

Numerical simulation of nuclear blast wave impact on protective elements of anthropogenic structures

Krzysztof KOSIUCZENKO ^{1*}

¹ *Military Institute of Armored and Automotive Technology, Okuniewska 1, 05-070 Sulejówkę, Poland*

Abstract

The paper presents the use of LS-DYNA software for numerical simulation of nuclear blast wave effects on protective structures. Brode's function was employed for blast wave modeling, and the Johnson-Cook material model was used to describe steel behavior. The results indicate the effectiveness of combining empirical methods with advanced numerical models in analyzing these types of phenomena.

Keywords: blast wave, finite element method, nuclear burst, simulation, structure strength

1 Introduction

The safety of anthropogenic objects is one of the key areas of modern engineering, particularly in the context of threats associated with potential nuclear weapons use. The development of nuclear technologies presents significant challenges for safety engineering in terms of designing and protecting structures against the effects of air nuclear explosions, where numerical methods and computer simulations play a crucial role.

Analysis of structural resistance to blast wave effects requires an interdisciplinary approach, combining knowledge from nuclear explosion physics, structural mechanics, and materials engineering [1, 2, 3, 4, 5]. The peak overpressure of the wave, depending on the yield and distance from the epicenter of the explosion, can reach values from tens to thousands of kPa, which constitutes an extreme load requiring advanced computational methods for predicting effects and designing protective measures.

In the first phase of the explosion, a fireball containing gases under extremely high pressure is formed. The rapid expansion of these gases leads to the formation of a blast wave, characterized by a sudden pressure increase at the front and gradual decrease toward the explosion center. A significant aspect of this phenomenon is the occurrence of

* **Corresponding author:** E-mail address: (krzysztof.kosciuczenko@witpis.eu) Krzysztof KOSIUCZENKO

a negative phase and dynamic pressure associated with strong winds accompanying the wave passage. All these phenomena weaken with distance from the explosion center, however, their effects can be felt over a significant area.

Significant progress in understanding blast wave interaction mechanisms and development of computational methods was brought by nuclear tests conducted between 1958-1962 over the Pacific Ocean and South Atlantic. These experiments, although carried out in the context of the Cold War arms race, provided invaluable validation data for modern numerical models, forming the basis for understanding complex interactions between nuclear energy and engineering structures (Fig. 1).

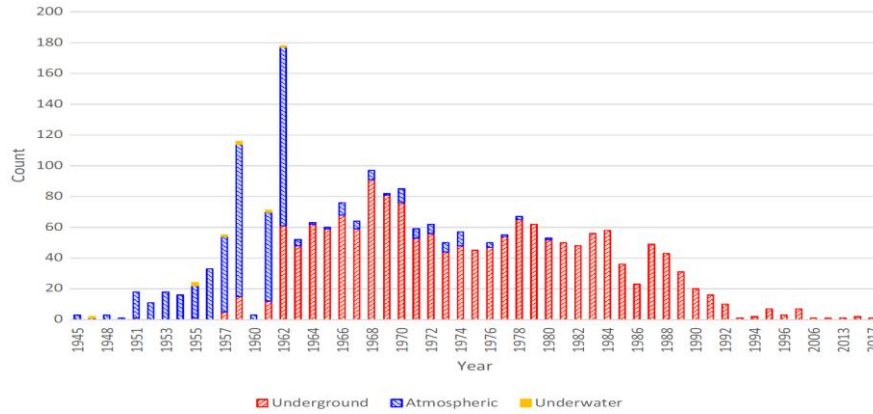


Fig. 1. Number of nuclear explosions detonated each year, color-coded by event type: underground, atmospheric, and underwater [4]

Contemporary limitations in conducting nuclear tests and increasing requirements for structural safety mean that numerical simulations now play a key role in the design process. The LS-DYNA program with implemented Brode's function and Johnson-Cook material model provides an effective tool for analyzing structural behavior under nuclear blast wave impact. This enables detailed analysis of structural behavior and optimization of protective solutions at significantly lower costs and without environmental hazards.

The use of imperial units (feet, KT) in this work stems from the historical context of nuclear weapons research. Since most fundamental experimental and theoretical work in this field was conducted in the USA in the 1950s and 1960s, to maintain precision and enable direct comparison with source data, the original units were retained in certain parts of the work, with their SI equivalents added in parentheses. This allows avoiding potential errors in converting and rounding values.

2 Simulation methods for modeling explosion phenomena

The contemporary approach to analyzing blast wave effects encompasses several main computational methods. The Finite Element Method (FEM) implemented in LS-DYNA represents the most advanced and comprehensive tool, allowing for complex analysis of explosion-related phenomena while accounting for nonlinear material properties and fluid-structure interaction.

Alternative approaches include the SPH (Smoothed Particle Hydrodynamics) method, particularly useful in analyzing large deformations and fragmentation, though it has limitations in accurate contact modeling between bodies. The DEM (Discrete Element Method) is mainly applied in analyzing material fragmentation and crack propagation but is not optimal for continuous media.

Simplified analytical methods, based on empirical formulas such as Brode's equations or ConWep, offer quick estimation of basic blast wave parameters but do not allow for detailed analysis of local effects and complex interactions. CFD (Computational Fluid Dynamics) methods effectively describe wave propagation in gaseous media but have limitations in modeling structural deformation.

LS-DYNA, utilizing advanced FEM solvers and the ability to combine various numerical techniques (such as ALE or coupling with empirical methods), enables the most comprehensive and accurate modeling of the entire explosion phenomenon, from detonation through blast wave propagation to the dynamic response of the structure. Additionally, its rich library of material models and finite elements enables precise representation of actual physical conditions.

3 Peak overpressure modeling using Brode's function

Detailed description of the explosion phenomenon along with its characteristics presented in the form of equations, tables, and graphs can be found in works [1, 2, 3]. These were primarily developed in the 1950s-1980s, as only then, due to the international political situation and applicable moratoriums, were full-scale nuclear experiments conducted. In the case of an air burst, the resulting blast wave exhibits characteristic behavior during atmospheric propagation. Immediately after the explosion, the wave propagates spherically from the detonation point, and its parameters change with distance from the explosion center.

In the near field, extending several hundred meters from ground zero, regular reflection of the wave from the ground surface occurs. In this zone, interference between the incident wave and the reflected wave leads to significant amplification of peak pressure. This is the area where the highest overpressure values are observed.

After exceeding the near field boundary, Mach wave formation occurs. This is a complex phenomenon during which the incident and reflected waves merge, creating a single, strong shock wave. The pressure decay characteristics in this zone change, adopting a different profile than in the near field.

It should be emphasized that the actual behavior of the blast wave may deviate from the theoretical model due to local atmospheric conditions, terrain configuration, and the presence of obstacles. These factors can significantly modify the wave propagation pattern and the values of its characteristic parameters.

The literature describes several computational methods for blast wave peak overpressure [1, 2]. The most important are the Glasstone and Dolan method and the Brode method. The Glasstone and Dolan method is based on nuclear test data and accounts for complex blast wave phenomena, including the negative pressure phase and dynamic pressure. It relies on empirical data and uses scaled distance and empirical tables to estimate pressure, wave arrival time, and duration. This method considers ground reflection effects and burst height, as well as unique thermal energy and radiation effects characteristic of nuclear explosions. Due to its complexity, it is less frequently used.

In Brode's method, peak overpressure is calculated based on a graph showing the relationship between peak overpressure and distance from the explosion center. This graph was developed for a 1 KT air burst under standard sea-level atmospheric pressure conditions (Fig. 2). It accounts for the blast wave reflection effect from the ground surface, which significantly increases peak pressure at ground zero due to the superposition of incident and reflected waves.

According to the Hopkinson-Cranz scaling law, which states that similar blast waves are produced at proportionally similar distances, for points below 1525 m ASL (5000 feet) and for burst heights below 12200 m (40000 feet), the range of a given peak overpressure (distance to the point where a specific overpressure value is achieved) for any yield W scales according to the cube root of the explosion yield (1):

$$\begin{aligned}
 D &= D_1 \times W^{(1/3)} \\
 d &= d_1 \times W^{(1/3)} \\
 h &= h_1 \times W^{(1/3)}
 \end{aligned}
 \tag{1}$$

where:

D - overall distance (slant range) from burst point to target for any yield W

D_1 - distance (slant range) from burst point to target for 1 KT yield

d - horizontal distance (ground range) from ground zero to target for any yield W

d_1 - horizontal distance from ground zero to target for 1 KT yield

h - height of burst (HOB) for any yield W

h_1 - height of burst for 1 KT yield.

a

b

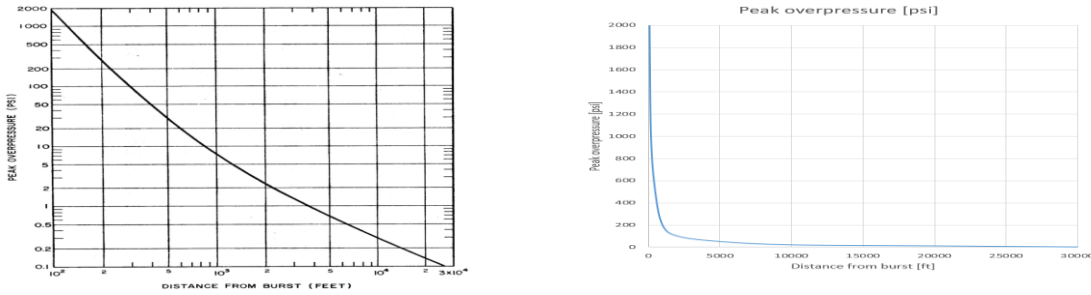


Fig. 2. Peak overpressure from a 1-kiloton free air burst for sea-level ambient conditions: a - nonlinear scale [2], b - linear scale [own elaboration]

Ground zero is the point on the earth's surface located directly below or above the nuclear explosion site. In the case of an air burst, ground zero is located exactly below the detonation point on the earth's surface. The relationships between the various distances from equation (1) follow directly from the Pythagorean theorem and are shown in Figure 3.

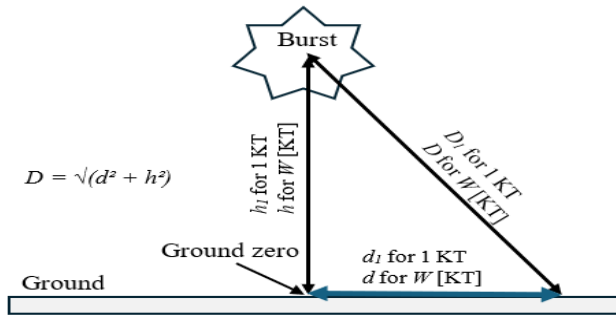


Fig. 3. Geometric interrelationships of parameters (ground range): D, d, h [own elaboration]

It should be noted that the explosion yield W is also subject to scaling (multiplication by the blast efficiency factor). This can be done, for example, based on data from the table contained in [1], which the author has presented in graph form in Fig. 4.

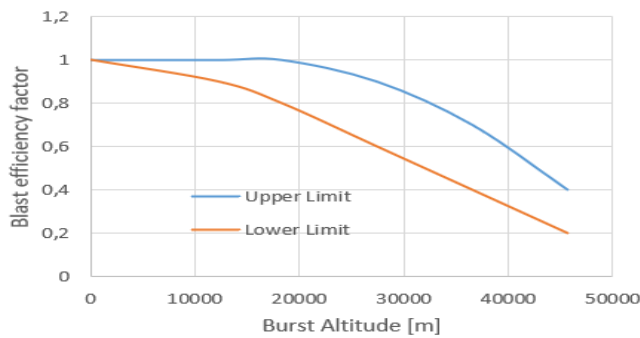


Fig. 4. Blast efficiency factors ef [-] vs high altitude bursts (ef)

Additional correction factors (multipliers) related to burst height are also used in calculations, including the pressure coefficient S_p . Based on literature data [1], the author developed a graph showing the relationship between this coefficient and detonation height (Fig. 5).

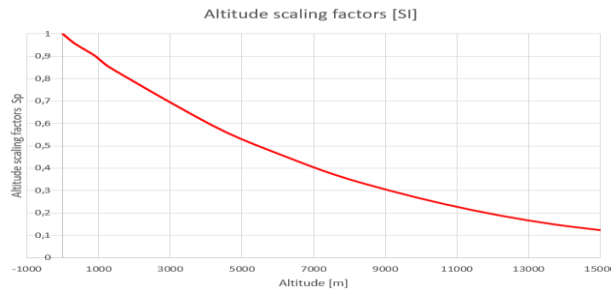


Fig. 5. Altitude scaling factor S_p [-] graph as a function of burst height [m] [own elaboration]

The peak overpressure calculation process begins with determining the effective yield by multiplying by the blast efficiency factor, which is read from Fig. 4 for a given detonation height. Then, using equation (1), we convert the actual explosion geometry to reference conditions by scaling the burst height and horizontal distance from ground zero. In the next step, using the Pythagorean theorem, we determine the slant range for reference conditions, considering the relationship between the previously calculated reference height and reference horizontal distance. The obtained reference slant range value allows reading the base overpressure value from Fig. 2. The final step is to account for the height effect on overpressure by applying the appropriate pressure coefficient S_p read from Fig. 4. It should be emphasized that the time coefficient St , also available in [1], is not used to correct peak overpressure values, as it serves other computational purposes.

Typical small tactical warheads have yields up to 2 KT, while micro warheads are up to 1 KT. For civilian research on structural protection, including numerical modeling, the range of 0.25-5 KT is usually considered representative for analyzing structural resistance to small nuclear explosions.

It should be emphasized that these data come from historical materials and publicly available sources concerning weapons already withdrawn from use. I focus on this information solely in the context of research on civil structure protection.

In this work, therefore, the case of a $W= 0.25$ KT yield explosion at a height of $h= 200$ m above the target was analyzed. After scaling the data from Fig. 2b using equation (1) and accounting for the blast efficiency factor $ef=1$ and pressure coefficient $S_p= 0.99$, the peak overpressure at ground zero was calculated to be $P_s= 52.03$ kPa. This overpressure value decreases with distance from ground zero (Fig. 6).

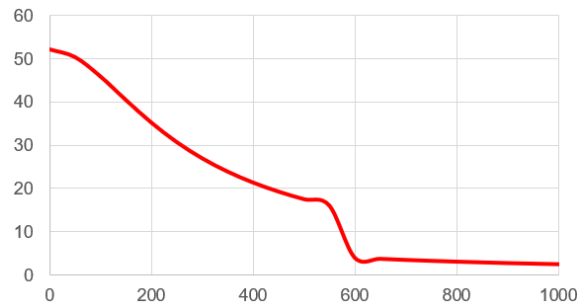


Fig. 6. Peak overpressure from a 0.25 KT free air burst [kPa] vs. distance from ground zero [m] [own elaboration]

4 Implementation of Brode's function in explosion simulations in LS-DYNA

The LS-DYNA system offers three basic methods for simulating blast wave effects: the empirical Load Blast Enhanced (LBE) method, the Arbitrary Lagrangian Eulerian (ALE) method, and a hybrid method combining both approaches. Special attention should be paid to empirical methods, including the Brode and ConWep methods, which form the basis for the LBE function [6, 7].

The Brode method, based on extensive experimental research, provides precise relationships between peak overpressure and normalized distance from the explosion center. Its key advantage is the ability to scale results for different charge masses according to the cube root principle. This method allows for quick and accurate calculations for explosions ranging from several kilograms to many KT, with its accuracy verified through numerous field tests.

The ConWep implementation in LS-DYNA, based on Kingery and Bulmash's experimental data, extends the capabilities of the Brode method by incorporating additional effects, such as blast wave incidence angle and burst height influence. This system automatically calculates both incident and reflected pressures, which is particularly important when analyzing explosion effects on structures.

Unlike the computationally more complex ALE method, empirical methods offer exceptional computational efficiency. Analysis of a sample explosion case showed that the LBE method requires only a few minutes of computational time, while an analogous simulation using the ALE method takes many hours. The accuracy of empirical methods is comparable or in some cases even better than the ALE method, particularly in predicting peak overpressures.

A significant advantage of empirical methods is their ability to account for various atmospheric and topographic conditions. The Brode method allows calculations for heights up to 12,200 m above sea level, automatically considering atmospheric pressure effects on blast wave parameters. Additionally, these methods enable precise determination of blast wave arrival time and the duration of positive and negative phases.

The LS-DYNA implementation allows easy use of these methods through the *LOAD_BLAST_ENHANCED function. The system automatically calculates all blast wave parameters based on charge mass, its position, and environmental characteristics. Particularly important is the ability to account for wave reflections and interference through appropriate amplification factors.

Empirical methods show particular effectiveness in analyzing structures with simple geometry and cases where the blast wave propagates in open space. In such situations, they offer an ideal compromise between accuracy and computational efficiency. The only significant limitation is the requirement for direct line of sight between the charge and the analyzed point of the structure.

In cases requiring analysis of complex wave propagation effects, such as multiple reflections or interference, empirical methods can be effectively combined with the ALE approach within the hybrid method. Such combination maintains high calculation accuracy at a significantly lower computational cost than pure ALE method, as confirmed by test results showing approximately 20% difference in calculation time.

In conclusion, the Brode and ConWep empirical methods form the foundation of modern blast effect analyses on structures in the LS-DYNA environment. Their main advantages are high accuracy, computational efficiency, and solid experimental foundations. Combined with the ability to scale results and automate calculations, these methods offer an extremely practical tool for designing blast-resistant structures.

5 Description of the research object and its physical representation

From the author's experience in explosion modeling [9], a model of a rectangularly shaped plate fixed at its perimeter serves as a justified simplification for studying structural resistance to nuclear blast waves for several important reasons.

Such configuration enables analysis of basic structural failure mechanisms under extreme dynamic loading characteristic of nuclear explosions. In real objects, such as airports or critical infrastructure, there are extensive flat surfaces exposed to direct blast wave action. The study of single plate behavior provides fundamental information about the material's capacity to absorb explosion energy and its deformation mechanisms.

This model also enables precise examination of boundary conditions' influence on structural behavior. Rigid fixation at the perimeter reflects typical structural connections present in real objects, where plates are often integral with load-bearing elements. This is particularly important in the context of designing structures with enhanced blast resistance, where proper connection design is crucial for maintaining the integrity of the entire structure.

Moreover, the geometric simplicity of the model allows for detailed analysis of complex physical phenomena, such as stress wave propagation, local thermal effects, or material failure mechanisms, without introducing additional complications arising from complex geometry. This, in turn, enables the development of more effective structural and material solutions for objects exposed to blast wave effects.

The physical model was developed as a rectangular plate with dimensions of 1x1 m and thickness of 0.01 m, fixed at its perimeter using a rigid frame. The explosion center was located 200 m (HOB) above ground zero, corresponding to the plate center (Fig. 7).

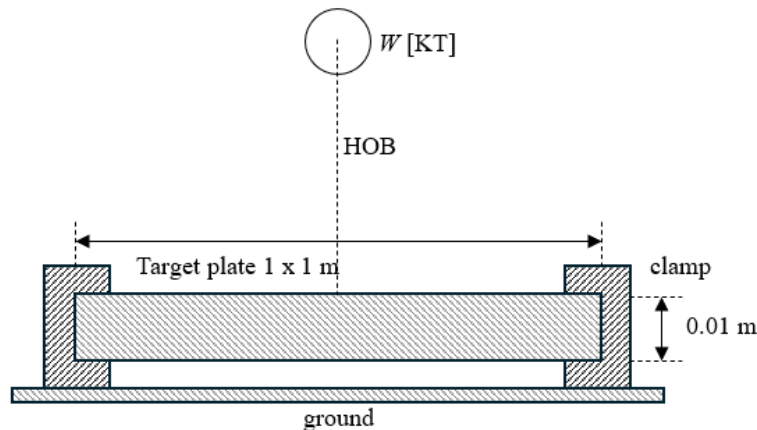


Fig. 7. Schematic design of the physical model (the original scale is not maintained)

6 Material properties representation

In simulating blast wave effects on a rectangular steel plate, a crucial aspect is the appropriate selection of a material model that accounts for both the specifics of dynamic loading and the material properties (Hardox 450). LS-DYNA offers several material models capable of describing steel behavior under high strain rate conditions [8].

The elastic-plastic model with isotropic hardening (*MAT_PIECEWISE_LINEAR_PLASTICITY) allows for basic description of steel behavior through definition of the hardening curve, however, it does not account for strain rate and temperature effects, which are crucial in blast loading conditions. Similarly, the Cowper-Symonds model (*MAT_PLASTIC_KINEMATIC), despite incorporating basic strain rate effects, does not offer the possibility of modeling thermal effects.

The Zerilli-Armstrong model (*MAT_ZERILLI_ARMSTRONG) accounts for temperature and strain rate effects through empirical relationships based on dislocation mechanisms. However, its application is limited due to the complexity of material parameter identification and lesser availability of experimental data for this model.

The Johnson-Cook model (*MAT_JOHNSON_COOK) demonstrates optimal characteristics for the analyzed case for several key reasons. First, it jointly accounts for the effects of plastic strain, strain rate, and temperature on yield stress through a multiplicative form of the constitutive equation (2):

$$\sigma = (A + B\varepsilon^n) \left(1 + C \ln(\varepsilon^*) \right) (1 - T^*) \quad (2)$$

where:

A - initial yield stress at room temperature under quasi-static conditions (Pa),

B - strain hardening coefficient (Pa), describing the effect of plastic strain on yield stress,

n - strain hardening exponent, characterizing the shape of the material hardening curve,

C - strain rate sensitivity coefficient, determining the effect of dynamic loading on material strength

m - thermal softening exponent, describing the influence of temperature increase on material strength reduction

ε^* - normalized strain rate ($\varepsilon/\varepsilon_0$), where ε_0 is the reference strain rate

T^* - homologous temperature ($(T-T_0)/(T_m-T_0)$), where T_0 is room temperature and T_m is the material melting temperature.

Secondly, this model offers an integrated failure criterion that accounts for stress state, strain rate, and temperature, which is crucial for accurate prediction of plate damage under blast wave impact. Additionally, Johnson-Cook model parameters are widely available in literature for various structural steel grades, which significantly facilitates practical application.

The effectiveness of the Johnson-Cook model in blast wave impact simulations has been confirmed by numerous validation studies. This model shows good agreement with experimental results both in terms of deformation prediction and damage propagation. Its advantage over other models stems from an optimal compromise between accuracy of physical deformation mechanism description and practical implementation and computational efficiency.

Another significant advantage is the numerical stability of the Johnson-Cook model across a wide range of loading conditions, which is particularly important in case of sudden blast effects. This model is also well integrated with various finite element formulations available in LS-DYNA, allowing for effective implementation in complex simulations involving fluid-structure interaction. For the purposes of this work, the author used material data from literature [9].

7 Mesh elements and boundary and initial simulation conditions

The numerical model represents a square steel plate with dimensions of 1m x 1m, mounted in a rigid frame at its perimeter (Fig. 8). The geometry was modeled using shell elements (SHELL) in the LS-DYNA environment, with a dense mesh consisting of 256,272 elements. For the model with an applied 500x500 element mesh and a bias factor of BIAS=10, elements with the following dimensions were obtained: maximum (at plate edges) 4.8 mm x 4.8 mm, minimum (at plate center) 0.48 mm x 0.48 mm, average 2.0 mm x 2.0 mm.

The main plate was modeled using the Johnson-Cook material model (*MAT_JOHNSON_COOK), which accounts for strain rate effects and thermal effects characteristic of blast loading. This model is particularly suitable for simulating rapidly varying dynamic processes where large plastic deformations and local thermal effects occur.

The mounting frame was modeled as a rigid body (*MAT_RIGID), which allows for significant reduction in computation time while maintaining proper boundary conditions. Kinematic constraints restricting all degrees of freedom (12 DOF at four support points) were applied at eight corners of the frame, corresponding to actual plate mounting conditions in the test stand. Contact between the frame and steel plate was implemented using the *CONTACT_AUTOMATIC_NODES_TO_SURFACE card.

Model discretization was optimized through the use of a non-uniform finite element mesh. Mesh refinement was employed in the central part of the plate (BIAS=10), where the largest deformations and stress gradients are expected. Such element size variation allows for accurate analysis of local effects at the plate center while maintaining reasonable computation time through larger elements in less critical zones. The applied refinement factor ensures smooth transition between elements of different sizes, which is important for numerical stability of the solution.

The use of two different material properties allows for appropriate definition of behavior for both the deformable plate and the rigid mounting frame. The model was prepared for dynamic analysis with explicit time integration of motion equations, which is the standard approach for blast load simulations in LS-DYNA. The dense mesh at the plate center allows for accurate representation of local dynamic effects and possible material failure modes under nuclear blast wave impact.

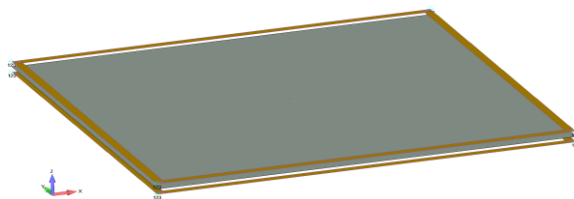


Fig. 8. *The visual appearance of the numerical model (triangles symbolize the imposed constraints)*

To model the nuclear blast wave effect on the steel plate, a combination of *LOAD_BRODE function and *LOAD_SEGMENT card was used in LS-DYNA. The Brode function was used to generate the time-spatial characteristics of the blast wave from a 0.25 KT yield explosion at 200 m height above the plate.

In the *LOAD_BRODE card, explosion parameters were defined, including charge yield (2KT TNT), detonation point coordinates relative to plate center (0, 0, 200 m), and environmental parameters such as atmospheric pressure

at sea level. This function automatically generates pressure-time profiles, accounting for Hopkinson-Cranz scaling law and height of burst correction.

The load was applied to the plate surface through the *LOAD_SEGMENT card, which maps the pressure generated by the Brode function onto individual SHELL elements. For each plate surface segment, pressure is calculated considering the blast wave incidence angle and distance from the explosion point. Both incident and reflected pressures were included in the load definition, which is particularly important for normal wave incidence on the plate surface.

This implementation allows for precise representation of temporal and spatial load variation, accounting for effects related to blast wave propagation in the atmosphere and its interaction with the plate surface. The model automatically includes characteristic interaction phases, including overpressure and underpressure phases, which is crucial for proper analysis of the structure's dynamic response.

For more accurate representation of dynamics and real environmental conditions, gravity acting in the direction normal to the plate (OZ) was included in the boundary conditions definition. This was implemented using the *LOAD_BODY_Z function with a constant value of 9.81 m/s^2 .

8 Numerical results

Numerical calculations were performed in the LS-DYNA environment [7, 8, 9] using the OKEANOS supercomputer (Interdisciplinary Centre for Mathematical and Computer Modeling at the University of Warsaw). The analysis yielded a series of instantaneous stress maps, displacements and strains, as well as structural damage patterns.

For detailed analysis of results, the LS-PREPOST post-processor was used, which enabled visualization of stress and displacement distributions in color scale (warm colors - high values, cold - low), identification of critical structural points, and analysis of stress tensor components (principal, shear, and von Mises). Particular attention was paid to extreme states of stress and strain (Fig. 9-10) of the steel plate, which was the main subject of analysis.

Analysis of displacement maps (Fig. 9) showed that the maximum displacement of the plate's central point was approximately 1.04 mm and occurred in the direction opposite to blast wave propagation. The displacement distribution was axially symmetric, corresponding to the nature of the applied load.

The distribution of von Mises equivalent stresses (Fig. 11) revealed stress concentration in the central part of the plate, where they reached a maximum value of approximately 2.3 MPa (visible on the edge). Temporal analysis of stress histories allowed observation of the wave-like character of stress propagation in the plate and their attenuation process.

Observation of the system's kinetic energy time histories (Fig. 12) enabled analysis of the plate's vibration damping process. In the initial phase of interaction, a sudden increase in kinetic energy to maximum value was observed, followed by its gradual attenuation through plastic deformation of the material and energy dissipation mechanisms in the system.

The obtained results confirm the capability of the applied numerical model to represent complex dynamic phenomena accompanying nuclear blast wave impact on the plate structure.

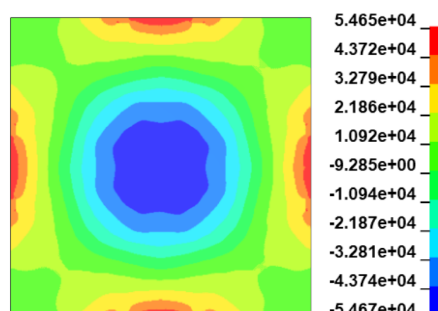


Fig. 9. Map of extreme pressure [Pa] on the plate surface ($t = 0.018 \text{ s}$)

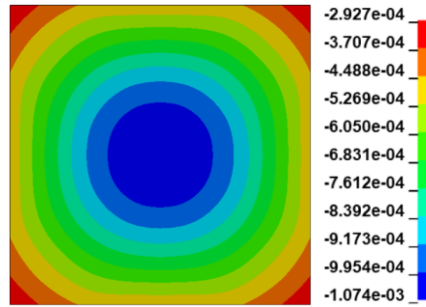


Fig. 10. Map of extreme displacement [m] on the plate surface ($t= 0.018$ s)

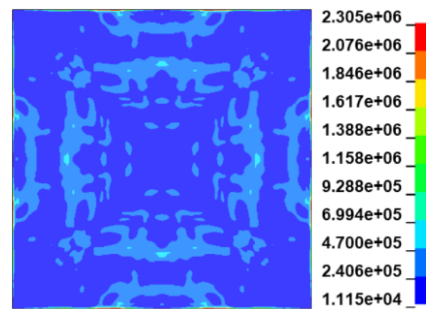


Fig. 11. Map of maximum von Mises equivalent stresses [Pa] on the plate surface ($t= 0.018$ s)

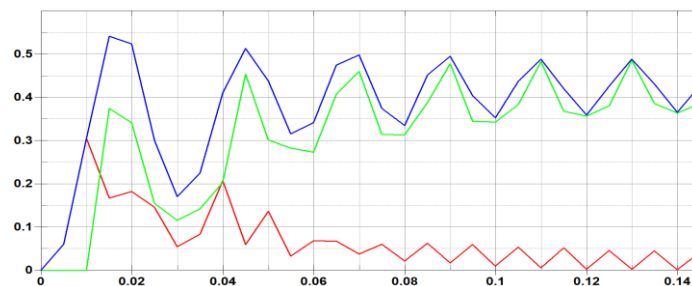


Fig. 12. Time [s] history of plate energy [kJ] damping: kinetic (red line), internal (green line) and total (blue line)

8 Conclusions

The numerical studies conducted using LS-DYNA and the implemented Brode function confirmed the effectiveness of the adopted methodology in analyzing nuclear blast wave effects on protective structures. The combination of empirical methods with the advanced Johnson-Cook material model enabled effective representation of complex phenomena accompanying nuclear explosions, while accounting for key parameters such as charge yield, burst height, and atmospheric conditions.

From a modeling technique perspective, the use of non-uniform finite element mesh with refinement in the critical zone proved particularly important. This approach enabled detailed analysis of local effects while maintaining reasonable computation time. The Johnson-Cook material model demonstrated high effectiveness in representing steel behavior under dynamic conditions, properly accounting for strain rate and temperature effects.

In the context of structural safety, the developed methodology enables precise determination of stress and displacement distributions, which is fundamental for structural integrity assessment. The ability to analyze various explosion scenarios allows for optimization of structural solutions at the design stage, while identification of critical zones and failure mechanisms enables introduction of appropriate modifications to increase structural resistance.

Practical application of the presented methodology is particularly important in designing critical infrastructure facilities and other structures requiring protection against nuclear blast effects. The computational model enables rapid assessment of various structural variants without the need for costly experimental research, while the ability to account for real environmental conditions significantly increases the reliability of obtained results.

However, it should be noted that further development of the methodology should focus on conducting additional validation studies for various structural configurations and explosion conditions. It is also advisable to extend analysis capabilities to more complex structural systems and interactions between elements. Development of optimization procedures utilizing the presented methodology will also be an important direction for future work.

In conclusion, the presented methodology constitutes a valuable tool in the process of designing structures resistant to nuclear blast wave effects. Its main advantages are high accuracy at relatively low computational cost and the ability to account for a wide spectrum of parameters influencing structural behavior. Further development of this methodology, aimed at expanding its application capabilities and increasing accuracy in predicting structural behavior under extreme dynamic loading conditions, can significantly contribute to improving the safety of strategic facilities.

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Bibliography

1. H., L. Brode, Airblast from nuclear bursts—analytic approximations (Technical Report), Defense Nuclear Agency, 1987
2. S. Glasstone, P. J. Dolan, The Effects of Nuclear Weapons, Online Edition 2022, United States Department of Defense and United States Department of Energy, 1997
3. Collective work, Structures to resist effects of accidental explosions, Departments of the Army, the Navy, the Air Force, TM 5-1300/NAVPAC P-3971A.YR 88-22, 1988
4. V. Oancea, Y. Kung, J. R. Murphy, P. Piraino, And J. W. Given, Waveforms from Nuclear Explosions (WFNE) Repository, Pure and applied geophysics (pageoph), 2023. DOI: 10.1007/s00024-024-03536-7
5. M. S. Rahman, A. Mohamed, A. Sweis, J. Chavez and P. Vorobieff, Development of a novel method to characterize shock waves interaction with solid objects, Scientific Reports, 14:28956, 2024. DOI: 10.1038/s41598-024-79220-6
6. K. Kosiuczenko, P. Simiński, M. Gmitrzuk, M. Nowakowski, Experimental and numerical validation of an armor plate test stand, Journal Advances in Military Technology, 2024. DOI: 10.3849/aimt.01855
7. L. Schwer, H. Teng and M. Souli, "LS-DYNA Air Blast Techniques: Comparisons with Experiments for Close-in Charges," in 10th European LS-DYNA Conference, Würzburg, Germany, 2015
8. LS-Dyna Manual vol. I R.13.0. Livermore Software Technology Corporation (LSTC). Retrieved from <https://www.dynasupport.com/manuals/ls-dyna-manuals>, access date: 0.02.2025
9. LS-Dyna Manual vol. II R.13.0. Livermore Software Technology Corporation (LSTC). Retrieved from <https://www.dynasupport.com/manuals/ls-dyna-manuals>.