SAKARYA UNIVERSITY
JOURNAL OF SCIENCE

e-ISSN: 2147-835X
http://www.saujs.sakarya.edu.tr

Recieved	Accepted	DOI
2017-11-24	2018-04-06	10.16984/saufenbilder.357629

On evaluation and comparison of blast loading methods used in numerical simulations

Atıl Erdik*[1], Vahdet Uçar[2]

ABSTRACT

Dynamic behavior of structures exposed to blast loading have been widely investigated to assess the integrity of structures and to examine structural factors influencing survivability of occupants. Numerical simulation techniques are efficient design tools to estimate the response of structures under blast loading. This study investigates numerical simulation of blast loading by using LS-DYNA explicit solver. In LS-DYNA, blast simulations are carried out through the following methods: CONWEP, Arbitrary Lagrangian Eulerian (ALE), and hybrid CONWEP-ALE. The aim of this study is to evaluate three blast loading approaches in order to get better understanding on the requirements of computational effort, accuracy of blast loading scheme, and influence of element size. Therefore, an experimental testing of a flat plate subjected to blast loading is modeled using these three blast loading methods in LS-DYNA. Mesh resolution study of ALE formulation is also carried out to determine the effect of element mesh size on predicting blast loading effects that is converted through fluid structure interaction algorithm from Eulerian to Lagrangian type of elements. It is drawn a comparison between peak pressures calculated in simulations and maximum dynamic deformation measured in the field test. Finally, the discussion and conclusion are provided.

Keywords: Blast loading, CONWEP, Arbitrary Lagrangian Eulerian (ALE) method, LS-DYNA, Numerical simulation, Mesh resolution study.

1. INTRODUCTION

World War II had a great impact on investigating dynamic behavior of materials at high strain rates since resistance against anti-tank mines and protection from high caliber ballistic missiles changed the way that combat tanks and vehicles were designed. From that time, blast loading calculations have been intensely studied using both empirical formulations and numerical analysis techniques to interpret behavior of structures under blast loading.

Chemical explosions release large amounts of energy that yields very high pressures. The local pressure disturbance moves outwards and grows into a blast wave subsequently. When a blast wave interacts with a structure such as a vehicle, target is engulfed and crushed. There occurs a “squashing” overpressure acting on the target and this dynamic loading acts long enough to move

* Corresponding Author
[1] Otokar Otomotiv ve Savunma Sanayi, Sakarya, Turkey, aerdik@otokar.com.tr
[2] Department of Mechanical Engineering, Sakarya University, Turkey, ucar@sakarya.edu.tr

target and resulting damage will occur as a consequence of this motion [1].

Advances in computational power of machines in last decade makes it possible to exploit complex numerical solution techniques in determining blast loading affecting on military vehicles, buildings, infrastructures of cities, etc.

LS-DYNA employs nonlinear, transient dynamic finite element analyses using explicit time integration and provides three methods for simulating blast loading: CONWEP method, based on empirical equations obtained from blast experiments, Arbitrary Lagrangian Eulerian (ALE) method, and hybrid CONWEP - ALE method.

Conventional Weapons Effects, namely CONWEP is a specific calculation tool utilizing the equations and curves of TM 5-855-1, "Design and Analysis of Hardened Structures to Conventional Weapons Effects [2]". CONWEP blast loading calculation was implemented into LS-DYNA hydrocode by Randers-Pehrson and Bannister [3] through *LOAD_BLAST function [4]. *LOAD_BLAST method provides simplified pressure distribution to the target structure under blast loads. The function is appropriate for constructing basic design of structure where the fast solution runtime is primary concern. On the other hand, in this method, it is not possible to observe shock waves propagating through fluid domain and to investigate blast waves reflecting from target. The other major drawback is that it cannot simulate localized or focused impulse sensitive blast loads resulting from a blast source such as steel pot. Slawinski et al. [5] examined a numerical simulation study of a simple model of a lightweight armored vehicle exposed to blast loading by utilizing CONWEP method. They investigated the influence of a detonation of TNT under a vehicle with different protection systems. Authors concluded that the CONWEP method helps verify their various protection alternatives with an adequate accuracy.

The second method in LS-DYNA is the Arbitrary Lagrangian Eulerian (ALE) technique [6]. The ALE technique is a combination of pure Lagrangian and Eulerian simulations. It enables coupling of Lagrangian and Eulerian elements through the Fluid Structure Interaction (FSI) algorithm. High explosive charge and surrounding medium are modeled as Eulerian type of mesh, whereas the target structure is modeled as the Lagrangian mesh. The ALE approach has some advantages over other blast loading methods such that the dissipation of shock waves through fluid medium can be modeled and it enables analysts to determine the physical quantities around where detonation occurs such as particle velocity, shock front velocity, temperatures inside and outside high explosive, incident overpressure, etc. Lee et al. [7] studied shock response analysis of a bulkhead in order to investigate the survivability of a ship under internal blast using the ALE technique. They found that the ALE technique provides reasonable results compared with the experimental measurements by taking into account FSI parameters, damage model, and welding method.

The hybrid CONWEP-ALE technique, called *LOAD_BLAST ENHANCED in LS-DYNA combines the advantages of the CONWEP and ALE methods [8]. The Lagrangian approach help avoid modeling the fluid medium between the explosive and target structure, which provides computational cost savings. This method eliminates the modeling of the explosive and a great portion of fluid medium when using the ALE approach. Only the fluid medium around the structure necessitates modeling. Tan et al. [9] compared this method with experimental measurements. They found that impulse values obtained from Hybrid CONWEP-ALE underestimates the test results.

In this study, three blast loading methods are investigated based on the blast experiment of Tabatabaei [10]. The goal of this study is to compare three different blast loading methods in terms of accuracy, efficiency, and calculation time. Reflected and incident overpressure results are calculated separately using CONWEP, ALE, and hybrid CONWEP-ALE methods and numerical results are then compared with the experimental pressure measurements. In addition, mesh resolution study is performed to determine the optimum mesh size for the ALE simulation model. This study not only draws a clear analogy among those blast loading methods and offers some fresh insights into modeling such a blast simulation, but also helps researchers to determine optimum mesh size for their future studies.

2. BLAST TEST

Tabatabaei [10]'s blast test setup is utilized to establish the finite element model of setup itself. In the field test, TNT explosive with a weight of

34 kg is positioned over a rigid reflecting panel with the dimensions of 1830 x 1830 x 165 mm Standoff distance of the high explosive to the target is 1675 mm. As it can be seen in Fig 1 and Fig 2, respectively**,** the incident pressure probes are located at 7420 mm far away from the center of the explosive and the reflected pressure probe denoted as (x) is affixed at the center of the panel. It is worth noting that incident pressure probes is adopted to gather information about propagation and dissipation of shock waves throughout air medium, whereas reflected pressure sensor is used to collect impulse and reflected overpressure histories over time.

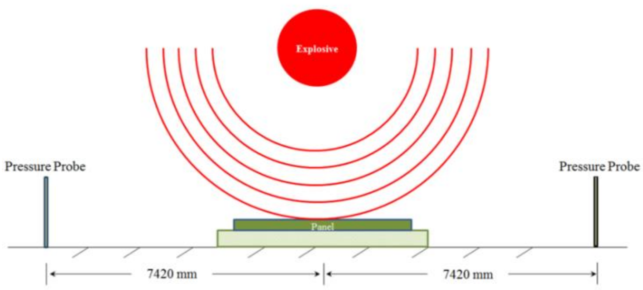

Figure 1 Locations of explosive and incident pressure probes

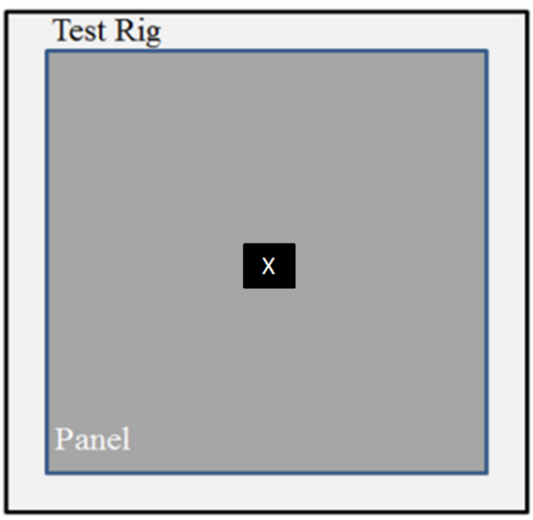

Figure 2 Location of the reflected pressure probe

3. MODELING TECHNIQUES FOR BLAST LOADING

3.1. CONWEP Blast Technique

Kingery and Bulmash [11] performed a series of blast experiments so as to investigate behavior of structures under blast loading. Various amounts of TNT explosive with the shape of sphere and hemi-sphere were detonated at different standoff distances to the target plate to obtain blast parameters. These parameters were then used to formulate the linear polynomial equation of states, which are the basis of CONWEP computer program. CONWEP is implemented in LS-DYNA as *LOAD_BLAST function. The blast load equation is:

$$P(x) = P_x \cos\theta^2 + P_S(1 + \cos\theta^2 - 2\cos\theta) \qquad (1)$$

"θ" is the incident angle in (1). This function can be used for airburst of a spherical high explosive, ground detonation of a charge or surface burst of a hemispherical high explosive.

3.2. Arbitrary Lagrangian Eulerian (ALE) Blast Technique

Arbitrary Lagrangian Eulerian (ALE) method provides coupled approach allowing for interaction between structure and calculation domain that encloses high explosive and products of detonation. The activation of this algorithm in LS-DYNA is generated by *CONSTRAINED_LAGRANGE_IN_SOLID (CLIS) keyword, one for the detonation products and one for the air. Note that material models and equation of states that designate propagation of blast waves and pressure/volume relationships in calculation domain should be defined. ELTYPE=11 is used for the ALE elements [12].

Calculation domain, namely, Eulerian domain consists of high explosive and air medium. The following keywords parameters in *CLIS keyword are used for the ALE simulation: DIRECT=2, ILEAK=1, and NQUAD=2. Hourglass control card with a value of 0.00001 is added to the air elements in order to prevent instability in fluid domain [9].

3.2.1. High Explosive

Explosive type and detonation process are defined using *MAT_HIGH_EXPLOSIVE function. Ignition is also started with *INITIAL_DETONATION function. Shock wave propagation after detonation is described using Jones-Wilkins-Lee (JWL) equation of state. Pressure is described as a function of volume/density and energy given in the equation below:

$$p = A\left[1 - \frac{w}{R_1 V}\right]e^{-R_1 V} + B\left[1 - \frac{w}{R_2 V}\right]e^{-R_2 V} + \frac{wE}{V} \quad (2)$$

In (2), p is pressure, V is relative volume, E is internal energy per initial volume, w, A, B, R_1, and

R_2 are constants and these parameters are gained from the study of Dobratz [13].

3.2.2. Air Medium

Air medium is often defined using ideal gas equation and assuming it as a function of Linear Polynomial equation of state in blast simulations. The air is adopted through *EOS_LINEAR_POLYNOMIAL in LS-DYNA [14]. This approach is given in the following equation:

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

where, E is the internal energy, C_1 - C_6 are constants and μ variable is depending on the volumetric ratio, V (4) defines the relationship between μ and V:

$$\mu = \frac{1}{V} - 1 \quad (4)$$

Coefficients of μ^2 are set to 0 in expanded elements, hence C_2 and C_6 will be zero.

Gaseous materials can be modeled using gamma law in linear polynomial equation of state. Assuming C_0, C_1, C_2, C_3, and C_6 zero gives the equation below:

$$C_4 = C_5 = \gamma - 1 \quad (5)$$

In (5), γ is the ratio of specific heat. The pressure is then attained in (6):

$$p = (\gamma - 1)\frac{\rho}{\rho_0}E \quad (6)$$

Equation of states and material models that are used in this study are demonstrated in Table 1. It should be noted that unit system of simulation is cm, g, Mbar, and microsecond.

Table 1 Material properties and equation of state parameters for air and explosive [13]

Eulerian Domain						
Explosive	Material Model parameters					
	RO	***D***	***PCJ***			
	1.63	0.693	0.21			
	Equation of state parameters					
	A	***B***	***R_1***	***R_2***	***w***	***E_0***
	3.71	0.0323	4.15	0.95	0.3	0.07
Air medium	Material Model parameters					
	RO					
	0.00129					
	Equation of state parameters					
	C_4	***C_5***				
	0.4	0.4				
	E_0	***V_0***				
	$2.58.10^{-6}$	1.0				

3.3. Hybrid CONWEP-ALE Technique

The hybrid blast modeling technique takes advantages of both CONWEP and ALE methods. The method is carried out through *LOAD_BLAST_ENHANCED keyword in LS-DYNA. Benefits of using this technique are to increase the accuracy of propagation of blast pressures and to shorten the solution time. In this technique, blast pressure for a given amount of explosive is obtained from solution history in CONWEP method and is then applied to the boundary layer facing through the target structure. Eventually, the blast pressure is transferred from the boundary layer to the ALE calculation domain [8, 15]. Note that the boundary layer elements should have properties of ALE ambient elements and must share their inner nodes with elements of air domain. Fig 3 shows the schematic drawing of the hybrid method.

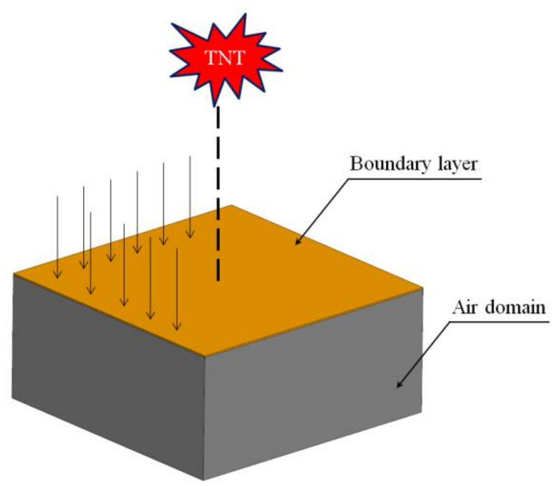

Figure 3 Modeling of hybrid CONWEP-ALE technique

3.4. Rigid Reflecting Panel

The panel is consisting of 166,419 hexahedral solid elements. MAT_RIGID keyword is used for the material model of panel. Mechanical properties of steel material are assigned to the elements.

4. ALE MESH RESOLUTION STUDY

The mesh resolution study is performed to determine the optimum element length used in the ALE model. Dimensions of calculation domain are selected as 2100x2100x3000 mm. Five different cubic mesh domains are modeled as hexahedral 8-noded solid elements for the edge lengths of 6.25, 12.5, 25, 50, and 100 mm. 34 kg of TNT is detonated at 1675 mm far away from the target. TNT is meshed as a cube with hexahedral elements. Reflected overpressures are calculated on a single rigid reflecting surface. Numerical simulations are performed on a high performance compute cluster with 36 CPUs and 216 GB RAM. Table 2 gives runtimes and the total number of elements for these mesh domains.

Table 2 Number of total elements and runtimes

Element length [mm]	Number of total elements	Runtime [s]
100	13,230	94
50	105,840	477
25	846,720	3,845
12.5	6,773,760	32,278
6.25	54,190,080	294,461

The blast simulations of test set-up are conducted for each mesh resolution to examine the effect of mesh resolution on the results. For five mesh resolutions, peak values of reflected pressures are calculated in numerical simulations and compared to those of measured in blast experiment. Fig 4 demonstrates the variation of reflected pressure with respect to the mesh resolutions. The best approximation for reflected overpressure is obtained for the mesh size of 6.25 mm. 12.5 mm might be good choice when compute clusters are used for the calculations. However, 25 mm element length would be more convenient for such a blast simulation when ordinary personal computers are considered to run simulation. On the other hand, reflected overpressure values calculated in the Eulerian domain that is made up of both 50 and 100 mm mesh sizes highly underestimate the reflected overpressure; 50 mm mesh size gives 1/3 of reflected overpressure in blast test, whereas 100 mm mesh size provides 1/9 of the measured peak pressure.

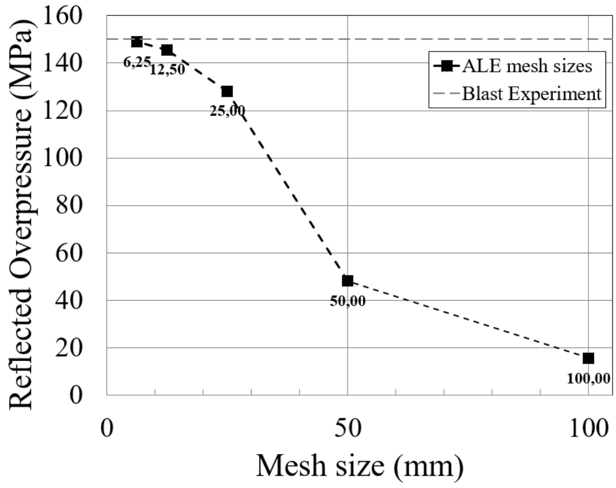

Figure 4 Mesh resolution study for ALE domain

5. NUMERICAL RESULTS OF RIGID REFLECTING PANEL

Table 3 shows total number of elements as well as runtimes for the CONWEP, ALE, and hybrid CONWEP-ALE methods. It should be noted that element legth of 25 mm is opted for ALE and hybrid CONWEP-ALE simulations. When calculation times are compared, the solving time of the ALE simulation is about ten times larger than that of Hybrid ALE-CONWEP simulation. On the other hand, empirical CONWEP method gives the result in seconds.

Table 3 Number of elements and runtimes

Model	Total number of elements	Runtime [s]
ALE	6,773,760	3,845
Hybrid ALE-CONWEP	1,894,440	328
CONWEP	1	2

Sequential progression of shock waves at the instances of 200, 400, 600, and 800 µs in air medium for the element length of 25 mm in ALE simulation is shown in Fig 5, respectively. Though the calculation domain is in Cartesian coordinates, the propagation of shock waves is almost ideal sphere and the mesh resolution is adequate to capture the propagation of shock waves through the mesh lines. In addition, reflection of shock waves from the target plate is clearly observed at the instances of 600 and 800 µs.

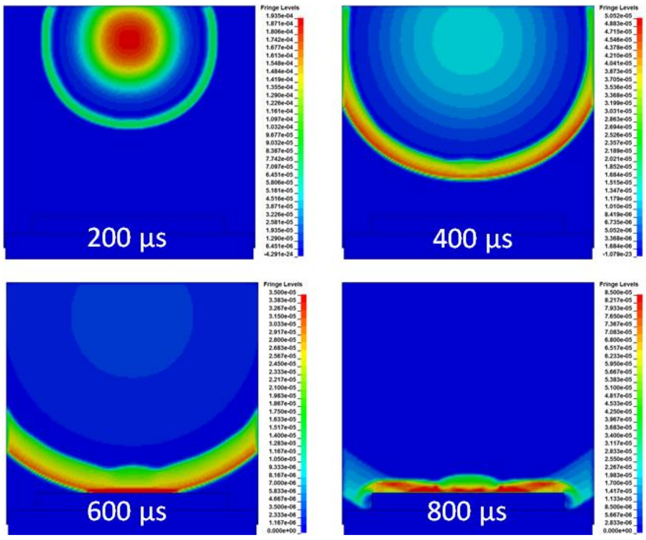

Figure 5 Progression of shock waves at various instances

Table 4 gives the peak pressures obtained from three numerical simulations are compared with pressure collected from blast experiment. Based on the test result, the most promising result is attained from the ALE simulation. The results obtained from the CONWEP method questioned whether this method is appropriate for such a large amount of explosives and standoff distances.

Table 4 Comparison of peak overpressure

	Peak pressure [Mbar]
Test Result [7]	1.50×10^{-3}
CONWEP	0.35×10^{-3}
ALE	1.28×10^{-3}
Hybrid ALE-CONWEP	1.14×10^{-3}

6. CONCLUSIONS

The method of blast loading has strong influence on the results of blast simulation. The CONWEP method could be beneficial for preliminary blast calculations when prompt response is needed. One of the main drawbacks of this method is to use TNT equivalence instead of TNT itself. Moreover, it does not have a capability of simulating shadowing and focusing effects.

Hybrid CONWEP-ALE method can be an alternative to the ALE method when attempting blast loading predictions. This method is computationally efficient and is capable of simulating target response with a good approximation if a sophisticated method is then used as a primary and final choice.

Three dimensional ALE simulations were conducted for both blast testing and mesh resolution study. Five mesh refinements were attempted using 100, 50, 25, 12.5, and 6.25 mm air meshes described previously. Edge length of 6.25 mm provides the best approximation seen in Figure 4, but it has about 54 millions of elements and computationally almost unreachable without using supercomputers. 12.5 mm ensures very promising results if computer clusters are preferred to run simulations. On the other hand, 25 mm offers good approximation with a deviation percentage of 15 from the test result. Its runtime is quite lower than the runtime of 12.5 mm simulation. When it comes to 50 and 100 mm element lengths, it appears from the results that course meshes yield inaccurate results in the fluid domain and those sizes are not appropriate for such a simulation. To sum up, mesh resolution study made possible to determine the optimum mesh size for three dimensional ALE simulation of rigid reflecting plate considering both computational expense and accuracy.

REFERENCES

[1] P. D. Smith and J. G. Hetherington, *Blast and ballistic loading of structures*. 2003, Eastbourne, Great Britain: Antony Rowe Ltd.

[2] U.S. Army Corps of Engineers, N.F.E.C., Air Force Civil Engineering Support Agency, *Design and analysis of hardened structures to conventional weapons effects*, in *Supersedes TM 5-855-1/NAVFAC P-1080/AFJAM32/DSWA DAHSCWEMAN-97 August 1998*. 2002, Department of the Army: US Army Corps of Engineers and Defense Special Weapons Agency, Washington, DC.

[3] G. Randers-Pehrson and K. A. Bannister, *Airblast Loading Model for DYNA2D and DYNA3D*, in *ARL-TR-1310*. 1997, US Army Research Laboratory: Aberdeen Proving Ground.

[4] J. O. Hallquist, *LS-DYNA keyword user's manual*. 2007, Livermore Software Technology Corporation: California, U.S.A.

[5] G. Sławiński, M. Świerczewski, and P. Malesa, *Modelling and numerical analysis of explosion underneath the vehicle*. Journal of KONES Powertrain and Transport, 2017. **24**(4).

[6] J. Donea, S. Giuliani, and J.-P. Halleux, *An arbitrary Lagrangian-Eulerian finite element method for transient dynamic fluid-structure*

interactions. Computer methods in applied mechanics and engineering, 1982. **33**(1-3): p. 689-723.

[7] S. G. Lee, et al., *Shock Response Analysis of Blast Hardened Bulkhead in Partial Chamber Model under Internal Blast.* Procedia Engineering, 2017. **173**: p. 511-518.

[8] T. P. Slavik, *A Coupling of Empirical Explosive Blast Loads to ALE Air Domains in LS-DYNA.* in *7th European LS-DYNA Conference*. 2009. Salzburg, Austria: Livermore Software Technology Corporation.

[9] S. H. Than, et al., *Fluid-Structure Interaction involving Close-in Detonation Effects on Column using LBE MM-ALE Method*, in *9th European LS-DYNA Users Conference*. 2013, Dynamore: Manchester, UK.

[10] Z. S. Tabatabaei, et al., *Experimental and numerical analyses of long carbon fiber reinforced concrete panels exposed to blast loading.* International Journal of Impact Engineering, 2013. **57**: p. 70-80.

[11] C. N. Kingery and G. Bulmash, *Airblast parameters from TNT spherical air burst and hemispherical surface burst*. 1984, Ballistic Research Laboratory, Aberdeen Proving Ground, Aberdeen, MD.

[12] A. L. Kozak, et al., *Validation of the ALE Methodology by Comparison with the Experimental Data Obtained from a Sloshing Tank*, in *14th International LS-DYNA Users Conference*. 2016: Detroit.

[13] B. M. Dobratz, *LLNL explosives handbook: properties of chemical explosives and explosives and explosive simulants*. 1981, Lawrence Livermore National Laboratory: California, U.S.A.

[14] J. O. Hallquist, *LS-DYNA theory manual*, in, Livermore Software Technology Corporation, 2006.

[15] L. Schwer, H. Teng, and M. Souli, *LS-DYNA Air Blast Techniques: Comparisons with Experiments for Close-in Charges. 10th European LS-DYNA Conference 2015.* Würzburg, Germany2015, 2015.