Correlative Approach to Mine Blast Effects via Conducting Real Test Campaigns and Simulating in LS-DYNA

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1 Abstract

In this study, pressure data were collected by conducting free field blast tests with explosives placed inside the steel pot to verify the explosive model. Free field blast analysis was performed using the Structured Arbitrarily Lagrangian -Eulerian (SALE) method in the LS-DYNA® software under the same boundary conditions, and the pressure values obtained from the test were compared. Plate tests were performed in consideration of the verified explosive model with explosives placed inside the steel pot. Tests were carried out for 3 different designs, which consist of flat plate, twisted plate, and plate with deflector. Elastic and plastic displacement measurements were taken during the tests. LS-DYNA® software was used to perform analyses using the Johnson-Cook material model obtained from Split Hopkinson bar tests for plate materials and the SALE method. The effect of the distance between the plate and the explosive, the behavior of the source during the explosion, the effect of plate geometry, and the comparison with analysis results were investigated as a result of the plate tests.

2 Introduction

One of the primary expectations of military vehicles is to take effective measures against mine threats. In pursuit of this goal, these vehicles are certified according to the protection levels determined by the STANAG standards.

Following the production process of the vehicles, mine tests are conducted to determine their protection levels against mine threats. However, due to the high costs associated with these tests, there is an increasing demand for simulation techniques in today's context. Nevertheless, it is of paramount importance to understand the physical characteristics of the explosive material and its interaction with vehicle structures accurately before conducting mine simulations at the vehicle level.

In this research, free field blast tests and plate tests were conducted as the initial steps. Free field blast tests provided significant data for examining the physical properties of the explosive material. Furthermore, the interaction between the explosive material and structures was analyzed through plate tests involving various designs of plates. Figure 1 show that test setup and designs of plates. The results of these tests were compared with simulations conducted under the same boundary conditions to assess the accuracy and reliability of the simulations.

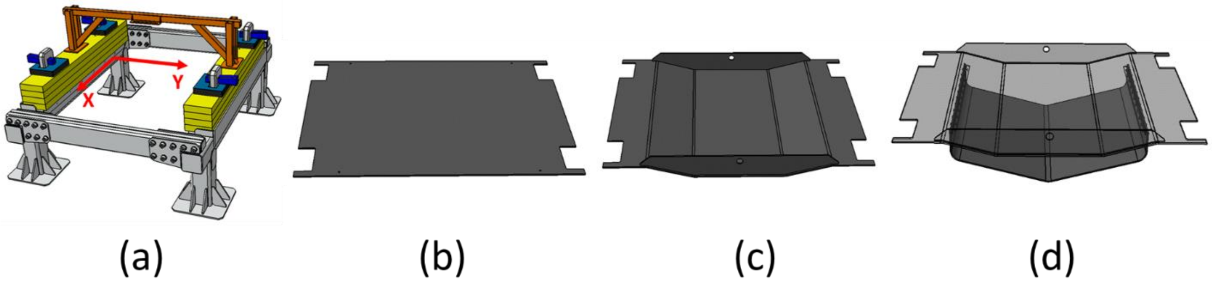

Fig.1: Test setup, tested / analysed plates. (a) Test setup (b) Flat plate (c) Twisted plate (d) Plate with deflector

3 Explosive and Explosion Techniques

Explosives are generally classified into different types based on their areas of use and explosion characteristics. For military applications TNT, C4, or PETN-B explosives are mostly preferred.

3.1 Explosive Characteristics

An explosion is a physical phenomenon characterized by a sudden and extremely rapid release of energy. This event typically lasts for only a few milliseconds, yet during this short time, it generates very high temperatures and pressures. When a detonation occurs, the hot gases produced by the explosion rapidly expand to fill the available space, creating a wave-like propagation that spreads spherically through the surrounding medium without any boundary constraints.

In the case of air blasts, not only do the produced gases expand, but also the air in the vicinity of the explosion undergoes a similar process. The molecules of the air pile up, leading to the formation of a blast wave and shock front. The blast wave carries a significant portion of the energy released during the detonation and travels faster than the speed of sound. [1]

Figure 2 show that ideal blast wave profile. Prior to shock front arrival, the pressure is ambient pressure P_0. At arrival time t_A, the pressure rises quite abruptly to a peak value P_{S0}. The time needed for the pressure to reach its peak value is very small and for design purposes it is assumed to be equal to zero. The peak pressure P_{S0} is also known as side-on overpressure. The pressure then decays to ambient in total time $t_A + t_0$, drops to a partial vacuum of amplitude $P_{S0}{}^-$ and eventually returns to P_0 in total time $t_A + t_0 + t_0{}^-$. The portion of the time history above initial ambient pressure is called the positive phase of duration t_0. That portion below P_0, amplitude $P_{S0}{}^-$ and duration $t_0{}^-$is called the negative or suction phase. In most blast studies, the negative phase of the blast wave is ignored and only blast parameters associated with the positive phase are considered. [2]

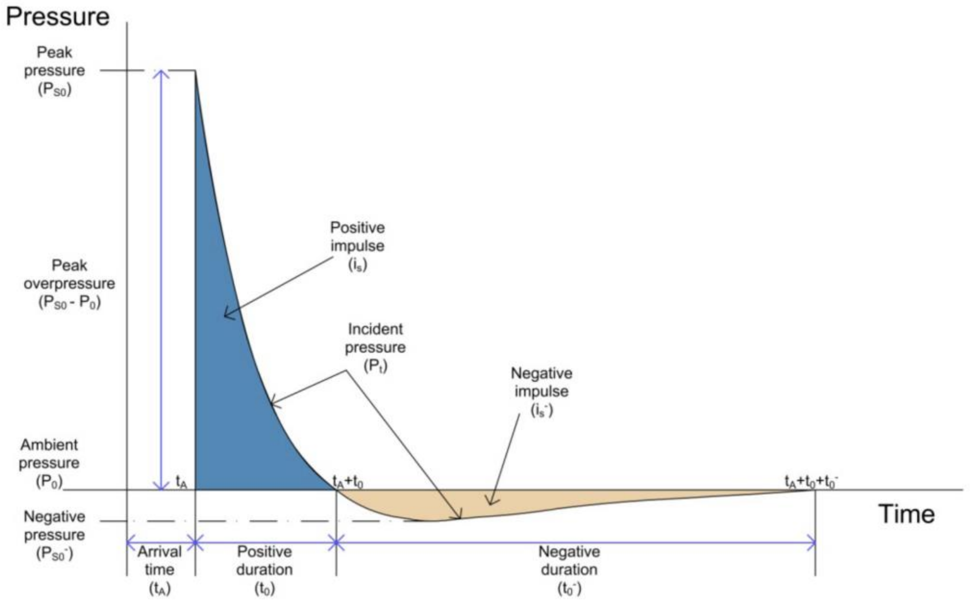

Fig.2: Ideal blast wave profile [3]

3.2 Explosion Techniques

NATO AEP-55 STANAG 4569 is a NATO Standardization Agreement covering the standards for the "Protection Levels for Occupants of Logistic and Light Armored Vehicles. AEP-55 Volume 2 include procedures for evaluating the protection level of armoured vehicles about mine threat. This standard propose two techniques for blast test. [4]

1. Surrogate Mine in Water Saturated Sandy Gravel
2. Surrogate Mine in Steel Pot

Techniques 1 propose for TNT explosive. Water saturated sandy gravel is prepared according to the conditions recommended by the standard.

Techniques 2 propose for C4 or PETN-B explosives. Testing using the steel pot method provides easier to control and reproducible test conditions. In this study, steel pot method was used.

Figure 3 illustrates the geometrical specifications of the charge and steel pot. Geometrical details are decided to the requirement of the desired threat level.

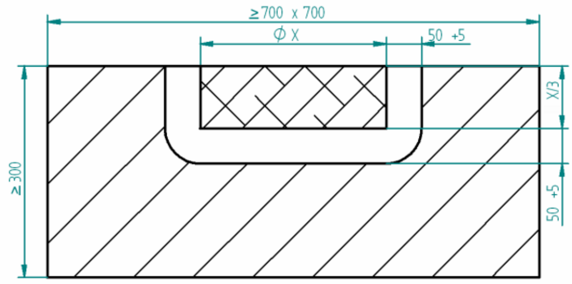

Fig.3: Geometrical specifications of charge and steel pot [4]

4 Real Test Campaigns and Blast Simulation in LS-DYNA®

Free field blast tests yielded valuable data for investigating the physical characteristics of the explosive substance. Additionally, the interaction between the explosive material and structures was assessed by conducting plate tests with diverse plate designs such as flat plate, twisted plate, and plate with a deflector. Pressure and displacement data obtained from these tests were used for verification with analysis.

The LS-DYNA® software was employed for simulating mine detonations, utilizing different methods including Conweb (Load_Blast), ALE, S-ALE, SPH, CESE, and DEM methods. In this study, the 2D S-ALE method was utilized for open detonation tests, while the 3D S-ALE method was employed for plate tests.

4.1 Free Field Blast Test

It was conducted with the purpose of observing the behaviour of the explosive. C4 explosive placed within a steel pot was measured for pressure levels using pencil probes pressure sensors positioned at distances of 2m and 2.5m. The free field air detonation test is depicted in Figure 4 below.

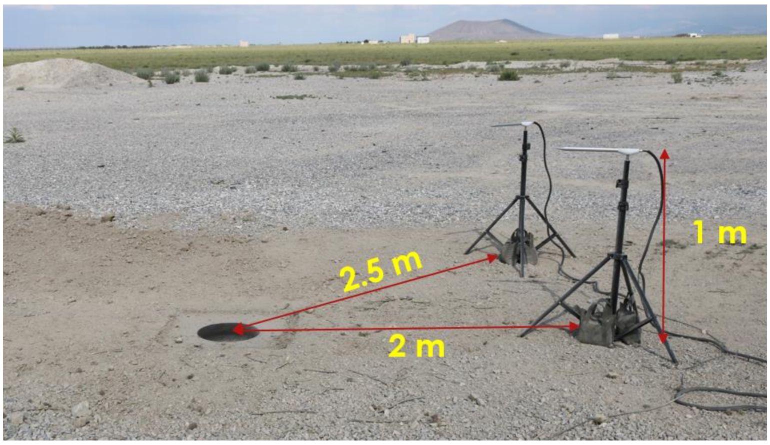

Fig.4: Free field blast test setup

Test boundary conditions were simulated using the 2D axisymmetric S-ALE method within the LS-DYNA® software. Thanks to 2D axisymmetric S-ALE method, can use more fine model and get result with less compute time. Tracers were added to the pressure sensor coordinates to obtain incident pressure values. By comparing test data with simulation results, the finite element model of the explosive was validated.

For the explosive, “mat_high_explosive_burn” and “eos_jwl” material models were utilized [5], while “mat_null” and “eos_linear_polynomial” material models were employed for air. The 2D S-ALE model was constructed using “initial_volume_fraction_geometry”. The S-ALE elements were controlled according to the explosion scenario using the “control_ale” card.

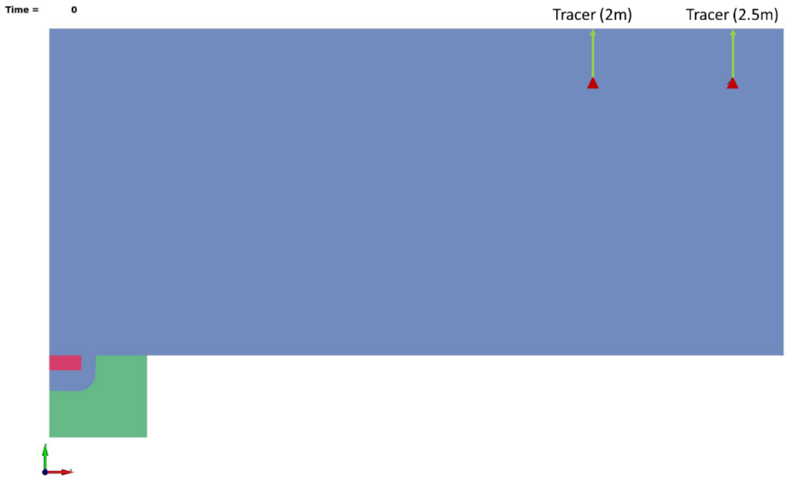

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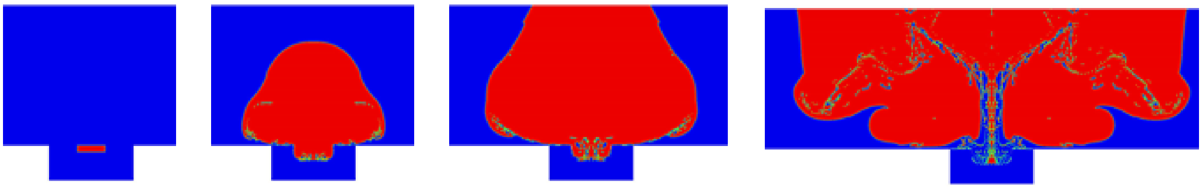
Fig.5: Free field air blast analysis model at LS-DYNA®



t=0 ms t=0.25 ms t= 0.50 ms t=2 ms

Fig.6: Volumetric fracture of the explosive during free field blast

The graph below compares the pressure results between the test and simulation:

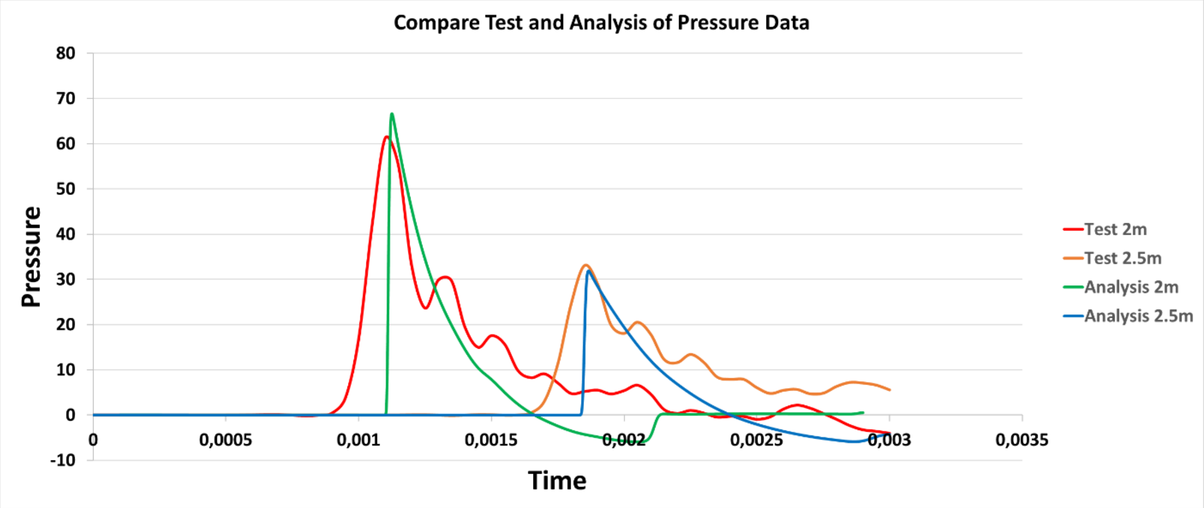


Fig.7: Compare test and analysis pressure curves versus time

		Test	**Analysis**	**Error [%]**
2 m	Incident Pressure	61.25	66.64	8
	Arrive Time	0.0011	0.00122	-
2.5 m	Incident Pressure	33.05	31.87	3
	Arrive Time	0.00185	0.00186	-

Table 1: Compare test and analysis results for incident pressure and arrived time

The analysis study yielded highly successful results in correlating the incident pressure measured from defined tracers at LS-DYNA® with the pressure values obtained from the test.

4.2 Flat Plate Blast Test

The first set of studies conducted to simulate the interaction between the explosive and the structure is the flat plate test. Displacements were measured using the displacement cone in the fixture and at the center of the plate.


(a) (b)

Fig.8: Flat plate test (a) Before test (b) After test

The explosion simulation was conducted using the Structured ALE Method in LS-DYNA® software. The steel pot, explosive, and air were modeled using S-ALE, while other structural components were modeled using Lagrange element models.

The analysis model is depicted below.

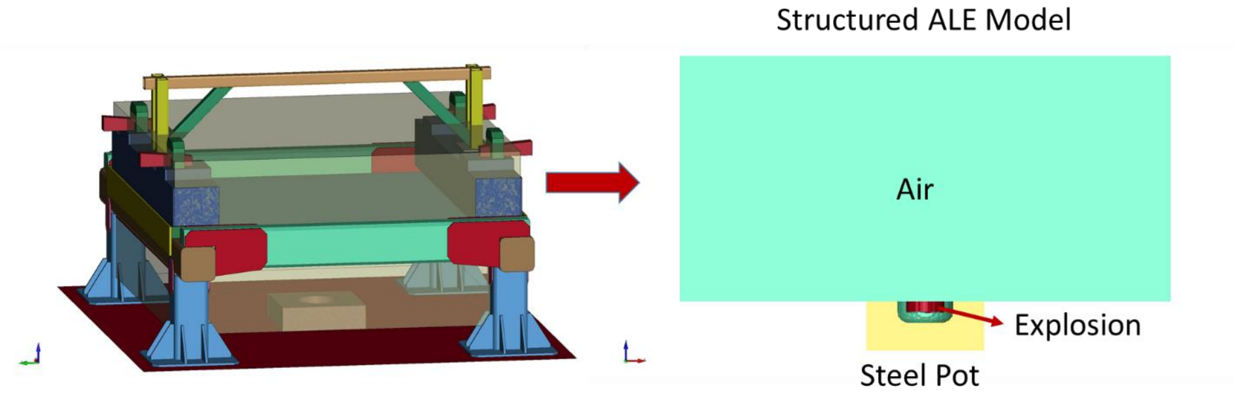


Fig.9: Flat plate analysis model and Detailed Structured ALE Model

In explicit analysis studies such as explosion simulations, which involve short events and high deformations, material definition is crucial for observing material behavior in the simulation. In this study, the plates were modeled using the “mat_simplified_johnson_cook” material model obtained from split Hopkinson bar tests. The “mat_plastic_kinematic” material model was used for the test setup.

The relationship between the structural elements modeled as Langrange and the S-ALE model has been established using the “constrained_lagrange_in_solid“ card.

Automatic single surface contact has been defined between the test setup and the flat plate.

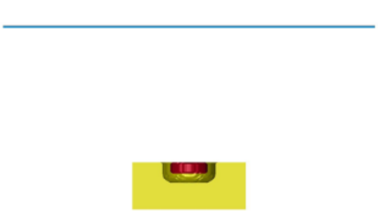
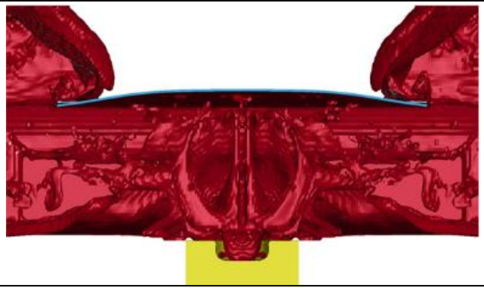
t=0 ms	**t=0.50 ms**
	
t= 3 ms	**t=4 ms**
	

Fig.10: Stages of explosion simulation / explosive and flat plate interaction.

No leakage issues were observed in the simulation results.

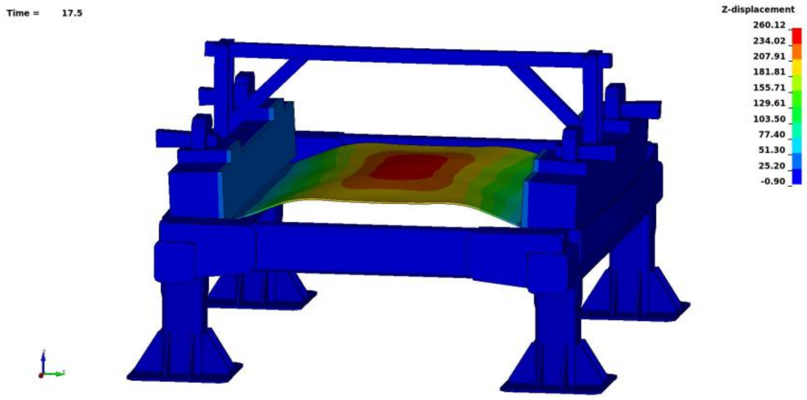


Fig.11: Maximum displacement of flat plate analysis

	Test	**Analysis**	**Error [%]**
Elastic Displacement	235 mm	251 mm	6.8

Table 2: Compare test and analysis displacement results

Elastic displacement was obtained relative displacement between middle of the twisted plate and upper support bar.

4.3 Twisted Plate Blast Test

The interaction between the explosive and the plate was investigated through a twisted plate test. Additional plates were welded to the edges of the twisted plate to enhance its rigidity.


(a) (b)

Fig.12: Twisted plate test (a) Before test (b) After test

The explosion simulation was set up with boundary conditions similar to those of a flat plate. In the test setup, an automatic single surface was used to model the contact between the test setup and the twisted plate, and the additional plates welded to the twisted plate were modeled using type of surface to surface tied-break contact.

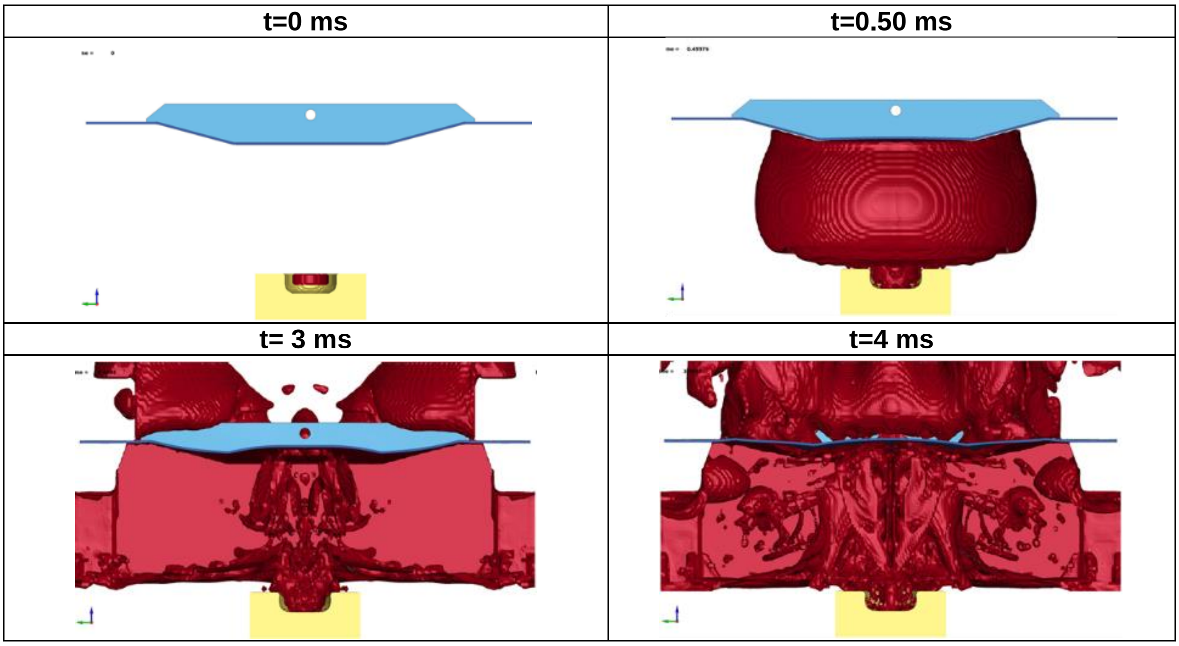


Fig.13: Stages of explosion simulation / explosive and twisted plate interaction.

No leakage issues were observed in the simulation results.

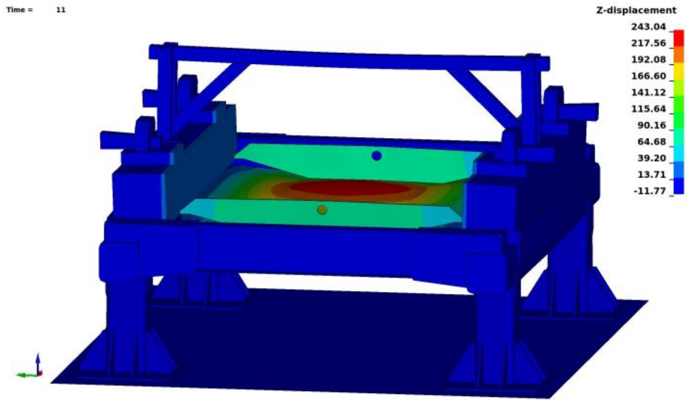


Fig.14: Maximum displacement of twsited plate analysis

	Test	Analysis	Error [%]
Elastic Displacement	231 mm	244 mm	5.6

Table 3: Compare test and analysis displacement results

Elastic displacement was obtained relative displacement between middle of the twisted plate and upper support bar.

4.4 Plate with Deflector Blast Test

One of the most effective methods for countering mine protection threats in armored vehicles is the implementation of a deflector system added to the vehicle's underbelly. This test aimed to examine the impact of the deflector. The deflector was mechanically attached to the additional perforated plates, welded onto the twisted plate, using bolts.

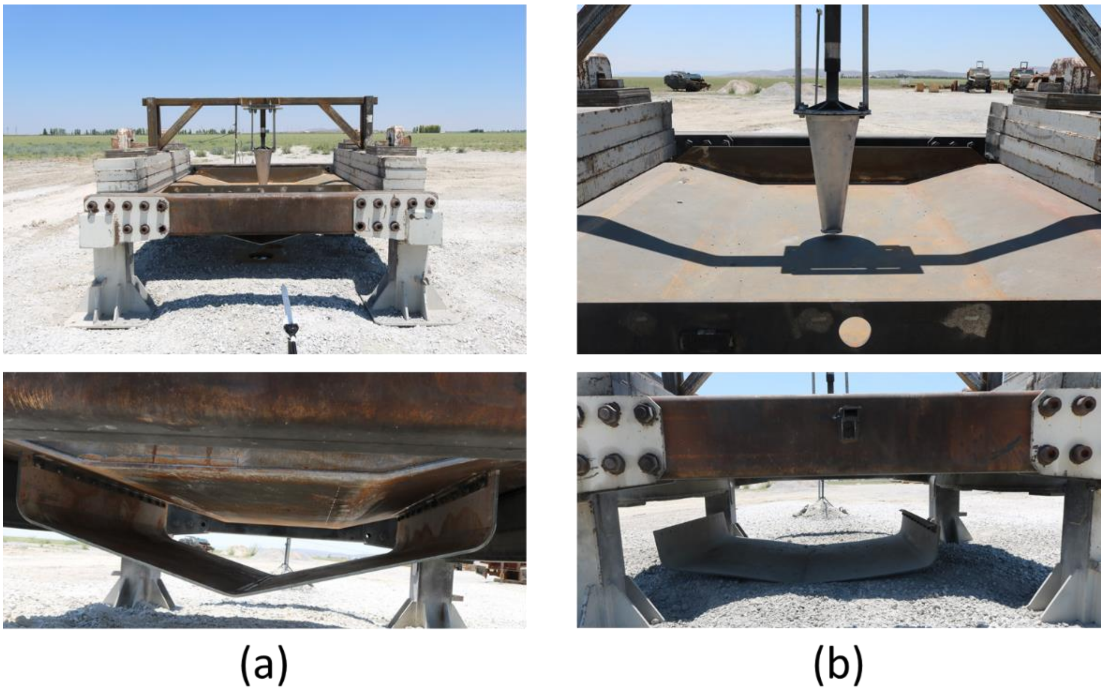


Fig.15: Plate with deflector blast test (a) Before test (b) After test

The boundary conditions for the explosion simulation were set up in a manner consistent with previous analyses. The additional plates welded to the twisted plate were modeled using surface to surface tied-break contact. Bolts were used for the mechanical connections between the deflector and the twisted plate, and these connections were modeled using the 1D beam. 1D beams are modelled “mat_spotweld” material model.

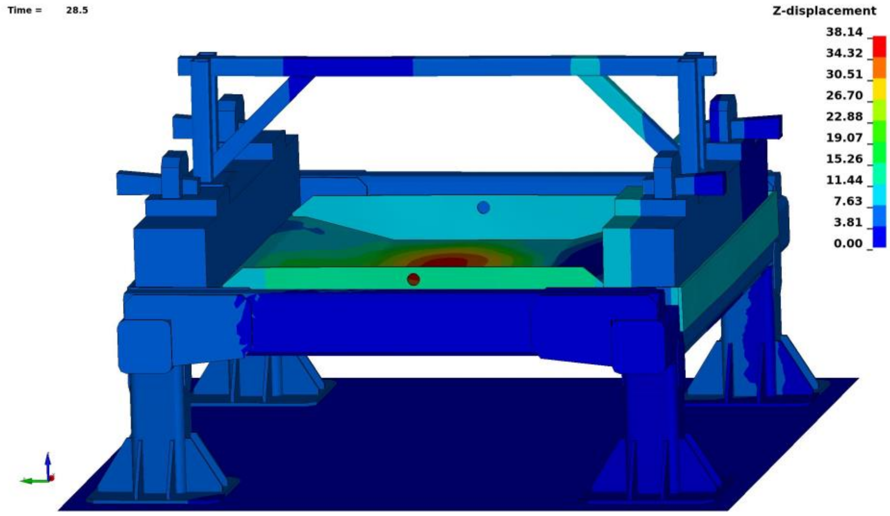
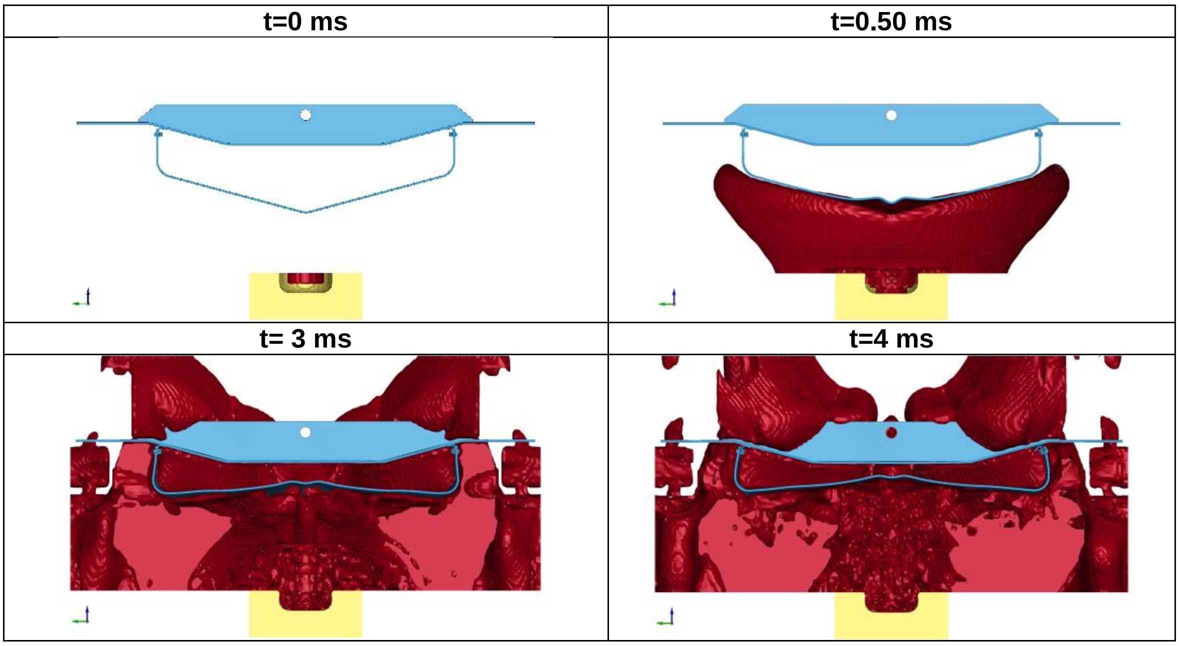


Fig.16: Maximum displacement of plate with deflector analysis


t=0 ms

t=0.50 ms

t= 3 ms

t=4 ms

Fig.17: Stages of explosion simulation / explosive and plate with deflector interaction.

No leakage issues were observed in the simulation results.

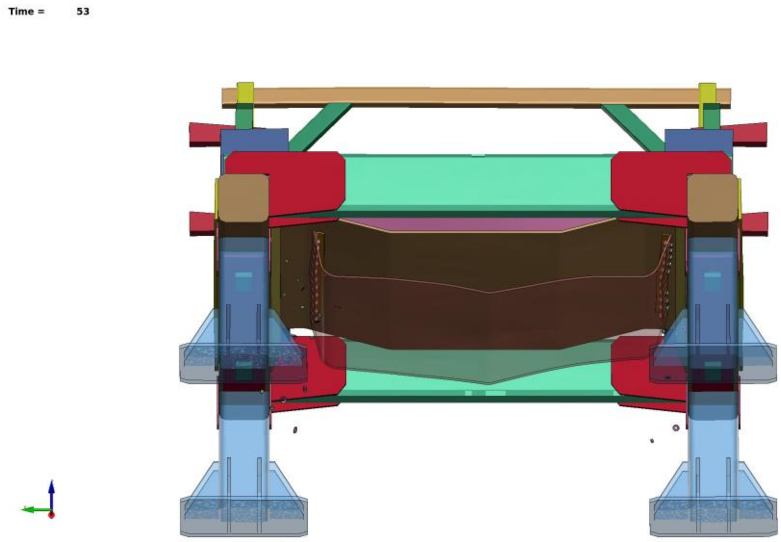


Fig.18: End of the analysis stage

Following the analysis, it was observed that similar to the plate with deflector test, all bolts on one side had sheared off, while on the other side, the contact with the additional perforated plate had separated.

	Test	**Analysis**	**Error [%]**
Elastic Displacement	19 mm	31 mm	63

Table 4: Compare test and analysis displacement results

Elastic displacement was obtained relative displacement between middle of the twisted plate and upper support bar.

Upon reviewing the analysis and test results, it has been observed that the behaviour of the deflector is similar to that observed during the test. However, there is a significant discrepancy between the elastic displacement values measured on the twisted plate and the obtained results. Therefore, in order to validate the accuracy of the measured displacement values, it may be necessary to repeat the test.

5 Acknowledgements

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6 Summary

In this study, 4 different blast test was tested and analysed at LS-DYNA® software. The main purpose of these tests is to validate the explosion simulation.

Free field blast tests provided insights into the general behavior and physical characteristics of the explosive. When comparing the pressure data obtained from the test and the analysis, it was observed that a successful validation study had been conducted.

The validated explosive characteristics obtained from free field blast tests were utilized in the plate analysis. Plate tests were conducted to examine the interactions between the explosive and the structure. No leakage issues were encountered during the all plate analyses.Validation studies were conducted by comparing the analyses of flat plate and twisted plate tests, revealing displacement differences of 6.8% and 5.6%, respectively.

In the final test involving the plate with deflector, although the behavior of the deflector was validated, a significant deviation was observed in the displacement values of the twisted plate. For the validation of this test, a retest may be conducted in the coming years.

7 Literature

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