# Dynamic Analysis of Hardened Double Bulkhead Structure Subjected to Blast Loading

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**Abstract**

The set of the construction elements which are designed to divide the boat structure into compartments and enable the maintenance of the balance of the boat by keeping the water entering the hull in a certain region in case of any damage is called watertight bulkhead. The main factor taken into consideration while determining the number of watertight bulkheads and their structural strength properties is to protect the stability of the ship in case of filling with water after a collision and to ensure that the bulkhead has a resistance level that can endure this water pressure. In warships, these bulkheads can be used for other purposes and may be exposed to a number of military loads in addition to operational loads. This study examines the reinforced watertight double bulkhead structure designed to reduce the effects of blast caused by the explosion in the compartment after the weapon hit on warships and fragmentation effects only under blast loads.

**Keywords:** Hardened Double Bulkhead, Blast Loads, Warships

# Patlama Yükleri Altında Güçlendirilmiş Çift Perde Yapısının Dinamik Analizi

**Öz**

Tekne yapısını bölmelere ayırmak için tasarlanan, gemilerin yaralanmaları durumunda tekne gövdesine giren suyu belli bir bölgede tutarak geminin denge durumunu korumasını sağlayan yapı elemanları bütününe su geçirmez perde adı verilir. Su geçirmez perdelerin sayısı ve yapısal dayanım özellikleri belirlenirken göz önüne alınan ana unsur geminin çatışma sonrasında su alması durumunda gemi stabilitesinin korunması ve perdenin bu su basıncını taşıyabilecek dayanım seviyesinde olmasıdır. Savaş gemilerinde ise bu perdeler, başka amaçlarla da kullanılabilmekte ve operasyonel yüklerin yanı sıra bir takım askeri yüklere maruz kalabilmektedirler. Bu çalışmada savaş gemilerinde silah isabeti sonrası kompartıman içinde patlamanın oluşturduğu şok ve parça tesiri etkilerinin azaltılmasına yönelik dizayn edilen güçlendirilmiş çift perde yapısı sadece patlama yükleri altında incelenmiştir.

**Anahtar Kelimeler:** Güçlendirilmiş Çift Perde, Patlama Yükleri, Savaş Gemileri

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# 1. Introduction

Surface warships are vessels that are used in military operations. Since modern combat environments may include unpredictable and undetermined threats, surface warships should be equipped with sufficient capabilities in both offense and defense (ISTK report, 2012). Survivability is a critical defensive capability for surface warships that is divided into three categories (Ball & Calvano, 1994). One of these categories, susceptibility, is the inability of a vessel to avoid damage. The second one, vulnerability, is the inability of a vessel to resist damage mechanisms by threatening weapons. Finally, recoverability defines a warship's ability to prevent losses and restore the mission (Said 1995). Due to the unpredictability of modern combat situations, surface warships should be designed to be as invulnerable as possible to help minimize damage by unforeseen hits (Kim 2011).

In the design and construction processes of warships, certain engineering disciplines need to be operated in addition to civil ship design and construction processes. The concept of vulnerability, which is included in the concept of survivability, leads to the existence of more watertight bulkheads in warships compared to civilian ships and the implementation of a design for these bulkheads to be exposed to more than expected load components in a commercial ship (Piperakis, 2012).

In addition to the watertight bulkheads on warships, blast and fragmentation resistant double bulkhead applications aim to prevent the blast effects to reach other spaces by being absorbed by the bulkhead during a blast that can occur in the compartment. The shock wave formed as a result of the blast transmits the energy it carries by hitting the resistance elements inside the compartment. As a result of this incident, pressure increases with the effect of heat in the space (Smith et al, 2003). In order to prevent this pressure from passing to the other compartments of the ship and damaging the equipment, it is aimed that the resistance elements on the bulkhead absorb as much energy as possible before reaching the plastic limit and the bulkhead is not damage by preventing the accumulations of stress. For this purpose, it is suitable to use high hardness and low ductility material in bulkhead manufacturing.

Blast hardened bulkheads (BHBs) are transversely installed within warships against internal explosion threats to effectively improve invulnerability. However, conventional watertight bulkheads are designed not to withstand internal blast pressure, but to resist hydrostatic pressure (SNAK, 2012). BHBs prevent internal explosions by spreading the blast force to adjacent spaces (ROKN, 2009). However, installing such structures also increases the total weight of the vessel, leading to reduced mobility. Thus, the calculation of the risk–benefit ratio of BHBs (reduced speed vs. better survivability) is crucial in the early design stage.

In this study, the structural behavior of double bulkhead of a warship is investigated using finite element method by simulating the blast load help of the Load Blast Enhanced theory. As a result of these examinations, improvements have been made on the parts of the bulkhead that were not resistant to blast load, and in the subsequent studies, the internal blast is simulated by making the finite element model of the ship compartment. Then, detailed stress and displacement results are given in the last section.

# 2. Method

## 2.1. Protection Concept

While designing warships, it is aimed that the ships fulfill the task expected from them by preserving their capabilities to fight and move in an environment where the enemy threat is present. In accordance with this purpose, hardened double bulkhead is applied to the compartments, which have vital systems and equipment for the strike-stand power of the ship, to prevent the blast effects that may occur in other spaces (Piperakis, 2012).

## 2.2. Blast Loads and Solution Methods

Car crashes, drop tests of electronic devices, bird strike to turbine blades and exposure of structures to shock and blast loads can be given as examples for high-energy dynamic events. Dynamic simulations are often used to predict potential damages on the structures.

Traditional implicit analysis is used as an approach to this type of dynamic simulations. This type of analysis, which is used by the majority of commercial finite element software, uses the closed-time integration technique. Although this technique uses relatively large time steps, it may need many convergence iterations for nonlinear behaviors. In addition, it can be time-consuming since the inverse of the matrix needs to be calculated at each iteration.

Another approach to simulate high-energy events is the use of the explicit method. This method is called the open time integration scheme where the matrices are not inverted and are updated only at the end of each time step. To eliminate the need for convergence iterations, very small time steps that can be between $10^{-6}$ and $10^{-8}$ seconds are used depending on the model. Accordingly, unlike the implicit method, each time step is resolved very quickly; however, it often takes thousands of time steps to complete the solution. The need for a small time step limits this method to short-term events that typically take place in milliseconds or shorter periods. However, time scaling methods can be used to solve events that last longer.

The explicit method, which does not need convergence controls and uses very small time steps, saves users from most of the limitations of the implicit method for high-energy dynamic analyses. It can accurately simulate the propagation and interaction of stress waves caused by impacts and solve nonlinear and structurally unstable problems that cannot be easily solved with implicit methods due to convergence difficulties.

Explicit method is used by commercial finite element software such as LS-Dyna. LS-Dyna finalizes nonlinear and transient dynamic finite element analyses by using explicit time integration and provides 3 different methods for the simulation of blast load. These methods are Load Blast Enhanced (LBE), Arbitrary Lagrangian Eulerian (ALE) and hybrid LBE-ALE methods (Rebelo et al,2017):

### 2.2.1. Load Blast Enhanced (LBE) Method

With the Load Blast Enhanced LBE method, which is the first method in Ls-Dyna, blast loads are calculated with the help of a hydrocode that developed by Randers-Pehrson and Bannister (Randers-Pehrson et al, 1997). There is a simplified pressure distribution caused by the blast loads on the structure without modeling the fluid between explosive and target. In structure designs where fast solution processes are privileged, it is appropriate to use the LBE method. However, in this method, it is not possible to observe and examine the shock waves reflected from the target and spreading in the fluid (Erdik et al, 2018)

Kingery and Bulmash carried out some experiments to investigate the behaviors of structures under blast load [6]. To obtain the blast parameters, they exploded various amounts of TNT explosives with sphere and hemisphere forms at different distances in front of a plate. These parameters constitute the basis of the CONWEP computer program (U.S. Army Corps of Engineers, 2002). CONWEP was implemented in Ls-Dyna under the *LOAD_BLAST_ENHANCED and *LOAD_BLAST_SEGMENT_SET keywords (Hallquist et al, 2006). Simplest form of blast wave is shown as Figure 1, the blast load can be calculated by Equation (1). This equation can be used to find air blast loads caused by the spherical explosive.
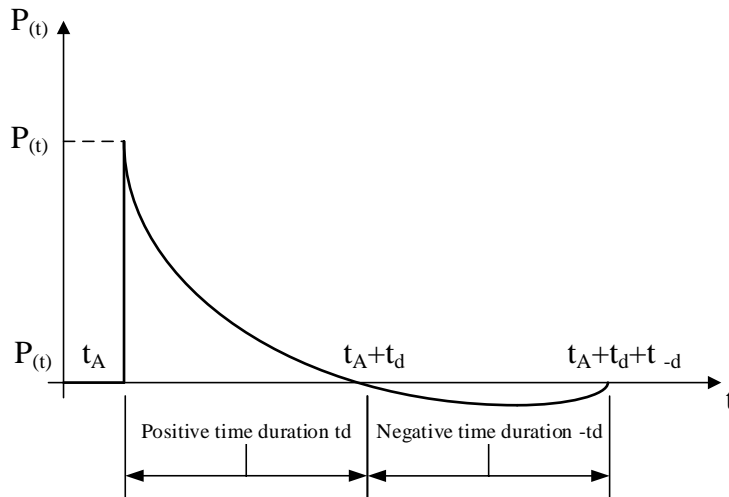


Figure 1. A Friedlander waveform is the simplest form of a blast wave (Lam et al, 2007)

$$P_e = P_0 + P_{so} \cdot \left(1 - \frac{t}{t_d}\right) \cdot e^{-\frac{t}{t_d}} \tag{1}$$

$P_e$ is effective pressure, $P_0$ is the atmospheric pressure, Pso is the peak positive pressure, t is current time and $t_d$ is time duration of positive pressure (Karlos et al, 2015).

### 2.2.2. Arbitrary Lagrange Eulerian (ALE) Method

The ALE method, which is the second method, is a combination of Lagrangian and Eulerian simulations (Donea et al, 1982). The combination of Lagrangian and Eulerian elements is performed thanks to the Fluid Structure Interaction (FSI) algorithm. The explosive and air fluid surrounding the explosive are modeled with the Eulerian mesh, while the target structure is modeled with the Lagrangian mesh. ALE method has certain advantages compared to other blast methods. The propagation of shock waves through the fluid medium can be simulated. In addition, physical values such as pressure, temperature and particle velocity on any point can be controlled (Kozak et al, 2016).

The Lagrangian approach, where the deformation of the finite element digital network occurs according to the deformation of the material, is not convenient for fluid modeling due to the large deformation of the fluid material (LS-DYNA Aerospace Working Group, 2013).

Unlike the Lagrangian solution, the Eulerian approach ensures that the material flow is in the constant Eulerian mesh in space. So that this modeling method is more convenient for fluid material and explosives (LS-DYNA Aerospace Working Group, 2013).

The ALE method provides an approach that allows interaction between the air domain and structure surrounded by high explosive. This approach is applied separately for air and explosive in the Ls-Dyna with the functions. The equations determining the material model and blast wave propagation status and pressure/volume relationships should be defined in the calculation domain. Calculation domain, i.e. Euler domain, consists of explosive and air.

### 2.2.3. Hybrid LBE-ALE Method

The hybrid LBE-ALE method allows for modeling by combining the advantages of these two methods. In this method, as in the LBE method, the loads calculated from the explosive modeling are transmitted on a specific fluid model that surrounds the target structure and simulated with the ALE method (Slavik et al, 2009). The blast loads are transmitted to the target structure through the fluid model shown as Figure 2.  Thus, the whole fluid is not modeled and quick solution is achieved.
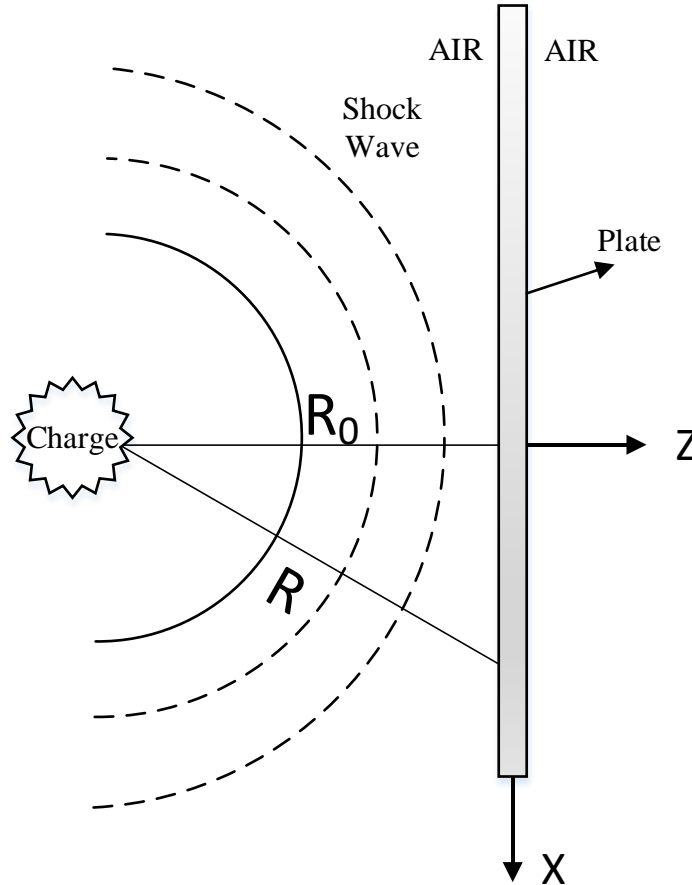


*Figure 2. The basic hybrit LBE-ALE application (Erdik et al, 2018)*

## 3. Geometric and Finite Element Model

### 3.1. Geometric Model Introduction

The ship structure is modeled as shown in the Figure 3 with all primary and secondary elements, blast and particle impact resistant double curtain is designed and shock brackets applications shown in detail C and detail D are applied. The purpose of these shock brackets is to absorb as much energy as possible without reaching the plastic limit by preventing burst effects thanks to its special geometry and to prevent tearing of the bulkhead by preventing stress accumulation.
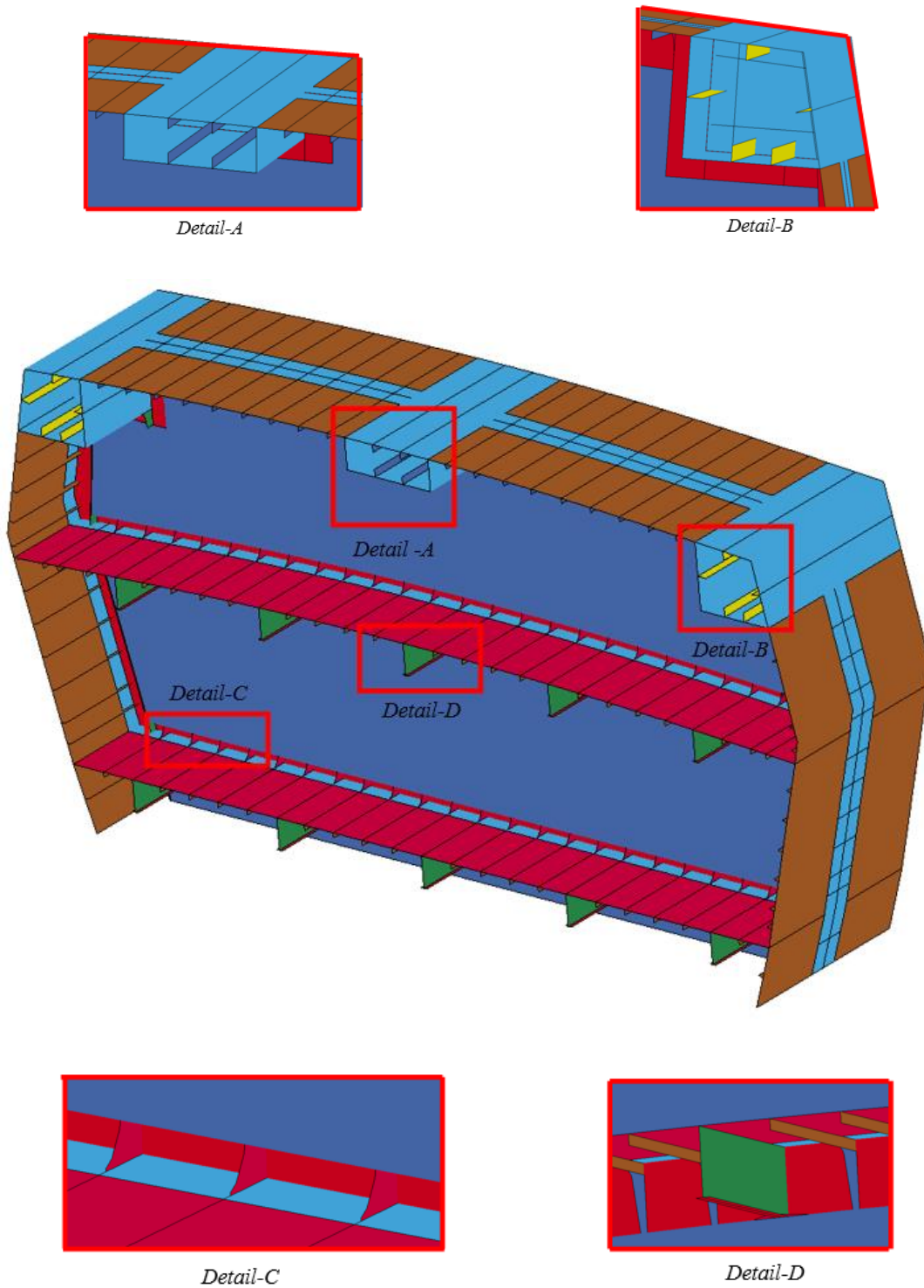
*Figure 3. Hardened double bulkhead structure geometry*

## 3.2. Finite Element Model Introduction

Finite element method is used to simulate and model the compartment structure and blast physics of the ship. The finite element method, which is widely used today, was first developed in 1956 for the stress analysis of fuselages and started to be used in the solution of applied sciences and engineering applications within the next ten years. The main logic in the finite element method is to solve a complicated problem by simplifying it. In this method, the solution region is divided into small, simple and interconnected sub-regions called finite element. With the finite element method, a solution of a very large model is simplified by cutting into pieces that are interconnected with many nodes. The structure resembling a grid formed by the nodes is called digital network (mesh). This network is programmed with the material information determining how the structure will behave under certain loading conditions.

Nodes give the stress levels of the structure emerging under operating conditions. The behavior of the structure under the relevant load is seen according to the calculated stress level (Korkut, 2019).

### 3.2.1. Selecting Shell Elements for Ship Structure

The steel structure used in ship linings and all deep construction is modeled as a shell element in finite element analysis. There are many formulations in the Ls-Dyna software for shell elements and the fully-integrated shell elements are used, which differ in the number of integration points and calculation algorithms.

### 3.2.2. Creating the Material Model

The behavior of the metal structure must be properly identified in order to analyze the response of the ship structure correctly in explosion analyses. This identification is realized by transferring the mathematical material model is used in the dynamic analysis to simulations. Johnson-Cook mathematical material model is included in the Ls-Dyna program and used to create the behavior of the dynamic behavior of the high strength DH-36 steel structure. The parameters of the Johnson-Cook model and DH-36 steel material used in the bulkhead structure are given as Table 1 and Table 2. The general formula of the mathematical model is given Equation (2):

$$\sigma = [A + B.\varepsilon^n][1 + C.\ln\dot{\varepsilon}^*][1 - T^{*m}] \tag{2}$$

here $\sigma$ is the equivalent stress, and $\varepsilon$ is the equivalent plastic strain. The material constants are A, B, n, C and m. A is the yield stress of the material under reference conditions, B is the strain hardening constant, n is the strain hardening coefficient, C is the strengthening coefficient of strain rate, and m is the thermal softening coefficient (Cao et al,2014).

The three parenthesis components in Equation (2) represent, from left to right, the strain hardening effect, the strain rate strengthening effect and the temperature effect, which influences the flow stress values (Murugesan et al,2017). In the flow stress model, $\dot{\varepsilon}^*$ and $T^*$ are

$$\dot{\varepsilon}^* = \frac{\dot{\varepsilon}}{\dot{\varepsilon}_{ref}} \tag{3} \qquad T^* = \frac{T - T_{ref}}{T_m - T_{ref}} \tag{4}$$

$\dot{\varepsilon}^*$ is the dimensionless strain rate, $T^*$ is the homologous temperature, $T_m$ is the melting temperature of the material, and T is the deformation temperature. $\dot{\varepsilon}_{ref}$ and $T_{ref}$ are the reference strain rate and the reference deformation temperature (Murugesan et al,2017).

*Table 1. Johnson-Cook material model parameters (Klepaczko et al,2009)*

| Johnson-Cook Material Model Parameters | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| A (Mpa) | B (Mpa) | C | n | $\varepsilon$ (1/s) | m | $T=T_{ref}$ (K) | $T_m$ (K) | $\dot{\varepsilon}=\dot{\varepsilon}_{ref}$ (1/s) |
| 1020 | 1530 | 0.015 | 0.4 | $1\times10^1$ | 0.32 | 50 | 1773 | $1\times10^1$ |

*Table 2. DH-36 material properties*

| Material | Elasticity Modulus ($N/mm^2$) | Poisson Ratio | Density ($ton/mm^3$) | Yield Strength ($N/mm^2$) | Tensile Strength ($N/mm^2$) |
|---|---|---|---|---|---|
| DH-36 Steel | $2.1\times10^5$ | 0.28 | $7.85\times10^{-9}$ | 355 | 490 |

### 3.2.3. Defining Boundary Conditions

Boundary conditions are constraints that necessary for the solution of the structural analysis. The way that the model is constrained can significantly affect the results expected from the structure and requires special consideration. Over or under constrained models can give results especially stress and displacement inaccurate. In order to reduce the effects of boundary conditions, all points 1 meter away from hardened double bulkhead in the direction of the stem and stern were defined as ALLDOF = 0 in Ls-Dyna as shown in the Figure 4.
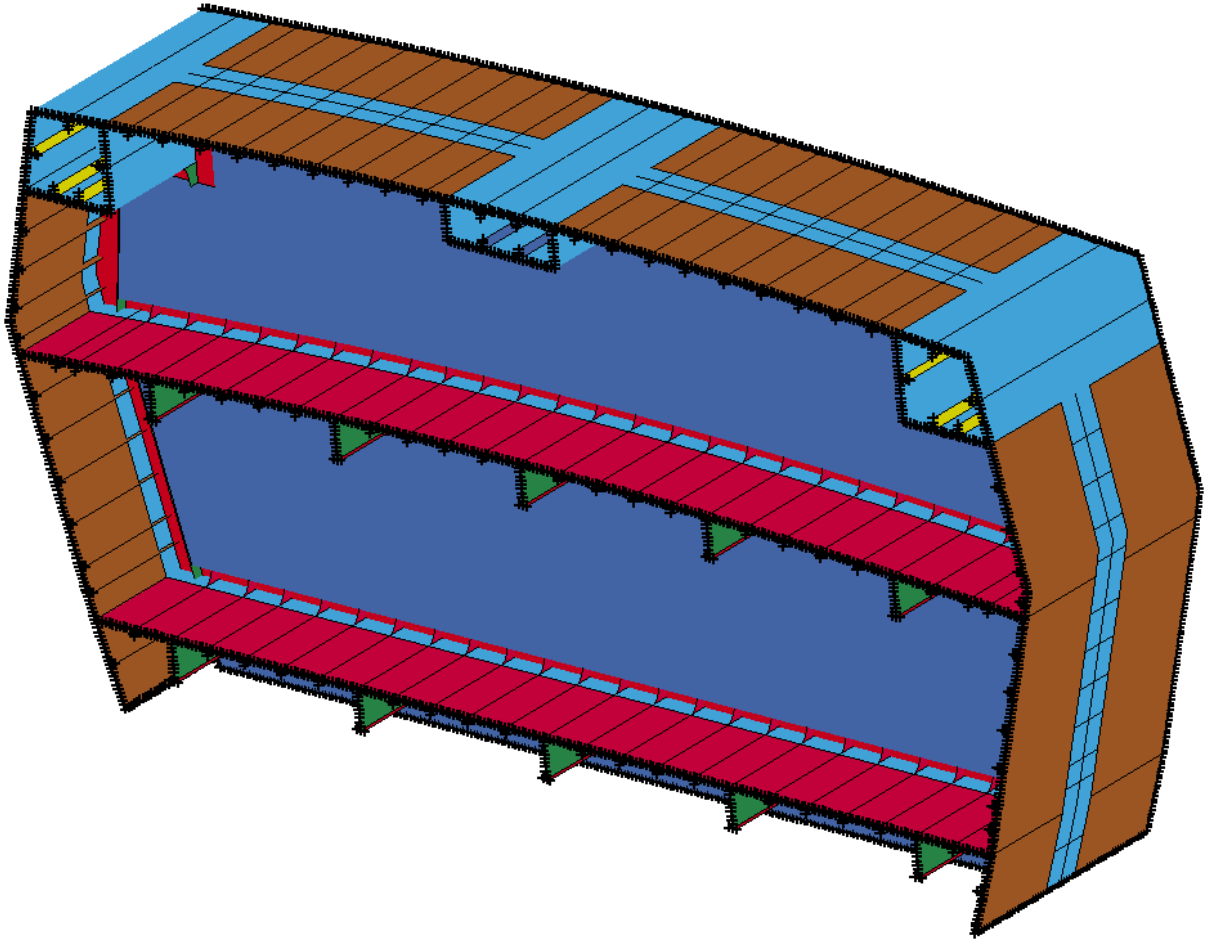
*Figure 4. Boundary conditions*

### 3.2.4. Explosive and Segment Set

In the light of the NATO standards, 0.845 tonnes TNT P-700 Granit Anti Ship Missile charge is located 5 meters away from the segment origin at naval ship compartment volume center as shown in the Figure 5. In addition, the time step is also an important parameter for blast analysis. The time step on the analyses is selected 1.8896E-03 s which is enough to handle the whole distribution of the pressure and stresses on the structure.
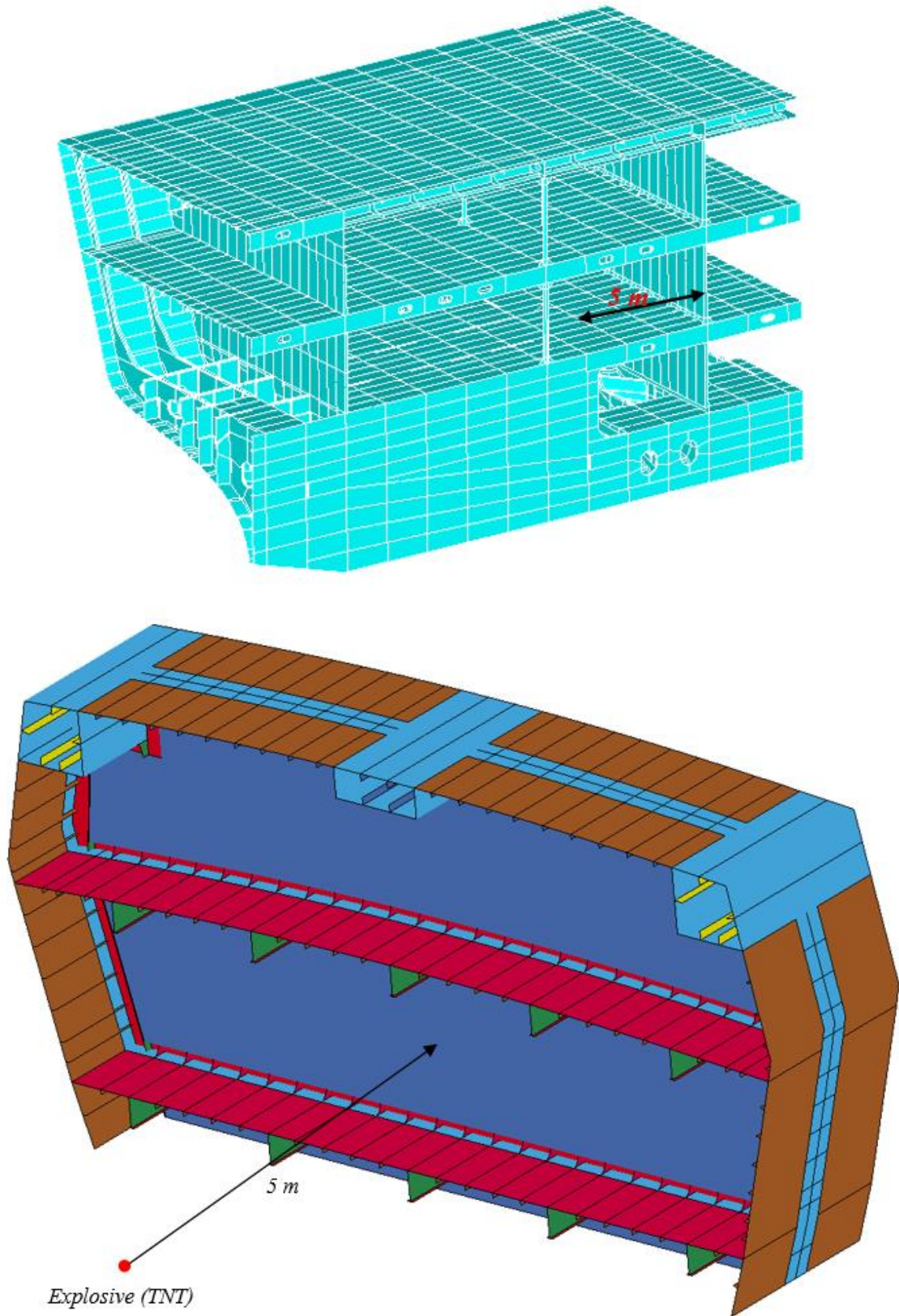
*Figure 5. Explosive location*

Explosive for the Load Blast Enhanced method is defined using two keywords, the keywords parameters are given in Table 3 and Table 4.

*Table 3. Load blast enhanced keyword parameters in Ls-Dyna*

| *LOAD_BLAST_ENHANCED (metric ton,milimeter,second,Mpa) | | | |
|---|---|---|---|
| BID | M | XBO | YBO |
| 1 | 0.845 | 5000.0 | 0 |
| ZBO | TBO | UNIT | BLAST |
| 0 | -1.8896E-03 | 7 | 2 |

The second required keyword surface segments of elements have been defined as a *SET_SEGMENT with a SSID=1, these segments are to be loaded by the explosive with BID=1 (defined in the above *LOAD_BLAST_ENHANCED keyword). Blast segments area is shown in Figure 6.
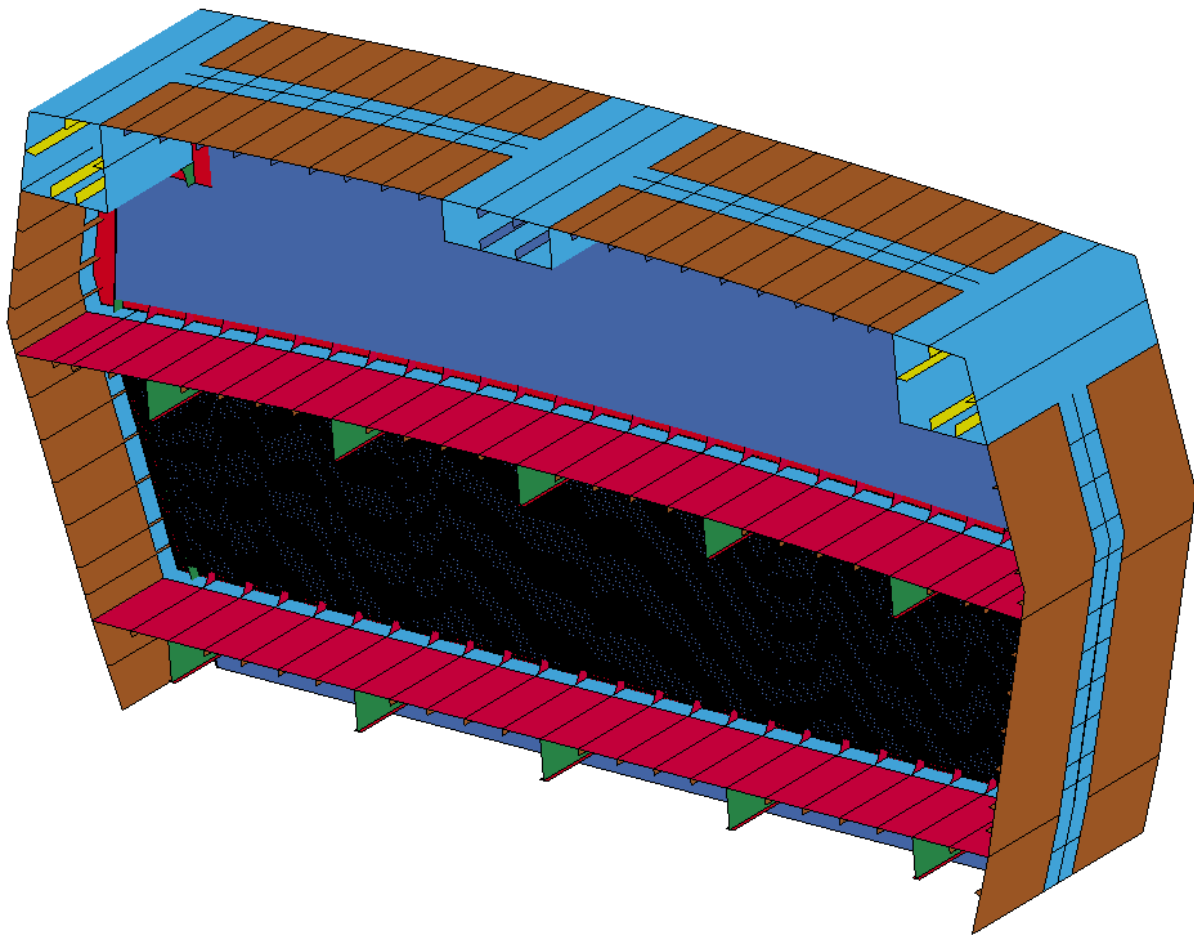


*Figure 6. Blast Segments Area is shown as black*

*Table 4. Load blast segment set keyword parameters in Ls-Dyna*

| *LOAD_BLAST_SEGMENT_SET | | | | |
|---|---|---|---|---|
| BID | SSID | ALEPID | SFNRB | SCALEP |
| 1 | 1 | 0 | 0.0 | 1.0000000 |

### *3.2.5. Mesh Size, Number of Elements and Number of Nodes*

Before starting the blast analyses of the bulkhead structure, a study is conducted on how the element size, especially the mesh convergence, affects the results. For this purpose 3 different mesh sized model are prepared and the stress results are investigated. The Finite element models are shown in Figure 7 and the max effective Von-Mises stress values depending on mesh size are given in Table 5.
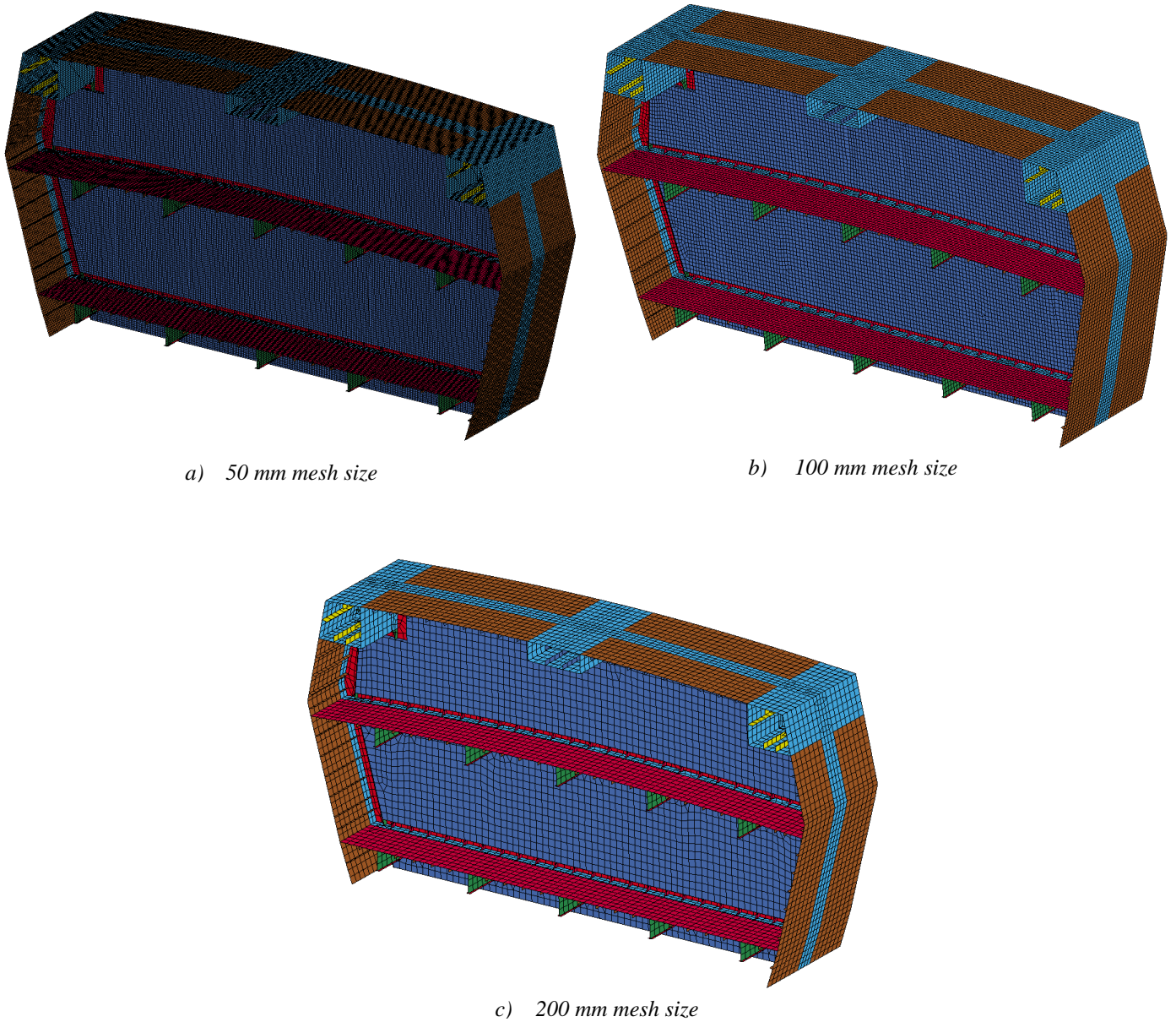


*a) 50 mm mesh size*

*b) 100 mm mesh size*



*c) 200 mm mesh size*

*Figure 7. Mesh view of finite element model*

The max effective Von-Mises stress results are given in Table 5 and it is decided to use 50 mm mesh size for the dynamic blast analyses of the hardened double bulkhead structure.

*Table 5. Mesh size, number of elements and nodes*

| Mesh Size | Max Effective Von-Mises Stress |
|---|---|
| 200 mm | 713.216 Mpa |
| 100 mm | 764.000 Mpa |
| 50 mm | 772.400 Mpa |

# 4. Blast Analyses of Bulkhead Structure

After making the necessary definitions and modeling studies in Ls-Prepost program, blast analysis was done with the help of Load Blast Enhanced (LBE) method in Ls-Dyna solver. Three control points (S8075, S7044, and S738) were selected from the center outwards on the segment and the pressure formed as a result of the blast coming on them was shown in the Figure 8, and these values were plotted on the Figure 9.
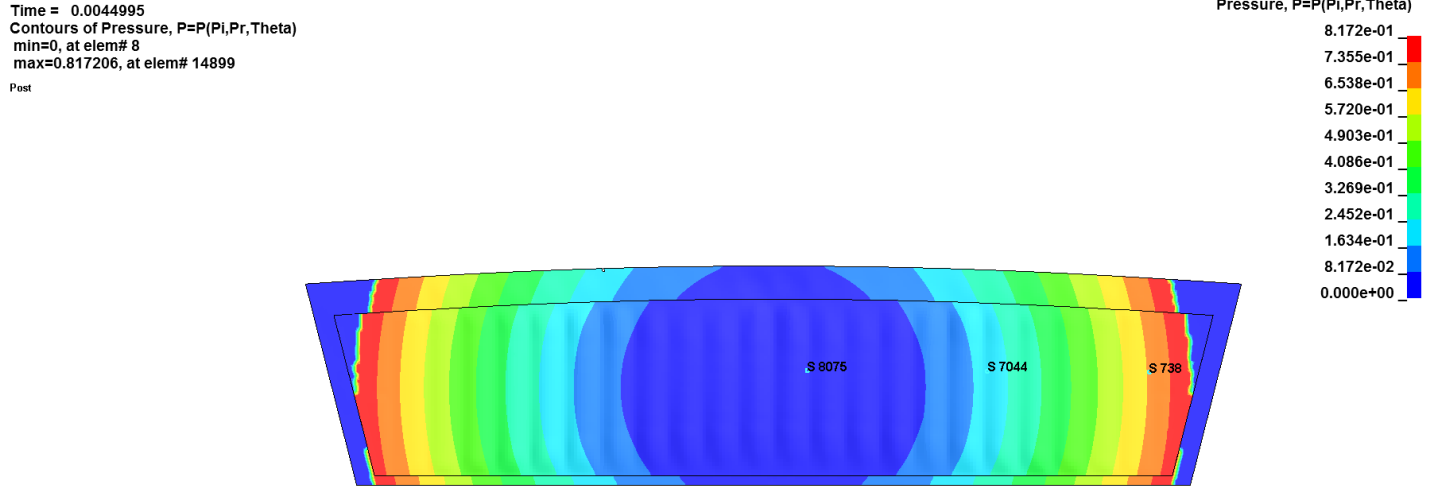


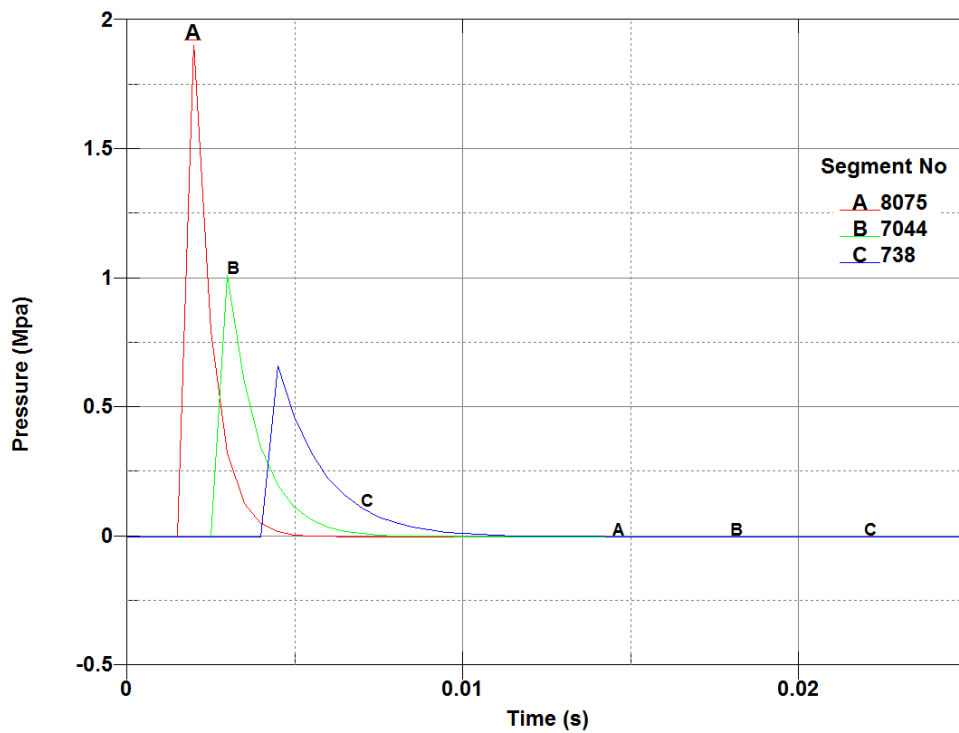*Figure 8. Blast pressure distribution on blast segments area*



*Figure 9. Effective pressure on control points*

The Load Blast Enhanced (LBE) method of LS-DYNA is based on empirical explosive data analyzed by Kingery, (Kingery et al,1984) which has been implemented in LS-DYNA (Randers-Pehrson et al, 1997) and the algorithm basically calculates a Friedlander type load curve as shown in Figure 1, which is applied to all exposed elements of a target structure modelled with a Lagrangian mesh and lying in the line of sight of the point of detonation.The parameters of the curve will depend on the distance and angle of incidence of the wave blast and as shown in Figure 9, the blast induced pressure curves are suitable for the simplest form of a blast wave as shown Figure 1.
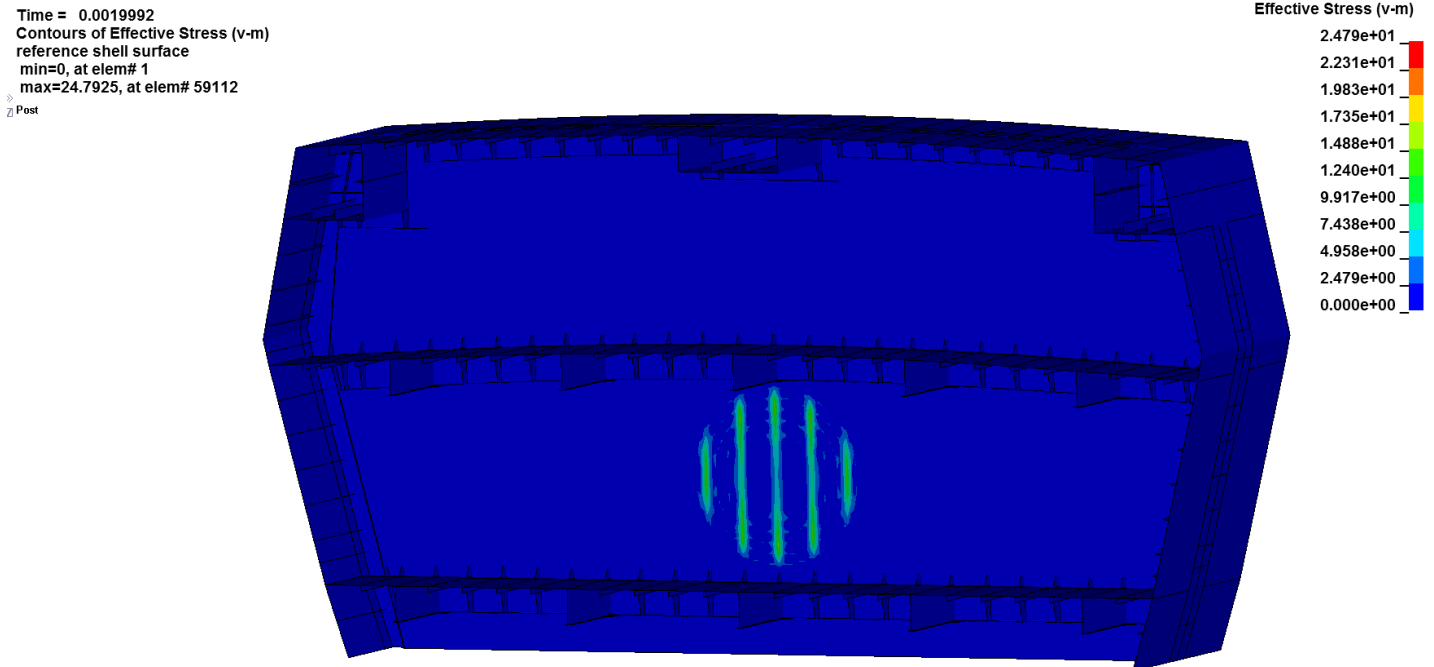


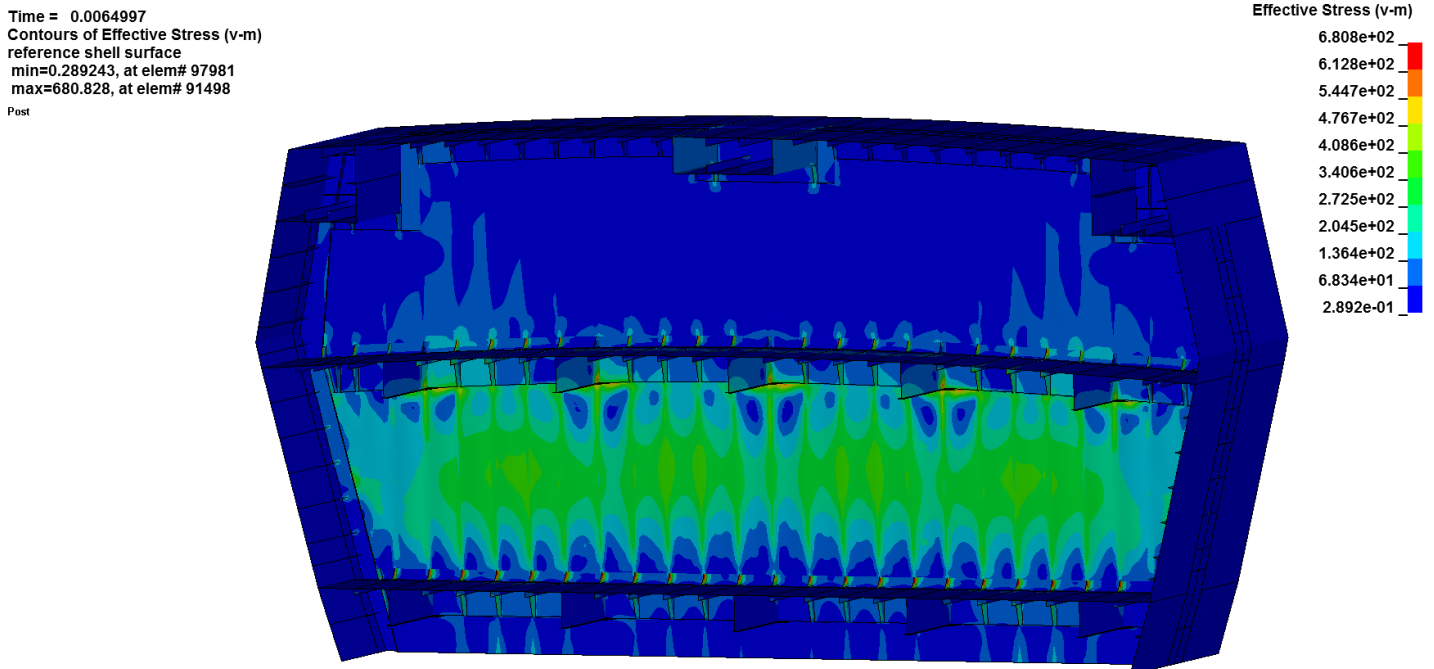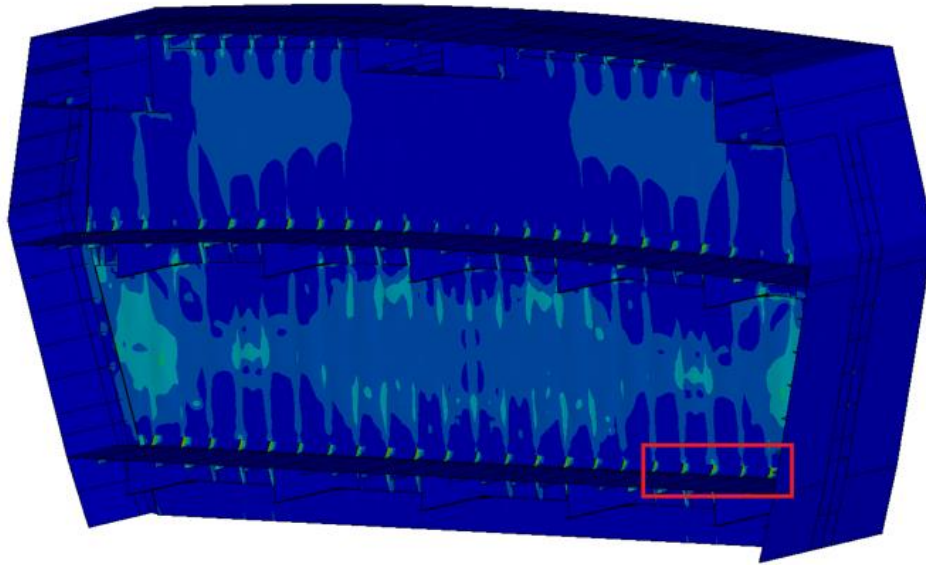*Figure 10. The fist effects of blast wave on structure*



*Figure 11. Distribution of blast wave on structure*

The effective Von-Misses stress on the bulkhead structure shown in Figure 11 does not exceed 490 MPa tensile limit of the DH-36 Steel used for the ship section.

*Figure 12. Maximum effective stress on shock brackets*

However, the blast analysis shows that the maximum effective Von-Misses stress is calculated on the shock brackets and 772.419 MPa after 0.020999 seconds the start of the blast as shown Detail E in Figure 12 and exceeds the tensile limit of the DH-36 Steel used for the ship section.
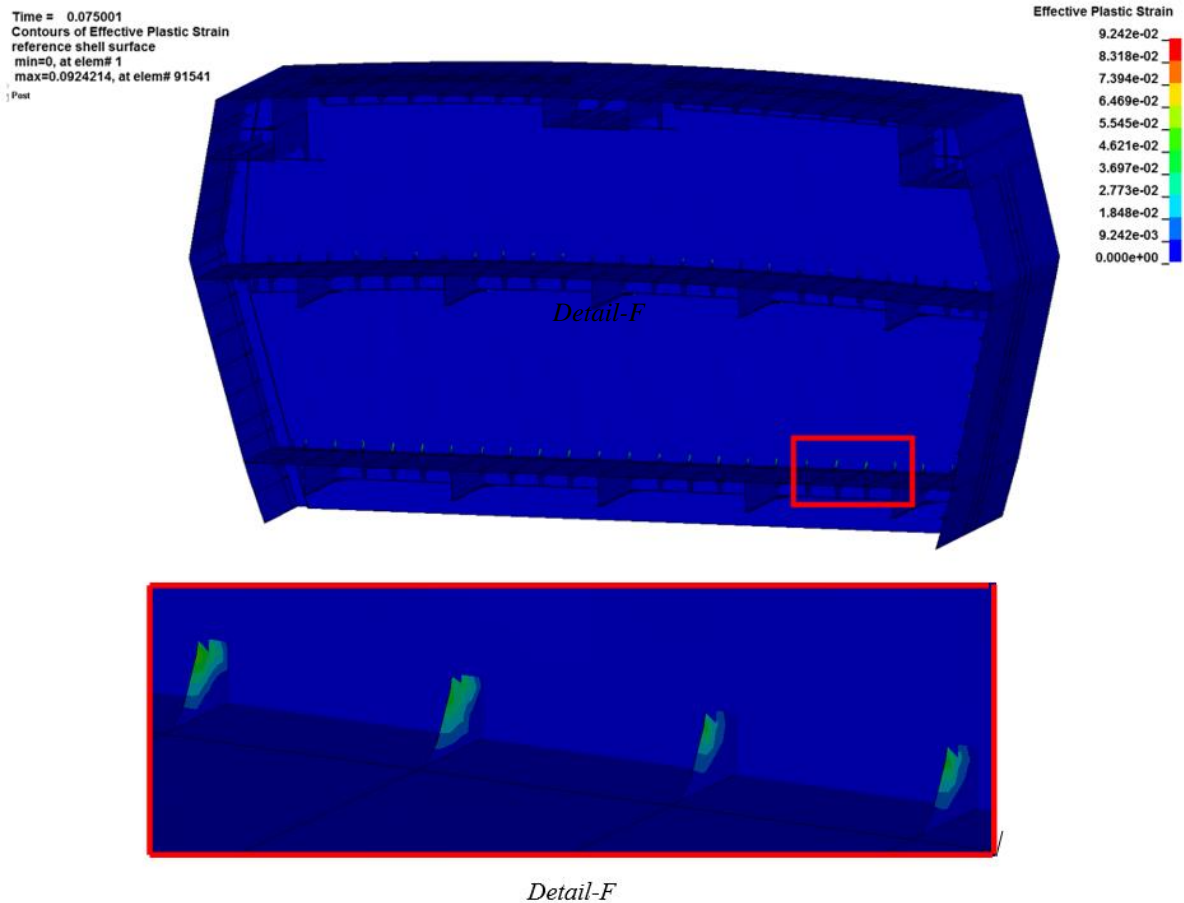
*Figure 13. Maximum effective plastic strain on shock brackets*

As shown in the Figure 13, the effective plastic strain value is measured as maximum 9.242e-02 (9.242%) on the shock brackets, and the shock brackets exceeds the maximum effective plastic strain = 0.1 defined as failure criteria. It means that plastic deformation will occur in these brackets.

# 5. Conclusion and Further Works

It is necessary to restrict the damage zone for the ship survivability under the internal blast loading. Within the scope of this study, the hardened double bulkhead structure is designed with all its primary and secondary elements, and the finite element model is prepared for the blast simulations. Blast analyses are performed using LS-Dyna software and it is observed that the structural elements forming the hardened double bulkhead structure did not suffer structural damage from the blast loading scenario stated on the NATO standards. However, as shown in the Figure 13, the efective plastic strain value on the shock brackets exceeds the maximum effective plastic defined as failure criteria. That means plastic deformation will occur on these brackets, but the limit on the strain is below the ultimate strain value. Therefore, it is acceptable for the dynamic blast loading.

On the other hand, the results from analysis of double bulkhead structure showed that to get appropriate results from a blast analysis, proper discreatization of the entire model is very important. Also the effect of mesh density and time-step size plays an important role. As a future work, the internal blast simulation of a ship's compartment containing the hardened double bulkhead structure can be performed using ALE method. This method provides more accurate results on stress and pressure and less time consuming.

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