Ş Murat and S. Tulumcu / Hacettepe J. Biol. & Chem., 2024, 52 (5), 267-281, Special Issue

Research Article

Hacettepe Journal of Biology and Chemistry

journal homepage: www.hjbc.hacettepe.edu.tr

Numerical Analysis of Explosion-Induced Deformations on Steel Panels in Urban Environments

Kentsel Ortamlarda Çelik Panellerde Patlamaya Bağlı Deformasyonların Sayısal Analizi

Murat Şahin[1], **Sedat Tulumcu**[2*]

[1]Mechanical Engineering Department, National Defence University, Ankara, Turkiye.

[2]National Defence University, Alparslan Defence Sciences and National Security Institute, Ankara, Turkiye.

ABSTRACT

Explosion proof structures are designed to be very heavy and non-functional using conventional systems so that they can be resistant to blast effects. As a result, not only the emergence of non-economic structures, but also their operational performance decreases. To effectively mitigate these challenges, a substantial body of research has focused on the development and application of designs and materials specifically engineered to withstand explosive load impacts. In this study, the strength of steel plates under explosives with different energies was tested. Related tests were performed using Ls-Dyna finite element software. An experimental literature was used to calibrate the numerical model. When the results obtained as a result of the calibration were compared with the experimental data, a high level of agreement was obtained. The calibrated numerical model was subjected to burst loads by varying the panel thicknesses and its dynamic responses were simulated. The displacement values were analyzed by placing the explosives equidistant from the panel centers. By comparing the analysis results, explosive energies were compared. The most effective explosive types could be listed according to the amount of change that the evaluated explosives in the same amount caused on the panel surfaces. In line with these studies, information will be gained about what type of steel materials will be used against which type of explosives in areas that need to be protected in urban areas.

Key Words

Explosion resistance, numerical simulation, near-field explosion, optimum design.

ÖZ

Patlamaya dayanıklı yapılar, patlama etkilerine karşı dayanıklı olabilmeleri için geleneksel sistemler kullanılarak çok ağır ve işlevsiz olacak şekilde tasarlanır. Sonuç olarak, sadece ekonomik olmayan yapıların ortaya çıkması değil, aynı zamanda operasyonel performansları da azalır. Bu zorlukları etkili bir şekilde azaltmak için, önemli miktarda araştırma, patlayıcı yük etkilerine dayanacak şekilde özel olarak tasarlanmış tasarımların ve malzemelerin geliştirilmesine ve uygulanmasına odaklanmıştır. Bu çalışmada, farklı enerjilere sahip patlayıcılar altında çelik plakaların mukavemeti test edilmiştir. İlgili testler Ls-Dyna sonlu elemanlar yazılımı kullanılarak gerçekleştirilmiştir. Sayısal modeli kalibre etmek için deneysel bir literatür kullanılmıştır. Kalibrasyon sonucunda elde edilen sonuçlar deneysel verilerle karşılaştırıldığında yüksek düzeyde bir uyum elde edilmiştir. Kalibre edilmiş sayısal model, panel kalınlıkları değiştirilerek patlama yüklerine tabi tutulmuş ve dinamik tepkileri simüle edilmiştir. Yer değiştirme değerleri, patlayıcılar panel merkezlerinden eşit uzaklıkta yerleştirilerek analiz edilmiştir. Analiz sonuçları karşılaştırılarak patlayıcı enerjileri karşılaştırılmıştır. Aynı miktarda değerlendirilen patlayıcıların panel yüzeylerinde meydana getirdiği değişim miktarına göre en etkili patlayıcı tipleri sıralanabilir. Bu çalışmalar doğrultusunda kentsel alanlarda korunması gereken alanlarda hangi tip patlayıcılara karşı hangi tip çelik malzemenin kullanılacağı hakkında bilgi edinilecektir.

Anahtar Kelimeler

Patlama direnci, sayısal simülasyon, yakın patlama, optimum tasarım.

Article History: Received: Oct 31, 2024; Accepted: Dec 2, 2024; Available Online: Dec 9, 2024.

DOI: https://doi.org/10.15671/hjbc.1574877

Correspondence to: S. Tulumcu, National Defence University, Alparslan Defence Sciences and National Security Institute, Ankara, Turkiye.

E-Mail: msahin@kho.msu.edu.tr

INTRODUCTION

Explosion is a major threat to structural safety and blast loading has a critical damaging effect on any structure. Since such threats will be faced as long as life exists on Earth, it is a subject of great interest. A great deal of work has been done to produce explosion-proof structures and structural elements. As a result, it has been shown to mitigate explosion impacts.

Sandwich panels, as a type of explosion-proof structures that can emit a high amount of explosion energy with their high plastic deformation ability under explosion and impact energies, are widely used in many various fields such as aviation, defense and automotive [1,2]. It has been shown that the impact resistance of the double-layer sandwich plate is better than the single-layer plate of the same mass, which is subjected to higher thrust force, with a good agreement between the analytical prediction and numerical results [3].

It has been shown that the most effective design for increasing the resistance on the material under blast loads depends on the density of the inner core between the sandwich panels. When the relative density is at a low level, a prominent approach has been to place products in the core by increasing the slope to have greater energy dissipation capacity [4]. In addition to these studies, composite derivative materials were tried to be developed by taking inspiration from nature [5].

The upper surface of the different number of door panels to be exposed to explosion has geometrically different configurations, and the highest displacement on the panel was observed in the flat panel. In other panels with different configurations, less displacements were detected compared to the flat panel [6].

The incorporation of elastomers, such as polymers, into protective structures to withstand high-energy dynamic loads has received much attention. The effect of a Polyurea coating on the blast response in steel plates is investigated. Polyurea coated steel plates were tested under near field burst loads produced by detonating a 1 kg spherical nitromethane charge at a distance of 150 mm. The front (load facing) and back sides of the 10 mm thick mild steel (XLERPLATE 350) and high strength steel (BIS80) plates are Polyurea coated in 6 mm and 12 mm thicknesses. Numerical simulations were made using the nonlinear finite element code LS-DYNA. The strain-dependent behavior of steel and Polyurea was represented by the Johnson-cook and Money-Rivlin structure models, respectively. Numerical models were validated by comparing the plate deflection results obtained from the experiments. The results showed that the back face coating contributes to a reduction in deformation of approximately 20% and the melting of the Polyurea layer, while the front face coating can be used to provide additional clearance to the steel plates.[7]

A surface explosion creates both ground shock and air blast pressure on nearby structures. Although the ground shock usually reaches the foundation of a structure earlier than the air pressure due to the different wave propagation velocities in geomaterials and air, ground shock and air burst can act on the structure at the same time depending on the distance between the explosion center and the structure. Even if they do not move at the same time, the ground shock will set the structure in motion and the structure will not respond with a zero initial condition from the air pressure. Therefore, an accurate analysis of the structure's response and damage to a nearby surface explosion must take into account both ground shock and airborne pressure [8].

This study performs numerical simulations to investigate the effectiveness of the response of steel plates to different thicknesses and different explosives, which will provide strength under blast thrust forces. Commercial software Ls-Dyna was used to analyze the explosion resistance of steel panels and the energy capacity of different types of explosives [9]. In order to ensure the calibration of the numerical model, the results of the experimental and numerically tested panels by other researchers were simulated numerically to provide validation. The numerical simulation results were compared with the experimental results used for validation. The calibrated models will be used to simulate steel panels formed in different configurations under various burst loads and types.

In light of the relevant studies, it will be a useful study in determining the structural elements that defense industry companies working with explosives will use in practice against explosive types and loads. It will be possible to obtain information about the precautions that can be taken against both external attacks and accidental explosions that may occur inside.

NUMERICAL ANALYSIS VALIDATION

Analyzes were performed using Ls-Dyna. It is a finite element program that can simulate complex problems. Ls-Dyna, a Finite Element Method program, is a powerful simulation tool for nonlinear structural analysis. It is widely used to analyze problems related to structure response to high velocity pressures, high deformation, burst load and strain rate behavior. Structural responses and resulting deformations as a result of explosions have been proven to yield high accuracy results.

Consider a sandwich panel comprising two solid metal face sheets and a metal core that is rigidly supported along its edges, where an explosive charge is detonated above the system. Many groups have studied the dynamic response of sandwich structures to impact loading [10,11]. Detailed finite element calculations using fully meshed geometries, square honeycomb geometries, prismatic grooves and pyramidal lattice topologies made of materials defined by yield strength, strain hardening rate and strain rate sensitivity are performed. These studies demonstrate a complex dynamic structural response. For close range blasts, a shock wave is emitted and reflected from the blast source to the front face. The pressure from the shock wave decreases with time and distance from the explosion source. When a shock wave encounters a hard surface, its front undergoes reflection. This requires that the forward-moving air molecules that make up the shock wave are deposited and further compressed, inducing a reflected overpressure of greater magnitude than the excess pressure from the wall [12]. In the test setup to be calibrated (Figure 2.1), a pressure is applied to the front of the structure, at the time of the pressure impact reaching the front face, it is twice the size of the free field shock (for large distances and weak explosions). up to (under ideal gas). In the case of air molecules dissociation in free field shock, real gas effects occur and even larger pressure reflection coefficients emerge [12].

To verify the reliability of the numerical model in LS-DYNA, a tested and numerically modeled steel panel was used for calibration [4]. A series of burst tests were performed to investigate the response of a 12.7 mm thick steel faceplate subjected to burst loads from a 1 kg explosive on top of the panel. In the tests, the distance of the charge is 280 mm. The 610 x 610 mm faceplate steel plate is bolted to two I-beams to a 19 mm thick steel plate. The 610 x 610 mm steel frame is supported as shown in Figure 1. The test data obtained here were used to calibrate the numerical model developed in Ls-Dyna in this study.

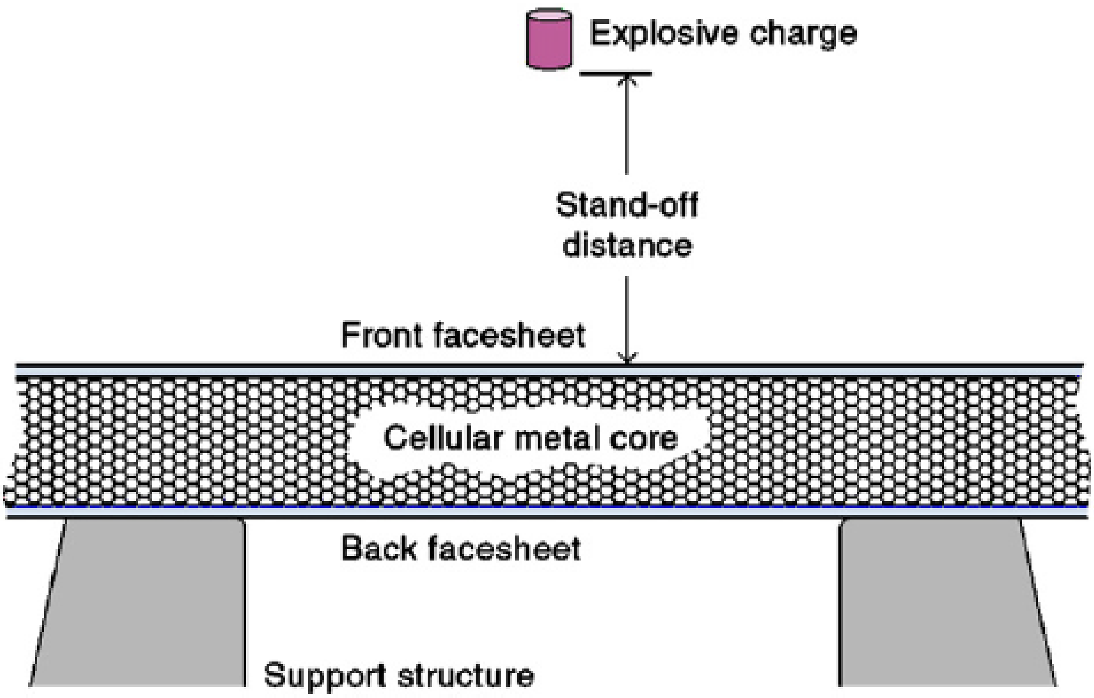

Figure 1. Schematic experiment setup [16].

Material Model

The structural design of the panel used for the relevant test is shown in Figure 2. In these panels used for testing, it is important to face high deformation loads and to form strong connections between the plate inner structure and the surface plates. To achieve this, small top plates are used to create a larger contact area between the plate inner structure and the outer layer.

In this study, the square mesh plate core panels were designed at a plate core density of about 6%. The internal structure of this plate is 0.76 mm thick.

Determining the thickness of the surface plate and the height of the plate inner structure was determined by the method of preventing the deformation of the surface plates and providing the strength of the sandwich panel with a plate with the same area density.

A 12.7 mm thick plate was used for the plate tests used in the tests described here. The square mesh plate inner structure and outer surface plate are made of a high ductility stainless steel alloy with a composition of approximately 49Fe–24Ni–21Cr–6Mo (weight).

A 12.7 mm thick solid plate was used for the basic solid plate experiments in a series of tests reported here. The square honeycomb inner core and surface plate are made of a high ductility stainless steel alloy with a composition of approximately 49Fe–24Ni–21Cr–6Mo (weight).

Air Blast

Tests were carried out by fixing the distance of the explosive to the test panel and changing the amount of explosive. Three tests with TNT cylindrical structure were carried out with 1, 2 and 3 kg explosives placed at 10 cm distance with sample test panels. Tests were carried out using the same amount of explosive for the three-plate test, which is equivalent to the density of the sandwich panels used in the tests.

For each simulation, a cylindrical detonator with a length/diameter aspect ratio very close to 1 was placed on top of an assembly, with the detonator and panel center aligned. Its front face is 10 cm away from the front of the plate (Figure 3). In the construction of each test, sandwich panels or boards were mounted on a 19 mm thick steel plate, which was attached to two I-beams. In the middle of this 19 mm thick supporting steel plate, 410 mm square holes are cut to provide deformation in the sandwich test panels to provide an open space. To hold the tested slabs stable, a frame was formed from four flat bars and four 51 mm square pipes. Square tubes acted as spacers between the plates and bar frames that support the panels. The bar strips that create a picture frame effect in front of the test panels used in the test setups were mounted on the backing plate and tightened with a torque of 34Nm. Explosion operations were performed by repeating the explosive placement and assembly of panels for each sandwich panel and plates. In order to measure the deformations in the panels after the burst tests, a quarter of each panel was cut with wire and examined.

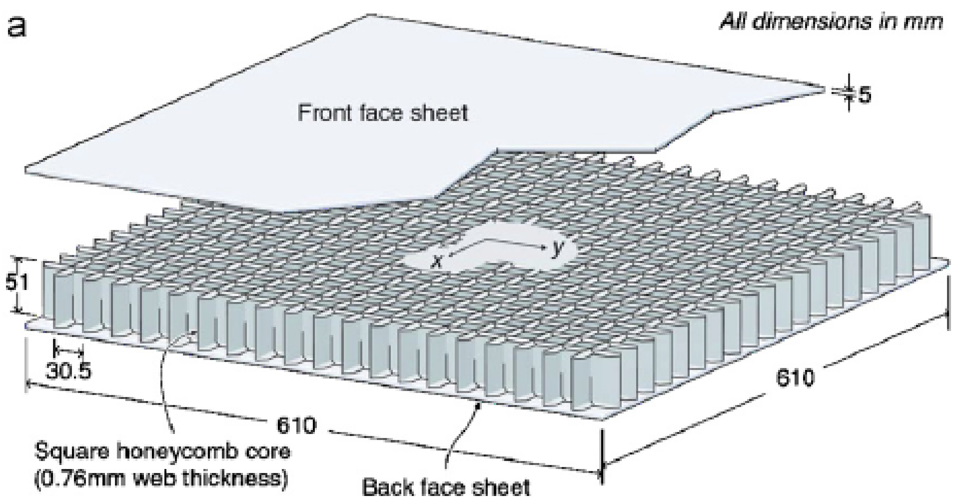

Figure 2. Flat test panel structure [16].

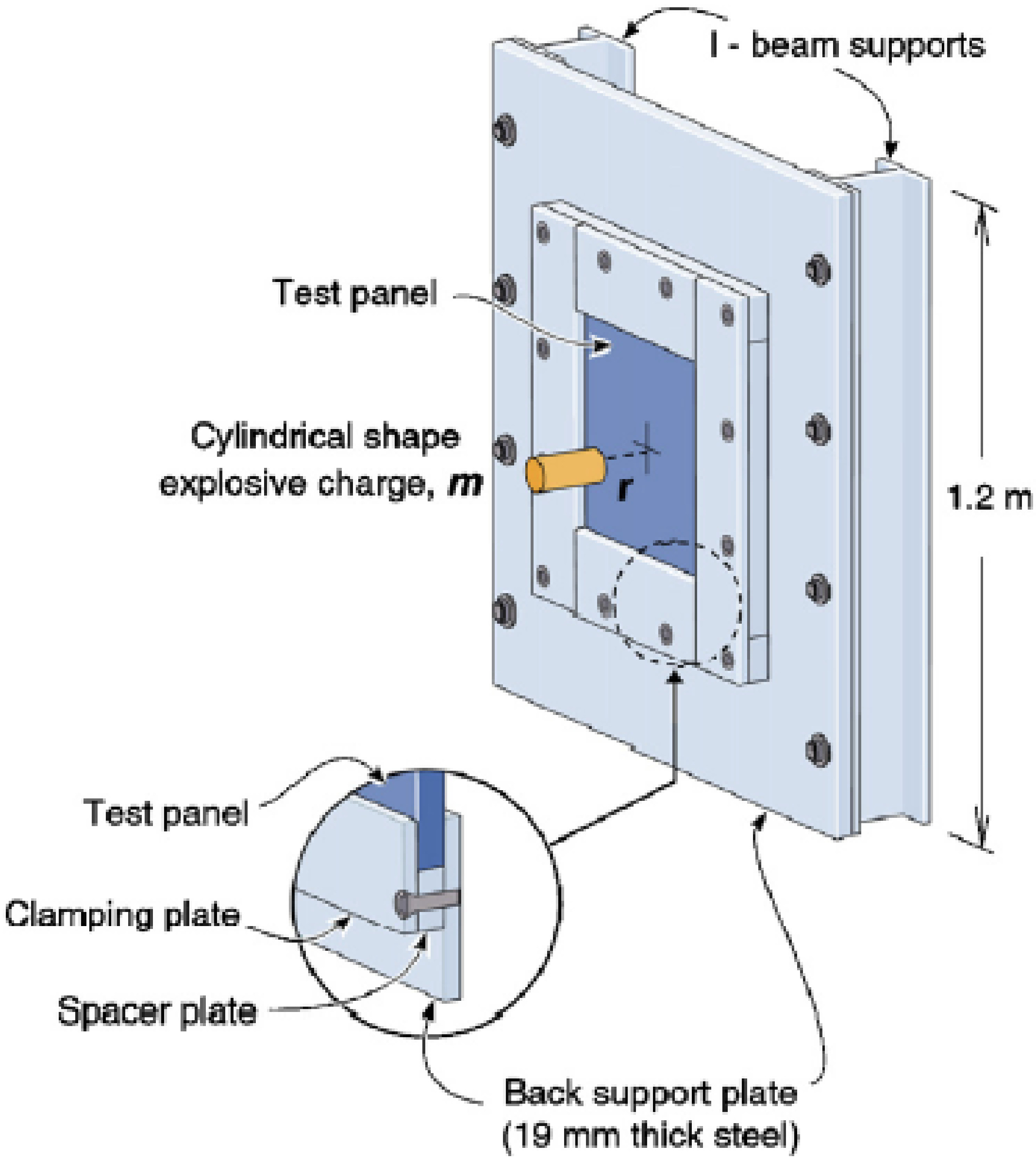

Figure 3. Schematic explosion assembly.

Numerical Models

Burst tests are a way to understand the behavior of sandwich panels under dynamic loading conditions Today's finite element codes allow simulations to be performed under these dynamic conditions without the need for destructive explosion experiments [13] Three-dimensional dynamic finite element analyses were conducted in ABAQUS/Explicit [14] to simulate the tests. The faces of the sandwich panels were fully interlocked through the use eight-node linear brick elements with reduced integration. Such elements can accurately capture stresses and strains. Each shell element utilized five integration points, applied in accordance with Simpson's integration rule. These elements allow large turns and finite membrane deformation, making them particularly suitable for postbuckling analysis. Thirty layers of elements are evenly distributed throughout the core thickness. The support structures were modeled as idealized rigid surfaces and assumed to be "welded" to the respective rigid wall at all ends of the front and rear faces of the sandwich panels. In the model, the effects of nuclear wall self-contact due to folding of the cell wall as well as the contact between the nuclear cell wall and the surface layers due to plastic buckling are considered. The contact is made without friction. For the explosive material, charge weight and distance values used for the experiment, pressure was applied to the front face surface as time-varying and spatially distributed functions from the calculations made with ConWep. Although ConWep assumes a spherical airburst (not a cylindrical load), it is believed to provide a reasonable estimate of the blast wave pressure loading profile, with center-burst cylindrical loads with length/diameter aspect ratios close to 1. For any point on the faceplate surface, its distance from the center of the obverse surface is noted as d, and the pressure at that point can then be expressed as a function of d and t such that

$$p(d,t) = p(t)e^{-\left(\frac{d}{d_0}\right)-\left(\frac{d}{d_0}\right)^2} \qquad (1)$$

where d0, the reference distance is established by fitting the results from calculations with ConWep, and p(t) is given by Equation.

Young's modulus E = 200 GPa, Poisson's ratio n = 0:3; initial yield stress 300 MPa and tangent modulus Et = 2.0 GPa. Taken as. Dynamic measurements in stainless steels are well represented using values of m = 0.154 [18]. Additional three-dimensional finite element calculations have been made for solid plates of equivalent mass and the results are presented in Section 2.5. The material properties and boundary conditions were similar to those applied to sandwich panels.

Results

From a series of basic experiments carried out in this study, the displacement values of 12.7 mm steel plate as a result of 1 kg of TNT explosion were compared with the plate validated with the LS-DYNA finite element program. As a result of the finite element simulation, it has been determined that the displacement graph overlaps successfully.

When looking at the displacement values calculated at every 50 mm intervals starting from the center of the steel panel, it has been determined that they coincide with the maximum deviation values of 20%. There are many unknown factors in explosion analysis, and situations such as different estimates may be encountered. Unexpected shock wave reflections, manufacturing methods, quality of materials, etc. it differs for each situation. When such unknowns are taken into account, we can say that the validation study was successful.

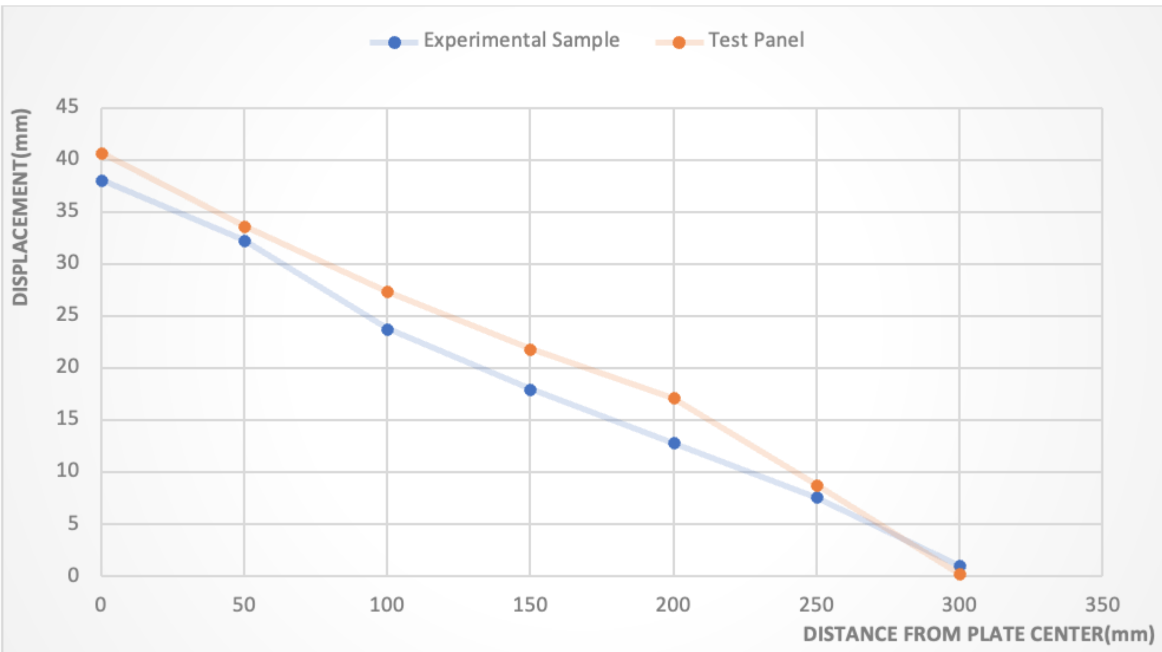

Figure 4. Validation results.

NUMERICAL ANALYSIS

LS-Dyna is indirect finite element software that can be used successfully for a variety of dynamic engineering problems, including structure-fluid and structure-soil interactions. In this study, LS-Dyna was chosen as the numerical analysis platform because of its high degree of flexibility and its success in modeling linear inelastic behavior. Response quantities including peak displacement, permanent displacement, internal energy absorption and boundary reaction forces are subtracted and compared to evaluate the effectiveness of different panel designs on their burst resistance capacities.

Manually entering all parameters related to the model during the tests takes a long time. However, entering this information allows you to have a good command of both the material details and environmental factors on the work to be done.

Material Model

With the LS-Dyna software, which uses the finite element method (FEM), which can consider nonlinear behavior sources, the nonlinear behavior of steel plates under burst loads can be examined. Three-dimensional analyzes were carried out for the performance evaluation of steel plates under burst loads.

As shown in Figure 3.1, 3 different steel plate simulation environments with 610x610 mm dimensions and 8, 16 and 24 mm thicknesses were prepared. The panels are modeled rigidly along all their edges. For the explosive materials used for the experiment, charge weight and distance values, the pressure was reflected to the surface as functions varying with time and spatially distributed from the calculations made with ALE (Arbitrary Lagrange Eulerian).

Explicit modeling of the detonation process involves constructing a physical finite element (FE) model of the explosive and surrounding air. First, it involves creating FE networks for air and explosive and applying appropriate boundary conditions. The FE model consists of a Lagrangian network for solids and an Euler network for gases or liquids. The Arbitrary Lagrange-Eulerian (ALE) formulation, a formulation combining both Lagrangian and Euler techniques, can also be used to model explosions and fluid structure interaction [15]. Second, it is to determine the material properties and initial conditions by determining the initial energy, the mass of the explosive, and the initial temperature and pressure of the surrounding air. An EOS, representing the relationship between pressure p, specific internal energy E, and density ρ, is assigned to both air and explosion products. Such an unambiguous modeling of the detonation process not only allows for detailed modeling of the detonation process and wave propagation throughout the explosive, but also enables the subsequent passage of the shock wave through the surrounding air and the resulting fluid-structure interactions, if any. The advantage of explicitly modeling the detonation event is that no simplifying assumptions are made and the analyst has complete freedom to model any charge shape, size, geometry, and detonation point in the explosive; this should allow for an accurate assessment of the explosion.

Steels exhibit different behavior under short-term rapid loading. In these tests, which we will call burst loads, the increase factors specified in the UFC 3-340-02 document are reflected. Finite element types of steel plates are modeled as nonlinear shell.

The geometric model of the steel plates used in the simulations is shown in Figure 9 and has 10,000 elements. The geometric model of the air is shown in Figure 10. Air is modeled as a 610 mm cube and has 1,092,727 elements. Due to the symmetrical nature of the problem, only a quarter of the panel could be modeled, but since it was not a very large model, the whole was modeled.

Table 1. Geometric and material properties of steel plates.

Plate width	Plate height	Plate thickness	Young's Modulus	Poisson's Ratio	Yield Stress	**Tangent Modulus**
610 mm	610 mm	8 mm	200 GPa	0.3	300 MPa	2.0 GPa
610 mm	610 mm	16 mm	200 GPa	0.3	300 MPa	2.0 GPa
610 mm	610 mm	24 mm	200 GPa	0.3	300 MPa	2.0 GPa

The explosive charge used in the tests is spherical. Eight-node (solid) elements with ALE (Arbitrary Lagrange Euler) formulation [19] are adopted for the explosive sphere. The ALE approach uses lattices that are embedded in the material and deform with the material. It combines the best features of both Lagrange and Euler methods and allows the mesh to be used in any material.

The simulation continues to be adjusted continuously in arbitrary and predefined ways as the calculation progresses, thus providing a continuous and automatic rezoning capability. Therefore, it is very convenient to use an ALE approach to analyze solid and liquid motions when the material strain rate is large and significant, such as the detonation of the explosive and the volume expansion of the detonation products.

The samples used in the tests were made of 304L stainless steel alloy. In the simulations, the mechanical behavior of the stainless steel alloy is modeled with material type 24 (*MAT PIECEWISE_LINEAR_PLASTICITY). Includes load curve and tabulation describing effective plastic stress versus effective stress in LS-DYNA, two linear elasto-plastic structure relationships containing formulations. The input parameters of the stainless steel alloy material model are: Bulk density (ρ), Young's modulus (E), Poisson's ratio (ν), Yield stress (σY), Tangential modulus (Ethane) and Error (Failure) [19].

Air Blast Model

An explosion is actually an extremely fast and exothermal chemical reaction lasting only a few milliseconds. During the explosion, the hot gases produced by this chemical reaction expand rapidly, and so does the air around the explosion for the high temperatures produced instantly. The result is a blast shock wave, which propagates much faster than the speed of sound and is characterized by a thin region of air where the pressure is discontinuous.

The rapid expansion of the detonation products creates a shock wave with discontinuities in pressure, density, temperature, and velocity [12]. A shock wave traveling across a solid surface causes an almost instantaneous increase in air pressure at the surface, which drops very quickly to ambient pressure; this is the positive phase of the explosion. Then the pressure drops further, below ambient pressure and then rises back to ambient pressure, but over a longer period of time; this is the negative phase of the explosion, see fig. Figure 3.7. The shock wave is the main mechanical effect of an explosion on a structure, but not its only effect: the expanding hot gases produce the so-called dynamic pressure, which has the lowest value and propagates at a slower rate than the shock wave. The shock wave hitting the surface can be reflected by solid surfaces and re-acted as a reflected shock wave on other surfaces.

The shock wave propagating through the air consists of highly compressed air particles that exert pressure on all surfaces they encounter. With the pressure rising from ambient pressure (po) to burst pressure (pso), there is a discontinuous jump in shock pre-pressure. The pressure difference (pso-po) is called the burst overpressure (Fig. 3.7). At a fixed location in space, the pressure decreases exponentially with time, followed by a negative phase. An ideal blast wave pressure pulse has a very short duration of time and is typically measured in fractions of a millisecond.

$$P_s(t) = P_{so}\left(1 - \frac{t}{t_0}\right)e^{-b\frac{t}{t_0}} \quad (2)$$

The form of the blast wave pressure-time history is usually represented by the Friedlander equation, as shown in Equation (2), which was adopted to show the drop in blast pressure values. This equation depends on the time t measured from the moment the blast wave reaches the point of interest, as shown below:

Pso is the peak overpressure,
to is the positive phase duration,
b is the distortion coefficient of the waveform, and
t is the elapsed time measured from the moment of the explosion.

When the shock wave encounters a surface, it is reflected, raising the incident overpressure. Magnification is highly non-linear and depends on incident shock strength and angle of incidence. For a weak shock, the resulting detonation charges are doubled by reflection of the shock wave. If air is considered an ideal linear-elastic fluid, the air particles must rebound freely from the surface, giving a Pr equal to twice the incoming pressure. Normally, however, Pro/Pso > 2, because an explosion is actually a non-linear shock phenomenon, where the reflection of the particles is blocked by the

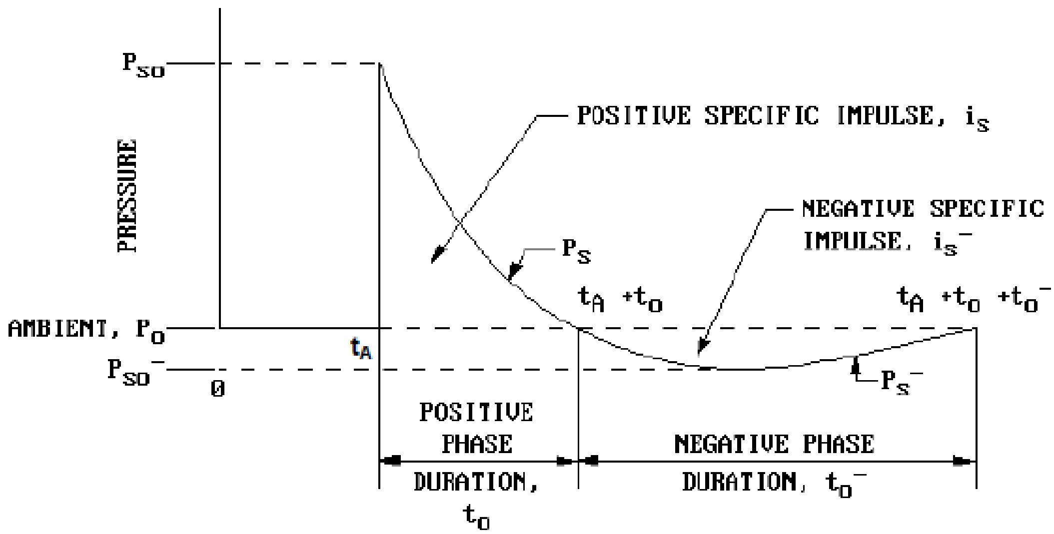

Figure 5. Time after explosion.

subsequent air particles, resulting in a much higher reflected pressure. It is calculated as shown in Equation (3.2) for normal shock waves.

Different explosive types were tested on steel plates and the deformation effects were compared. Three different explosive types specified in Table 3 were used in numerical models. In the selection of the relevant explosives, the selection of explosives was made by paying attention to the fact that the differences between detonation rates and pressure values were not close.

Experiments were made with 1 kg spherical explosives at a distance of 145 mm from the center of the steel panels. Each explosive was tested separately on steel plates of 3 different thicknesses.

Material type 8 (*MAT_HIGH_EXPLOSIVE_BURN) in LS-DYNA is used to describe the material property of high-energy explosive charges. It allows the detonation of a high explosive to be modeled with three parameters: the bulk density of the charge (ρM), the detonation velocity (V), and the Chapman-Jouget pressure (P). Likewise, an explosive combustible material model and an equation of state called the Jones-Wilkins-Lee (JWL) equation must be defined. Defines pressure as a function of relative volume, V* = ρ0 /ρ and internal energy per initial volume, Em0, as

$$P = A(1-\frac{\omega p}{R_1 \rho_0})e^{-R_1\frac{\rho_0}{\rho}} + B(1-\frac{\omega p}{R_2 \rho_0})e^{-R_2\frac{\rho_0}{\rho}} + \frac{\omega p}{p_0}E_{m^0} \quad (3)$$

where P is the detonation pressure, ρ is the explosive density, ρ0 is the explosive density at the beginning of the detonation process, A, B, R1, R2 and ω are the material constants that can be found and depend on the explosive type.

Table 2. Explosive types used in numerical models.

	C-J Explosion Velocity (m/s)	C-J Pressure (GPa)	Density (kg/m^t)
TNT	6930	21	1630
C4	8193	28	1601
ANFO	4160	5.15	931
HMX	9110	42	1891
PETN	8300	33.5	1770

Table 3. Explosive EOS values used in numerical models.

	A(GPa)	B(GPa)	R1	R2		E0
TNT	371.2	3.23	5.15	0.95	0.3	7
C4	609.77	12.95	4.5	1.4	0.25	9
ANFO	49.46	1.98	3.9	1.12	0.33	2.48
HMX	778.28	7.07	4.2	1	0.3	10.5
PETN	617	16.9	4.4	1.2	0.25	10.1

An initial fraction of the air volume occupied by the explosive is retained in the air mesh via the *INITIAL_VOLUME_FRACTION_GEOMETRY option in LS-DYNA. This option is used with the ALE multi-material formulation. The explosive geometry is formed as a sphere. *The explosion was initiated with the INITIAL_DETONATION card.

The equation of state (EOS) for an explosive solution or empirical data for the expansion of gases is required. For explosion problems, EOS is a thermodynamic relationship between pressure p, density ρ, state variables, and the specific internal energy E of the material. The EOS must be specified together with the material properties of the explosive and the surrounding air to model the airborne propagation of the blast wave.

RESULTS and DISCUSSION

The nonlinear behavior of steel panels under burst load was investigated with the LS-DYNA software, which uses the finite element method (FEM), which can consider nonlinear behavior sources. Actual values are used for material properties. According to the experimental test procedures, which are explained in detail in the third chapter, the tests applied with 3 different thickness plates and 5 different explosive types and their results are detailed.

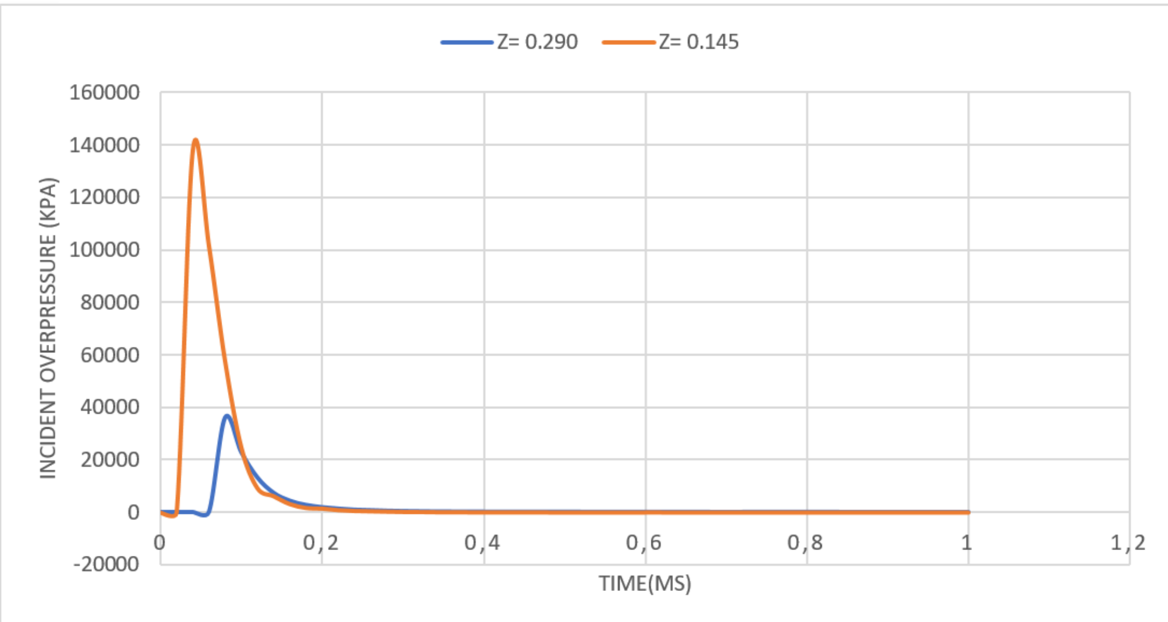

Figure 6. Shows a decrease in peak pressure values of 1 kg HMX explosive with increasing distance from the detonation source to the target surface.

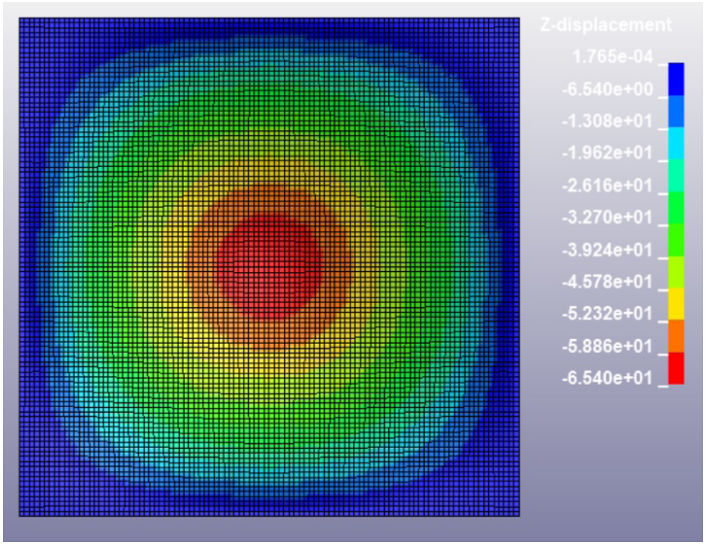

Figure 7. 8 mm steel panel displacement at 1 Kg HMX load.

HMX Simulation

One of the most critical parameters for blast load calculations is the distance of the blast point from the relevant structure. Peak pressure values of blast waves with parameters Z: 0.145 m/kg1/3 and Z: 0.290 m/kg1/3 were tested for 1 kg of TNT, C4, HMX, PETN and ANFO explosives. In Figure 5, it is seen that the peak pressure values of 1 kg HMX explosive decrease as the distance between the detonation source and the target surface is increased. Only the positive phases of the detonation waves are shown in the figure.

In the simulation made with 1 kg HMX explosive charge on three separate 8, 16 and 24 mm steel plates, calculations were made over the Z: 0.145 m/kg1/3 parameter.

The same numerical simulations were made for the other 4 different explosives and no discrepancy was observed between the results.

In Figures 6 and 7, the displacement values occurring in the 8 mm steel panel under 1 kg of HMX explosive are observed.

When the displacement values of 8, 16 and 24 mm steel panels under 1 kg HMX explosion load are examined; As can be seen in Table 4. and Figure 8., the displacement amounts decrease as the thickness increases. When it is increased from 8 mm to 16 mm, it can be seen that the panel displacements decrease proportionally.

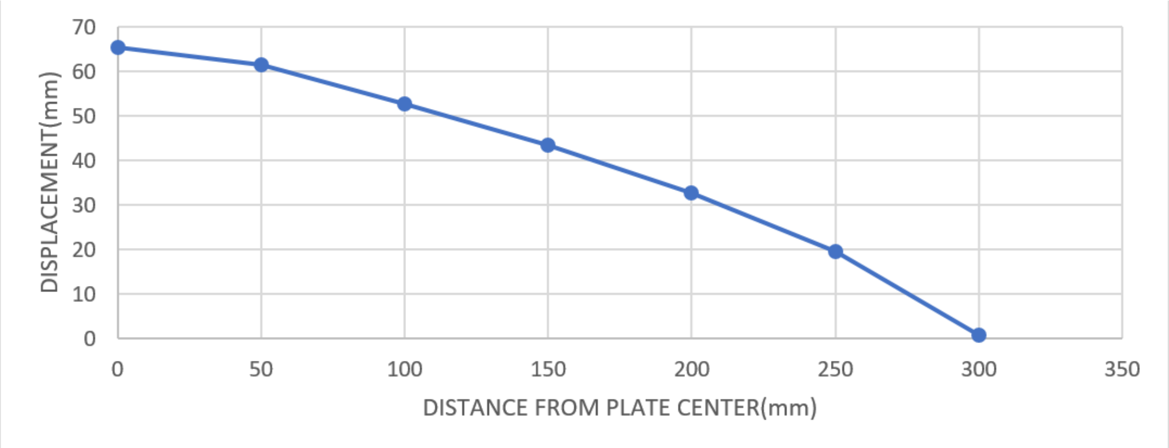

Figure 8. 8 mm steel panel / 1 Kg HMX load.

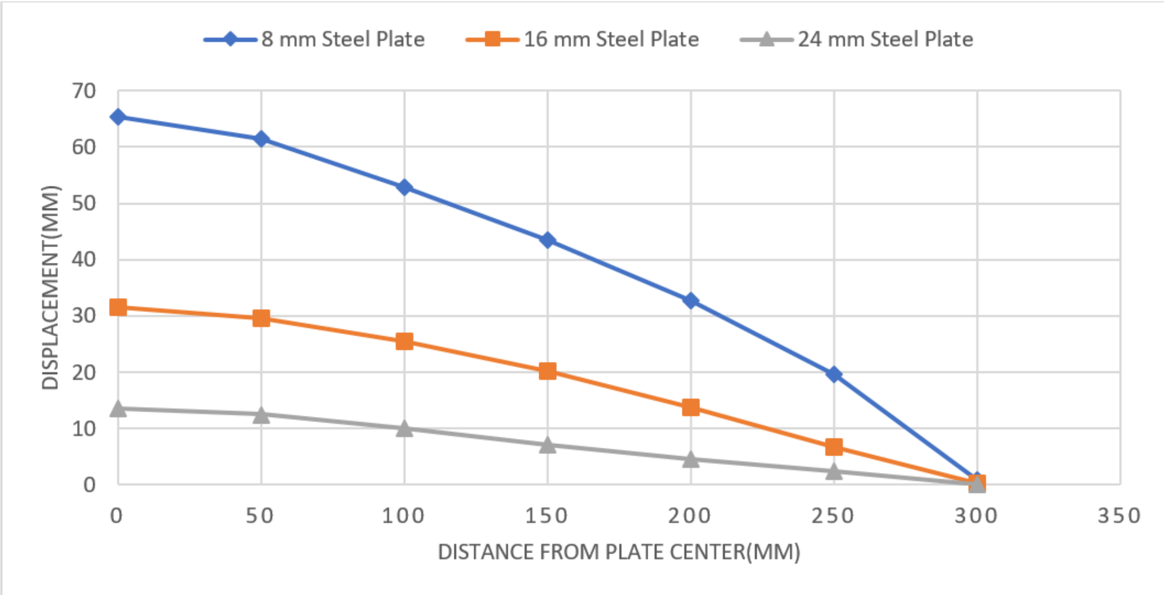

Figure 9. Displacement curves in steel panels at 1 Kg HMX load.

Table 4. Displacements of steel panels at 1 Kg HMX load.

Distance From Plate Center (mm)	8 mm Steel Plate Displacement (mm)	16 mm Steel Plate Displacement (mm)	24 mm Steel Plate Displacement (mm)
0	65.399	31.456	13.61
50	61.488	29.57	12.451
100	52.884	25.472	9.945
150	43.395	20.158	7.145
200	32.712	13.716	4.572
250	19.604	6.585	2.309
300	0.815	0.152	0.103

24 mm Steel Plates

In the explosion simulations made with TNT, C4, ANFO, HMX and PETN with 1 kg explosion load, the displacement values they create on the 24 mm steel panel are seen as can be seen in Figure 10. Analyzes performed using the finite element method with LS DYNA were tested under the same ambient conditions. By looking at the deformations caused by these analyzes carried out under the same explosion load, on the 24 mm steel plate; We can say that PETN and HMX explosives perform the most deformation.

The displacement caused by PETN and HMX explosives at the center point of the plate is approximately 7% more than the deformation caused by the C4 explosive.

The displacement caused by the C4 explosive at the center point of the plate is approximately 30% more than the deformation caused by the TNT explosive.

The displacement caused by the TNT explosive at the center point of the plate is approximately 86% higher than the deformation caused by the ANFO explosive.

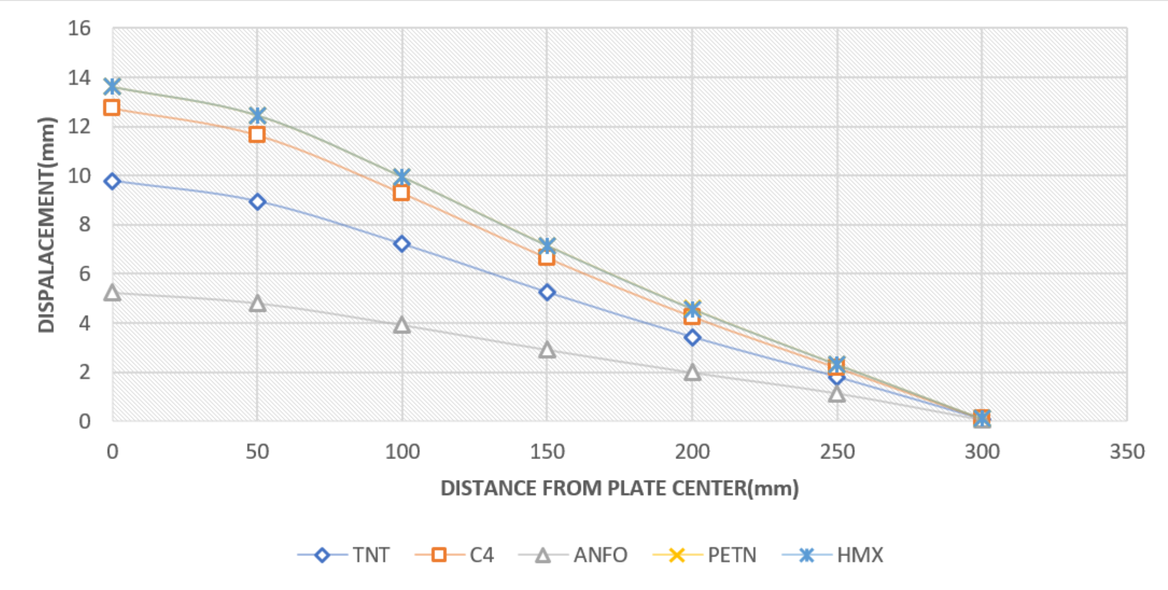

Figure 10. Displacement curves of 5 different explosive types at 1 Kg load in 24 mm steel panels.

Peak Pressure Comparisons

The peak pressure values of the blast waves are shown in Figure 4.44 for 1 kg of HMX, TNT, PETN, C4 and ANFO explosives, based on the parameter Z: 0.145 m/kg1/3. Only the positive phases of the detonation waves are shown in the figure. When the peak pressure values are examined, the displacement values they create on the steel plates are listed as HXM, PETN, C4, TNT and ANFO, in order of the strongest pressure values.

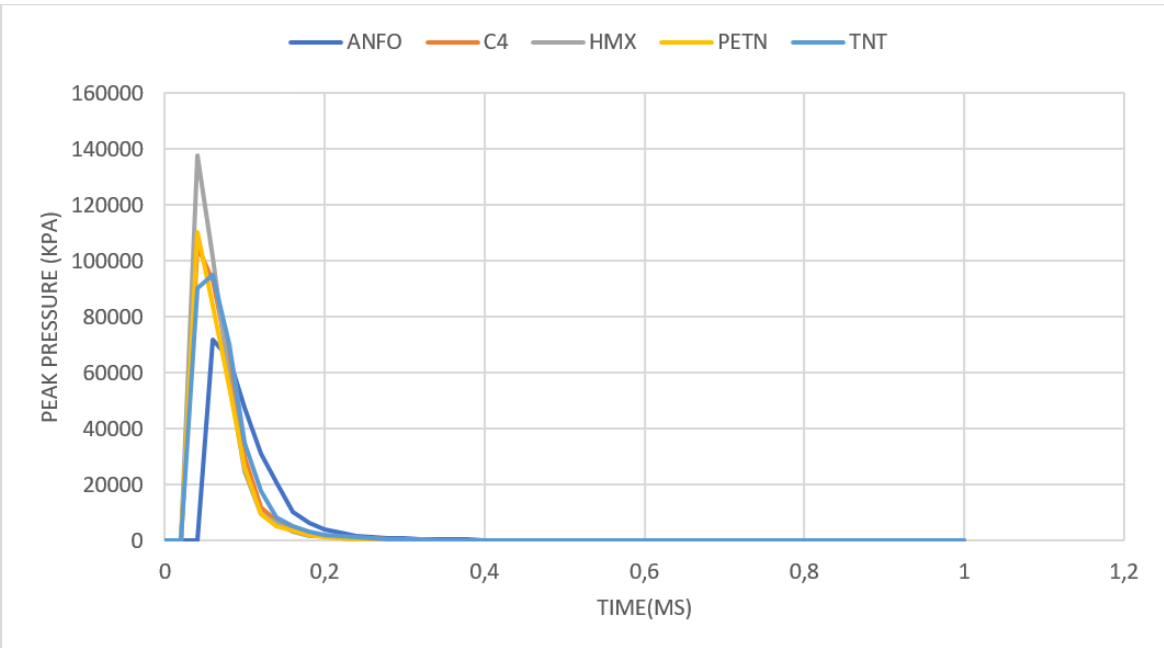

Figure 11. Peak pressure comparison of 5 different explosive types at 1 Kg load. Z=0.145 m/kg1/3.

Conclusion

Within the scope of this study, the experimental sample of the stainless steel alloy plate specified in Chapter 2 was validated using the finite element method in LS DYNA software. Different simulations were made with the test setup, which was successfully validated. In the validation study, researches on material properties, experimental environment and test parameters were carried out. In this context, a serious literature review was carried out to see the detail parameters of explosives and their usage areas. The deformations of the stainless steel alloy material against the explosion effect at different thicknesses are detailed.

All tests and simulations performed within the scope of the study are described in Chapter 3 Numerical Simulations, the findings section details burst tests and deformation results.

In line with the results obtained, it has been determined that explosives with high explosive energy cause more damage to the structure exposed to the explosion. When the wall thickness of stainless steel plates is increased, the damage rate decreases.

As a result of the tests, attention should be paid to the energy of the explosives rather than the amount of explosives. It is seen that high deformation can be achieved with low amounts of explosives but high energy.

Under 1 kg of TNT load, when the thickness of the steel plate is increased by 2 times, the amount of deformation decreased by about 54%, and when the amount of deformation is increased by 3 times, the amount of deformation decreased by about 83%.

Under 1 kg of C4 load, when the thickness of the steel plate is increased by 2 times, the amount of deformation decreased by approximately 50%, and when increased by 3 times, the amount of deformation decreased by approximately 80%.

Under 1 kg ANFO load, when the thickness of the steel plate is increased by 2 times, the amount of deformation decreased by approximately 53%, and when increased by 3 times, the amount of deformation decreased by approximately 89%.

Under 1 kg HMX load, when the thickness of the steel plate is increased by 2 times, the amount of deformation decreased by approximately 52%, and when increased by 3 times, the amount of deformation decreased by approximately 79%.

Under 1 kg PETN load, when the thickness of the steel plate is increased by 2 times, the amount of deformation decreased by approximately 52%, and when increased by 3 times, the amount of deformation decreased by approximately 79%.

References

1. M.G. Rashed, M. Ashraf , R.A.W. Mines, Metallic microlattice materials: a current state of the art on manufacturing, Mechanical properties and applications, 33, (2016), 95-518 .
2. A. Vaziri, W. J. Hutchinson, Metal sandwich plates subject to intense air shocks, International Journal of Solids and Structures, 44, (2007), 2021-2035.
3. Z. Jianxun, Z. Renfang, W. Mingshi, Q. Qinghua, Y. Yang, T.J. Wang, Dynamic response of double-layer rectangular sandwich plates with metal foam cores subjected to blast loading, International Journal of Impact Engineering, 122, (2018), 265-275.
4. C. Ganchao, C. Yuansheng, Z. Pan, C. Sipei, L. Jun, Blast resistance of metallic double arrowhead honeycomb sandwich panels with different core configurations under the paper tube-guided air blast loading, International Journal of Mechanical Sciences, 201, (2021), 106-457.
5. W. Yinghan, L. Qiang, F. Jie, L. Qing, H. David, Dynamic crash responses of bio-inspired aluminum honeycomb sandwich structures with CFRP panels, Composites Part B: Engineering, 121, (2017), 122-133.
6. T. Thippeswamy, P. Shirbhate, J. Mandal, S. Inderpal, Manmohan, Numerical investigation on the blast resistance of a door panel, Materials Today, 2020.
7. M. Damith, P. Fernando, W. Dakshitha, A. Remennikov, Evaluation of effectiveness of polymer coatings in reducing blast-induced deformation of steel plates, 17, (2021), 1895-1904.
8. W. Chengqing, H. Hong, Modeling of simultaneous ground shock and airblast pressure on nearby structures from surface explosions, International Journal of Impact Engineering., 31, (2005), 699–717.
9. LSTC, LS-DYNA Version 971 Keyword User's Manual_Rev5-beta, Livermore Software Technology Corporation, 2010.
10. J.W. Hutchinson, Z.Xue, Metal Sandwich Plates Optimized For Pressure Impulses, Int. J. Mech. Sci., 47, (2005), 545–69.
11. NA. Fleck, VS. Deshpande, The Resistance Of Clamped Sandwich Beams To Shock Loading, J Appl Mech., 71, (2004), 386–401.
12. Baker W. E., Explosions in Air, University of Texas Press, Austin, 1973.
13. S. Chung, GN. Nurick, Experimental and numerical studies on the response of quadrangular stiffened plates. Part I: Subjected to uniform blast load., Int. J. Impact Eng. 31(1), (2005), 55–83.
14. Hibbit, Karlsson and Sorenson Inc., ABAQUS/Explicit user's manual, Version 6.0, Pennsylvania, USA, 2001.

15. M.S. Chafi, G. Karami, M. Ziejewski, Numerical analysis of blast-induced wave propagation using FSI and ALE multi-material formulations, International Journal of Impact Engineering, 36(10-11), (2009), 1269-1275.
16. P. Kumar, N.G. Haydn, X. Wadleya, W. John Hutchinson, Mechanical response of metallic honeycomb sandwich panel structures to high-intensity dynamic loading, International Journal of Impact Engineering, 35, (2008), 1063–1074.
17. X. Zhenyu, J.W. Hutchinson, Preliminary assessment of sandwich plates subject to blast loads, International Journal of Mechanical Sciences, 45, (2003), 687-705.
18. N. Nemat, Thermomechanical response of AL-6XN stainless steel over a wide range of strain rates and temperatures, Journal of The Mechanics and Physics of Solids, 49, (2001), 1823-1846.
19. Hallquist J.O., LS-DYNA Users Manual." Livermore Software Technology Corporation, LSTC, Livermore, California, 1998.