

SHIP STRUCTURES SUBJECT TO HIGH EXPLOSIVE DETONATION

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Abbreviations:

ALE - Arbitrary Lagrangian-Eulerian
EOS - Equation of State
FEA - Finite Element Analysis
JWL - Jones-Wilkins-Lee
TNT - Trinitrotoluene

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ABSTRACT

Predicting the structural response of a naval vessel to a high explosive detonation is an important requirement in naval shipbuilding. Unfortunately, current analysis methods do not provide high level of confidence leading to the utilization of large structural design safety factors. As a result, ships are heavier and more expensive to construct and maintain than may actually be required. Moreover, more reliable predictions can support innovative structural configurations, which provide lower life-cycle costs with increased survivability.

In the currently used approaches, pressure-time history is initially generated from empirical equations and/or test data, and then the time dependent pressure is applied to the structure. These approaches have many limitations and use various approximations.

This paper highlights a numerical simulation procedure for the prediction of the effect of the detonation of high explosive compounds on steel structure. The dynamic simulation interfaces the blast wave predicted by the Jones-Wilkins-Lee (JWL) equation of state for high explosives (built-in the LS-DYNA equation of state library), with time dependent spatial response of the structure. The air surrounding the structure is modeled to represent the medium in which the blast propagates using the LS-DYNA multi-material elements. A linear polynomial equation of state is used to simulate the proper behavior of air.

Several explosion tests with different configurations (internal and external) were conducted in order to quantify the effect of a detonation on different structurally representative test articles. It was established that the numerical simulation demonstrates good correlation with the empirical results.

INTRODUCTION

The methods which are currently used in the field of naval shipbuilding for the analysis of structures subjected to high explosive detonation rely either on extrapolation of empirical data or on very conservative analytical methods (e.g., see Joint Departments of the Army, the Navy, and the Air Force, 1990, NAVSEA, 1995). In the most accurate of the existing methods (e.g., Kingery and Bulmash, 1984 and Randers-Pehrson and Bannister, 1997), pressure-time history is initially generated from empirical equations and/or test data, and then the time dependent pressure is applied to the structure.

The latter approaches have many limitations and use various crude approximations. Some of the more important limitations of these approaches are as follows:

- The existing methods do not take into account any confinement or tunnel effects,
- The existing methods do not take into account the shape of the explosive charge, which for small standoffs can be very important,
- The existing methods do not account for shadowing by intervening objects,
- In the existing methods, the explosive is usually reduced to TNT equivalent, and
- Usually, the existing methods use very rough approximations of temporal and spatial pressure field distribution.

APPROACH

In the presented simulation, pressure is applied to the investigated structure indirectly. Its time and space distribution is generated by an LS-DYNA algorithm, which utilizes the equation of state for high explosives to compute the pressure field in a gaseous medium due to detonation. A finite element model of the structure, as well as, the air surrounding the explosive charge and the structure, is generated. The mix of the air and explosion reaction products is modeled using LS-DYNA multi-material capabilities (*ALE_MULTI-MATERIAL_GROUP_OPTION). The blast pressure wave traveling through the air, interacts with the structure by means of a gas-structure interfacing algorithm (*CONSTRAINED_LAGRANGE_IN_SOLID). Physical quantities such as: stresses, displacements, velocities, and accelerations in the structure are computed. As a consequence, the presented methodology is not constrained by the limitations existing in the other approaches.

The Algorithm

The algorithm utilizes three major components to define the procedure as shown in Figure 1:

1. Equations of state for air and the products of the explosion in conjunction with FEA model (Eulerian formulation),
2. Structural FEA model (Lagrangian formulation),
3. Gas – Structure interaction module.

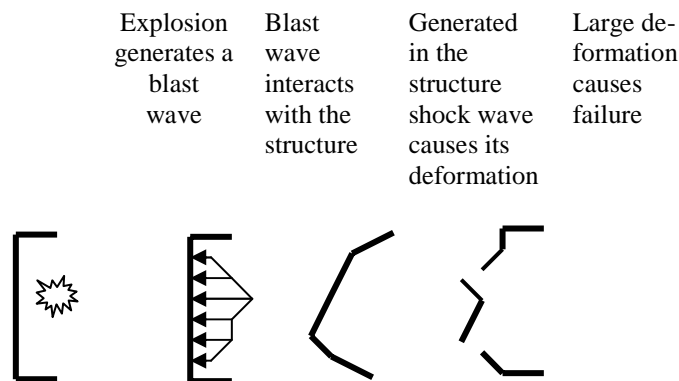


Figure 1. Defining the Procedure

The Main Equations – Explosive and Air

The empirical JWL Equation of State (EOS) was used in the simulation of the ignition and growth of the products of the explosive reaction. It has the form,

$$P = A \left(1 - \frac{\omega}{R_1 V} \right) e^{-R_1 V} + B \left(1 - \frac{\omega}{R_2 V} \right) e^{-R_2 V} + \frac{\omega E}{V} \quad (1)$$

where, $P=P(x,y,z,t)$ is the pressure field, V is the volume of the material at pressure P divided by the initial volume of the unreacted explosive, E is the specific internal energy and $A, B, R_1, R_2,$ and ω are adjustable parameters. The parameters in the equation of state are chosen to satisfy the following conditions (Lee, Horning, and Kury, 1968):

1. The measured Chapman-Jouget state,
2. The measured expansion behavior in the cylinder test,
3. The thermodynamic limitations at large expansions, and
4. The hydrodynamic continuity.

For example, for TNT, $A=3.712$ Mbar, $B=0.0323$ Mbar, $R_1=4.15$, $R_2=0.95$, and $\omega=0.30$ (Dobratz and Crawford, 1985).

The air was modeled to represent the medium in which the blast wave propagates. A linear polynomial equation of state was used to simulate the proper air behavior:

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

where, $m = \rho/\rho_0 - 1$ with ρ/ρ_0 the ratio of current density to the initial density, and C_i are constants. For gases for which the gamma law equation of state applies such as air, $C_0=C_1=C_2=C_3=C_6=0$, and $C_4=C_5=\gamma-1$, with, γ the ratio of specific heats. Therefore, for air equation (2) reduces to,

$$P = (\gamma - 1) \frac{\rho}{\rho_0} E \quad (3)$$

The Test Description

Several explosion tests with different configurations were conducted in order to quantify the effect of a detonation on different structurally representative test articles. In one sequence of the tests, steel plates of various thickness were exposed to a detonation of explosive charges suspended in free air (see the test setup illustration in Figure 2). The test article (1) was welded along its edges to a steel foundation (2) such that it was placed over a square opening in the much thicker foundation. The steel foundation was placed over a deep pit (4) such that it was simply supported by the soil (3) surrounding the pit. The uncased explosive charge (TNT) (5) was cylindrically shaped and suspended horizontally in the air above the test article.

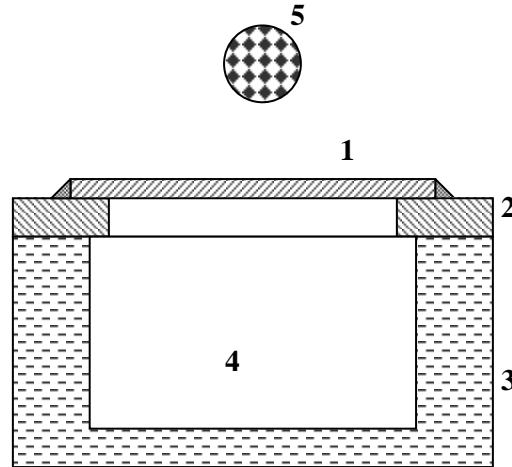


Figure 2. Cross-sectional View of Test Setup along Pit

Finite Element Model and Boundary Conditions

A finite element model representing the discrete mathematical model of a steel plate subjected to a cylindrically shaped explosive charge was generated to represent the test setup illustrated in Figure 2. The plate was modeled using quadrilateral and triangular Belytschko-Tsay shell elements. Welds were modeled with 1-Dimensional Hughes-Liu beam elements. The base plate was assumed to be rigid and contact conditions were applied to the surfaces at the plate interface. Due to the symmetry of the problem (geometry and loading), only one quarter of the physical problem was modeled (Figure 3). The explosive and the air surrounding the structure were modeled using 3-Dimensional 8-node solid (brick) elements (1 point ALE multi-material element).

Boundary conditions were applied to reflect symmetry in the internal cut-off planes. All degrees of freedom in the weld ends not connected to the plate were constrained.

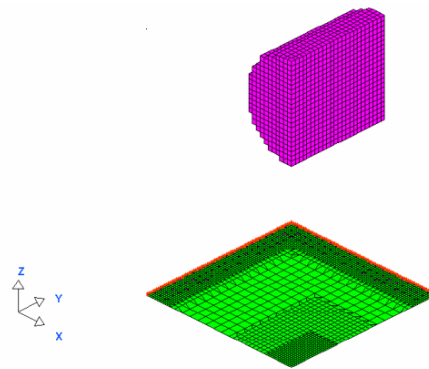


Figure 3. Finite Element Model of the Explosive and Structure

The material characteristics of the plate and the welds were represented as piecewise linear plasticity material model with a strain-to-failure flag (material type 24 in the LS-DYNA material library).

In cases involving high-speed loading, such as an explosion, the strength of steel increases with the rate of strain. This behavior was accounted for by the use of the Johnson-Cook material model for high strength steel (Czyryca, Link, and Wong (1989)).

$$\sigma = (110 + 1075 \cdot \epsilon_p^{0.125}) \cdot (1 + 0.0125 \cdot \ln \dot{\epsilon}) \cdot (1 - [(T - T_{room}) / (T_{melt} - T_{room})]^{0.9}) \quad (4)$$

where, ϵ_p is a plastic strain, $\dot{\epsilon}$ is a strain rate, T is a temperature in degrees Kelvin.

Typical inelastic strain rates associated with permanent damage are of the order of 1-100 sec^{-1} , with local rates at strain concentration sites (corners, cracks, etc.) reaching and perhaps exceeding 1000 sec^{-1} (NMAB Committee on the Dynamic Response of Materials Subjected to High Strain Loading, 1978).

Gas – Structure Interaction Procedure

LS-DYNA provides several schemes to model gas-structural interactions:

1. Acceleration at the interface locations is constrained (for example, where air contacts the structure, the accelerations of the air particles are the same as the contacting points on the structure),
2. Acceleration and velocity are constrained,
3. Acceleration and velocity are constrained only in the normal direction to the plane of interaction, and
4. Distribution of the nodal (structural) force vector $F = -Kd$, where K is the structure stiffness matrix and d is the structure displacement vector, to the gas nodes. (Penalty Coupling).

Due to the highly non-linear character of detonation problems, and due to the complexity of the corresponding mathematical models and algorithms, the simulation predictions are problem dependent. Therefore, the simulation predictions are expected to be sensitive to the selected gas-structure interfacing scheme, as well as, gas and structure mesh sizes.

DISCUSSION OF RESULTS

In the simulation of the plate deformation due to detonation in accordance with the test setup illustrated in Figure 2, the Penalty Coupling scheme (interaction algorithm number 4) was employed due to its suitability to the problem at hand. In Figure 4, the shape of the deformed plate at 10 ms subsequent to the onset of the detonation is shown (this shape is close to the final deformed shape). The final shape of the simulated plate was compared with the shape of the test article after the explosion. The predicted vertical plate displacements along the plate diagonal (direction 1-2) are compared with the corresponding displacements of the test article and summarized in table 1. The displacements are calculated as the difference in the Z coordinate of the point 1 to the Z coordinates of the points of interest. The maximum difference in displacements between the test article and the predicted shape do not exceed 23%.

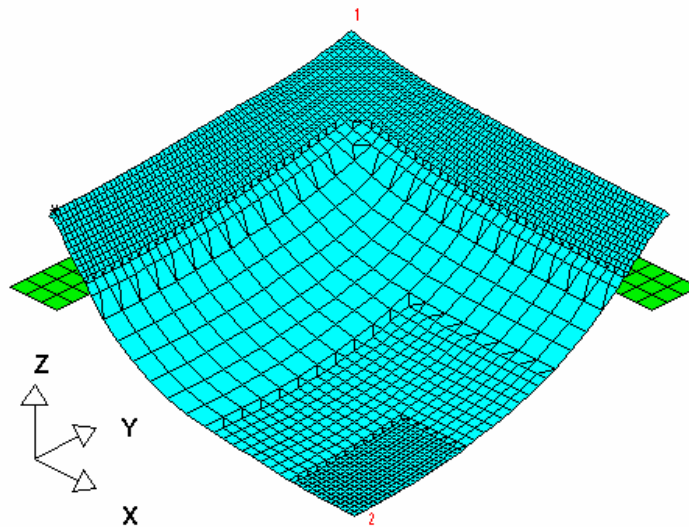


Figure 4. Deformed Plate Configuration.

Table 1. Comparison of the Deformations of the Test Article and Simulated Plate

Point Distance Along Diagonal	Test Article Displacements, mm	Predicted Displacements, mm	% Difference
0 (point 1)	0	0	0
0.177L	38	39	2.6
0.303L	81	74	8.6
0.486L	147	121	17.7
0.723L	197	155	21.3
0.855L	211	166	21.3
0.950L	216	167	22.7
L (point 2)	217	167	23.0

Note: L is the length of the diagonal of the undeformed plate.

Recreating other test configurations using this procedure corroborated this approach capability. As an example, the simulation of the impact of an internal explosion on a structure was also performed and showed a similar correlation with actual test results.

SUMMARY

Existing explosion predictions show deviations of up to 100% and even higher (e.g., Marco et al, 1994) with respect to test data. Therefore, the results of the above described simulation procedure can be considered as a significant improvement.

In the simulated tests, the ratios of the standoffs to the equivalent radius of the charge were varied between 3 and 7. The equivalent radius of the charge is defined as a radius of the sphere containing the same volume as the TNT equivalent of the explosive, while the standoff is a shortest distance from the center of gravity of the explosive to the structure being examined. For these standoff ratios the procedure gives maximum under-predictions in the displacements of the structure that varies from 20 to 40% from test to test - the bigger the standoff ratio, the bigger under-predictions. This can be attributed to either energy dissipation (Hilding, 2001) or the way JWL equation of state was calibrated (it appears that a cylinder test (Lee, Horning, and Kury, 1968) does not account for aerobic burning of explosion products), or both. For standoff ratios varying between 3 and 7, since the under-predicted values are known, there is no need to change the EOS parameters. In contrast, for bigger standoffs the JWL EOS needs to be re-calibrated (see, for example, Zukas and Walters, 1998). Authors of this paper are using tabulated pressure in the open-air values for the re-calibration procedure.

Nevertheless, achieving the right pressure in the open air does not guarantee the right pressure on the structure. The simulation results are very sensitive to LS-DYNA advection method, gas-structure interaction method, as well as Eulerian and Lagrangian mesh sizes. There could be several solution families, and to select the right one from amongst them requires additional investigation. For example, there always are some resulting values, which could be easily seen wrong from a physical stand point, and that family of solutions can be dropped. Experience in dealing with such problems is imperative.

The method described above is suitable for utilization in the design of structures that are subjected to explosive loads. Moreover, it can be used to investigate designs that reduce ship vulnerability to internal and external explosions. Using the results of the described simulation, the structural designer will be able to determine the minimum scantlings required for the ship structure to withstand blast waves. Also, this approach can be used for simulating the effect of structural modifications that redirect the blast wave, and to check the effectiveness of double wall design, among others.

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