COMPARING PLATE-LEVEL BLAST ANALYSIS USING ALE, S-ALE AND CONWEP METHODS

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1 Abstract

The military land vehicle industry is increasingly requiring increased protection levels, leading engineers to create more complex design and simulation scenarios. In most cases, the most commonly used method for blast simulations is the Arbitrary Lagrange Eularian (ALE) method, which is also known for its ability to determine the structural effects of blast loads. This paper examines the effects of different methods; traditional ALE solver, Structured mesh (S-ALE) and ConWep methods. It also examines the solution times, fluid-structure interaction performance for solid interfaces.

2 Introduction

An explosion can be defined as a rapid chemical reaction involving a solid, dust, or gas, during which there is a swift release of hot gases and energy. This phenomenon occurs within a matter of milliseconds and leads to the generation of extremely high temperatures and pressures. During the detonation process, the hot gases generated expand to fill the available space, resulting in the propagation of a spherical wave through the surrounding medium. In the case of air blasts, the surrounding air also expands, causing its molecules to accumulate and form a blast wave and shock front. The blast wave contains a significant portion of the released energy and travels at a speed exceeding that of sound.

The protection of military vehicles against explosions is of paramount importance. These vehicles must be capable of enduring the forces resulting from explosions and the subsequent fragmentation. To assess vehicle survivability, both plate-level and full-scale mine blast tests are conducted. Additionally, computer simulations are commonly employed, but their accuracy must be reasonable to ensure an effective final design. The protection against blast loads, particularly the bottom plate, plays a crucial role in safeguarding the vehicle. During hull design, careful consideration is given to the deformation behavior of the bottom plate to determine its placement. Given the critical nature of blast protection in the design process, vehicle hull structures are constructed using high-strength materials with greater thickness compared to commercial vehicles.

The simulation analyses of the explosion were performed using three different methods: LBE (Lagrangian-based Eulerian), and ALE (Arbitrary Lagrangian-Eulerian), S-ALE (Structured ALE). The reference point cloud data obtained from the scanning process after the explosion tests conducted on a 12 mm thick M400 steel plate indicated a deformation of approximately 12.5 cm at a Y-directional (blast axis) distance between the measured points. Based on this measurement, the explosion analyses were simulated using the these three methods. The scenario involved the detonation of 6 kg of TNT beneath the structure.

3 Test

3.1 Plate Level Blast Test

As stated in Stanag 4569 level 2, 6 kg of tnt was buried in the soil from a certain distance by opening a pit at the depth specified in the standard. The prepared torso was brought to the test area and the explosion test was carried out by adding weights on the torso so that the plate would not fly due to the explosion.

Fig. 1 Real Test Pictures

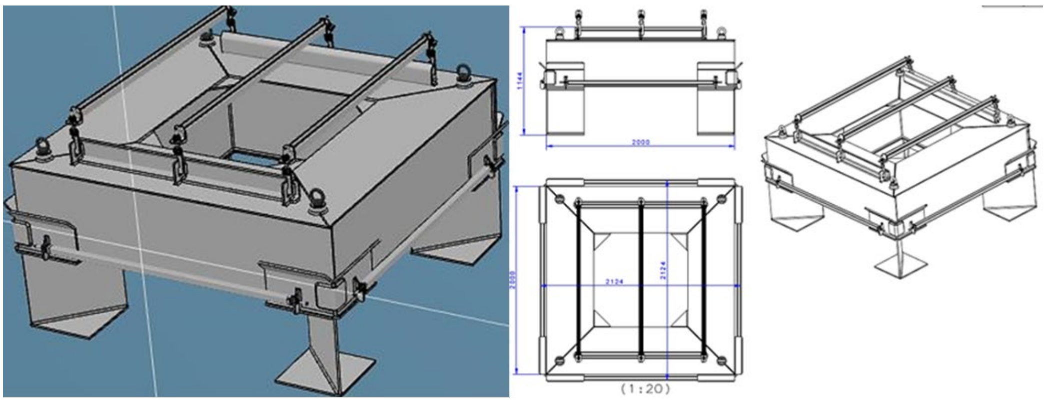


Fig. 2 Test torso CAD data's and 2D drawings

Test area preparation

- The test area was determined and the area where the explosion would take place was excavated with dimensions of 2000 mm x 2000 mm x1500 mm.
- The excavated soil was mixed with water to a height of 1300 mm and placed in the excavated area.

Fig. 3 Test Pit and buried TNT height images

- When the height of the soil mixed with water reached 1500 mm, 6 kg TNT explosive was placed on the prepared soil.
- A detonator was placed under the TNT explosive with a gap of approximately 50 mm.
- The TNT explosive was covered with soil again and a total height of 1500 mm was reached.

Fig. 4 Deformed armoured plate and scanned data

-Deformed plate data was obtained by scanning the plate after the explosion.

3.2 Material Test

With the Split Hopkinson Bar test, the compressive stress-strain behavior of the materials at different deformation rates is determined, as well as the impact properties at low speeds and the wave transition in multi-layer materials. When combined with static velocity experiments, structural equations can be created that can be used to model materials in impact events with numerical methods or programs.

High strain rates of deformation can occur in a variety of applications, including accidental events (such as penetration and explosion), as well as engineering applications (e.g., crashworthiness of vehicle bodies, bullet proof armor, impact-resistant pressure vessel, shipping cask, nuclear materials, etc.). High strain rates can also occur in forming processes such as extrusion, roll-off, and high-speed machining.

When designing and analyzing components with high-strain rates of loading, it is important to consider the composition behavior of the materials at these high strain rates.

Fig. 5 Split Hopkinson Bar Test Pictures

4 Analysis Methods

4.1 Ale / S-Ale

The Arbitrary Lagrangian-Eulerian (ALE) method is a computational technique used in fluid dynamics and mechanics to solve problems with moving boundaries or deformable domains. The ALE mesh refers to a computational mesh that can adapt and deform to accommodate the motion of the underlying domain. Unlike the Lagrangian approach that tracks the material motion or the Eulerian approach that uses a fixed mesh, the ALE method combines both by allowing the mesh to deform while maintaining a fixed computational framework. This approach is particularly useful for problems involving large deformations, complex geometries, or fluid-structure interactions. By using the ALE method and mesh, simulations can accurately capture the motion and deformation of objects or materials, enabling realistic and reliable analysis in various scientific and engineering fields.

The S-ALE solver implemented recently is stated to reduce the solution time and the memory requirements [3]. It also brings simplicity in defining the ALE domain with a couple of keywords.

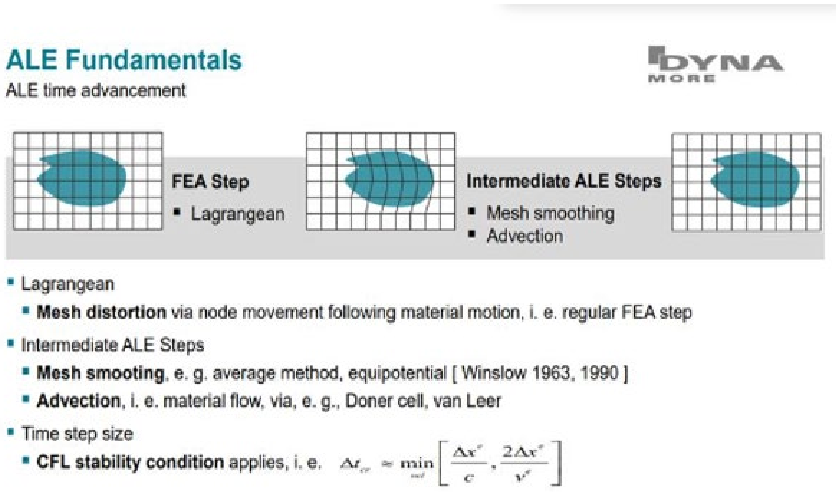


Fig. 6 ALE Fundamentals

Air domain material is defined with ***EOS_LINEAR_POLYNOMIAL and *MAT_NULL** keyword cards. For soil domain definitions, ***MAT_SOIL_AND_FOAM_FAILURE** is used. [6]
Also ***EOS_JWL** and ***MAT_HIGH_EXPLOSIVE_BURN** used for TNT model which is shown below figure. To define FSI (Fluid structure interaction) between explosive part, air, soil and test plate, ***CONSTRAINED_LAGRANGE_IN_SOLID** keyword and parameters are used from a literature study.[5]

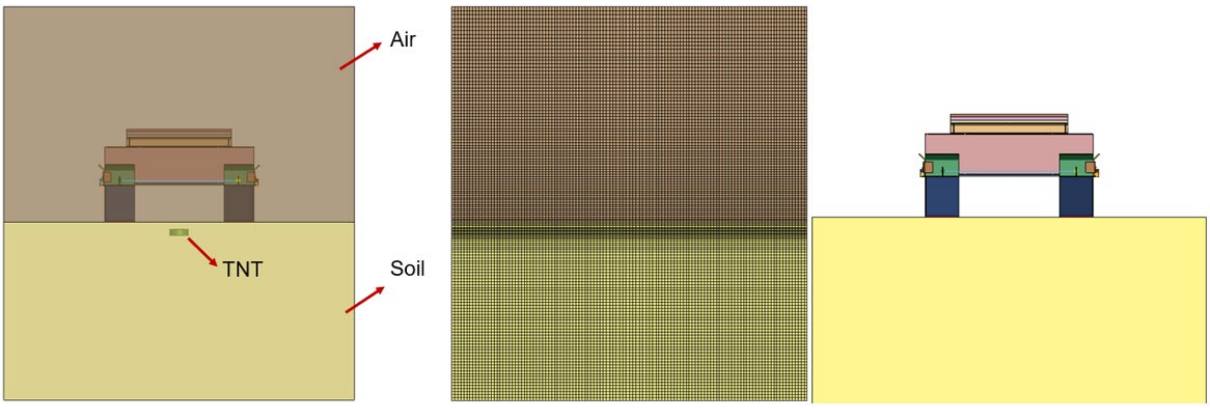
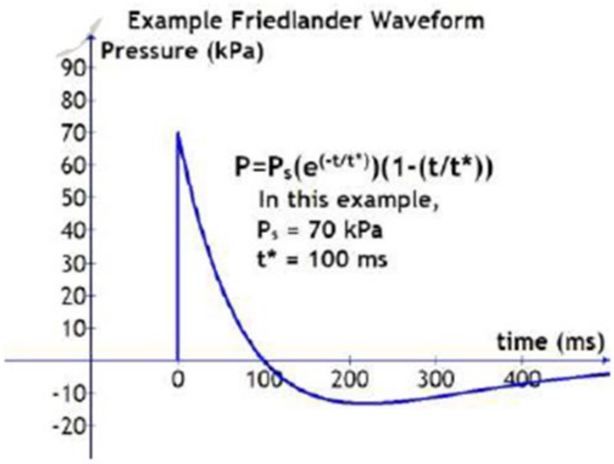


Fig. 7 ALE Domain

Unlike ALE models, the S-ALE model has several different keyword cards. **`*ALE_STRUCTURED_MESH`** and **`*ALE_STRUCTURED_CONTROL_POINTS`** cards are used in the model. In order to define the S-ALE domain, it is necessary to set the coordinates of these control points and the mesh element sizes. The important point here is to keep the mesh denser in the region where the blast wave will propagate while creating the element sizes, so that more accurate results will be obtained in the elements in the region that will enter the FSI. After creating the S-ALE domain, we assign the air, soil and TNT parts to this domain with the **`*ALE_MULTI-MATERIAL_GROUP`** card. After making this definition, we obtain 3 separate domains by dividing the single domain we have created with the **`*INITIAL_VOLUME_FRACTION_GEOMETRY`** card with coordinates.

3.2 ConWep

The CONWEP blast method is an established engineering tool used to estimate the effects of explosive detonations on structures and individuals. It employs empirical relationships and mathematical models to assess key blast wave parameters, including peak pressure, duration, impulse, and phase duration. By considering factors such as explosive yield, distance, and environmental conditions, the method provides an estimation of the potential damage and effects caused by the blast. Widely applied in military, civil engineering, and security contexts, the CONWEP blast method aids in evaluating structural vulnerabilities, human injury risks, and developing protective measures against explosive threats.



A Friedlander waveform is the simplest form of a blast wave in a free-field environment.

Fig. 8 Conwep Formulation [7]

Kingery and Bulmash [8] performed some calculations to predict the explosion parameters obtained from explosions in spherical air and explosions on semi-spherical ground.
In the CONWEP model, simple empirical equations can be used to calculate the variation of the pressure distribution on the structure with respect to time. This eliminates the need for a volumetric calculation network. On the other hand, CONWEP has some limitations. It is not possible to model the shadowing effects of obstacles and similar structures between the explosive and the target structure [9].

The relations and curves obtained in the CONWEP method were defined by Randers-Pehrson and Bannister [12] with the **`*LOAD_BLAST`** card in LS-DYNA software in order to see the behavior of structures subjected to explosion in the simulation environment.

In order to calculate the pressure, the equivalent TNT mass, blast type, blast location and target surface must be defined. Throughout the simulation, the pressure vector always remains normal to the surface of the shell, regardless of structural deformation. This coincides with the flow of the blast wave and can lead to errors if the deformation is large.

5 Torso FE Model

While modeling the torso CAD model with finite elements, modeling process was done using solid elements. Welded parts are connected to each other using ***CONTACT_TIED_SURFACE_TO_SURFACE_OFFSET** card. The connection of all parts with each other is also defined with ***CONTACT_AUTOMATIC_SINGLE_SURFACE** card.

In the material definition, the ***MAT_TABULATED_JOHNSON_COOK** card was used to define the plate material parameters. Since the deformations of the remaining structural parts will not be dealt with, they are defined with the ***MAT_ELASTIC** card.

But since the Air model is defined with the ***MAT_NULL** card, the material model needs EOS (Equation of State) definitions to simulate the fluid material behavior. EOS calculates the hydrostatic pressure in the material. EOS is required when the pressure in the material is well above the yield stress and/or high strain rates [10]. For this reason, the ***EOS_LINEAR_POLYNOMIAL** card definition has been added to the air model. In order to prevent hourglass formation on the elements during the explosion, ***HOURGLASS** card definitions were made.

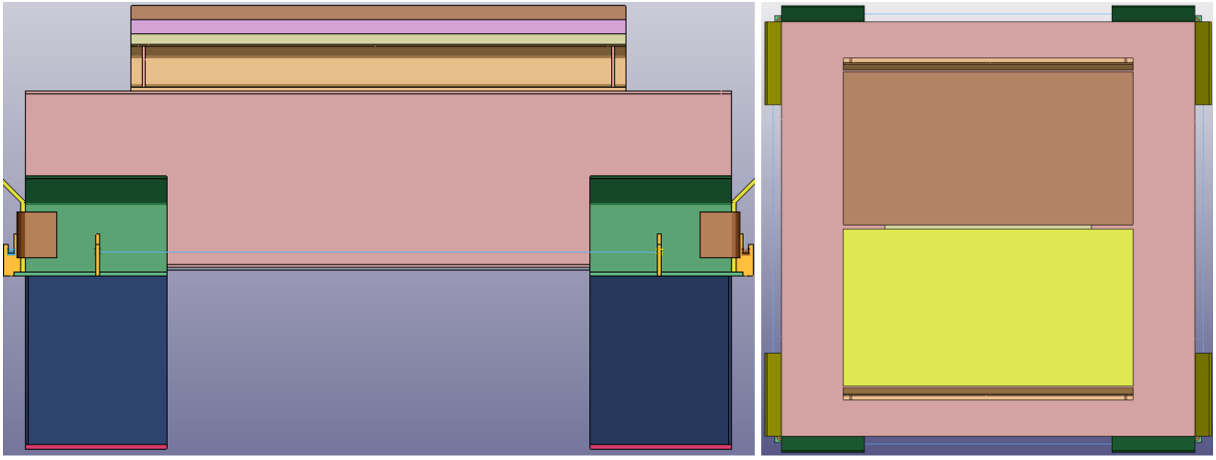


Fig. 9 Torso FE model

In Beam, Shell and Solid elements, the ELFORMs selected in the section card change the "element formulations" of the element. The recommended element formulation for those materials is the multi-material ALE formulation (ELFORM = 11 in ***SECTION_SOLID**).

In Figure 10, one of the formulations proposed for shell elements is the Belytschko-Lin-Tsay formulation shown as "ELFORM=2" which provides one integration point on the element surface. Another element formulation is the fully integrated shell formulation shown as "ELFORM=16" which provides four integration points on the element surface [11]
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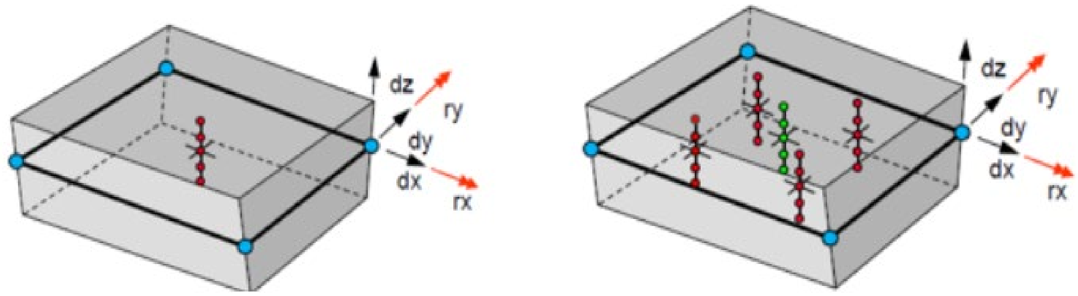

Fig. 10 Element formulations for quadrilateral shell elements [11]

6 Simulation Results

6.1 ConWep Results

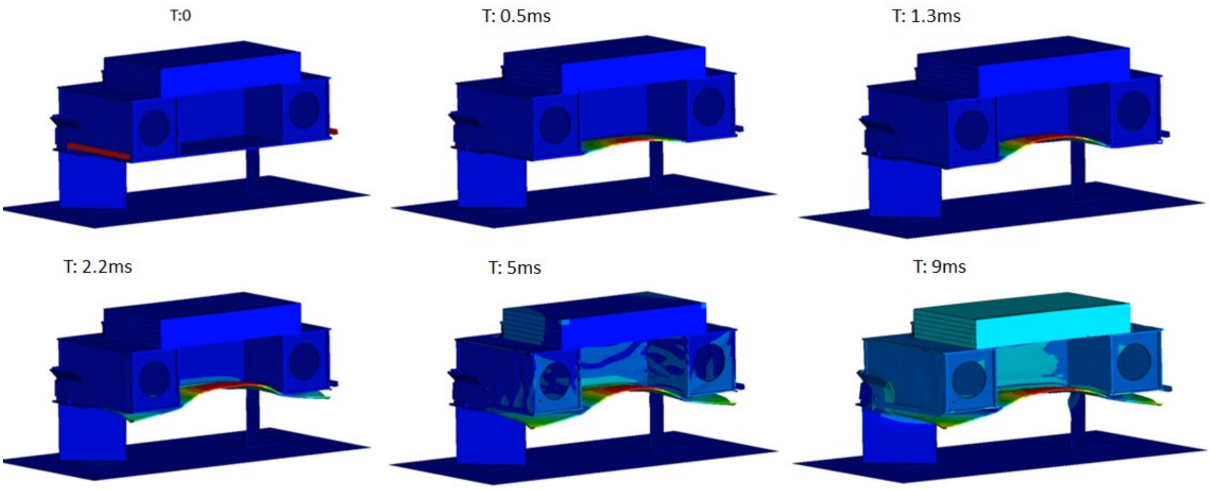

Fig. 11 Conwep Method Virtual Analysis Result

Unlike the ALE method, a domain is not defined in CONWEP management. For explosive definition, explosive mass, location and type of explosive are defined with **`*LOAD_BLAST_ENHANCED`** card. In order to define the structures that the explosive will interact with, element surfaces are selected with the **`*SET_SEGMENT`** card and the explosive and the surfaces it will interact with are defined in the **`*LOAD_BLAST_SEGMENT_SET`** card.

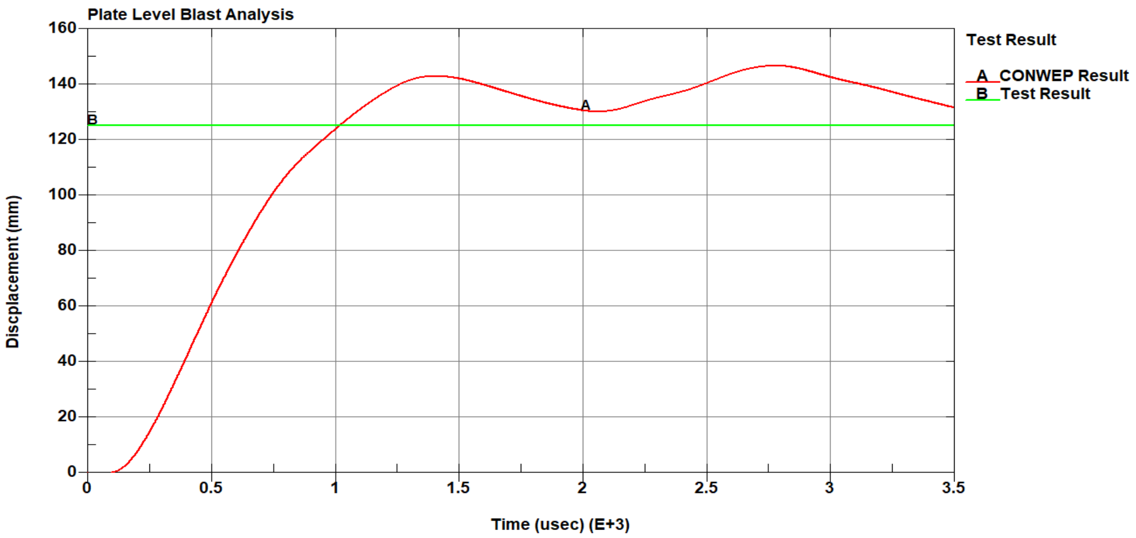

Fig. 12 CONWEP plate displacement curve comparison with test result

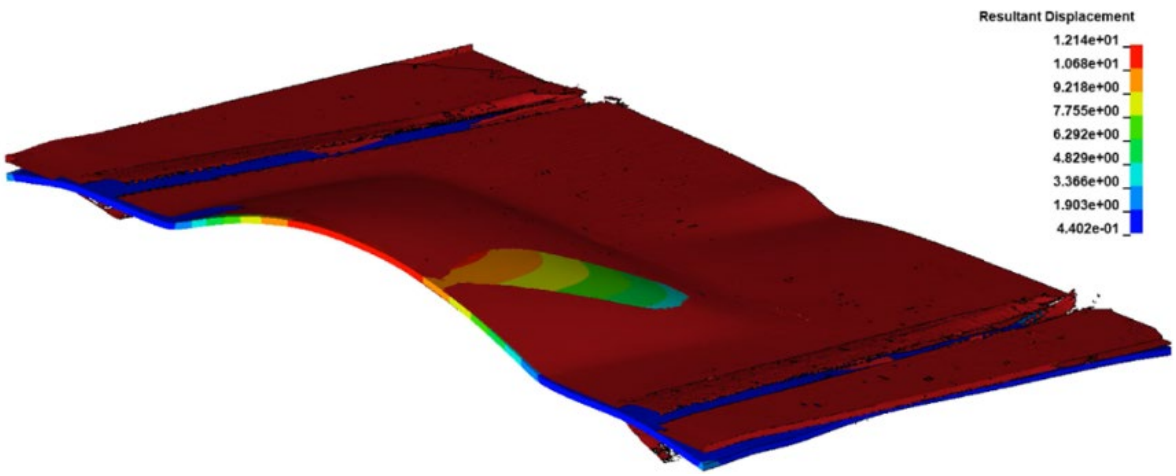

Fig. 13 Comparison of scanned deformed plate and CONWEP analysis

6.2 ALE Results

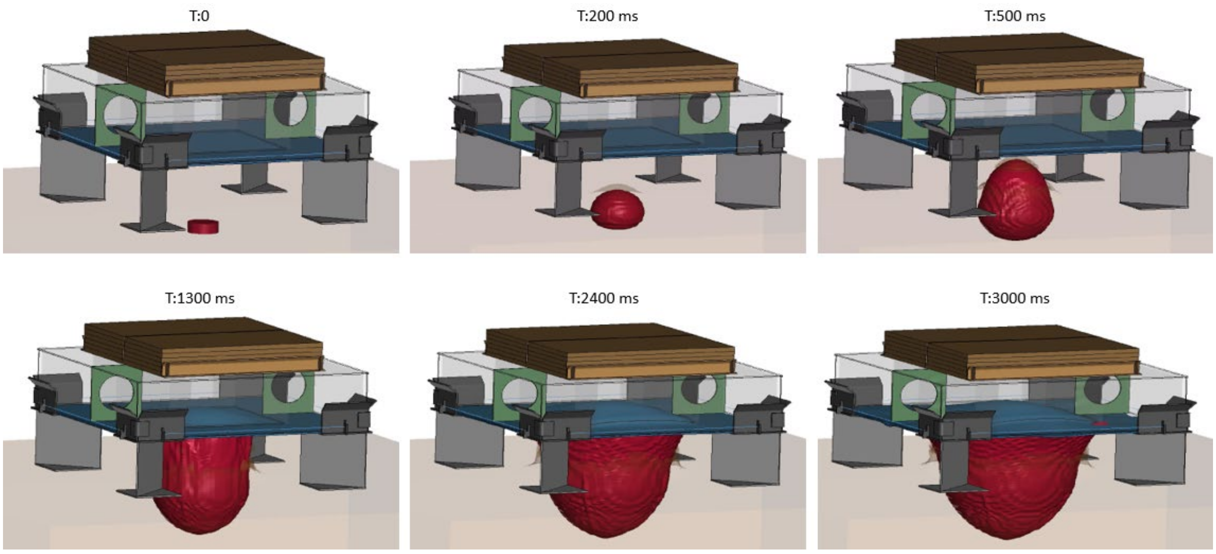

Fig. 14 ALE / *TNT location underneath plate and blast result*

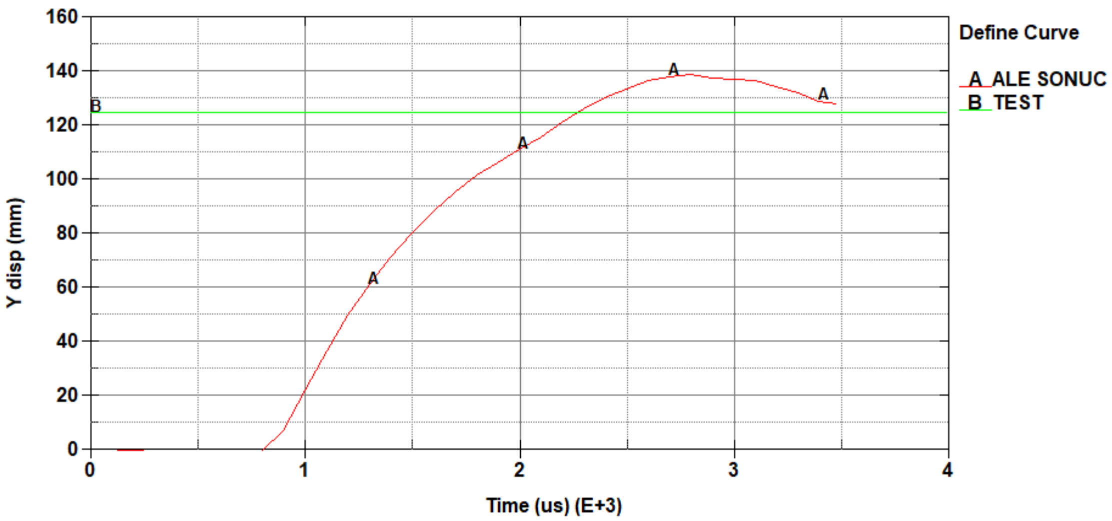

Fig. 15 ALE plate displacement curve comparison with test result

6.3 S-ALE Results

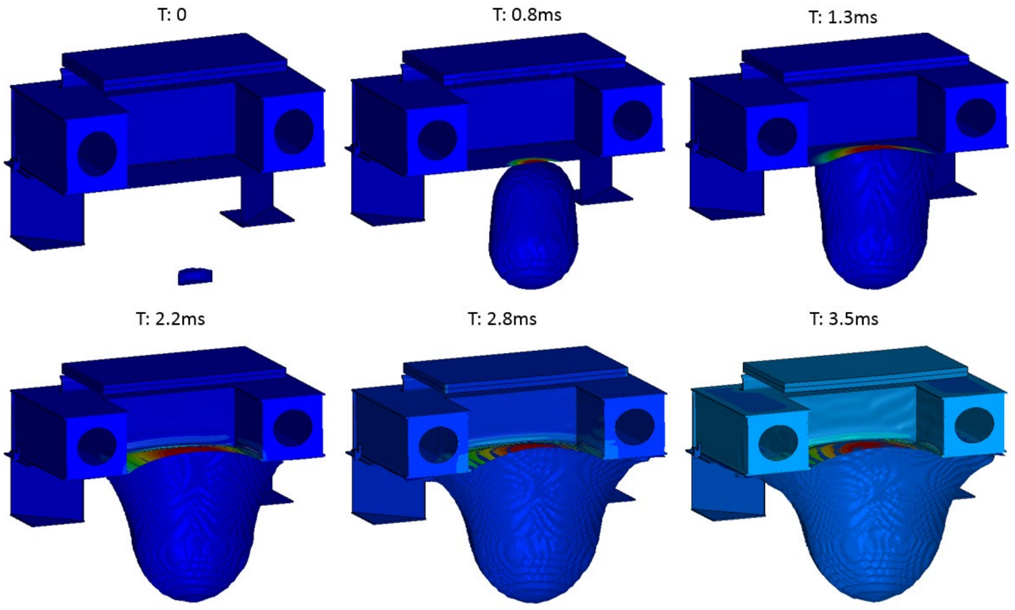

Fig. 16 S-ALE / *TNT location underneath plate and blast result*

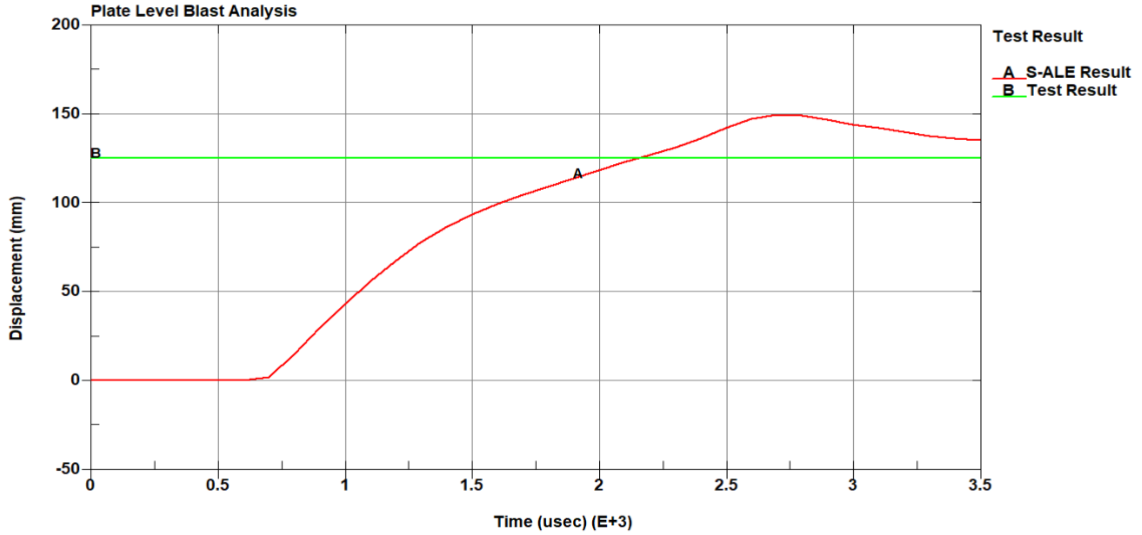

Fig. 17 S-ALE plate displacement curve comparison with test result

7 Summary

The plate deformation values were measured on the plate through explosion tests conducted for Stanag 4569 Level 2 blast testing. Subsequently, the deformed plate was scanned and converted into CAD data.

A mathematical model of the material used for Stanag 4569 Level 2 blast analysis was developed. Split Hopkinson bar tests were performed to characterize the material at high velocity. As a result of these tests, the Johnson-Cook stress and damage models for the material were obtained.
The obtained mathematical model was assigned to the finite element model of the plate using the Johnson-Cook material model.
Blast analyses for Stanag 4569 Level 2 was conducted using the prepared finite element model with different methods such as CONWEP, ALE, and S-ALE methods. The results were compared against the deformed scanned plate.

During the blast analyses, attention was given to comparing the different methods with the actual test results and analyzing the computation times.

Test Plate	Max. Displacement (cm)	Error Rate (%)	CPU Time (h)
Test Result	12,5	-	-
ConWep	13	3,8	0,5
ALE	12,72	1,76	17,5
S-ALE	13,8	9,4	1,5

Table 1: Displacement Results comparison between test and analyses

When the results in Table 1 are analyzed, it is seen that the 3 analysis methods mentioned in this paper are close to each other and consistent compared to the plate level test result.

The Conwep method is fast in terms of analysis time and simulation model preparation, but it is not suitable for use everywhere (non shadowing). Since there is no such problem in plate level simulation, it is logical to use it and it is suitable in terms of both cost and time.

In the Arbitrary Lagrangian Eulerian (ALE) method, since the explosive and the fluid environment in which the explosive is located are modeled, it has been observed that the values closest to the plate level test results are obtained. However, when analyzed in terms of time and cost, it is seen that it is a very expensive method.

In the S-ALE method, since there is no physical mesh in the ALE domain, it shortens the analysis time very much. When the results obtained are examined, it is seen that the analysis times of ALE and S-ALE are very different. When we compare it with the test results, it is seen that it is within the 10% error margin. It is appropriate to use in terms of time and cost.

8 Literature

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