.

formulation with five integration points and it is made of high hardness armour steel of which material properties are specified through Johnson-Cook (J-C) material model[11] allowing for large deformation at high strain rate loading conditions. Table 3 shows the J-C parameters for the high hardness steel provided by Nsiampa[12]. The blast simulation of the armoured vehicle is performed with a runtime of 51480 seconds.

Modelling details of the numerical simulation are given in Table 4. It summarises the total element numbers and nodes used in the computational domain.

Table 3. Johnson-Cook material parameters for high hardness armour steel[10]

A (MPa)	B (MPa)	c	m	n
1299	2230	0.044474	0.961240	0.55853

Table 4. Summary of computational domain

Number of solids in high explosive	1,518
Number of solids in steel pot	14,608
Number of solids in air domain	694,158
Number of shells in vehicle hull	307,113
Number of solids in subsystems	53,606
Number of beams	1,136
Number of rigid 1-D elements	27,958
Total number of elements	1,100,017
Total number of nodes	1,141,412

7. COMPARISON OF THE RESULTS

Experimental measurements in full-scale blast test of the armoured vehicle are compared to the computational results for ten displacement locations. Table 5 represents measured and computed maximum elastic plate deformations, and the deviation percentages. Tube #7 in the blast experiment yields the largest displacement with a normalised displacement of 1. Displacements at other tubes both in experiment and numerical simulation are given as the fractions of normalised value at tube #7.

8. DISCUSSION AND CONCLUSION

A computational analysis method dealing with the detonation of a landmine under the hull of the vehicle by using the ALE technique is developed for the assessment of structural response of the armoured vehicle. For this purpose, testing and numerical simulation of free field blast of explosive placed in a steel pot are conducted to scale the numerical simulation parameters. Numerical simulation over-estimates the experimental measurements by the deviation percentage of 10. The deviation might arise from various numerical model assumptions. In general, mechanical and physical properties of materials with insufficient parameters may result in deviations in numerical simulation. In this study, material models and equations of states of the air domain and explosive are widely used and validated with numerous studies, their negative influence on deviation is negligible. Similarly, material model of the steel pot has a minor contribution to the results but affects the durability of the device. However, the mesh resolution of the surrounding air may affect the computed overpressures as well as time of arrival, in particular, smaller mesh sizes yield better accuracy on contact forces between Eulerian and Lagrangian meshes. The mesh convergence study that might be examined to find out the optimum mesh resolution is beyond the scope of this study.

Table 5. Normalised displacement values and deviation percentages

Displacement Tubes (No#)	Experimental measurement	Numerical simulation	Deviation (%)
1	0.35	0.28	19
2	0.28	0.26	8
3	0.43	0.52	20
4	0.74	0.89	21
5	0.74	0.89	21
6	0.67	0.72	6
7	1.00	0.85	15
8	0.46	0.52	14
9	0.24	0.24	0
10	0.33	0.26	20

Full-scale testing and numerical simulation of an armoured vehicle subjected to landmine in a steel pot are carried out. The numerical simulation results with calibrated FSI parameters are compared with the maximum elastic displacements measured in the experiments. Numerical simulation produces good results.

To sum up, with the use of calibrated parameters in numerical simulation of armoured vehicle subjected to landmine blast, promising numerical results can be achieved. Inasmuch as numerical simulation is validated with the experimental measurements, it can be used as a prominent design tool for the development of mine protection studies of vehicles.

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ACKNOWLEDGEMENTS

The authors would like to thank Otokar Otomotiv ve Savunma Sanayi A.S. for the technical and financial support.

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