Structural Design of Transverse Bulkhead of a Handymax Bulk Carrier Built in Steel Sandwich Panels

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Master Thesis

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ABSTRACT:

New solutions and technologies offering the viable alternatives to the classical ship structures are permanently searched in the shipbuilding industry. The alternatives to the classical structures offer weight, cost and energy consumption reduction. One of the potential options is all-steel sandwich (corrugated core) panels, developed originally by Meyerwerft Shipyard. Possibilities of implementation of these structural components in a bulk-carrier's structure are investigated in the present dissertation. The concept of the sandwich panels, technology and state-of-the-art are presented. Structural layout of several different configurations was investigated with the focus on the weight calculation and structural applicability, strength and technological aspects; each configuration with different properties and layout. The most promising configuration was selected from these observations; keeping on mind various design variables. The selected option finally consists of a double steel sandwich structure with spacing elements placed in between. The design developed in the dissertation was compared to the classical corrugated bulkhead. Furthermore, the structural response of selected design was investigated and the structural capacity was verified by finite element method. Overall behavior of the structure is checked. The final remarks and comments of obtained results were given, including possible improvements and recommendations.

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NOMENCLATURE

W	Section modulus, *cm*^{3}
C_s	Coefficient, according to **3.3.**
a	Spacing of stiffeners, *m*
l	Unsupported span of the bulkhead, *m*
p	Pressure, *kPa*
t	Thickness, *mm*
c_p	Coefficient according to the **3.3**
t_K	Corrosion addition, *mm*
p_C	Pressure due to cargo in hold, *kN/m*^{2}
ρ_C	Density of the cargo in the hold, t/m^3
g	Gravity constant, 9.81 m/s^2
h_1	Distance between the lowest point and the highest level of the cargo in the hold, *m*
n	Coefficient of repose of the of the cargo
γ	Angle of repose of the of the cargo, *deg*
F_C	Force of the cargo acting on corrugation, *kN*
d_1	Height of the highest point of the cargo hold, *m*
h_{DB}	Height of the double bottom, *m*
h_{LS}	Height of the lower stool, *m*
$p_{C,f}$	Pressure due to the flooding of the cargo, *kN/m*^{2}
ρ	Sea water density, t/m^3
h_f	Vert. dist. between the obs. point and the highest point of flooding, *m*
$F_{C,f}$	Force due to the flooding of the cargo, *kN/m*^{2}
d_f	Vertical height of the highest point of flooding, *m*
$p_{Cf,le}$	Pressure on the lowest point of the bulkhead, *kN/m*^{2}
F	Resultant force calculated on the bulkhead, *kN*
M	Resultant bending moment calculated on the bulkhead, *kNm*
Q	Resulting shear force, *kN*
t_P	Thickness of the sandwich panel plate, *mm*
t_W	Thickness of the sandwich panel web, *mm*
h_W	Height of the sandwich panel plate, *mm*
E	Young’s modulus, *N/mm*^{2}
G	Shear modulus, *N/mm*^{2}
γ	Poisson’s ratio
M_x, M_y	Bending moments, *kNm*

σ_{x1}, σ_{x2}, σ_{y1}, σ_{y2}	Stresses in middle surfaces of the lower- and upper-facing plates, N/mm^2
ε_{x1}, ε_{x2}, ε_{y1} and ε_{y2}	The strains in the middle surfaces of the lower- and upper-facing plates
D_x, D_y	Bending stiffness, *Nmm*
D_{xy}	Twisting stiffness, *Nmm*
D_{Qx}, D_{Qy}	Transverse shear stiffness, *Nmm*
h_f	Panel depth, *mm*
$2p$	Unit pitch, *mm*
f	Shorter distance between the pair core webs, *mm*
t_f, t_c	Thicknesses of the facing plates and the web core respectively, *mm*
I_c	Moment of inertia per unit of width of the core, mm^3
I_f	Moment of inertia per unit of width of the face, mm^3

1. INTRODUCTION

1.1. General

Over the decades, steel structure of sea-going ships has been produced with traditional stiffened panels; generally consisted of the steel plates with the stiffening elements connected to the surface of the plate ensuring required strength and stiffness; or corrugated stiff structures. Those structures can be considered as classical steel ship configuration, since there have not been many revolutionary changes in the outline and technology of fabrication of steel structure for decades. Classical type of structure has relatively large structural dimensions and weight; for acceptable utilisation quality it requires certain amount of preparations, prefabrications, heat work and post-outfitting works.

Over the years, many different innovative metallic and non-metallic materials have been developed for application in shipbuilding industry in order to improve the properties and reduce the weight. That kind of materials are found in the industry of pleasure, high speed and sport vessels and due to high price and different disadvantages it has never seriously entered the market and industry of large commercial vessels.

Metal sandwich panels, or also called all-steel panels, are innovative and relatively new materials in the shipbuilding industry, but the application of these materials to new buildings is still at the minimum level. The reason can be found in fact that the structural material is still under development and research, therefore still not recognised as applicable and reliable by the industry.

This work tends to give some useful comparison between two designs of transversal bulkheads: the classical corrugated and steel sandwich panel. Advantages and disadvantages of the both structures as a contribution to the wider application of the steel panels in the general industry have been investigated and compared. The focus of the thesis is on the properties which improve the sandwich structures increasing the structural and production efficiency. The weight and/or cost reduction of the overall structure, the new possibilities of structural application as well as certain improvements are proposed. The structural strength of the developed structural design is verified using the finite element method

1.2. Lightweight Structures and Weight Reduction

The weight of a ship has important role in different aspects of the ship operation. Reduction of weight of overall classical steel structure of a ship is usually done by extensive structural optimisation and/or structural modifications. When the optimal design is reached and there is no weight reduction without influences on the safety, application of different innovative materials can be considered. The weight reduction can be achieved by replacing certain members, the parts of the structure, or the overall structure. This has to be done respecting the various technological constraints while not diminishing or threatening the strength, safety and capability of a structure. Weight reduction affects the overall structural properties on several fields such as:

- Bigger loading capacities, thus bigger profit margin
- Higher speeds for the empty ship can be obtained
- Lower fuel consumptions and emissions

Light and reliable ship structures with beneficial production and operational properties present the important step towards the modern and innovative shipbuilding industry Europe tends to become. These sorts of structures present a new approach to the shipbuilding industry demanding the high standards and low energy consumption necessary for the fabrication processes in obtaining the higher competitiveness of a shipyard.

2. INNOVATIVE MATERIALS AND THEIR UTILISATION IN SHIPBUILDING INDUSTRY

2.1. The Sandwich Concept

Practical applications of laser welded sandwich panels in shipbuilding were realised from the mid 1990's onwards. Extensive researches of steel sandwich panels have been performed by different universities and companies in US and EU. The present concept of sandwich panels represents the alternative to the classical steel structure in different technical aspects. The classical structure consists of structural elements placed relatively near to the neutral axis; therefore providing insufficient value of section modulus over the overall weight of the cross section. The sandwich concept offers an alternative to the relatively large dimensions of classical steel structure by having the large stiffness to weight ratio.

The general idea of the sandwich concept is presented in Figure 1. It is a solid body that consists of three fundamental elements:

- Upper and lower face
- Core
- Connection between core and faces

The main idea is to keep the faces away from the neutral axis, which has the strong impact on the value of moment of inertia, having the result of high section modulus over the overall mass.

The role of core is to keep the distance between the faces and to carry shear forces. There are different topologies and materials used for definition of the core element.

The connections are particularly important, as the sandwich panel cannot perform its initial function if the connection between faces and core is not good. The role of joints is to keep the co-operation between faces and core consistent.

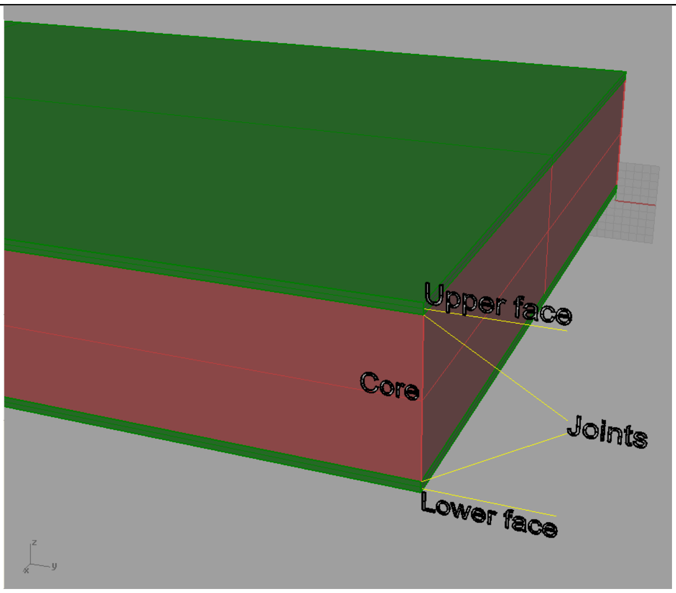


Figure 1: General sandwich concept (*DIAB Group AB, 2009*)

Usually, sandwich panels used in the industry are pre-fabricated panels, composed of two face plates separated by the core material. They are usually designed in such a way that the face plates carry the bending and in-plane loads as the face plates have relatively high stiffness and density. The core is designed to carry shear loads; it has relatively low density and stiffness. The face plates and core can be selected from various materials – metals, composites, plastics, and organic materials – but the core can also possess various topologies: a web, a honeycomb, and a cellular core. (*Romanoff 2007*). The general division of the sandwich panels according to the core topology is presented in Figure 2.

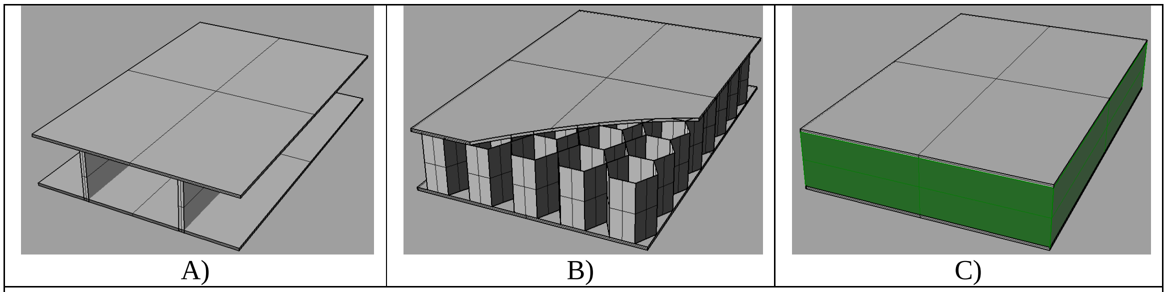

A) B) C)

Figure 2: Various core topologies: A) Web core, B) Honeycomb C) Cellular core (*Romanoff 2007*)

The honeycomb and cellular core sandwich panels are extensively used in various fields of industry, they exhibit a very good stiffness to weight ratio, but due to high price are usually not used in commercial shipbuilding.

2.2. Steel Sandwich Panels

The observed sandwich panels with the faces and the core made from the metallic materials – steel sandwich panels or all-steel panels. The steel sandwich panels consist of two steel faces, connected together with different types of steel core, keeping the distance between faces and carrying the shear forces. Prefabricated sandwich panels of standard dimensions, thicknesses and spacing are used. Internal dimensions as thickness can vary from 1 to 8 mm, web spacing are vary from 50 to 150 mm, depending on the design parameters. Standard dimensions are result of different optimisation and technological reasons. Sandwich panels in comparison with conventional orthotropic plate structures offer significant structural and production benefits, such as

- high structural strength
- improved fire safety and heat insulation
- sound insulation
- corrosion resistance
- high accuracy of assembly
- modular design and ease of assembly
- weight reduction
- fatigue resistance
- structural applicability (ducts and holes)
- explosion and ballistic penetration resistance
- space saving
- energy saving in production

Due to the fundamental nature of the sandwich panel, the core webs are longitudinally placed as periodic structures between the plates. Consequences of this geometry are different section moduli of the cross section in the longitudinal and transversal direction. Due to this kind of anisotropic nature and limited production variability of the sandwich panels, their application in the structure is therefore quite limited. They are mostly used in planar regions which are not subjected to the multi-axial loading, such as decks, ramps, walls, bulkheads etc. The application of the steel sandwich panels in various ship structures is still under development. An example of the sandwich structure application in the classical structure is presented in Figure 3.

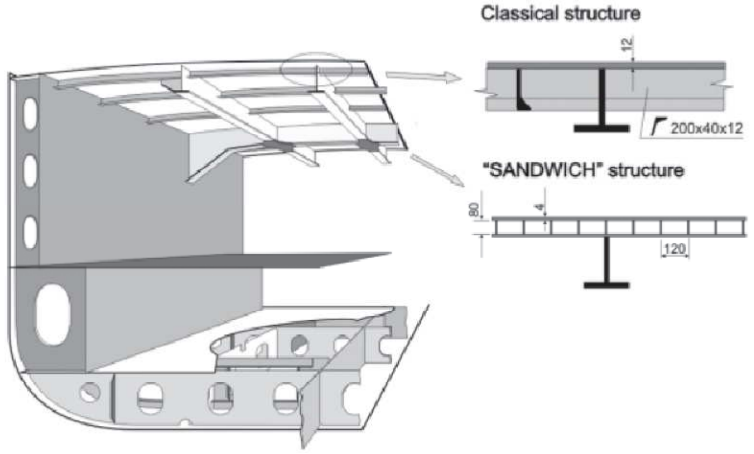


Figure 3: An example of deck structure configuration: classical and steel sandwich structure (*Kozak 2009*)

2.3. Fabrication Technology

The proposals for the sandwich components in various kinds of industries have been existed for decades, but the fabrication of such elements has been strictly limited by the technological constraints. As the fabrication technology was developing and the laser welding technology has reached the level of being affordable to commercial industrial applications, the possibilities to fabricate affordable materials for commercial use have increased. The technology for the fabrication of the steel sandwich panels has been a direct consequence of the long term industrial and technological development.

Conventional shipbuilding production techniques include large amounts of heat inserted on the ship structure, resulting in significant distortions and local material influence (especially for the thin wall structures). The amount of fairing and fitting operations is taking significant amount of shipbuilding time and cost, sometimes conflicting with already completed outfitting operations (*Roland, Manzon, Kujala, Brede and Weitzenböck 2004*). The possible alternative for the classical shipbuilding process is innovative technique of joining the prefabricated sandwich panels, as their production and assembly offer a different approach in the production and fabrication processes.

The technology of fabrication of I-core steel sandwich panels consists of welding the vertical webs on the horizontal plates forming t-joints using laser welding technology.

Laser-welded joint is formed due to heat generated by light beam acting from outside of a shell plate, forming a needle-shape joint from melted metal. Cross sectional area of such laser weld is significantly smaller than thickness of the joined stiffener. Moreover, regardless of how high quality welding process is, a gap between stiffener and adjacent plate always appears as a result of manufacturing process. (*Kozak 2009*). Particular advantages of the laser welding technology, general operational scheme and cross-section of the welds are shown in Figure 4.

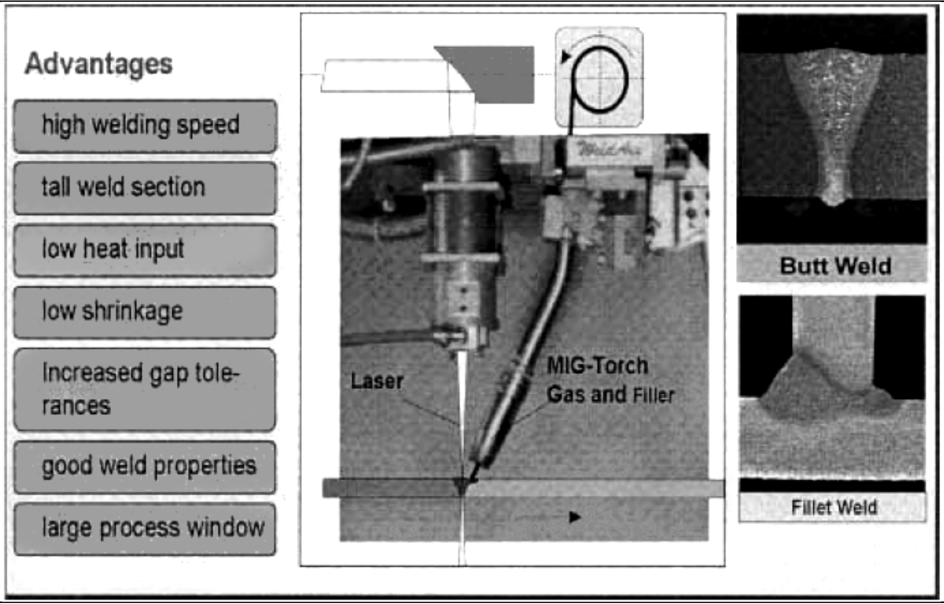


Figure 4: Laser welding process of the butt and fillet weld (*Roland, Manzon, Kujala, Brede and Weitzenböck 2004*)

The cross section of laser welded plate-web t-joint is presented on the sketch on the following figures, with the sketch of the T-joint presented in Figure 5 and actual photography of the T-joint along with the structural zones pointed.

For Meyer Werft shipyard, the I-core sandwich panel production facility procedure is briefly described:

Meyer Werft pioneered the application of laser welded sandwich panels, primarily with webs as internal stiffeners. This product is marketed under the brand name I-Core. (*Kujala, Klanac 2005*)

Two laser sources of 14kW and 12kW output power respectively are used to form the beam which is then guided by a system of water-cooled copper mirrors to the welding heads. Parabolic mirrors focus the laser beam to a spot of less than 0.5 mm in diameter on top of the work piece. The high intensity laser beam leads to a rapid vaporization of the work piece material and forms a keyhole which gives the characteristic deep and tall shape of the laser welds. Pressure rollers attached to the welding head are used to minimize the gap between the stiffeners and the covering sheet metal on top of them. (*Roland, Manzon, Kujala, Brede and Weitzenböck 2004*)

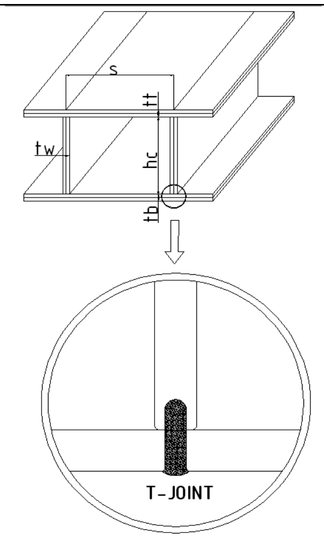


Figure 5: T-joint weld sketch (*Romanoff 2007*)

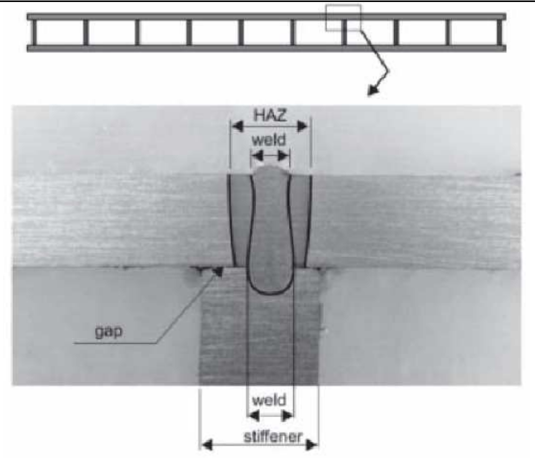


Figure 6: T-joint weld photography (*Kozak 2009*)

Compared to arc welding processes, laser beam welding offers a number of advantages for the manufacturing of metallic structures. The benefits include an appreciable decrease of heat distortions, high processing speed and a constant good weld quality. On the other hand, the required edge tolerances, high investment cost, limited experience on the long term behaviour of laser welded structures, with lack of acceptance rules and other factors still limit the applications in shipbuilding .A combination of laser with arc welding techniques in one process area, called “Laser-Hybrid-Welding”, will help to overcome the obstacles and lead to a wide range of applications in near future. (*Roland, Manzon, Kujala, Brede and Weitzenböck 2004*)

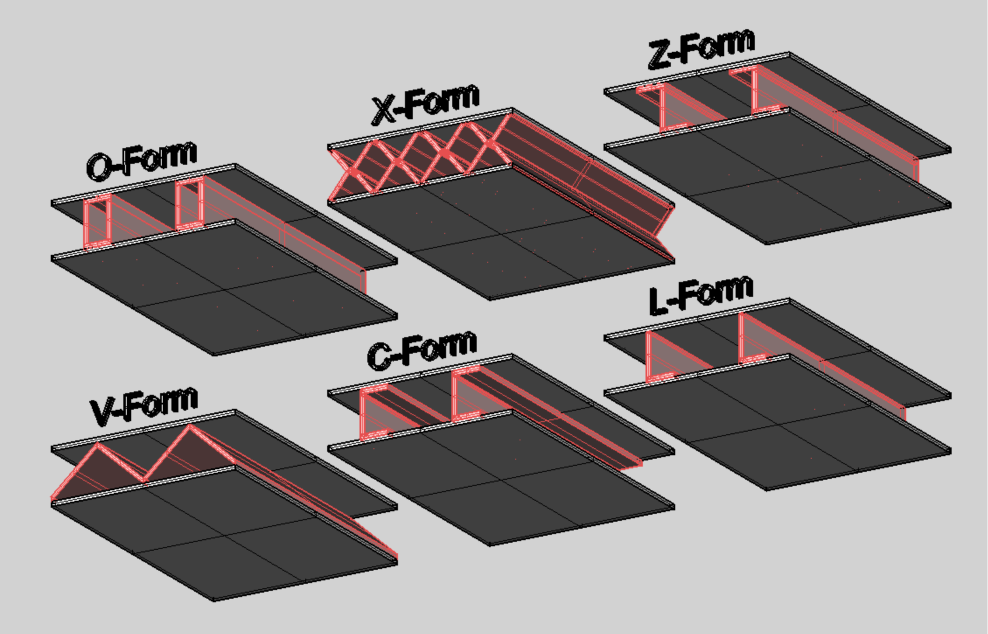


Figure 7: Steel sandwich panel general division (O, X, Z, V, C and L-Form) (*Urbański 2010*)

Different types of the core are available in the manufacturing of the steel sandwich panels, such as O, X, Z, V, C and L-form core steel sandwich panel, as shown in Figure 7. The metal material can be either regular, high tensile, stainless steel, or aluminium alloys. The choice of material depends on the designer and project variables. The standard cores such as Z-, tube- and hat profiles are easier to get and they are typically accurate enough for the demanding laser welding process. The special cores, such as corrugated core (V-type panel) and I-core, need specific equipment for production, but they usually result with the lightest panels. Naturally, during the production process or after welding of faceplates plates and core together, the steel sandwich panels can also be filled with some polymer, mineral or rock wool, concrete etc. to improve the behaviour for specific targets. (*Kujala, Klanac 2005*)

Adding the core materials for the steel sandwich panels does not significantly improve the strength properties of the structure nor has the considerable effect on the overall weight but several advantages can be obtained in additional improvement of the certain properties such as:

- Vibration damping
- Corrosion resistance (increased durability)
- Sound insulation
- Fatigue resistance
- Fire safety
- Explosion and impact resistance

2.4. Joints and Connections

The structural connections present the considerable part in the overall ship cost, according to Meyer Werft; the joining operations contribute about 50% of the total person hour consumption and building cost of a ship. (*Roland, Manzon, Kujala, Brede and Weitzenböck 2004*)

Joining the steel sandwich panels one to another, or to the surrounding steel structure presents the structural problem. This requires good design solutions to be done keeping the structural alignment and continuity.

Connections of the sandwich structure on the steel structure needs to be done respecting the good shipbuilding practise; similarly the way classical structures are fitted and assembled, with slight modifications. The example of joining the sandwich structure onto the classical structure is shown in Figure 8. The different sorts of solutions may vary depending on particular case of applications.

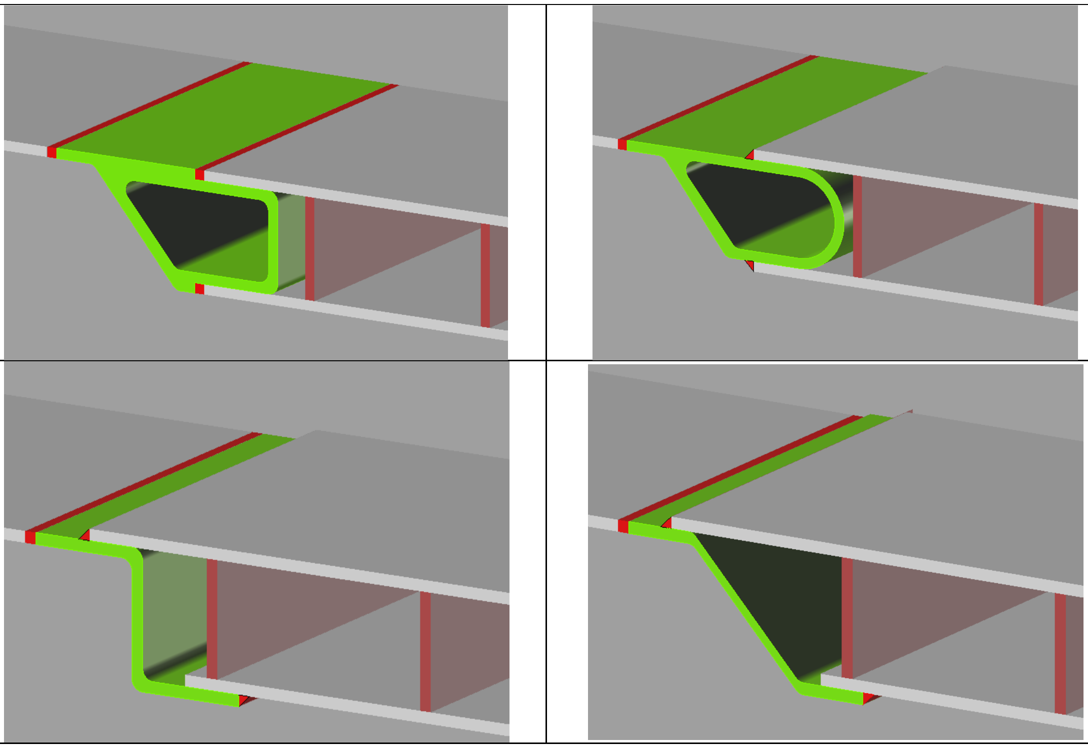


Figure 8: Different proposals for joining the sandwich panels to the classical structure (*Urbański 2010*)

There are different solutions developed for the joining the sandwich panels one to another. The connections have to maintain the continuity of the internal stiffener, but appropriate stiffness, manufacturing easiness and low post-welding distortions are also strictly required

(*Kozak 2009*). The steel sandwich panels can be connected in longitudinal and transversal direction, as schematically presented in Figure 9.

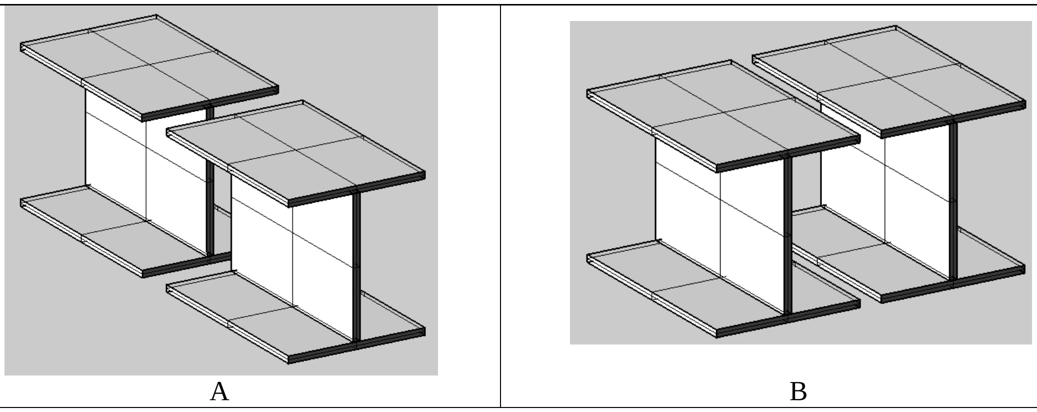


Figure 9: A) Longitudinal, B) Transversal possibility of joining I-core panels (*Kozak 2009*)

The application of different geometrical configurations of connection elements depends on the design and requires the optimisation justification. Some of joining possibilities are presented in Figure 10, done mostly by inserting the additional joining element.

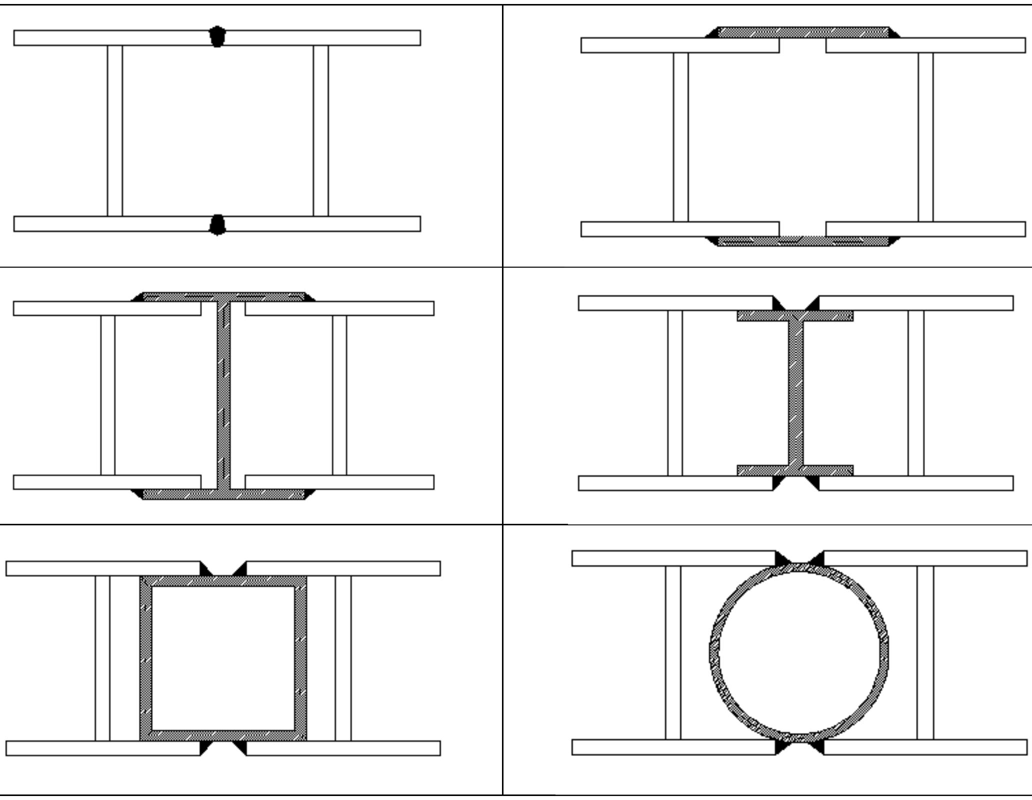


Figure 10: Different geometrical configurations of the connections (*Kozak 2009*)

Schematic presentation of the joining process of the steel sandwich panels are presented in Figure 11, with number 1 showing the prefabrication laser welds, and the number 2 shows the assembly weld made on the inserted connecting element.

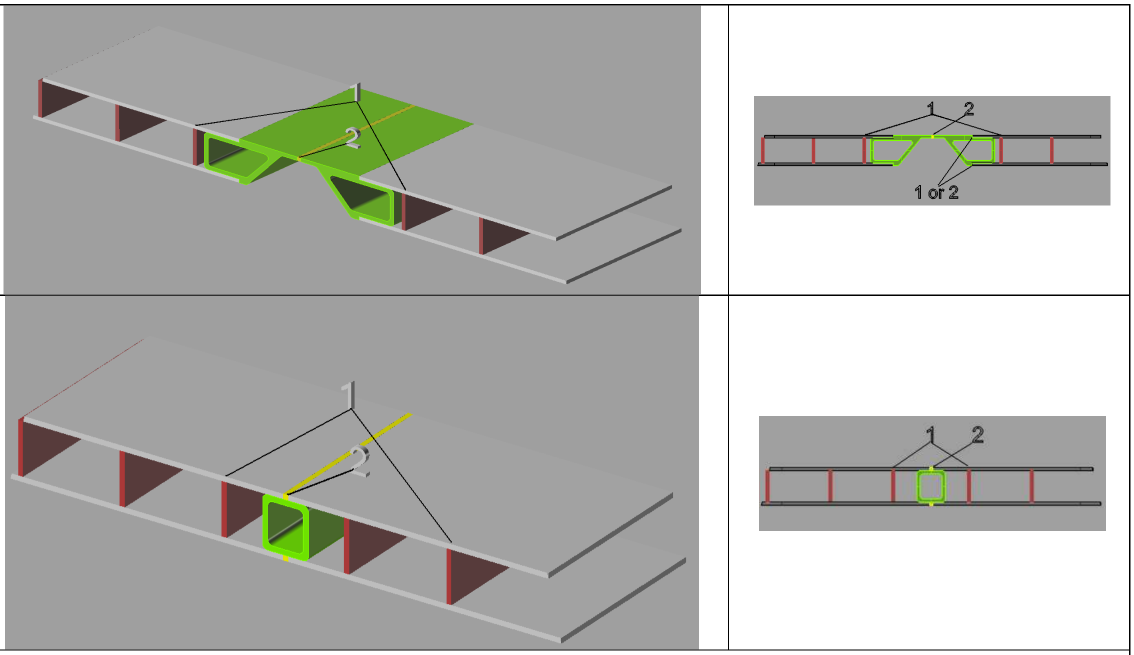


Figure 11: Joining of two I-core sandwich panels, the schematic model, whit 1-prefabrication laser welds, 2-fitting welds (*Urbański 2010*)

The joining techniques of this kind significantly reduce the amount of heat inserted on the structure in the assembly operations. The result is lower distortion of the joints, having the consequence the less labour force insertion and lowering the overall structural cost. All these factors, if done in right way, increase the overall productivity having the good influence on the shipyard efficiency. According to the researches provided by the Meyer Werft shipyard, the mentioned joints have the very good fabrication accuracy and fatigue resistance.

The new joining techniques are opening a door for the new design approach, which will be based on the tailor-made structures. This will lead to the changes in the general old-fashioned shipbuilding organisations.

2.5. Research and Other Data on the Sandwich Panels

Over the recent years, metal sandwich panels have increasing usage in various fields of industry such as offshore, marine, civil, rail and road industry. There are several research programs in Europe as SANDWICH, BONDSHIP, GROWTH, EUCLID, RTP3.21, which are aimed to investigate the possibilities of structural applications of the steel sandwich panels in the lightweight ship structures.

In Europe research related to all-metal sandwich panels has been carried out in Britain, Germany and Finland. The German shipyard, Meyer Werft, has performed theoretical and experimental investigations on the behaviour of laser-welded metal sandwich panels and their manufacturability. Studies of the design, optimisation and manufacture of all-steel sandwich panels have also been carried out at the Ship Laboratory of Helsinki Technical University. Various manufacturing techniques, such as resistance and spot welding and adhesive bonding, have been used for the production of all-metallic sandwich panels. As an alternative Meyer Werft has been developing and optimising a production technique based on laser welding. This technique offers high productivity and low heat input, which makes possible to connect thin metal sheets to form a light, strong and durable structure with minimal distortions. Sandwich panels are now used in various applications (e.g. decks and bulkheads) on board cruise ships and ferries. (*Kujala, Klanac 2005*)

2.6. Common Materials of the Lightweight Structures

The other lightweight materials used in shipbuilding industry along with general properties are briefly described as follows:

Fibre reinforced plastic (FRP) is used in both single-skin and sandwich configurations; in single-skin applications there is usually a system of stiffeners, but unstiffened monohull solutions are also to be found. FRP composites for marine applications are generally laminated composites. These consist of several layers of reinforcement fabric in a polymer resin matrix. In the case of sandwich construction there are two skin laminates with a core between that keeps the laminates in place and provides a shear connection between them. Roughly, the FRP is used for the ship up to 50 meters of length.

Aluminium alloys are commonly found in welded, stiffened plate configurations and in the form of extruded sections (both open and closed), but sandwich arrangements are also possible. Aluminium alloys for use in marine applications are normally of the 5xxx series (with magnesium as alloying element) or, for locations such as decks that are not in direct, continuous contact with sea water, the 6xxx series (with magnesium and silicon). 4 Plates are normally strain hardened (cold worked), giving an “H” temper designation. Stiffeners and deck planks are generally extruded. Aluminium is usually used for the ship up to 120 meters of length.

High strength steels although not normally considered to be lightweight materials, may also be used to reduce weight; these are to be found in stiffened plate and, recently, some sandwich configurations. High tensile steels are usually used for the structures of large ships. (*Noury, Hayman, McGeorge and Weitzenböck*)

There is increasing use of mixed solutions in which various materials are combined in one ship or superstructure, thus combining the advantages of the different materials. Current and potential applications of lightweight materials in ships are mainly related to high speed passenger and car ferries, patrol and rescue craft, smaller naval ships (e.g. mine countermeasure vessels), pleasure craft and sailing yachts. However, they are also used in superstructures of cruise ships and of larger naval ships (e.g. frigates). Furthermore they are used extensively in secondary structures and components for all types of ships, from masts and casings to moveable vehicle ramps and decks. (*Noury, Hayman, McGeorge and Weitzenböck*)

3. SCANTLINGS OF THE CORRUGATED STRUCTURE

As previously mentioned, the aim of this work is to analyse the existing structure found in the actual ship project and to offer an alternative which will be made of I-core steel sandwich panels. Different kinds of design, layout, materials and topology of the alternative structure will be offered and final verification of the project will be performed using the linear FE analysis.

Technical data of the new structure is based on the data acquired from the design office which had performed the initial calculations for a handysize bulk carrier and offered some initial information about the project. The available data acquired from the company was general arrangement, calculations of the still water bending moments and shear forces as result of the loading conditions. Due to the abortion of the project in the early phase there are no additional detailed drawings and calculations available, so preliminary scantlings and drawings of the structural members were done under the scope of this project.

The model data is provided by courtesy of Groot Ship Design, Szczecin; hereby is confirmed that the model has strictly been used for educational purposes.

The main aim of the calculations is to achieve an initial structural definition of corrugated bulkhead, as no preliminary structural details are available. Having performed the calculation of structural possibilities, it will be much more interesting to see the full comparison between all proposed corrugated structures and future sandwich panel alternatives.

3.1. General Ship Data

The data about the ship taken into consideration is a set of data acquired in the company Groot Ship Design (GSD). According to the available data, the ship is completely built using the classical structure; with double bottom and double side structure. The framing system is longitudinal, with plate floors spacing of three equivalent frame spacing. Due to the significant structure, the bilge plate floors are fitted on every frame to ensure additional stiffness on the bottom-side connection. The ship is intended for transport of the bulk cargo as grains and according to the ship owner’s demands; there are no wing and hopper tanks. The project is based on a container carrier design and has the structure different from the classical bulk carrier structure. The cranes and their presence on the structure will completely be ignored. The main dimensions of the model have is shown in the following table. GSD has provided the following data:

- General arrangement plan (GA)
- Loading conditions along with corresponding still water bending moments and shear forces

Main dimensions of the model are presented in Table 1.

Table 1: Main dimensions of the model

MAIN DIMENSIONS		
Length OA	177.00	m
Length BP	168.80	m
Beam moulded	27.00	m
Depth	15.40	m
Design draft approx.	10.75	m
Deadweight approx.	32000	ton
Gross tonnage approx.	21000	ton
Nett tonnage approx.	10820	ton

It is important to mention that the structural design has been performed respecting the IACS-Common Structural Rules for Bulk Carriers.

The dimensions and topology, along with the complete arrangement of the structural elements are given in general arrangement plan. The plan will be accepted as the main reference and orientation for design, with slight differences in layout to simplify the model. The GA can be found in the Appendix 1.

3.2. Development of the Preliminary Design Model of the Ship

Available data as GA and maximal still water bending moments were used as a basis for developing the 3D model. The global ship structure is modelled using commercial Germanischer Lloyd software Poseidon. The activities performed by Poseidon include:

- Definition of coordinate system
- Definition of plates, stiffeners and floors
- Definition of bulkheads
- Definition of cargo and ballast tanks
- Definition of void spaces
- Definition of loads
- Determination of scantlings
- Creation of FE model

The structure is completely developed following the dimensions given in GA plan, with certain modifications on the structure. The modifications are specially related to the structural details and brackets, as well as additional stiffening and adding the various elements. The objects as holes, cut-outs, passages and lightening are ignored, and will be added in further stages of the project not included in the domain of this thesis. The details of modelling the structure in the Poseidon software do not have any significant meaning, so will not be included in the content of the Thesis, but the global model will be included in Appendix 3 in order to give a better insight in the overall layout of the structure and its members.

As it is visible in Appendix 2, every bulkhead has the same or similar dimensions and it is locally loaded with similar loads. For this reason, under the scope of this project only one bulkhead will be examined as a representative of the other similar structures. It will only be examined for the static lateral cargo loads from one side, having the influence of global structural forces ignored

3.3. Rule-Based Design of the Corrugated Bulkheads

As previously mentioned, the initial transversal bulkhead of the ship has the corrugated cross section. The exact dimensions and materials concerning the transversal corrugated bulkhead are not available, so the dimensioning of such bulkhead will be performed under the scope of this work. The dimensioning of the bulkhead will be done according to the GL-Rules; each rule applied will be mentioned in order to provide the better orientation in the cases of uncertainties or revisions. The IACS-CSR BC have been respected for the general layout of the bulkhead. All the rules taken into consideration are part on I-Part 1; it will be shown by a remark if the rule was taken from another Part of the Rules. (*Germanischer Lloyd, 2011*)

According to **Sec 11 B 4.2**, the part related with corrugated bulkhead regulations, the minimal required section modulus of the cross section is to be calculated according to the **Sec 11 B 3.1B**:

$W = C_s \cdot a \cdot l^2 \cdot p \quad [cm^3]$, where definitions are given in **Section 11 B 1.3**

$C_s -$ Coefficient according to the **Table 1.11 in Section 11 B,** with $f = \frac{235}{R_{eH}}$

$a = 2.4$ m; spacing of stiffeners [m]

$l = 9.8$ m; unsupported span of the bulkhead, taken from the **Section 3 C**, which led to **Fig 23.9** in **Section 23 E**

$p = 9.81 \cdot h$ (The point one meter above the highest point of the bulkhead) or pressure of the bulk cargo according to **Section 23 E 2.3**

Transversal bulkhead has been checked to comply with the GL Rules. Since the project does not include the main dimensions and material specification, different possibilities were investigated.

Three different possibilities were taken into consideration, according to the different kinds of steel with different yield properties.

- R_{eH} = 235 N/mm²
- R_{eH} = 315 N/mm²
- R_{eH} = 355 N/mm²

The minimum thickness is given by several different formulations, keeping the highest values calculated according to the **Section 11 B 2.1**:

$t = c_p \cdot a \cdot \sqrt{p} + t_K \quad [mm]$ where definitions of constitutional members were given in the same section.

$c_p -$ Coefficient according to the **table 1.11 in Section 11 B,** with $f = \frac{235}{R_{eH}}$
$a =$ 2.4 m; spacing of stiffeners [m]

p – pressure (the point one meter above the highest point of the bulkhead) or pressure of the bulk cargo according to **Section 23 E 2.3**, whichever is higher.

$t_K =$ 0.5 mm, the addition for corrosion

Minimal required section moduli of the bulkheads together with required coefficients and thickness of the bulkhead plating are shown in the Table 2:

Table 2: Different coefficients used for further calculations

R_{eH} (N/mm^2)	**235**	**315**	**355**
f	1.00	0.75	0.66
Cs	0.36	0.27	0.24
t (mm)	10.03	7.61	6.81
W (cm^3)	5177.21	3862.36	3427.16

Respecting the calculated requirements, the different versions with different scantlings will be selected. Respecting the maximal value which is proposed by GA plan (one frame spacing 800 mm are available for spacing the corrugated bulkhead on the stool structure). The topology of the corrugated bulkhead according to the GL Rules is given in Figure 12, and the scantlings and calculated section moduli of the selected corrugated bulkheads are shown in Table 3.

$$W = t \cdot d \left(b + \frac{s}{3} \right) \quad [cm^3]$$

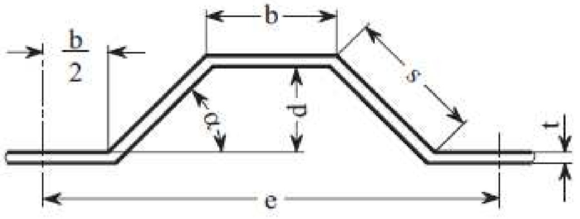


Fig. 11.2 Element of a corrugated bulkhead

Figure 12: Corrugated bulkhead – Image and nomenclature

Table 3: Structural properties and dimensions of the selected bulkheads

	ReH (N/mm^2)		
	235	315	355
Dimensions	CB2400*700*600*10	CB2400*700*600*8	CB2400*700*600*7
b (mm)	700	700	700
e (mm)	2400	2400	2400
s (mm)	781.02	781.02	781.02
t (mm)	10	8	7
d (mm)	600	600	600
W (cm^3)	5762.05	4609.64	4033.43
kg/m2	2317.80	1483.39	1135.72
Overall mass (t)	227.14	145.37	111.30

3.4. Capability Verification

In order to justify the capabilities of the proposed structures on the exerted loads, the procedure according to the rules is followed.

It is important to mention that according to the requirements the bulkhead must withstand the flooding of the whole cargo hold, so the various kinds of pressures are calculated according to the Rules.

Pressure and force for a non-flooded bulk cargo hold is calculated according to the **Section 23 E 2.3**.

The calculation of the pressure of cargo acting on corrugation:

$p_C = \rho_C \cdot g \cdot h_1 \cdot n$, (kN/m^2) where

$\rho_C = 0.7\ t/m^3$, the density of the cargo in the hold
$h_1 = 15.4 - 2.8 = 12.6\ m$, the distance between the observed point (the lowest point of the bulkhead structure) and the highest level of the cargo in the hold

$\gamma = 35°$ angle of repose of the of the cargo
$n = tan^2\left(45 - \frac{\gamma}{2}\right) = 0.73$

When all previous parameters were included, the final expression for the pressure is:
$p_C = 58.12\ (kN/m^2)$

The calculation of the force of the cargo acting on corrugation:

$F_C = \rho_C \cdot g \cdot e_1 \cdot \frac{d_1 - h_{DB} - h_{LS}}{2} \cdot n$, (kN/m^2) where
$\rho_C = 0.7\ t/m^3$, the density of the cargo in the hold
$d_1 = 14.35\ m$, the height of the highest point of the cargo hold
$h_{DB} = 1.75\ m$, the height of the double bottom
$h_{LS} = 4.55\ m$, the height of the stool
$\gamma = 35°$ angle of repose of the of the cargo
$n = tan^2\left(45 - \frac{\gamma}{2}\right) = 0.73$

When all the previous parameters were included, the force equals:
$F_C = 391.21\ kN$

The calculations of the forces and moments for the flooded case has been calculated by **Section 23 E 2.4.1**.

The calculations of the pressure due to flooding of the hold:

$p_{C,f} = \rho \cdot g \cdot h_f$, (kN/m^2) where:
$\rho = 1.025\ t/m^3$, the density of sea water
$h_f = 12.6\ m$, the vertical distance between the observed point and the highest point of flooding

When all the previous parameters were included, the final expression for the pressure due to the flooding of the cargo equals:
$p_{C,f} = 126.70\ kN/m^2$

The calculations of the force due to flooding of the hold:

$F_{C,f} = e_1 \cdot \left(\rho \cdot g \cdot \frac{(d_f - d_1)^2}{2} - \frac{\rho \cdot g \cdot (d_f - d_1)^2 + p_{Cf,le}}{2} \cdot (d_1 - h_{DB} - h_{LS})\right)\ (kN/m^2)$ where:
$\rho = 1.025\ t/m^3$, the density of sea water
$d_f = 15.4\ m$, the vertical hight of the highest point of flooding
$p_{Cf,le} = 116.14\ kN/m^2$ The pressure on the lowest point of the bulkhead

When all the parameters mentioned above were included, the final expression for the pressure due to the flooding of the cargo equals:
$F_{C,f} = 1217.19\ kN$

Resultant pressure and force are calculated according to **Section 23 E 2.5.1**. For the each point of the bulkhead the scantling pressure can be considered as:

$$p = p_{C,f} - 0.8 \cdot p_C = 126.70 - 0.8 \cdot 58.12 = 80.20\ kN/m^2$$

$$F = F_{C,f} - 0.8 \cdot F_C = 1217.19 - 0.8 \cdot 391.21 = 1111.59\ kN$$

The bending moment can now be calculated for the according to the **Section 23 E 3.1**.

$$M = \frac{F \cdot l}{8} = \frac{1111.59 \cdot 9.8}{8} = 1750.76\ kNm$$

The shear force can now be calculated according to the **Section 23 E 3.2**.

$$Q = 0.8 \cdot F = 889.27\ kN$$

After the moment and shear force were calculated, it is possible to perform the calculation of structural bending capacity of the structure **Section 23 E 4.2**.

$$\frac{M \cdot 10^3}{0.5 \cdot W_{le} \cdot \sigma_{a,le} + W_m \cdot \sigma_{a,m}} \le 0.95$$

W_{le} –Section modulus in half pitch of corrugation at the lower end of corrugation
$\sigma_{a,le}$ – Allowable stress in half pitch of corrugation at the lower end of corrugation
W_m –Section modulus in half pitch of corrugation at the mid-span of corrugation
$\sigma_{a,m}$ –Allowable stress in half pitch of corrugation at the lower end of corrugation

In Table 4, different capacity factors of the different selected designs of transverse bulkheads with selected scantlings are calculated. It is visible that calculated capacities for all the structures are smaller then the capacity factor required by the Rules. It is then possible to consider that the selected scantlings can be used for further design calculations

.

Table 4: Capacity check for bulkheads of different steels

ReH	235	315	355
$\sigma_{a,le}$, $\sigma_{a,m}$	235	315	355
Calculated section mod.	5762.05	4609.64	4033.43
Required capacity	0.95		
Calculated capacity	0.86	0.80	0.82

The figure with all structural scantlings indicated can be found in Appendix 2.

4. SANDWICH PANEL DESIGN OF THE BULKHEAD

Main idea of performing the design of the transverse bulkhead will follow the requirements set in the previous chapter. The primary property new structure needs to posses is to be adequately dimensioned to provide the structural performance correspondent to one of the classical corrugated structure. Having this requirement delivered, additional factors that increase the structural properties such as weight reduction, cost reduction, manufacturability will be investigated.

From general arrangement in Appendix 1 it can be seen that the ship has four bulkheads of very similar sizes and loads, as well as the one with smaller dimensions between cargo hold 1 and 2. The design of a bulkhead will be presented and it can be considered as the representative of all other bulkheads in the structure due to the fact that there is a high similarity between all transversal bulkhead structures.

4.1. Case Study – General Description

The introduced sandwich panels need to have the same structural performance as previously dimensioned equivalent corrugated structure. This is the primary condition present design has to fulfil; to completely ensure the structural capability to the external loads. The most probable loads acting on the structure during everyday operational conditions are cargo, ballast, and external hydrostatical loads (acting indirectly). The maximal load case is the load corresponding to the accidental limit state due to cargo hold flooding.

Several different designs will be taken under consideration, so the optimal and most convenient design can be selected.

Common global coordinate system 0xyz will be used, with *x* – coordinate in the longitudinal; *y* – transversal and *z* – coordinate in vertical direction.

The required section modulus is calculated according to the GL Rules. The calculations are carried out by calculating the required section modulus for the corrugated transverse bulkhead on different vertical point of the face of the bulkhead. Calculated moduli on the different vertical positions were then used in dimensioning of the sandwich structure.

In order to investigate different opportunities in development the applicable design, several solutions will be investigated. For instance, three initial sandwich panels will be introduced; with standard structural dimensions written below and with topology shown in Figure 13:

Dimensions of proposed sandwich panels are :($t_p - t_w - h_w$ [mm]):

- I-Core Panel 3-4-55
- I-Core Panel 4-5-55
- I-Core Panel 5-6-55
-

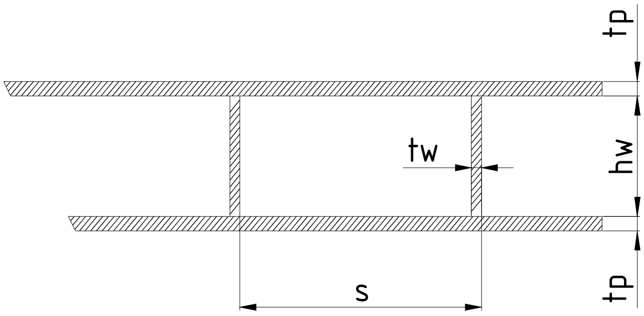


Figure 13: Sandwich panel dimensions

For each of three previously mentioned panel cases there will be an option for three different steel materials; with yield strength of 235, 315 and 355 N/mm^2.

4.2. Main Idea – the Concept

After calculations of moments of inertia it was observed that single sandwich panel is not offering sufficiently high moment of inertia to obtain requested structural performance. In order to increase the moment of inertia to the value required by the Rules, a new design solution is introduced. The solution consists of two separated sandwich panels which offer significantly higher section modulus. In order to assure the structural integrity of these structures, certain spacing elements are placed between double sandwich panel bulkhead faces. This combination is selected as a fundament for further calculations. These structures offer considerably higher section modulus then a single sandwich structure. That makes the double sandwich structure as more adequate configuration for utilisation on the bulkhead structures, as shown in Figure 14.

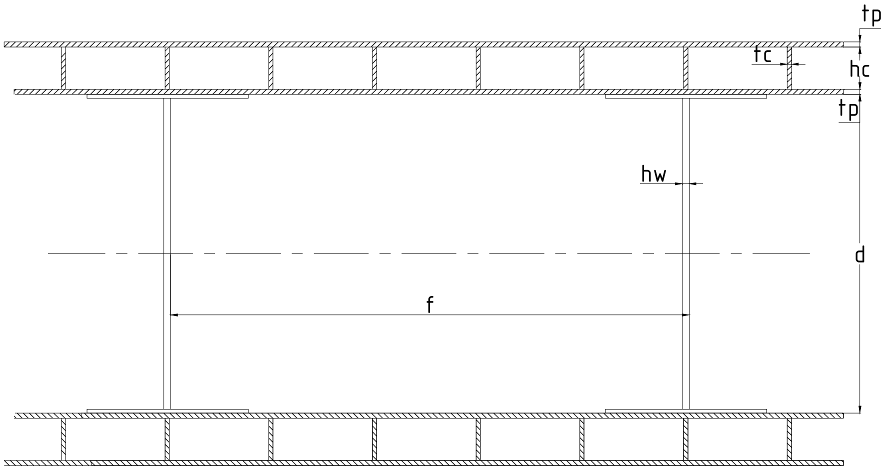


Figure 14: Double I-Core bulkhead design

Different layout options will be presented and described in the following steps of project. In order to investigate different design options, several layouts will be considered. This is performed to find the adequate and desirable design solution with different material properties taken into consideration.

The main idea is to offer and to investigate three structural candidates:

- The horizontal placement of the double sandwich panels with variable spacing
- The vertical placement of the double sandwich panels with variable spacing
- The vertical spacing of the double panels with constant spacing

Different options consist of combination of previously described properties. Weight comparisons between classical bulkheads and new proposals will be presented. The most suitable design will be selected and used for the final design and structural verification will be performed using FE analysis.

4.3. Section Modulus Calculation

The cross section of previously described double sandwich panel transversal bulkhead concept is presented in Figure 14.

As mentioned, the several candidates for bulkheads will be investigated. They consist of double I-Core Panels having the following cross sectional dimensions: 3-4-55, 4-5-55, 5-6-55 (t_p – t_w – h_w [mm]), according to Figure 13:. Different steel application will be considered as well, with yield strength R_{eH} equal 235, 315 and 355 N/mm^2. Calculated section modulus of the double panel bulkheads of different kinds, in dependence on structural variable *d* is shown in Figure 16. The observed width of the structure used for section modulus calculation of the sandwich panel is the same as the width of the corrugated structure for which the section modulus was previously calculated and it equals *s* = 2400 mm. The spacing elements are periodically placed collinearly to sandwich panel webs. Cross section of a spacing element keeps the structural integrity and the distance between the two panels and they are placed with constant longitudinal array with spacing of *f* = 600 mm. The additional plates are inserted between the spacing element and the inner surface of the double sandwich panel. This is proposed due to technological reasons, and for the weight and structure calculations it will not be taken into account.

The required sections are rule-based, and calculated according to the GL formulation as given in **Section 23 E 2.3**. The required section moduli are calculated for the two different external loads: for cargo load (blue line) and the cargo hold flooding load (red line), with different steel applications. All different requirements for different kinds of section moduli related to the height of bulkhead are given in Figure 15. The dimensioning of structure is carried out by checking the required section modulus on the lowest point of the panel – therefore having the highest possible required section modulus.

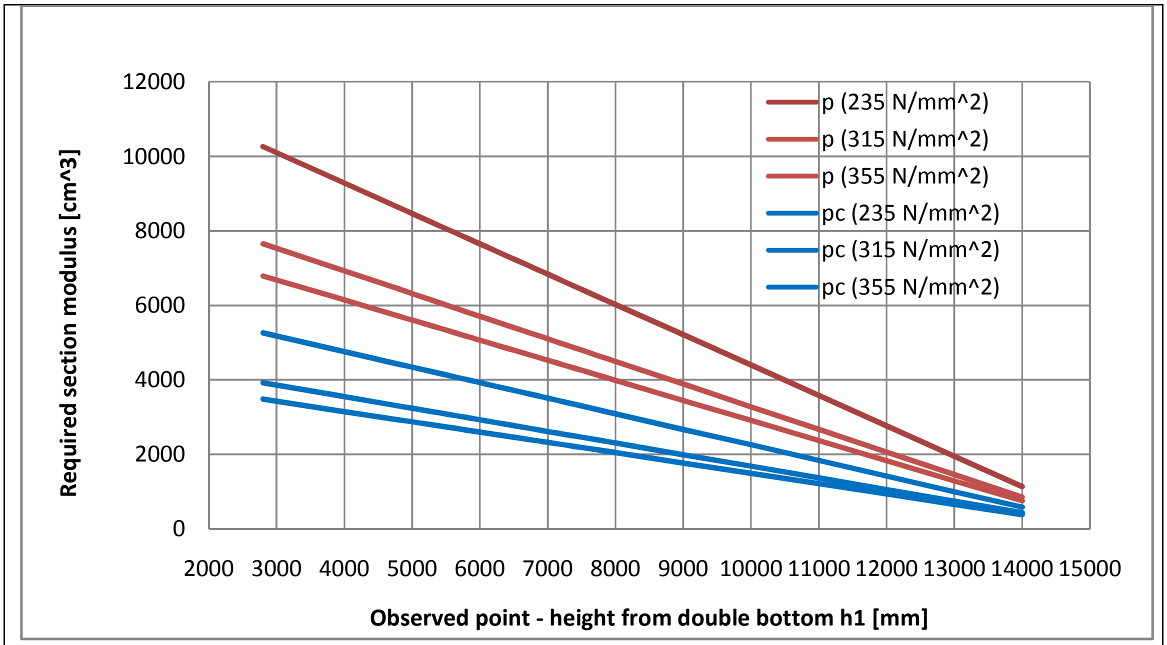


Figure 15: Required section moduli for corrugated bulkhead calculated according to **Section 23 E 2.3**

Double sandwich panel bulkheads provide the necessary section modulus by having the various spacing in between, as referred to the dimension *d* as a structural variable shown in Figure 14. The variation of section moduli of the various double bulkhead structures depends on spacing in between; the values are shown in Figure 16. The spacing is being increased from 150 to 670 mm, respecting the maximal possible bulkhead installation dimensions, constrained by available stool dimensions.

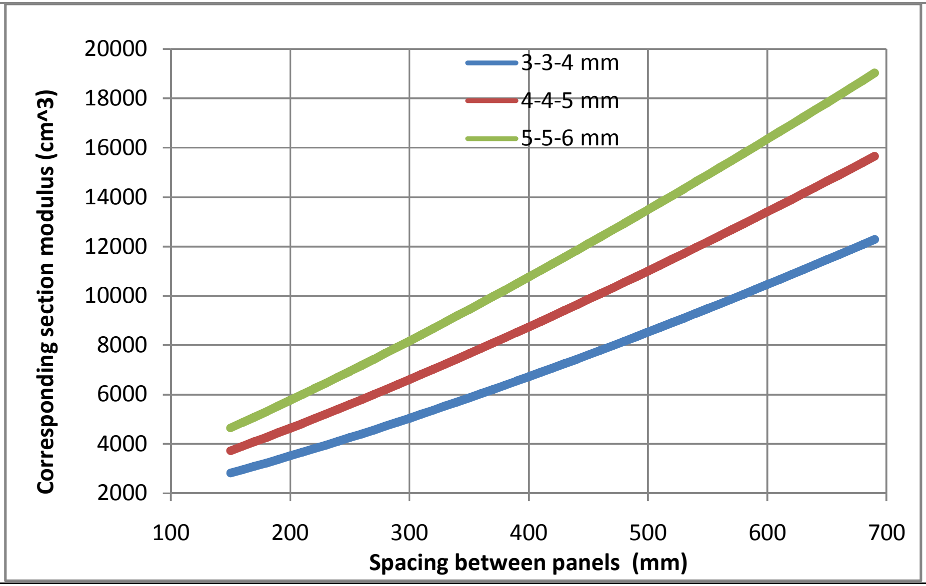


Figure 16: Section moduli of the bulkhead with different I-core panels and spacing in between

4.4. Present Structural Solutions

Transverse bulkhead needs to provide a sufficient structural resistance for external loads. These external loads are cargo loads or the flooding of the tank. In this structural case, the bulkhead is not intended to be loaded with any other loads, such as heavy loads of steel coils or iron ore. Important role which is to be fulfilled is water tightness, and the bulkhead should provide the full role.

Structural requirements described in the previous chapter will be respected in dimensioning and shaping the structure. The primary property the bulkhead needs to have is the structural capacity. When this design requirement has been fulfilled, it is then possible to consider other structural improvements such as manufacturability, weight/ cost reduction, material selection and connectivity. The continuity and structural alignment need to be respected as a common-sense of a structural design, along with a good shipbuilding practice. Different technical options will be observed and considered. On the end, all current possibilities will be compared. The most convenient design will be picked among the options, and it will finally be selected to continue the project and perform the structural analysis.

The sandwich bulkhead structure is considered to be well connected to the surrounding structure and the connection will be considered ideal. In the scope of this work the connections of the bulkhead with surrounding structure will be mentioned, but not specially considered, as this presents the problem which needs to be considered separately.

Three proposals of the structures will be observed and presented as fundamental versions, with major structural elements:

- Double layer of the steel sandwich panels
- Longitudinal and vertical spacing elements
- Joints and connections (not taken into account)

The structure consists of sandwich panels with the ribs oriented in the horizontal or transversal directions of the ship. The spacing between double panels is achieved by adding the spacing elements in between. The distance between the panels is a design variable and it is being increased to reach the sufficient section modulus. The section modulus has been calculated according to the Figure 15 on the lowest point of the panel; therefore the panel has been dimensioned according to the highest possible load according to its vertical position. The dimensions of plates are chosen in order to fit to the surrounding structure with keeping the constant dimensions wherever it is possible.

All structural details, holes, welds, joints and connections will be ignored. Calculations of fatigue and structural optimisation will not be performed in this stage of project under the scope of this work. In the scope of this work only the structural assessment of the ideal structure will be performed in the form of preliminary design. All the masses are calculated by directly adding the masses of structural elements.

4.4.1. Version 1 – Vertical Panel Placement, Variable Spacing

The sandwich panels are placed with ribs oriented in the vertical direction. These panels are further referred to as "vertical panels". The spacing elements are placed in the double panel structure, respecting the required section moduli. The bulkhead consists of quantity of panels with following dimensions as shown in Table 5. Respecting the required section moduli along the height of the structure, the different spacing between the double sandwich panels structure is applied in order to fulfil requirements by the Rules.

The vertical panels as well as corresponding dimensions and denotations can be seen in Figure 17, showing the general positioning scheme for the half of the structure.

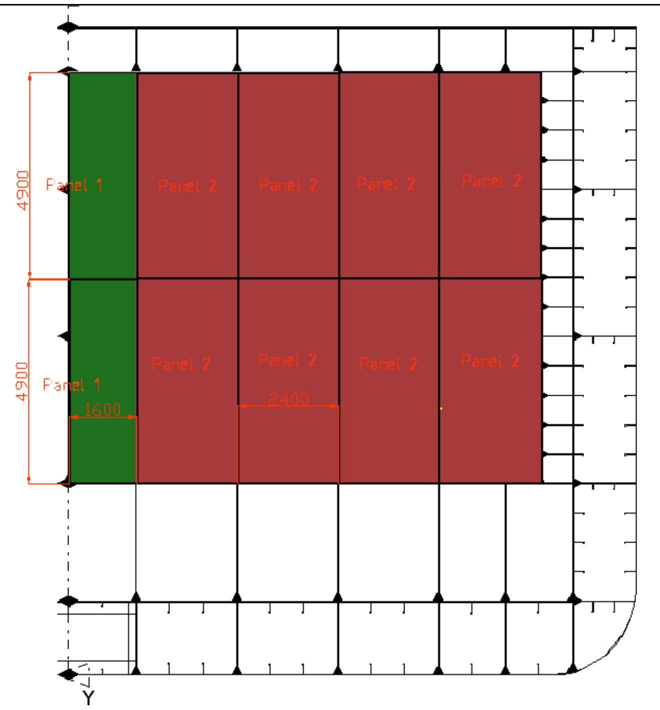


Figure 17: Vertical panel positions on the bulkhead

Table 5: Panel dimensions of the vertical bulkhead structure

Panel title	Vertical Panels		
	Quantity	Length (mm)	Width (mm)
Panel 1	4	4900	3200
Panel 2	32	4900	2400

Spacing of the vertically placed double structure elements determined according to the Rules. Complete series for various spacing for inner dimensions as well for the outer dimensions of various proposals of double structure can be seen on Table 6.

Table 6: Spacing of double bulkhead for different panel scantlings

Panel 3-4-55						
POSITION	**235 (N/mm^2)**		**315 (N/mm^2)**		**355 (N/mm^2)**	
	Inner spacing (mm)	Outer spacing (mm)	Inner spacing (mm)	Outer spacing (mm)	Inner spacing (mm)	Outer spacing (mm)
Panel 1	590	712	460	582	410	532
Panel 2	350	472	260	382	230	352
Panel 4-5-55						
POSITION	**235 (N/mm^2)**		**315 (N/mm^2)**		**355 (N/mm^2)**	
	Inner spacing (mm)	Outer spacing (mm)	Inner spacing (mm)	Outer spacing (mm)	Inner spacing (mm)	Outer spacing (mm)
Panel 1	470	596	350	476	310	436
Panel 2	260	386	190	316	160	286
Panel 5-6-55						
POSITION	**235 (N/mm^2)**		**315 (N/mm^2)**		**355 (N/mm^2)**	
	Inner spacing (mm)	Outer spacing (mm)	Inner spacing (mm)	Outer spacing (mm)	Inner spacing (mm)	Outer spacing (mm)
Panel 1	390	520	280	410	250	380
Panel 2	200	330	150	280	150	280

The combination of different materials and different panel types along with overall mass of the different cases of double sandwich bulkheads is presented in the Table 9. It shows the study of different material application in various versions of bulkhead structure. These calculated masses include the addition of all common structural elements. Welds and connections have not been included in the mass calculation, but can be added afterwards as calculated mass can be increased for certain percentage.

Table 7: Overall calculated masses for different bulkhead cases

	235 (N/mm^2)	**315 (N/mm^2)**	**355 (N/mm^2)**
PANEL	m (t)	m (t)	m (t)
Panel 3-4-55	37.69	35.44	34.49
Panel 4-5-55	44.01	41.77	40.95
Panel 5-6-55	50.83	48.91	48.52

4.4.2. Version 2 – Horizontal Panel Placement, Variable Spacing

The sandwich panels are placed with ribs oriented in the horizontal direction. These panels are placed horizontally in the double panel structure, respecting the required section moduli. The bulkhead consists of panels with dimensions as shown in Table 8. Respecting the required section moduli along the height of the structure, different spacing between the double sandwich panels structure is applied in order to fulfil requirements by the Rules. The horizontal panels as well as corresponding dimensions and denotations can be seen in Figure 18, showing the general positioning scheme for the half of the structure.

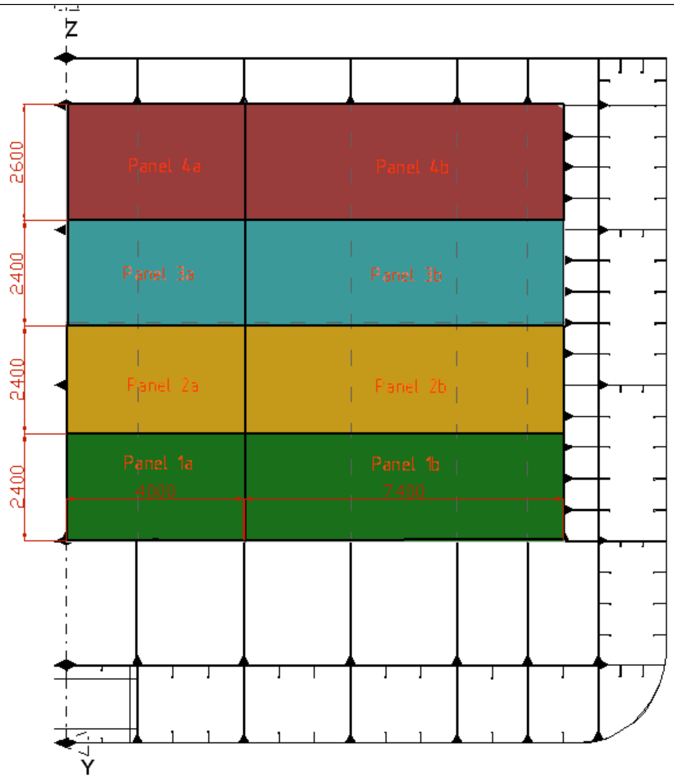


Figure 18: Horizontal panel positions on the double bulkhead

The placement of the horizontal panels along with corresponding dimensions and titles of the previously panels can be seen in Figure 18, showing the general positioning scheme for the half of the structure.

Table 8: Panel dimensions of the horizontal bulkhead structure

Panel title	Horizontal Panels		
	Quantity	Length (mm)	Width (mm)
Panel 1a	2	8000	2400
Panel 1b	4	7400	2400
Panel 2a	2	8000	2400
Panel 2b	4	7400	2400
Panel 3a	2	8000	2400
Panel 3b	4	7400	2400
Panel 4a	2	8000	2600
Panel 4b	4	7400	2600

Spacing of the horizontally placed double structure is determined according to the Rules. Complete series for various spacing for inner dimensions as well for the outer dimensions of various proposals of double structure can be seen on Table 9, Table 10 and Table 11.

Table 9: Different proposals of cases, along with structural dimensions for Panel 3-4-55

Panel 3-4-55						
POSITION	235 (N/mm^2)		315 (N/mm^2)		355 (N/mm^2)	
	Inner spacing (mm)	Outer spcng (mm)	Inner spacing (mm)	Outer spcng (mm)	Inner spacing (mm)	Outer spcng (mm)
Panel 1a	590	712	460	582	410	532
Panel 1b	590	712	460	582	410	532
Panel 2a	490	612	370	492	330	452
Panel 2b	490	612	370	492	330	452
Panel 3a	380	502	290	412	250	372
Panel 3b	380	502	290	412	250	372
Panel 4a	260	382	190	312	160	282
Panel 4b	260	382	190	312	160	282

Table 10: Different proposals of cases, along with structural dimensions for Panel 4-5-55

Panel 4-5-55						
POSITION	235 (N/mm^2)		315 (N/mm^2)		355 (N/mm^2)	
	Inner spacing (mm)	Outer spcng (mm)	Inner spacing (mm)	Outer spcng (mm)	Inner spacing (mm)	Outer spcng (mm)
Panel 1a	470	596	350	476	310	436
Panel 1b	470	596	350	476	310	436
Panel 2a	390	516	290	416	250	376
Panel 2b	390	516	290	416	250	376
Panel 3a	290	416	210	336	180	306
Panel 3b	290	416	210	336	180	306
Panel 4a	190	316	150	276	160	282
Panel 4b	190	316	150	276	160	282

Table 11: Different proposals of cases, along with structural dimensions for Panel 5-6-55

Panel 5-6-55						
POSITION	235 (N/mm^2)		315 (N/mm^2)		355 (N/mm^2)	
	Inner spacing (mm)	Outer spcng (mm)	Inner spacing (mm)	Outer spcng (mm)	Inner spacing (mm)	Outer spcng (mm)
Panel 1a	390	520	280	410	250	380
Panel 1b	390	520	280	410	250	380
Panel 2a	310	440	220	350	190	320
Panel 2b	310	440	220	350	190	320
Panel 3a	230	360	160	290	180	306
Panel 3b	230	360	160	290	180	306
Panel 4a	150	280	150	276	160	282
Panel 4b	150	280	150	276	160	282

The combination of different materials and different panel types along with overall mass of the different cases of double sandwich bulkheads has been presented in the Table 12. It shows the study of the appliance of different materials in various versions of bulkhead structure. These calculated masses include the addition of all common structural elements. Welds and connections have not been included in the mass calculation, but can be added afterwards as calculated mass can be increased for certain percentage.

Table 12: Masses of horizontal panel structure

	235 (N/mm^2)	315 (N/mm^2)	355 (N/mm^2)
PANEL	m (t)	m (t)	m (t)
Panel 3-4-55	37.34	34.96	34.03
Panel 4-5-55	43.73	41.77	38.92
Panel 5-6-55	50.82	47.00	42.45

Due to the low range of spacing of double structure for the panel 4-5-55 for 355 N/mm^2 steel and 5-6-55 for 315 and 355 N/mm^2, the structure is calculated and assembled by combining the different panels. That is the reason some values have been highlighted in different colour.

4.4.3. Version 3 – Simple Proposal, Constant Spacing

Version 3: The sandwich panels are placed with ribs orientated in vertical direction. The spacing elements are placed vertically in the double panel structure, but the spacing of the double structure remains constant along the height. This type of design tends to reduce the complexity of the structure while offering the lower price and ease of fitting and manufacturing. This kind of structure can be considered as more suitable option for fitting in the classical structure of commercial ships.

The dimensions and layout of the structure are the same as of the Version 1, with difference in constant spacing within the double structure. The layout and dimensions of structural elements can be seen in Table 5 and Figure 17. The study of spacing for the different proposals for the version 3 structure is presented in the Table 13, and Table 15.

Table 13: Constant spacing of present bulkhead for Panel 3-4-55

Panel 3-4-55						
POSITION	235 (N/mm^2)		315 (N/mm2)		355 (N/mm2)	
	Inner spacing (mm)	Outer spcng (mm)	Inner spacing (mm)	Outer spcng (mm)	Inner spacing (mm)	Outer spcng (mm)
Lower 1	590	712	460	582	410	532
Lower 2	590	712	460	582	410	532
Higher 1	590	712	460	582	410	532
Higher 2	590	712	460	582	410	532

Table 14: Constant spacing of proposed bulkhead for Panel 4-5-55

Panel 4-5-55						
POSITION	235 (N/mm^2)		315 (N/mm^2)		355 (N/mm^2)	
	Inner spacing (mm)	Outer spcng (mm)	Inner spacing (mm)	Outer spcng (mm)	Inner spacing (mm)	Outer spcng (mm)
Lower 1	470	596	410	532	350	476
Lower 2	470	596	410	532	350	476
Higher 1	470	596	410	532	350	476
Higher 2	470	596	410	532	350	476

Table 15: Constant spacing of proposed bulkhead for Panel 5-6-55

Panel 5-6-55						
POSITION	235 (N/mm^2)		315 (N/mm^2)		355 (N/mm^2)	
	Inner spacing (mm)	Outer spcng (mm)	Inner spacing (mm)	Outer spcng (mm)	Inner spacing (mm)	Outer spcng (mm)
Lower 1	310	436	390	520	280	410
Lower 2	310	436	390	520	280	410
Higher 1	310	436	390	520	280	410
Higher 2	310	436	390	520	280	410

The mass study of different proposals for the Version 3 is presented in Table 16.

Table 16: Calculated structural masses for the version 3

	235 (N/mm^2)	315 (N/mm^2)	355 (N/mm^2)
PANEL	m (t)	m (t)	m (t)
Panel 3-4-55	40.42	37.45	36.30
Panel 4-5-55	46.12	43.37	43.37
Panel 5-6-55	52.73	50.22	49.53

4.5. Overall Comparison

After calculation of different structural options, with various steel types and panel types included, the overall comparison with the classical corrugated steel structure can be presented. The combination of all achieved results is shown of the Table 17, and there will be presented the weight reduction of the sandwich structure in comparison with correspondent classical structure.

The comparison and weight reduction between different classical, corrugated structures and various sandwich structures is shown in Table 17.

Table 17: Final comparison of the different cases of sandwich structure design with classical corrugated bulkhead

	Dimensions	Weight (t)
Corrugated bulkhead CB1	CB2400*700*600*10	227.14
Corrugated bulkhead CB2	CB2400*700*600*8	145.37
Corrugated bulkhead CB3	CV2400*700*600*7	111.30

Table 18: Final comparison of the corrugated bulkhead for 235 N/mm^2

		for 235 N/mm^2				
		Weight (t)	(cm^3/t)	Reduction for CB1 (%)	Reduction for CB2 (%)	Reduction for CB3 (%)
Panel 3-4-55	Vertical	37.69	212.74	83.41	74.07	33.45
	Horizontal	37.34	196.23	83.56	74.32	33.23
	Simple	40.42	253.73	82.20	72.19	35.14
Panel 4-5-55	Vertical	44.01	182.19	80.62	69.73	37.35
	Horizontal	43.73	167.54	80.75	69.92	37.18
	Simple	46.12	222.39	79.70	68.27	38.66
Panel 5-6-55	Vertical	50.83	157.76	77.62	65.04	41.57
	Horizontal	50.82	144.16	77.63	65.04	41.56
	Simple	52.73	194.50	76.78	63.72	42.75

Table 19: Final comparison of the corrugated bulkhead for 315 N/mm^2

		for 315 N/mm^2				
		Weight (t)	(cm^3/t)	Reduction for CB1 (%)	Reduction for CB2 (%)	Reduction for CB3 (%)
Panel 3-4-55	Vertical	35.44	168.84	84.40	75.62	68.16
	Horizontal	34.96	156.38	84.61	75.95	68.59
	Simple	37.45	204.35	83.51	74.24	66.36
Panel 4-5-55	Vertical	41.77	143.26	81.61	71.27	62.48
	Horizontal	41.77	130.89	81.61	71.27	62.47
	Simple	43.37	176.43	80.91	70.16	61.03
Panel 5-6-55	Vertical	48.91	122.33	78.47	66.36	56.06
	Horizontal	47.00	116.32	79.31	67.67	57.77
	Simple	50.22	152.39	77.89	65.46	54.88

Table 20: Final comparison of the corrugated bulkhead with panels of 355 N/mm^2

		for 355 N/mm^2				
		Weight (t)	(cm^3/t)	Reduction for CB1 (%)	Reduction for CB2 (%)	Reduction for CB3 (%)
Panel 3-4-55	Vertical	34.49	154.01	84.81	76.27	69.01
	Horizontal	34.03	142.65	69.42	76.59	69.42
	Simple	36.30	187.09	67.38	75.03	67.38
Panel 4-5-55	Vertical	40.95	129.72	63.21	71.83	63.21
	Horizontal	38.92	124.73	65.03	73.23	65.03
	Simple	40.95	165.85	63.21	71.83	63.21
Panel 5-6-55	Vertical	48.52	109.48	56.40	66.62	56.40
	Horizontal	42.45	114.37	61.86	70.80	61.86
	Simple	49.53	137.13	55.50	65.93	55.50

4.6. Selection of the Design

The comparison of different acquired calculated values in one place gives the possibility to have the wide figure about the effects of the different materials and panels on the mass of overall structure. Selection of the optimal design includes the consideration of a number of benefits and drawbacks of the different structural options. In general, different options have different properties and it is on the designer to select the most favourable design. In this decision-making domain, the final result is a compromise between different properties; with beneficial or dismissing nature. The installation and material costs were not included in the calculation, due to limited amount of time available for development of the project. In commercial shipbuilding, especially for ships of lower structural complexity, the main objective is to achieve the lowest price. The other objective is to reduce weight in order to make possible to carry higher amounts of cargo, without threatening the safety of the structure. Additional optimisation of the project can be carried out using various optimisation algorithms, as in this work none of optimisation of this kind will be performed.

In order to select the most viable design, the main variable used for the selection process is reduction of structural mass and production price. The latter is considered to be done by reducing manufacturing complexity. It has the effect on reducing the amount of inserted labour. The design consists of standard elements as much as it is possible in order to reduce the structural complexity and overall cost.

Having in mind previously explained criteria, chosen design is double bulkhead with constant inner spacing of 390 *mm* (Version 3) 5-6-55 for 315 N/mm^2. This type of bulkhead will be used for all further calculations and analysis.

After the investigation of different possibilities it was observed that there are significant weight reductions among the proposed sandwich structures!

In the academical nature of the project; the following objectives were taken under consideration in comparison between classical and sandwich structures which was a compromise:

- Weight and cost reduction (keeping structural capacity)
- Structural complexity reduction
- Reduction of labour
- Increased use of standard members, better material utilisation

5. STRUCTURAL ANALYSIS

Having performed the investigation of different structural possibilities and considering the main design properties of each proposed design; the favourable design for continuation of project is selected. The next step is to analyse the selected design by performing the set of direct analyses, which are to justify the performance of the structure to the prescribed loads.

The thin wall structure of the sandwich panel, as it was described previously, consists of a number of structural elements which provide various beneficial properties. The behaviour of sandwich panel structure is usually analysed using the 3D FE method. The linear finite element analysis will finally verify the behaviour and results of the structural response of the static lateral load to obtain acceptably accurate results, substantially fine discretisation of the sandwich panels needs to be performed. Due to the geometry of panels, discretisation has to be performed using a large number of small elements, having the result in large amounts of degrees of freedom. This increases CPU time and reduces calculation efficiency.

5.1. Panel Homogenisation

The reduction of degrees of freedom and reduction of processing time, without major affect on the quality of results is one of the major problems in structural analysis. In order to achieve more efficient level of structural calculations, various simplifications of the original sandwich structure have been introduced by numerous authors.

In this case, simplification is done by transforming the original 3D sandwich panel model into the 2D homogeneous orthotropic thick plate continua, considerably reducing the degrees of freedom of the observed structure. The simplification formulation used in this work is developed by.

The truss-core unit can be transformed into an equivalent thick plate which is continuous, homogeneous and orthotropic with respect to the mutually perpendicular *x*- , *y*- and *z*-directions. The plate is symmetrical about its middle surface since the thickness of the two facing plates is identical.

5.1.1. Libove and Bartdorf Small Deflection Theory

The general small-deflection theory developed by Libove and Batdorf was adopted to describe the flexural behaviour of an orthotropic plate are (*Lok, Cheng and Heng 1999*):

$$\frac{\partial^2 w}{\partial x^2} = -\frac{M_x}{D_x} + \frac{\nu_y M_y}{D_y} + \frac{1}{D_{Qx}}\frac{\partial Q_x}{\partial x} \tag{1a}$$

$$\frac{\partial^2 w}{\partial y^2} = \frac{\nu_x M_x}{D_x} - \frac{M_y}{D_y} + \frac{1}{D_{Qy}}\frac{\partial Q_y}{\partial y} \tag{1b}$$

$$\frac{\partial^2 w}{\partial x \partial y} = \frac{M_{xy}}{D_{xy}} + \frac{1}{2}\frac{1}{D_{Qx}}\frac{\partial Q_x}{\partial x} + \frac{1}{2}\frac{1}{D_{Qy}}\frac{\partial Q_y}{\partial y} \tag{1c}$$

$$\gamma_x = \frac{Q_x}{D_{Qx}}, \qquad \gamma_y = \frac{Q_y}{D_{Qy}} \tag{1d}$$

Where Q_x and Q_y are internal transverse (shear) forces, M_x and M_y are internal bending moments and M_{xy} is the internal twisting moment.

$\frac{\partial^2 w}{\partial x^2}$, $\frac{\partial^2 w}{\partial y^2}$ and $\frac{\partial^2 w}{\partial x \partial y}$ are curvatures and twist about the middle plane, γ_x and γ_y are the shear strains (*Lok and Cheng 2000*).

Figure 19 shows forces and moments on an element of thick plate. Since the sandwich panel is symmetrical around its middle-plane, no middle-plane forces exist provided only by bending behaviour of the plate is considered.

In the derivation of stiffness parameters, the following assumptions are adopted:

- The deformation of the panel is small
- The core is sufficiently stiff such that the elastic modulus of the equivalent plate in the z-direction is infinite. Local buckling of the facing plates does not occur and the overall thickness of the panel is constant
- During distortion of the plate, straight lines normal to the middle-plane of the undeformed plate remain straight after deformation, but not necessarily normal to the middle-plane. This is due to the transverse strains, which can be significant for the sandwich panel because of the relatively flexible core.
- The facing plates are thin in comparison with the thickness of the core. This implies that the local bending stiffness of the facing plates is ignored.

5.1.2. Bending Stiffnesses and Poisson's Ratios

Figure 19 shows a truss-core sandwich unit made of an isotropic materialin which *E*, *G* and γ are elastic modulus, shear modulus and Poisson's ratios respectively. The unit is subjected to bending moments M_x and M_y.

Under the action of the moments alone, vertical lines in the cross-section between the points in the middle surfaces of the upper-facing plate and the lower-facing plate remain perpendicular to the middle-plane, and unchanged in length during distortion of the unit. In the middle surfaces of the facing plates, strains are developed in the *x*- and *y*- directions. In the other horizontal surfaces, the strains may be obtained by linear integration between the upper and the lower-facing middle surfaces. The curvatures are (*Lok, Cheng and Heng 1999*):

$$\frac{\partial^2 w}{\partial x^2} = \frac{\varepsilon_{x2} - \varepsilon_{x1}}{d}, \qquad \frac{\partial^2 w}{\partial y^2} = \frac{\varepsilon_{y2} - \varepsilon_{y1}}{d} \tag{2}$$

The moment M_y is resisted only by the extensional stiffness of the facing plates. Thus, the stresses σ_{y1} and σ_{y2}, in the *y*-direction in the middle surfaces of the lower- and upper-facing plates are (*Lok, Cheng and Heng 1999*):

$$\sigma_{y1} = \frac{M_y}{td}, \qquad \sigma_{y2} = -\frac{M_y}{td} \tag{3}$$

Both the bending stiffness of the core and the exstentional stiffness of the facing plates resist the moment M_x. Therefore (*Lok, Cheng and Heng 1999*):

$$M_x = \sigma_{x1}\frac{td}{2} - \sigma_{x2}\frac{td}{2} - EI_c\frac{\partial^2 w}{\partial x^2} \tag{4}$$

Where σ_{x1} and σ_{x2} are stresses in the *x*-direction in the middle surfaces of the lower- and upper-facing plates respectively. I_c is the moment of inertia per unit of width of the cross-section in *yz*-plane about the neutral axis, I_f is moment of inertia per unit of width of the faces of the sandwich panel and they equal (*Lok, Cheng and Heng 1999*):

$$I_c = \frac{st_c d_c^2}{12p}, \quad I_f = \frac{td^2}{2} \tag{5}$$

The strains in the x- and y-directions (ε_{x1} and ε_{x2}, ε_{y1} and ε_{y2}) in the middle surfaces of the lower- and upper-facing are determined from the plane-stress relation (*Lok, Cheng and Heng 1999*):

$$\varepsilon_{x1} = \frac{1}{E}\left(\sigma_{x1} - \nu\sigma_{y1}\right), \qquad \varepsilon_{x2} = \frac{1}{E}\left(\sigma_{x2} - \nu\sigma_{y2}\right), \tag{6a}$$

$$\varepsilon_{y1} = \frac{1}{E}\left(\sigma_{y1} - \nu\sigma_{x1}\right), \qquad \varepsilon_{y2} = \frac{1}{E}\left(\sigma_{y2} - \nu\sigma_{x2}\right), \tag{6b}$$

From Eqs (1) to (6), the curvature and moment relationship of the unit panel can be shown as (*Lok*, *Cheng and Heng 1999*):

$$\frac{\partial^2 w}{\partial x^2} = -\frac{M_x}{E(I_c + I_f)} + \frac{\nu M_y}{E(I_c + I_f)} \tag{7a}$$

$$\frac{\partial^2 w}{\partial y^2} = -\frac{\nu M_x}{E(I_c + I_f)} + \frac{1 - \frac{\nu^2 I_c}{I_c + I_f}}{E(I_c + I_f)} M_y \tag{7b}$$

Comparing Eqs (7) and (1) equivalent flexural stiffness and Poisson's ratios of the sandwich panel may be obtained respectively as (*Lok*, *Cheng and Heng 1999*):

$$D_x = E\left(I_c + I_f\right), \qquad D_y = \frac{E I_f}{1 - \frac{\nu^2 I_c}{I_c + I_f}} \tag{8}$$

Poisson's ratio can be obtained as:

$$\nu_x = \nu, \qquad \nu_y = \nu \frac{D_x}{D_y} \tag{9}$$

5.1.3. *Other Elastic Constants*

Seven elastic constants represent the properties of the thick plate. Formulations for various types of stiffeners may be derived by comparing the behaviour of a truss-core sandwich unit with the behaviour of a truss-core sandwich unit with the behaviour of the orthotropic thick plate. D_x and D_y represent bending stiffness, ν_x and ν_y are the bending Poisson ratios, D_{xy} is the twisting stiffness, and D_{Qx} and D_{Qy} are the transverse shear stiffness (see Figure 19). For a conventional orthotropic plate of thickness *h*, the stiffness is given as (*Lok and Cheng 2000*). These elastic constants will be presented in final version derived in *Lok, Cheng and Heng 1999*.

$$D_{xy} = GI_f \tag{10}$$

$$D_{Qx} = Gt_c \frac{\frac{d^2 t_f}{plt_c} + \frac{1}{6}(\frac{d_c}{p})^2}{\frac{t_f}{t_c} + \frac{ld_c}{3pd}}, \qquad D_{Qy} = Gt_c \frac{1}{\frac{(\delta_y^C + \delta_y^F)}{d} + \frac{\delta_z^C}{p}} \tag{11}$$

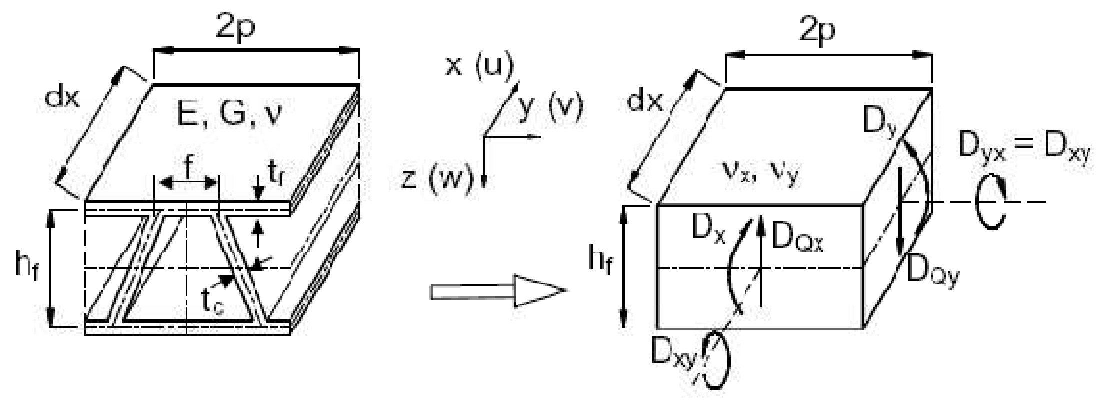


Figure 19: Transformation of the truss core unit into a homogeneous orthotropic thick plate continuum (*Lok and Cheng 2000*).

5.1.4. Execution of the Homogenisation Process

Equivalent elastic constants for the truss-core panel were derived by *Lok and Cheng 2000* and *Lok, Cheng and Heng 1999*. To express these elastic constants, sandwich panel unit shown in Figure 20 will be considered. The unit is symmetrical with respect to a vertical plane. The upper and lower facing plates have the same thickness (t_f) while the core's thickness (t_c) may differ from the facing plates. Independent geometric dimensions are described by *p*, *d*, t_f and t_c. Three dimensions, *f*, *l* and h are dependent on each other. Three other dimensions, d_c, b_c and f_0 are obtained from geometric properties. Material properties are elastic modulus *E*, shear modulus *G* and the Poisson ratio ν (*Lok and Cheng 2000*). The constants were calculated and applied to the properties of the orthotropic plate.

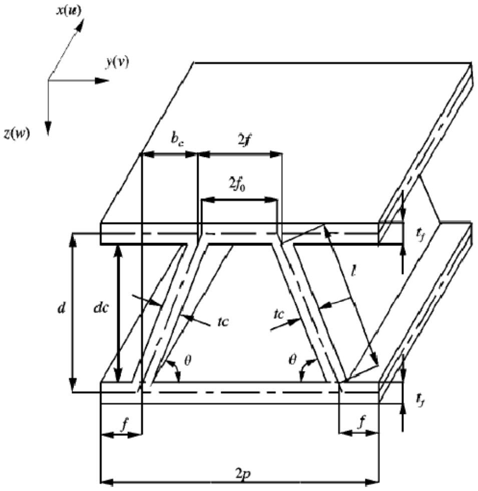


Figure 20: Dimensions of truss-core sandwich panel unit (*Lok and Cheng 2000*)

5.2. Verification of the Homogenisation

In order to justify the application of described formulation on the current sandwich structure and to examine the accuracy of the homogenisation process, some additional investigations will be done. The analysis of structural behaviour of the obtained analogous orthotropic plate will be performed by simple comparison between actual sandwich and analogous thick plate. Using the formulation proposed by the authors, the elastic properties of the orthotropic panel are calculated, and then the properties applied on the analogous plate.

5.2.1. Displacements of a Panel

Behaviour of the homogenised plate will be investigated on the same imposed loads as on the original sandwich panel. The dimensions of an examined plate are taken, having the length l=7400 mm, width b=2400 mm, and thickness of t=61 mm. The model of sandwich panel was meshed with 50×50 mm, having ~400,000 elements. Two different versions with different boundary conditions will be investigated.

In Figure 21 the comparison for case 1 is shown – the case with shorter edges of the panels clamped (perpendicular to the rib orientation), in Figure 22 the comparison for case 2 is shown – the case with longer edges of the panels clamped (parallel to the rib orientation).

The results of corresponding response analysis of the simple panels are presented on the following figures. The displacements are purposely exaggerated to emphasise the form and magnitude of displacement as result of the same applied loads.

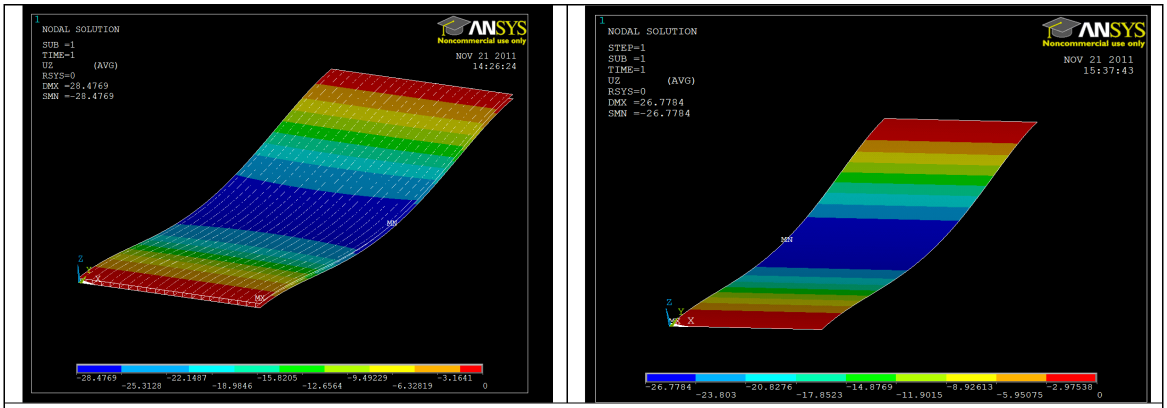


Figure 21: The comparison of structural response – Case 1

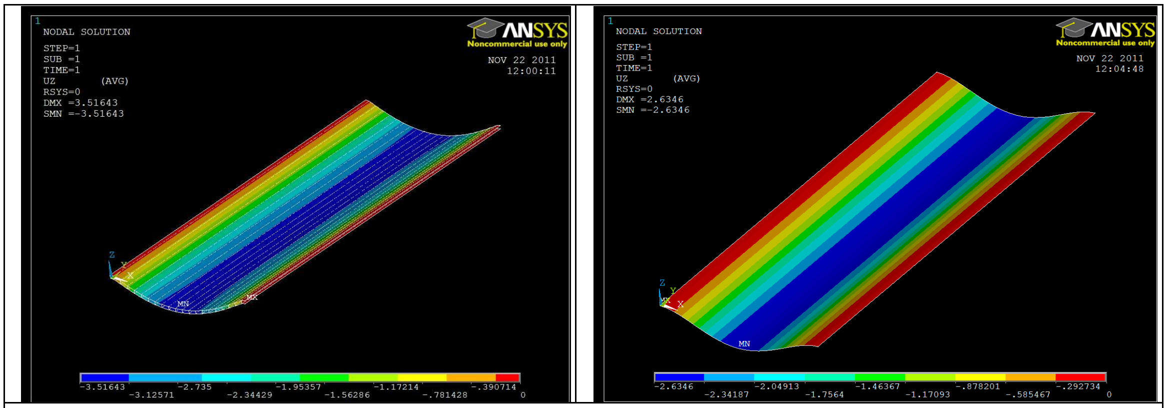


Figure 22: The comparison of structural response – Case 2

The displacements are observed in the middle of the plate, where the point of maximal displacement is located. The obtained displacements show high similarity for the case 1, and satisfactory similarity in case 2, as it is shown in Figure 32. These results have justified the homogenisation process, and proposed theory will be used in simplification of the panels in structural analysis of the sandwich structure.

Table 21: Comparison of different deformations for different cases

Output results	Total Deformations (mm)		Difference (%)
	Sandwich panel	Orthotropic plate	
Case 1	28.4761	26.7784	5.96
Case 2	3.51643	2.6246	25.36

In this case, for applied boundary conditions and loads, the homogenised orthotropic plate is exhibiting acceptable performance by means of vertical displacements. Obtained values are acceptable, and the overall shape of orthotropic plate shows good resemblance to the shape of original panel.

5.2.2. *Stress Distribution and Correction Factors*

In order to investigate stress distribution in the orthotropic plate, further calculations were carried out. The homogenization model described in Chapter 5.1.2 is suitable for representing stiffness of the actual I-core panel using the orthotropic properties. Following *Lok and Cheng 2000* formulation, obtained results were satisfactory from the displacement point of view, as it can be seen in Figure 22 and Table 21. However, the results in terms of stresses are not satisfactory. The results were smaller in order of magnitude and thus inacceptable. Due to this reason, several additional calculation procedures need to be done in order to justify the utilisation of proposed formulation on global structural scale. A procedure to evaluate the stress transfer coefficients has been therefore derived based on observation that the distribution of the stress components follow the same scheme over the area of the actual and orthotropic panels. This, unfortunately, does not apply to the combined stresses which must be calculated using rescaled components of the stress. In this case, combined loads will be calculated manually and presented in different manner than normal and shear stresses.

Investigation of stress distribution will be done on panels used in actual structure. In order to obtain suitable results in terms of stress which may perform a good resemblance between I-core panel and orthotropic plate stress distribution, two different structural elements will be taken under consideration. As seen previously, global double bulkhead structure consists of two types of sandwich panels with two types of outer dimensions: Panel 1 (2600x4900) and Panel 2 (3200x4900). Thickness of equivalent plate is the same as the outer scantlings of the sandwich panel cross-section and equals t = 65 mm. Both panel types will be taken under consideration, investigated and homogenised to obtain more acceptable results from the global analysis,

Observed sandwich panel is uniformly loaded with static 5 kPa loads. All relevant stresses in both sandwich panels are obtained for this magnitude of distributed load. The panel was clamped on all edges to have the more realistic stress layout as obtained in global structure.

Using *Lok and Cheng 2000* formulation, homogenisation process of the panels was performed and results were obtained. Applying the same uniform load for the original panels and equivalent plates, the results for nodal stresses in equivalent plate showed poor resemblance to the stresses obtained for corresponding sandwich panel. For this reason, uniform load for the equivalent plate was increased in order to obtain acceptable stress values in edges and mid-plate.

The original loads from sandwich panels were then multiplied with a correction factor *k* to increase the applied load on equivalent plate. This increasement of applied loads will lead to increasing of stresses to the values obtained for the sandwich panel. This approach is justified for the reason that the results are obtained in linear domain.

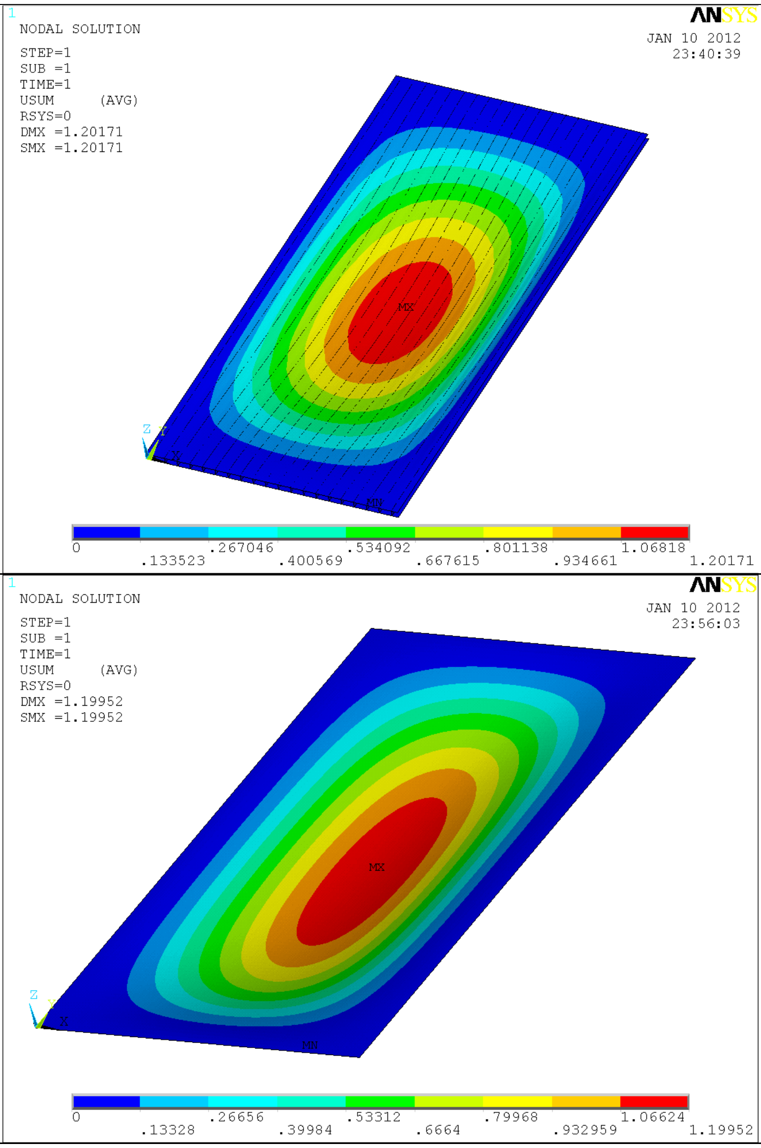
$$k = \frac{Increased\ load\ (equivalent\ plate)}{Original\ load\ (sandwich\ panel)} = \frac{load}{0.005} \tag{12}$$

The correction factors and obtained stresses for equivalent plates for both panel types will be shown in the following figures. The results will be shown in local coordinate system; with longitudinal direction in *y*- axis and transversal direction in *x*-axis.

50 mm mesh was used for all analysis, yielding ~400,000 elements for sandwich plate model, and ~100,000 elements for equivalent plate. Obviously, plate homogenisation applied to the FE model reduces the number of nodes, and therefore the computational time.

Panel 1 (2400x4900)

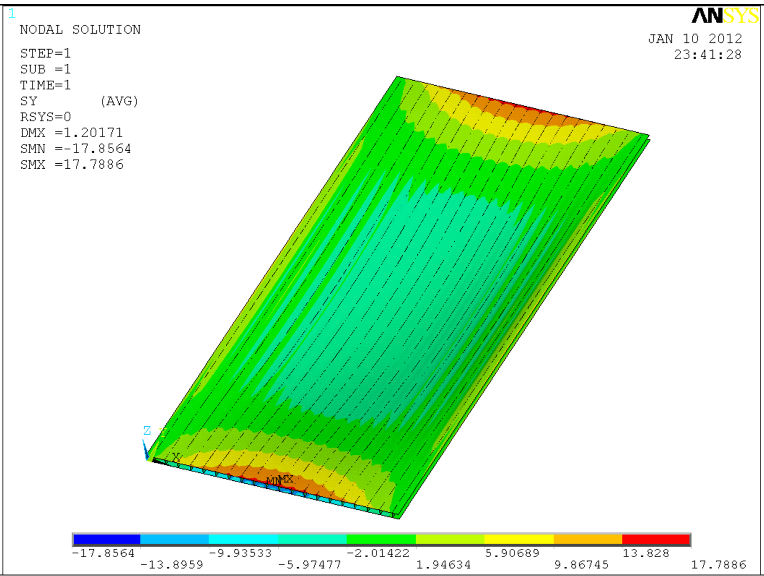
Nodal total displacement sum for both sandwich panel and equivalent plate is shown on is shown in Figure 23:

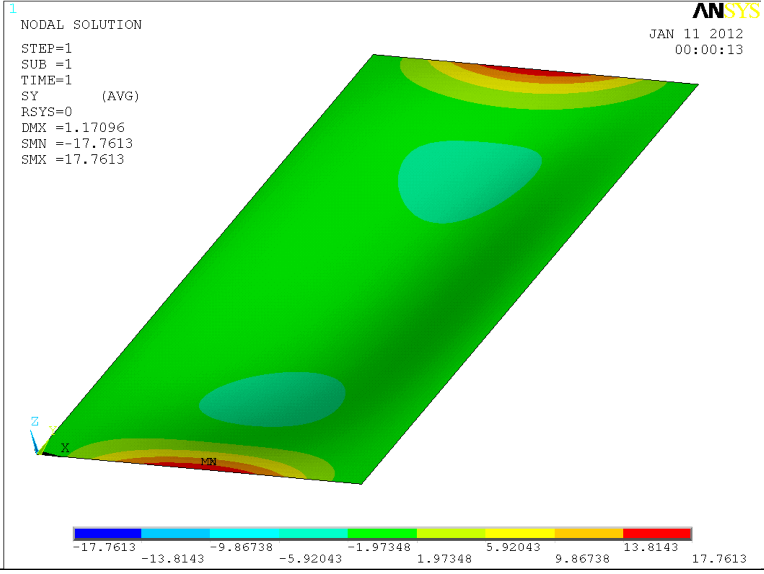


k=8.4

Figure 23: Total nodal displacement for panel 2400x4900

Longitudinal stress distribution for both sandwich panel and equivalent plate is shown on is presented in Figure 24

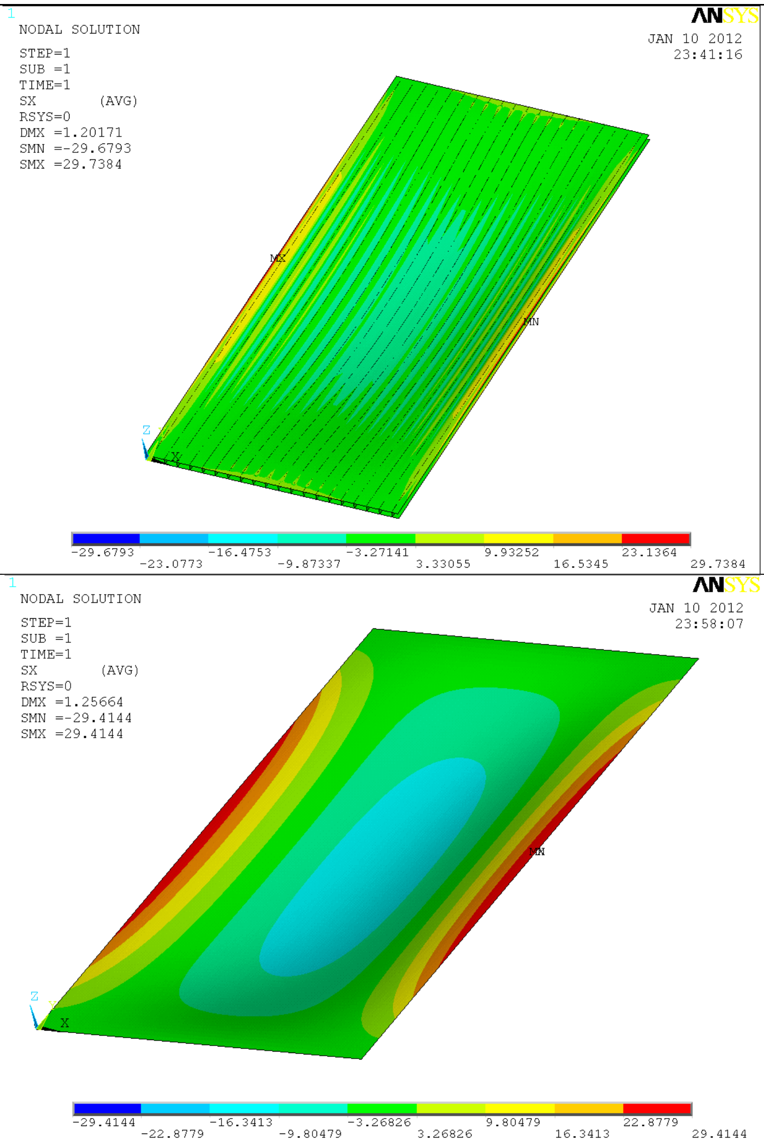




k=8.2

Figure 24: Longitudinal stress distribution for panel 2400x4900

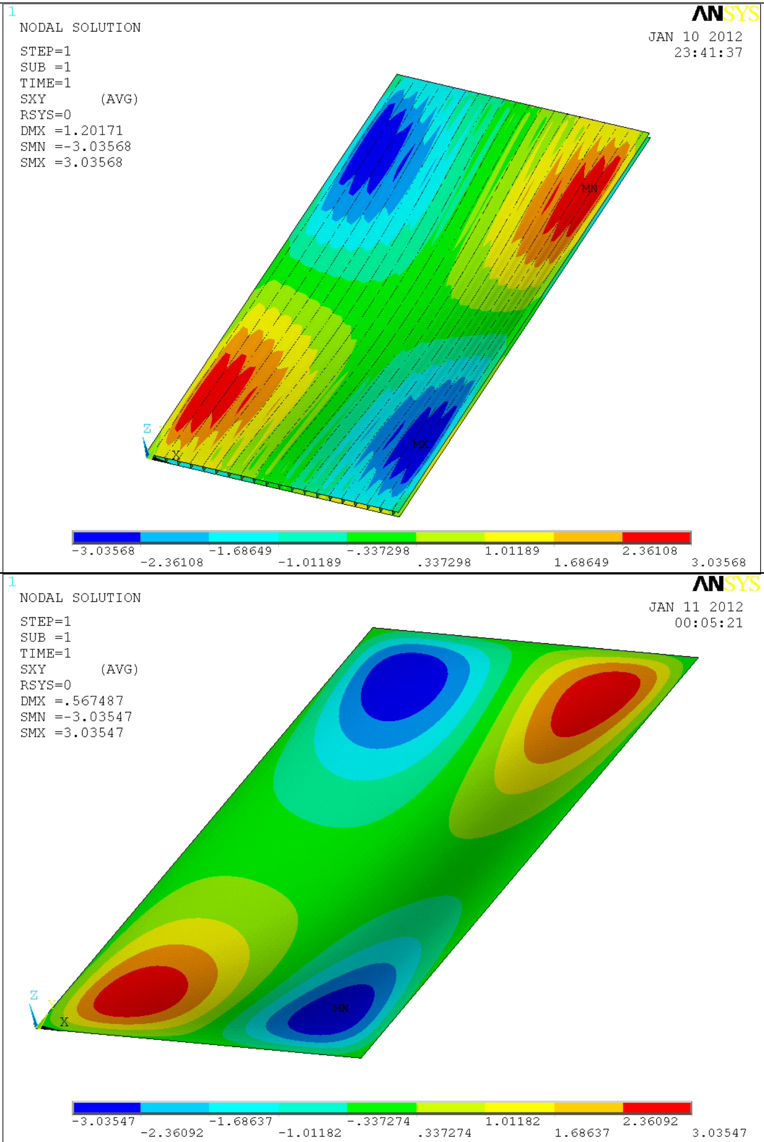
Transversal stress distribution for both sandwich panel and equivalent plate is shown in Figure 25.



k=8.8

Figure 25: Transversal stress distribution for panel 2400x4900

Shear stress distribution for both sandwich panel and equivalent plate is shown in Figure 26.

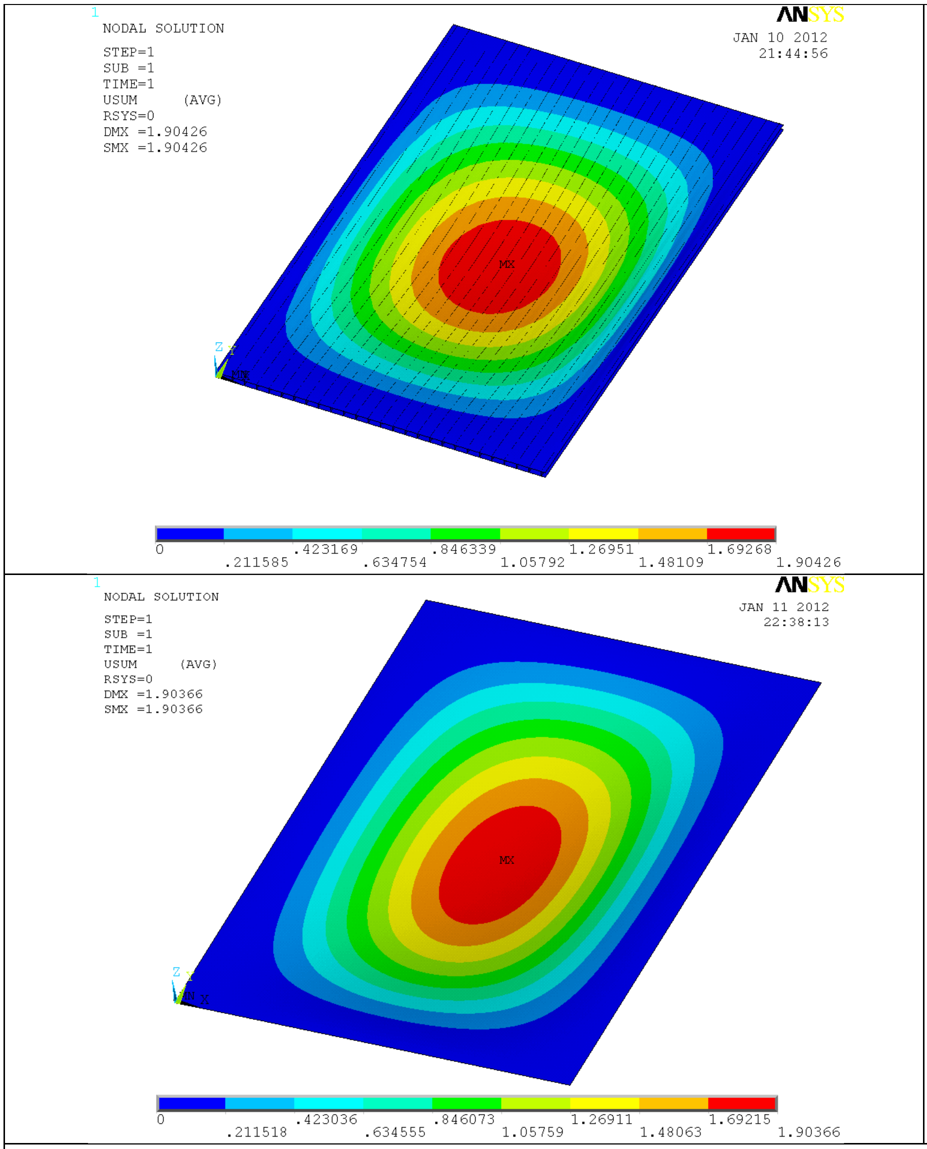


k=3.8

Figure 26: Shear stress distribution for panel 2400x4900

Panel 2 (3200x4900)

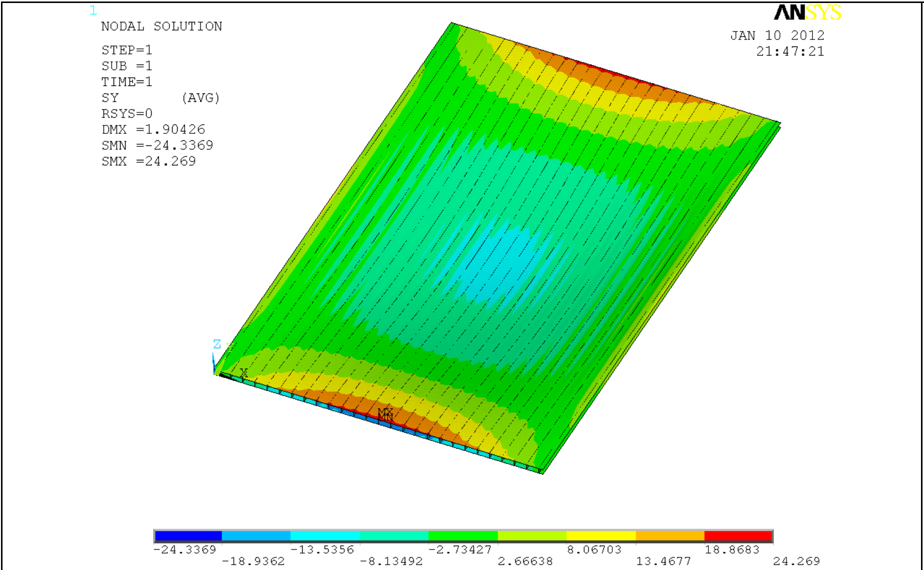
Nodal total displacement sum for both sandwich panel and equivalent plate is shown on is shown in Figure 27

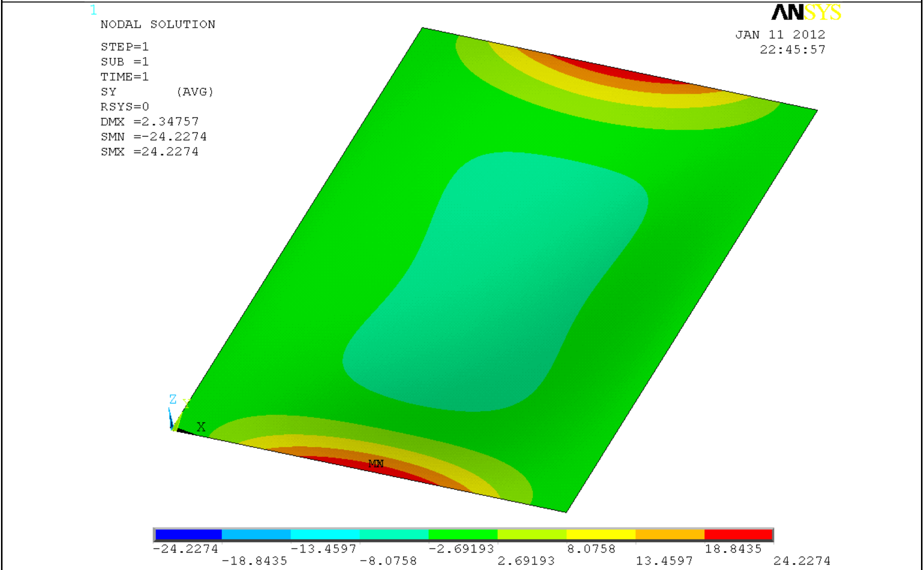


k=4.46

Figure 27: Total nodal displacement for panel 3200x4900

Longitudinal stress distribution for both sandwich panel and equivalent plate is shown on is presented in Figure 28.

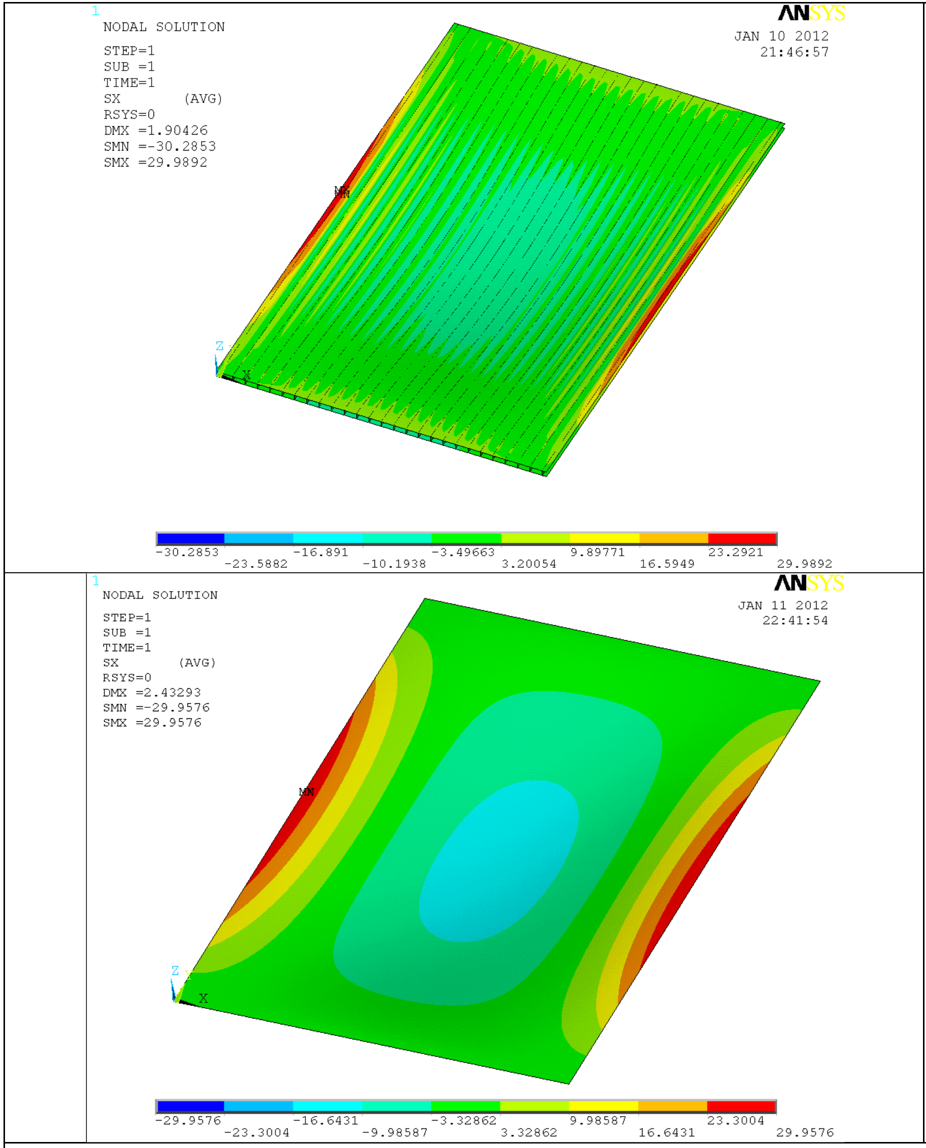




k=5.7

Figure 28: Longitudinal stress distribution for panel 3200x4900

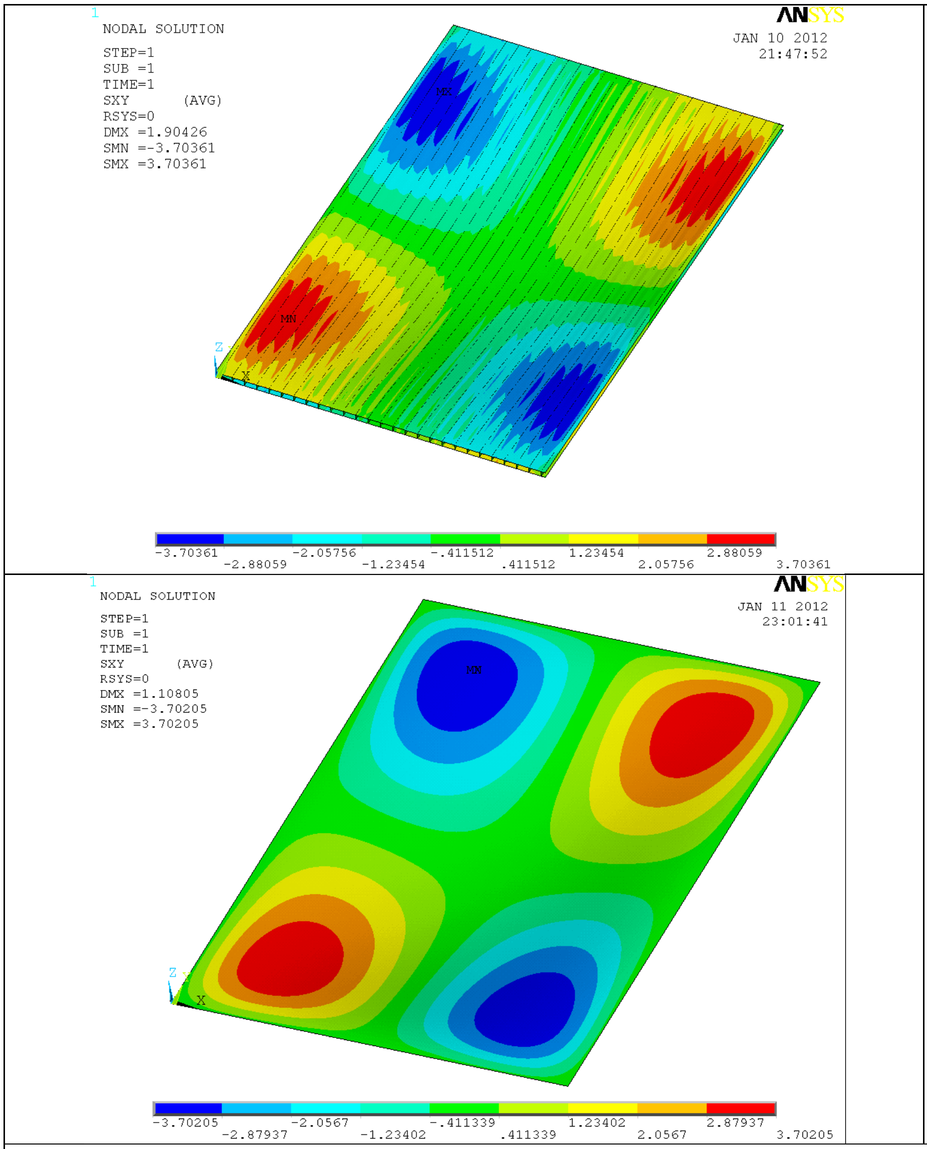
Transversal Stress distribution for both sandwich panel and equivalent plate is shown on is presented in Figure 29.



k=5.5

Figure 29: Transversal stress distribution for panel 3200x4900

Shear Stress distribution for both sandwich panel and equivalent plate is shown on is presented in Figure 30.



k=2.6

Figure 30: Shear stress distribution for panel 3200x4900

Series of applied loads and obtained correction factors are acquired for both panels and the values are presented in Table 22.

Table 22: Loads and correction factors for the equivalent plates

	Panel 2 (3200x4900)		**Panel 1 (2400x4900)**	
	Corrected Load (MPa)	Correction factor	Corrected Load (MPa)	Correction factor
Total displacement	0.0223	4.46	0.042	8.4
σ_x (trans. stress)	0.0285	5.70	0.044	8.8
σ_y (long. stress)	0.0275	5.50	0.041	8.2
σ_{xy} (shear stress)	0.01298	2.60	0.019	3.8

As seen from previously shown tables and figures, the overall results for the equivalent plate clamped by all edges show the acceptable similarity in behaviour to the corresponding original sandwich panel. This can be noticed both in terms of values of stresses and in stress distribution resemblance.

Correction factors are different for both Panel 1 and 2, what possibly can found the reason in different aspect ratios of two panels. The factors for normal stresses are of similar values for each panel case, unlike the factors for shear stresses. Due to this fact, output equivalent stresses for equivalent panels have unacceptable values. This requires additional focus on this problem which will be solved by calculating equivalent stresses manually.

5.3. Building of Structural Model of Double Sandwich Panel Bulkhead

Utilisation of equivalent panels and their behaviour on applied loads in form of stress distribution and nodal displacements was investigated and justified in the previous chapter. The panels will then be used in verification of global bulkhead structure and further structural investigations. These investigations will be done by direct approach, offering straightforward asses of structural behaviour and capacity of the overall structure, including the values of correction factors for different panel types and stresses.

The structure is modelled in Poseidon software, with boundary conditions and corresponding loads applied. In real-life operation, a majority of operational time a bulkhead will, the most probably, be loaded only by cargo and/or surrounding structural loads, such as loads from ballast tanks or hydrostatic loads exerted on the shell structure. There is also a possibility of cargo loads from both sides of the structure, having only tertiary stresses involved.

The output plots of obtained results will be given for every observed case. On the bottom of each figure, coloured scale is placed. Colour scale represents the obtained values presented in corresponding colour range. Calculated values are then represented according to the colour scale. The following results will be given for all observed cases calculation:

The model built in GL-Poseidon is then transferred to ANSYS, where material properties of homogenised orthotropic plate were performed. FE analysis is carried by building the structural model from shells and beams. For plate elements, the SHELL63 shell elements are used while for beam elements BEAM44 elements are used. These two types of elements are used in analysis, if not differently stated.
The stresses for the global structure will be shown in global coordinate system with longitudinal axis in *x*-direction, transversal axis in *y*-direction and vertical axis in *z*-direction.

5.4. The Sandwich Bulkhead Model Examined as an Isolated Problem

Basic structural behaviour of the double panel bulkhead structure will be examined as the first step of the overall structural analysis. Initially, the double bulkhead will initially be examined as an isolated problem, completely separated from the influence of surrounding structure. For this reason all edges of the structure are clamped, having the constraints for all degrees of freedom. 3D model of structure is shown on Figure 31.

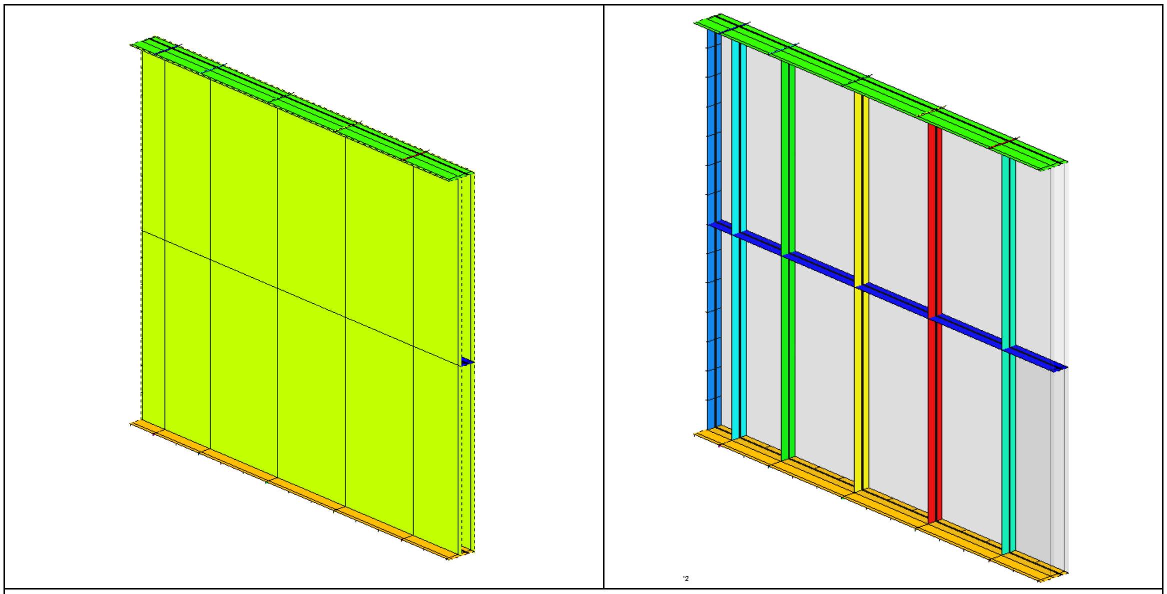


Figure 31: 3D model of observed bulkhead structure

On the lowest edge the bulkhead lays on the stool. The connection of the stool with double sandwich bulkhead is considered as ideal and the connection edge between the stool and double bulkhead is clamped.

On the lowest edge the bulkhead lays on the stool. The connection of the stool with double sandwich bulkhead is considered as ideal and the connection edge between the stool and double bulkhead is clamped. Upper side of the bulkhead is connection with upper stool. The connection between double bulkhead and upper stool is considered clamped as well.

Due to the fact that the structure is symmetrical, only a half of the structure will be taken under the consideration. This will also reduce the number of elements, increasing the effectiveness and decreasing the duration of calculations. The middle of bulkhead lays on the centreline, having the conditions of symmetry implied. Translation along y axis and rotation around z axis are therefore disabled.

The connections between the sandwich panels are considered ideal, therefore the influence of the connections on the stress layout can to be considered in broader scope of this project.

The structural behaviour of isolated double sandwich bulkhead structure is checked for the simple lateral cargo load, imposed from one cargo hold of the ship in upright position. This load is considered as static, with origins from the cargo density linearly distributed along the surface of the bulkhead in vertical position. All dynamical components have been ignored.

The geometry design, load application and meshing operations are all carried out using the GL-Poseidon pre-processing tool. The model consists of double sandwich bulkhead structure described with analogous panels and inner supporting and spacing elements. It consists of 144000 elements, with dimensions of elements of 100 mm. The deformations and stresses in complete structure are obtained from the final calculations carried out in ANSYS.

The undeformed FE model of isolated structure analysis is shown in Figure 32:

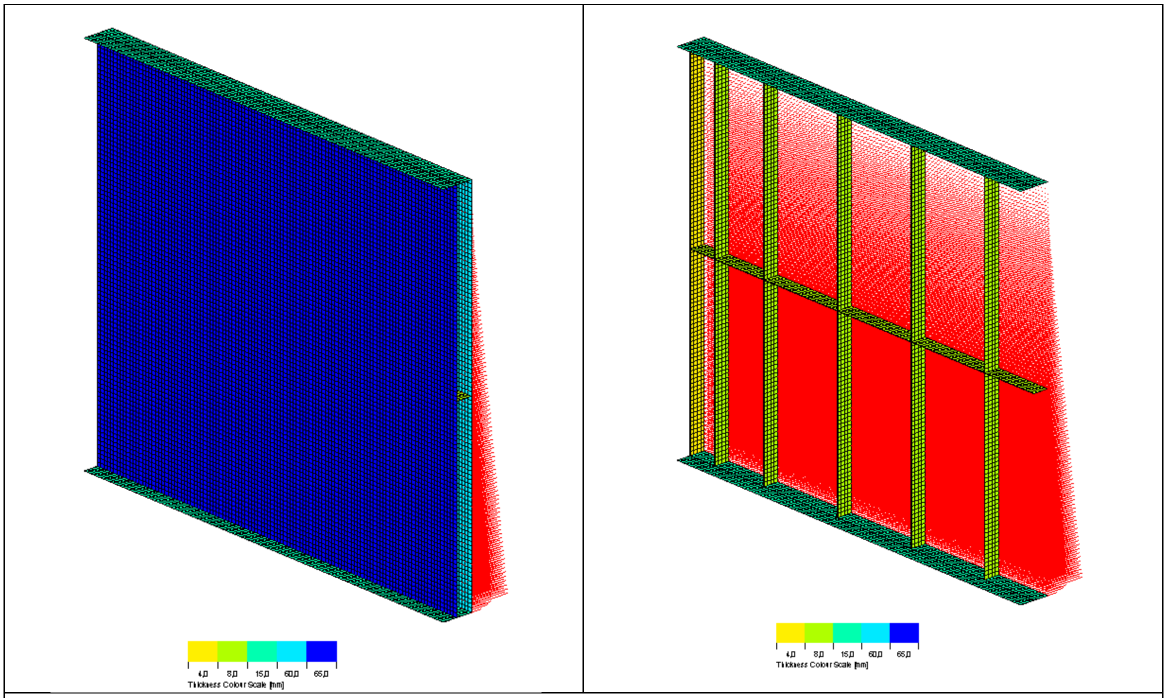


Figure 32: FE model of the isolated double bottom Left: Plate structure Right: Internal structure

After the FE model is generated along with boundary conditions and loads, it is then transferred to ANSYS, where the further analysis is carried out. The displacements were exaggerated for visualisation purposes.

Output results obtained for equivalent plate in analysis were multiplied with corresponding correction factor, depending on the observed position on the structure. One example of such stress transformation will be presented.

Since all structural members of the double sandwich bulkhead structure are made of same steel type, maximal permitted values of stresses are:

Table 23: Permissible stresses according to the Rules

ReH (N/mm^2)	k	GL Permissible stresses (N/mm^2)		
		Normal stress	Shear stress	Von Mises
315	0.75	201.06	134.04	307.13

5.4.1. *Stress Analysis of Equivalent Plates*

As explained previously, in order to reduce the number of elements and enable the more efficient calculations, the sandwich panel structure was substituted with equivalent homogenised plates.

In Figure 33, the scheme of the bulkhead skin structure is shown with a path marked on the position h = 7.05 m. On this line the results will be observed and their value will be plotted.

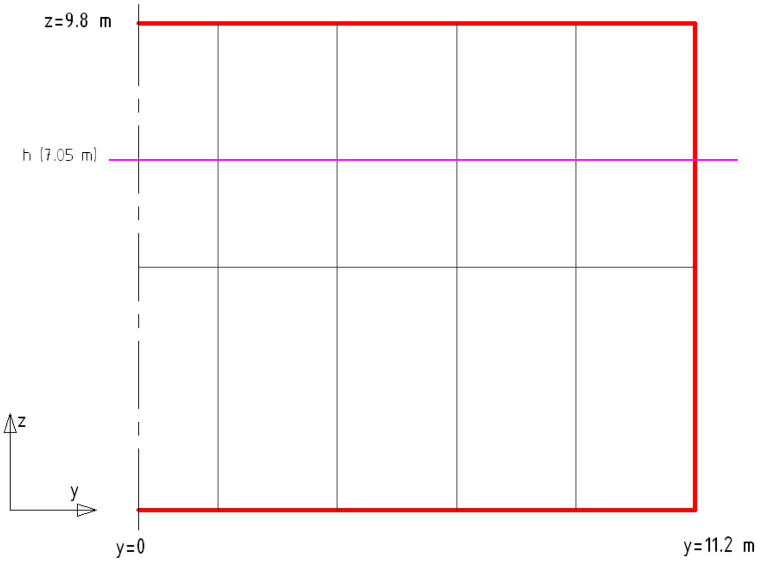


Figure 33: Observed cross-section

For selected path the distribution of transversal normal stresses σ_y is selected from the output results, and values will be plotted. Output results for selected cross-section are shown in Figure 34.

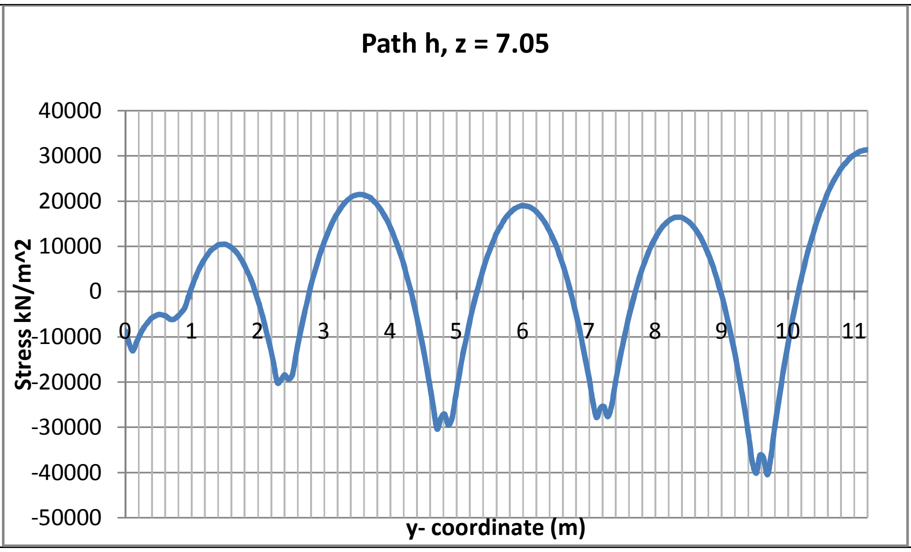


Figure 34: Output results for σ_y

Output results are obtain from the analysis of the structure consisting of homogenised plates, and it is previously shown that in order to obtain more realistic results, the stresses need to be multiplied with corresponding correction factors shown in Table 22. The output results are then multiplied with correction factor, and the obtained values are shown in Figure 35.

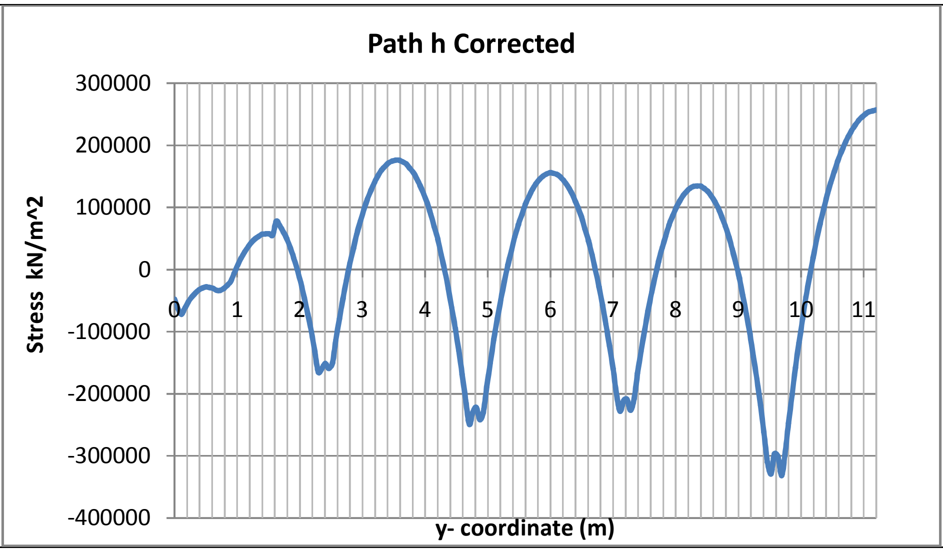


Figure 35: Corrected output results for σ_y

Following this technique, more realistic values of all stresses in homogenised orthotropic plate can be obtained. To obtain the equivalent von Mises stress criteria, this technique will be repeated on several different points. The structure is divided in 8 horizontal cross-sections on the lower and upper bulkhead edge and vertical positions of 0.5, 1.7, 3.2, 5.0, 6.8 and 8.4

m. Each section consists of 20 equally distributed points, forming the grid of distributed points across the surface of the structure. The positions of points at the horizontal cross-sections from which the values of stresses σ_y , σ_z and σ_{yz} are acquired for calculation of von Mises equivalent stresses will be presented in Figure 36.

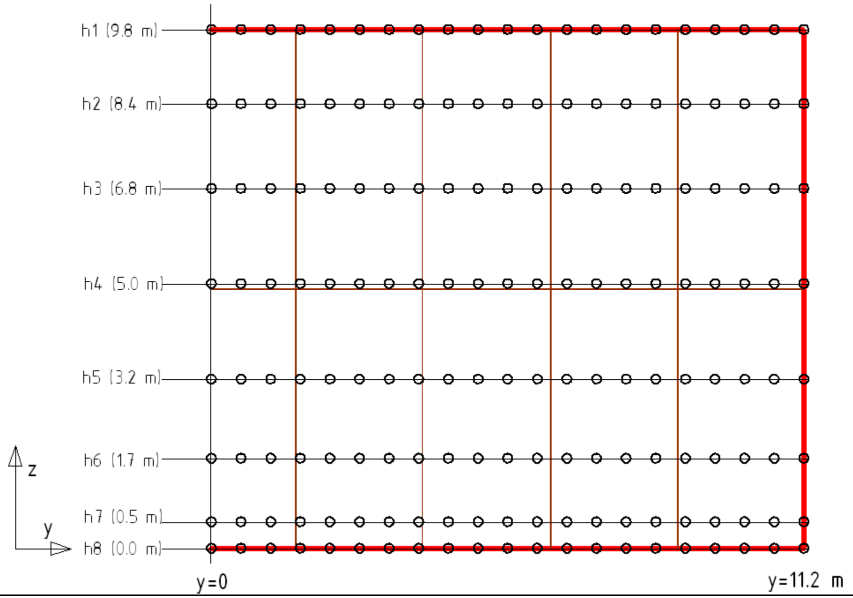


Figure 36: Selected points for manual calculation of von Mises stresses

The expression for calculating the equivalent stress is given in Eq 13.

$$\sigma_e = \sqrt{\sigma_y^2 + \sigma_z^2 - \sigma_y\sigma_z + 3\sigma_{yz}^2} \tag{13}$$

The results of von Mises stresses calculated in points on cross section paths shown in Figure 36 are presented in Table 24.

Table 24: Von Mises stresses calculated in selected points

VON-MISES STRESSES (kN/m^2)								
y	h1 (9.8 m)	h2 (8.4 m)	h3 (6.8 m)	h4 (5.0 m)	h5 (3.2 m)	h6 (1.7 m)	h7 (0.5 m)	h8 (0.0 m)
0	30993.7	31205.93	56700.33	83698.16	138242.8	156639.1	60535.53	140849.1
0.56	29294.5	28859.92	41834.15	68931.39	99998.01	120833.3	55739.89	125625.9
1.12	29861.8	30591.29	17554.88	34027.69	27827.14	50699.73	54525.2	92998.11
1.68	67178.39	47439.25	112563.5	34850.71	259281.2	266812.3	77887.61	141075.7
2.24	32610.62	31338.65	14121.15	32549.64	10156.51	38889.31	29444.89	113929.4
2.8	28460	29312.02	43411.93	50770.03	93248.12	120178.4	35687.89	127931.6
3.36	30653.5	31542.17	19446.22	39184.77	34916.47	63015.39	30614.9	114724.5
3.92	58120.04	38882.97	80924.87	34361.58	171893.6	184722.6	74116.84	127363.6
4.48	34393.34	34649.6	16990.08	37195.42	6338.596	41732.54	47342.11	112508.1
5.04	28546.46	33225.16	51046.24	61332.43	113712	138931.7	39970.75	132062
5.6	28150.2	30809.89	38245.7	54273.36	80656.9	104177.7	33888.64	123334.1
6.16	42165.88	34191.52	48382.81	28039.69	111134.4	120939.7	70317.24	110590
6.72	37541.97	32029.36	29916.74	34517.91	66785.43	76036.88	66369.82	108212.5
7.28	27900.05	34636.2	55276.36	67096.88	112754.2	132863.6	39147.16	128988.5
7.84	26037.53	38131.34	69072.07	73968.92	142582.3	159678.7	44709.08	131371.8
8.4	25728.52	30954.89	23489.84	46248.63	30801.28	46352.66	53446.7	100409.3
8.96	31296.12	14708.99	25582.27	30099.85	77947.34	99488.48	48121.4	90381.11
9.52	12286.35	20160.19	33957.06	44647.93	60134.56	68741.27	32037.11	72367.67
10.08	6273.479	14521.67	13218.27	48933.15	28005.95	39105.81	41698.58	51142.79
10.64	2788.822	11468.43	43193.71	49131.42	74512.49	52720.22	16725.12	19398.44
11.2	913.7253	20578.88	60987.28	149909.2	110051	84593.51	29321.66	1995.969

Maximal obtained value for von Mises stresses is 266812 kN/m^2, and it is obtained on cross-section h6 on point y=1.68 m. For this reason, the path of stress distribution in this cross-section will be individually plotted as the most unfavourable curve with maximal values of obtained equivalent stresses

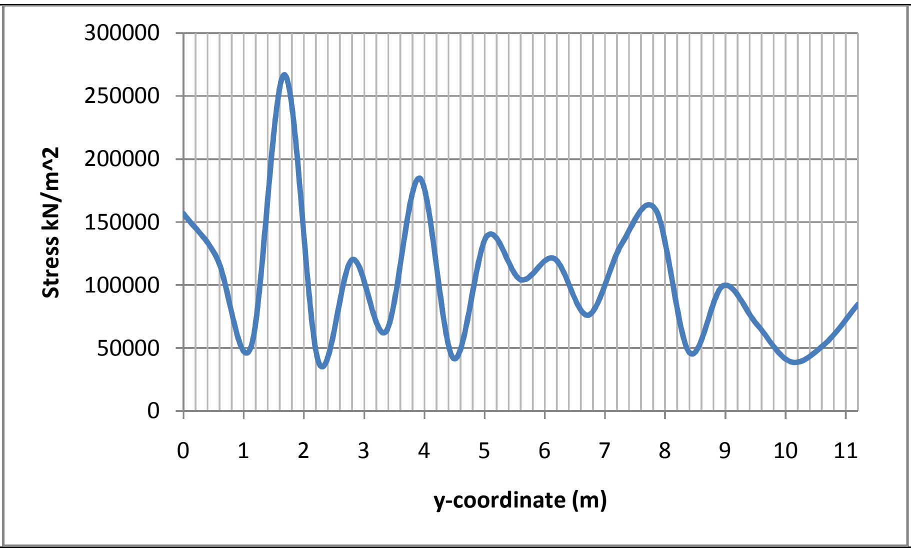


Figure 37: Corrected von Mises stress distribution in section h6

5.4.2. Displacement of Equivalent Panel Structure

The displacements of this structure are obtained from output results, but due to homogenisation process, the total nodal displacements need to be multiplied by corresponding correction factors from Table 22.

To adequately present the overall structural displacements, output results are shown in Figure 38.

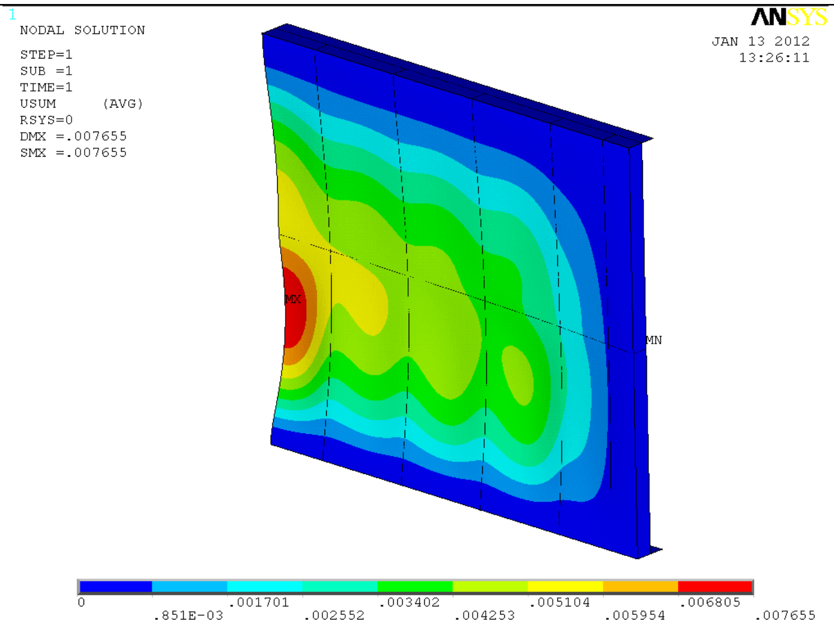


Figure 38: Total nodal displacements

The displacements will be multiplied with correction factors from Table 22. The cross section with maximal obtained nodal solution is traced, and the results were multiplied with the factors. Vertical position of traced path is on z = 2.8 m, and total nodal displacements are plotted and shown in Figure 39.

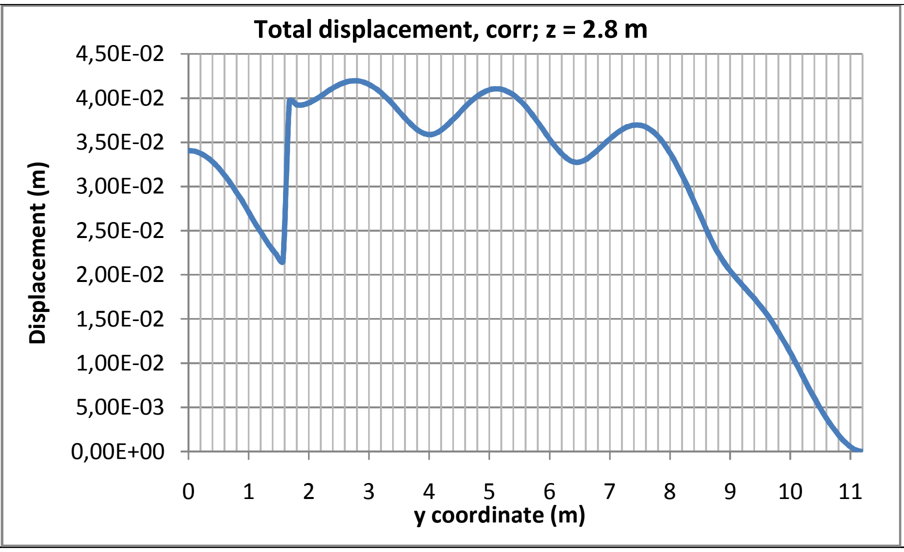


Figure 39: Total nodal displacements, corrected

The immediate jump of the results at approximate y=1.6 m occurs in vicinity of point of contact of two types of panels. The panels have the different coefficients of correction, and this discontinuity is result of coefficient difference.

5.4.3. *Stress Analysis of Internal Structural Members*

Internal structural members are the members placed in between the double sandwich panel structure and they serve as a supporting and spacing structure. As those members have classical plate structure, the homogenisation is not necessary and the structural analysis can be performed by directly observing the output results.

Stresses are presented in $kPa – kN/m^2$

The behaviour of following variables for internal elements will be investigated, and the values will be presented:

- Total node displacements in meters
- Normal stress distribution in transversal and longitudinal axis, in kPa
- Shear stress distribution, in kPa
- Equivalent stress distribution, (both for bulkhead plate and internal structure), in kPa

Total nodal displacement for internal structure is shown in Figure 40.

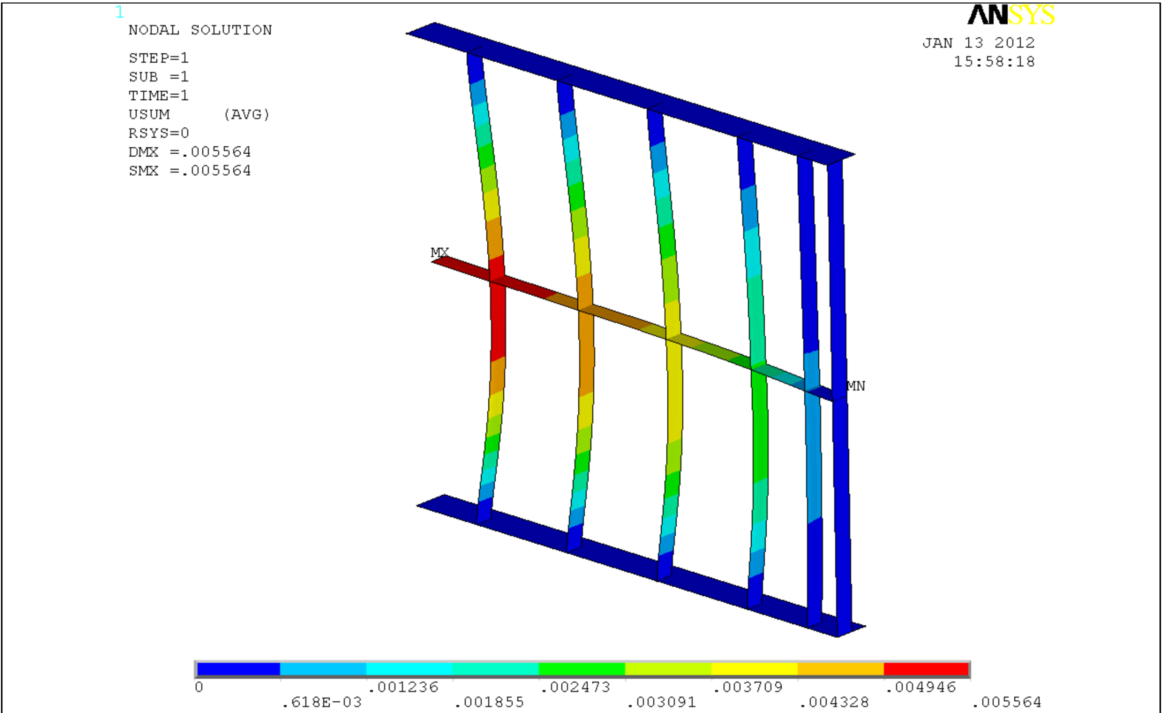


Figure 40: Total nodal displacements for internal structure

Distribution of transversal normal stresses for internal structure is shown in Figure 41.

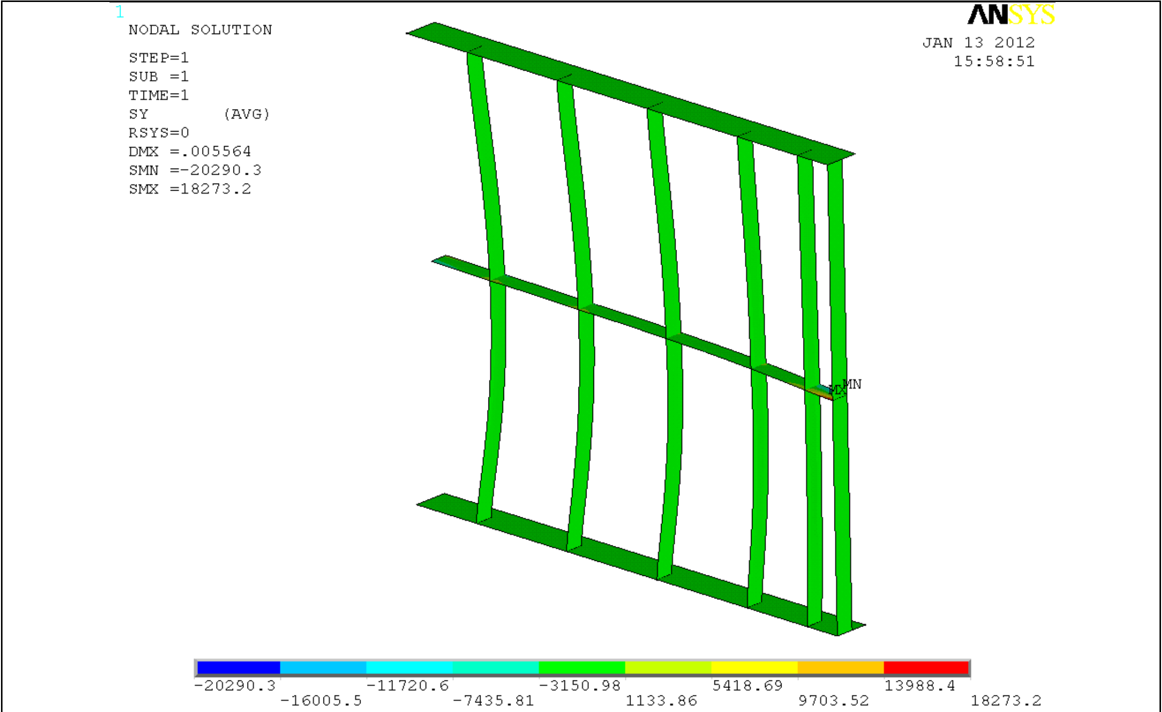


Figure 41: Transversal normal stress distribution for internal structure

Distribution of vertical normal stresses for internal structure is shown in Figure 42.

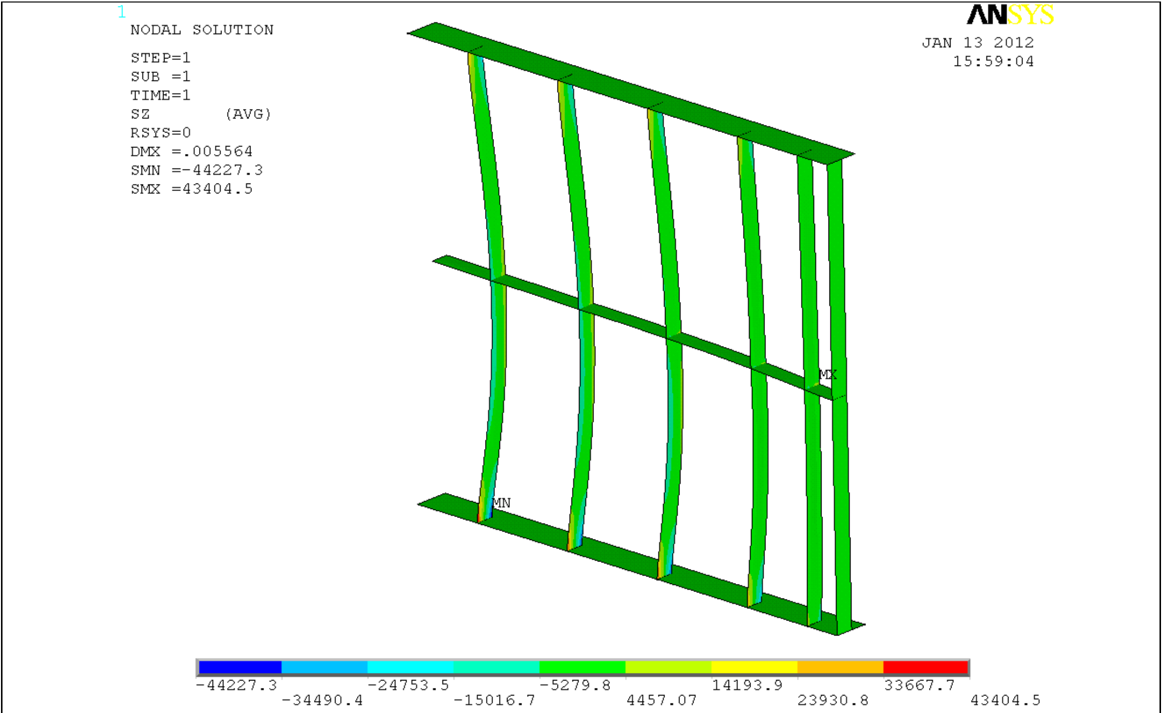


Figure 42: Vertical normal stress distribution for internal structure

Distribution of shear stresses for internal structure is shown in Figure 43.

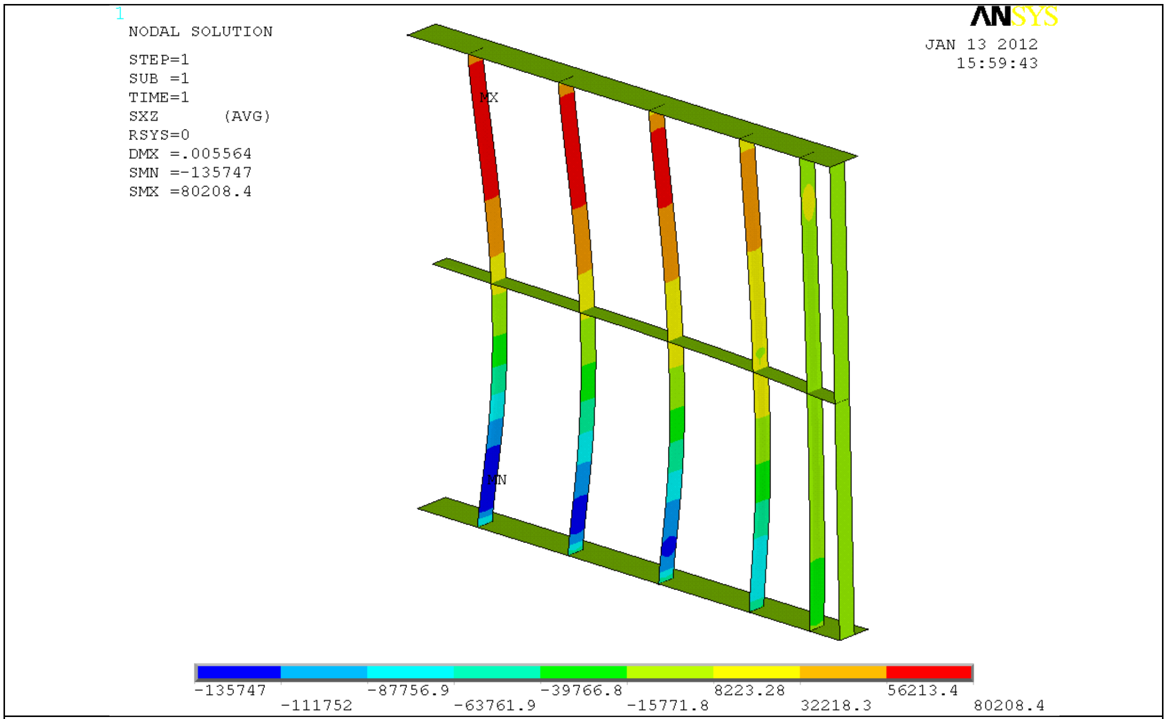


Figure 43: Shear stress distribution for internal structure

Distribution of equivalent von Mises stresses for internal structure is shown in Figure 44.

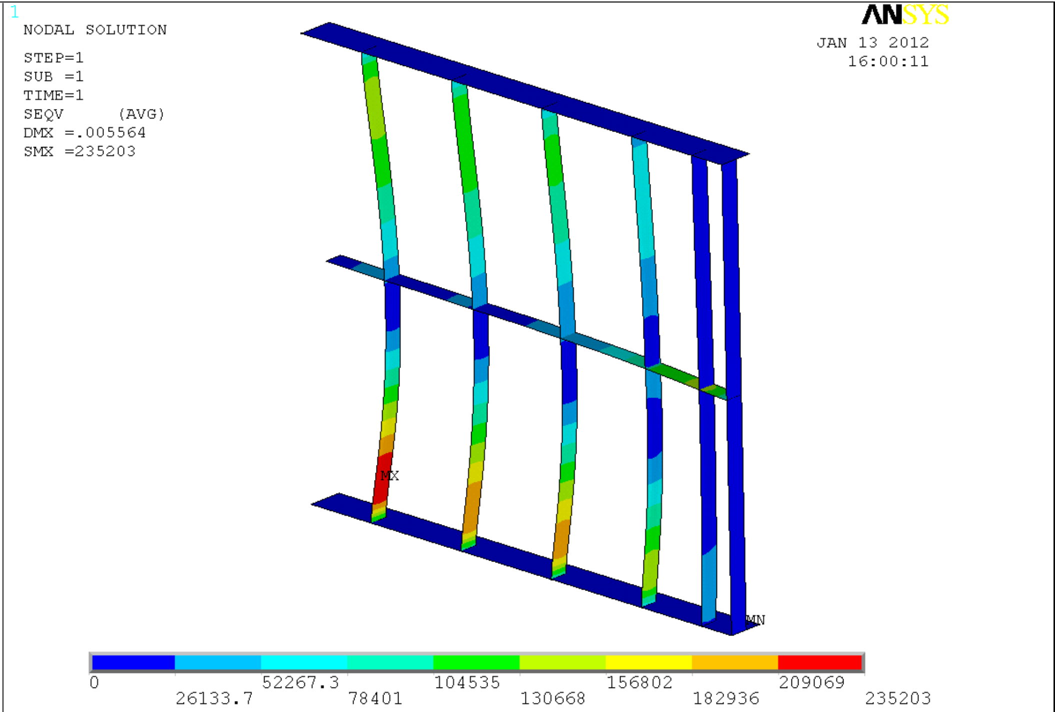


Figure 44: Von Mises equivalent stress distribution for internal structure

Von Mises equivalent stresses have acceptable values and the maximum is obtained on the same spacing element as maximum shear stress and equals approximately 235 MPa. That is acceptable value under the permitted one in Table 23. Also, there are no local concentrations of stresses encountered in the structure.

5.5. Sandwich Structure as a Part of Watertight Bulkhead Structure

Behaviour of the double sandwich structure as a constitutive member of the watertight bulkhead structure will be examined. The double sandwich bulkhead will be located as a part of the actual structure, presented along with other structural elements used as a connection between the bulkhead and the surrounding structure. This can be considered as local behaviour in interaction with neighbouring structural members, thus not completely presenting the interaction in global scope. The position of observed watertight bulkhead is between frames FR65 and FR 67 and it consists of the following structural members:

- Lower stool structure
- Double sandwich panel bulkhead structure
- Upper stool structure
- Adapter structure

Lower stool is used to hold the weight of the double bulkhead and to connect the bulkhead to the bottom structure and maintain the continuous stress transfer over the structure. The stool consists of stool plates, longitudinal stool elements and stool stiffeners

Connection between side shell of inner bottom and the bulkhead is performed inserting an adapter. The adapter is a stiff vertical box which consists of internal stiffening elements and has the role to transfer the stresses from stiff double bulkhead to the double bottom and yet further to other structural members. The dimensions and layout of the adapter correspond to the overall surrounding structure, enabling the graduate transport of the loads from the double bulkhead to the other structural members in double bottom. The other role is to adapt to the double bottom structure to enable the usage of the plates of the standard dimensions. This connection between adapter and side structure will be considered as clamped, with all degrees of freedom constrained.

Upper stool is a connection between the double bulkhead structures with the weather deck structure. It consists of stool plates and longitudinal stiffeners.

Connection of the lower stool/inner bottom, connection of the adapter to the inner side shell and connection of higher stool with the main deck are considered clamped.

The bulkhead will be examined for the influence of load from the hold no.2. Only the load from a single cargo hold will be considered, as this loading condition presents the most severe loading condition on the observed structure.

This analysis will be done to investigate the behaviour of equivalent plate structure in absence of directly imposed boundary conditions and their influence on results.

The FE model of the analysed structure is presented in Figure 45, offering the back view on plate and internal bulkhead from. The dimensions of finite elements are 100 mm and structural model consists of approximately 132,000 elements.

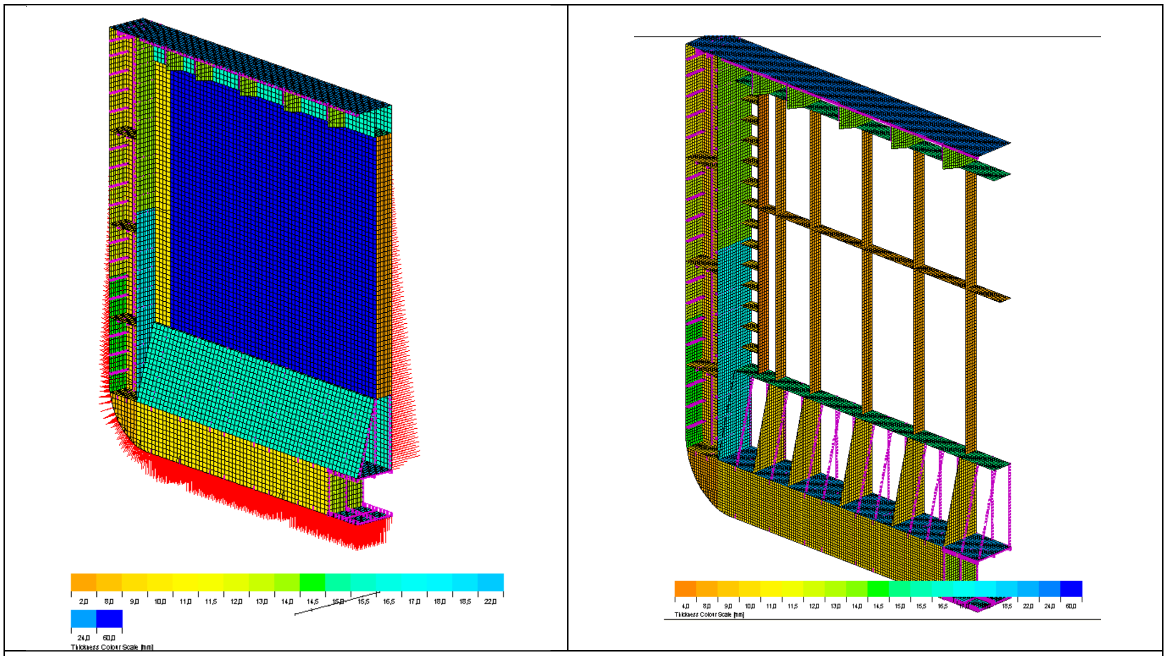


Figure 45: Front view of the FE model with loads. Left: plate structure. Right: internal structure

Maximal permitted values respectively to the different steels used in the structure are shown in the following table. The layout of cross section materials is shown in Appendix 2.

Table 25: Steels and permissible stresses according to the Rules

ReH (N/mm^2)	k	Permissible stresses (N/mm^2)		
		Normal stress	Shear stress	Von Mises
235	1.00	150.00	100.00	229.13
315	0.75	201.06	134.04	307.13
355	0.66	226.60	151.06	346.13

5.5.1. Analysis of Stresses in Equivalent Plate as a Part of Bulkhead Structure

Equivalent von Mises equivalent stresses in equivalent plates will be observed and presented. The observed structure is clamped on all edges, except for the edge y = 0 where symmetry boundary conditions are applied.

The structure is divided in 7 horizontal cross-sections on the lower and upper bulkhead edge and vertical positions of 0.35, 1.575, 3.675, 6.65 and 8.9 m. Each section consists of 20 equally distributed points, forming the grid of distributed points across the surface of the structure. The positions of points on horizontal cross-sections from which the values of stresses σ_y , σ_z and σ_{yz} are acquired for calculation of von Mises equivalent stresses will be presented in Figure 46.

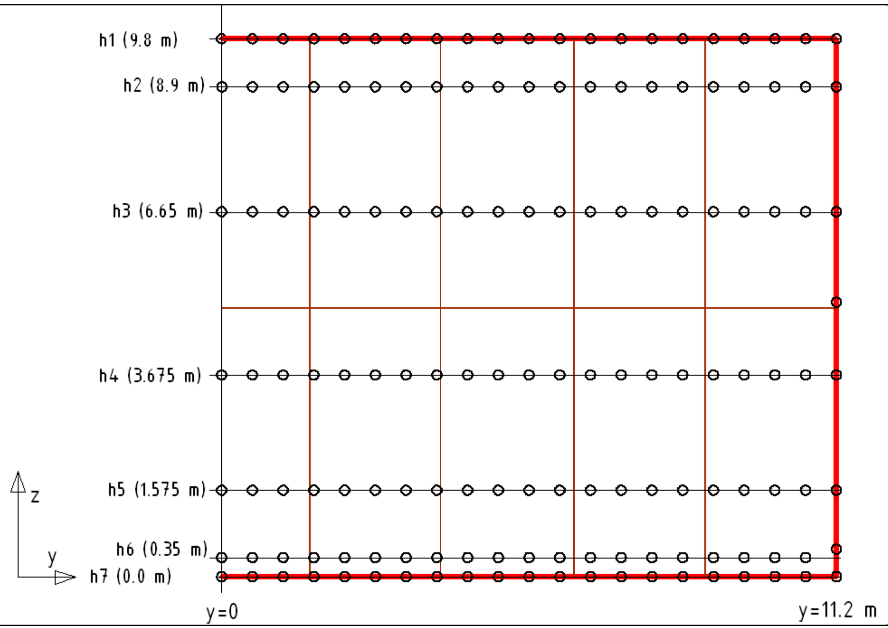


Figure 46: Von Mises equivalent stress distribution for internal structure

Using the obtained results, von Mises equivalent stresses are calculated. The obtained results for equivalent stresses are presented in Table 26. The path with maximal obtained result is highlighted and it is plotted in Figure 47.

Table 26: Corrected von Mises equivalent stresses for equivalent plates in global structure

VON MISES STRESSES (kN/m^2)							
y	h1 (9.8 m)	h2 (8.925 m)	h3 (6.65m)	h4 (3.675 m)	h5 (1.575 m)	h6 (0.35 m)	h7 (0 m)
0	18847.98	25417.51	53358	106366.9	149512.5	136834.5	400689
0.56	20508.56	42926.17	38224.18	90017.88	128771.9	136773.9	226817.2
1.12	37443.3	70644.3	43064.45	87092.27	118923.9	175545.3	164220.1
1.68	83637.88	38524.71	139045.8	241428.8	272888.1	51071.61	107602.1
2.24	29062.76	50155.91	60101.42	67732.16	66821.55	153109.8	208724.4
2.8	8667.23	8741.473	54474.08	86477.19	107695.1	85444.08	311528.9
3.36	25425.41	45363.31	51571.45	65199.9	66586.32	153947.1	219725
3.92	73675.93	33763.5	111424.4	182073	199159.3	67194.64	93265.81
4.48	38483.33	68520.66	67999.8	68644.65	91790.78	172621.1	214232.7
5.04	10677.94	26605.05	59099.18	94769.26	131070.9	104986.7	270125.7
5.6	15346.49	31830.18	45107.56	82102.98	99057.88	125724.1	315666.3
6.16	69150.1	68238.11	96093.31	157380.5	178045.8	154223.8	155208.1
6.72	53471.54	76641.4	89044.08	115912.4	142449.1	169481.4	202346.5
7.28	14288.17	41718.86	57434.71	82868.17	131181.3	109497.6	290269.5
7.84	11676.16	32139.84	59751.66	113596.1	154095.4	102004.2	258288.7
8.4	36281.93	62424.95	40010.74	94232.55	89467.84	180165.6	232476.6
8.96	39368.56	27247.55	86222.7	130906.1	128547	51832.92	105549.9
9.52	20941.41	14863	55538.12	77264.15	71333.53	56721.14	218310.7
10.08	34800.06	36964.22	50262.36	82080.9	68276.58	113830.4	178485.6
10.64	20985.16	13010.82	48090.06	77452.97	44933.99	19371.91	129826.9
11.2	55670.68	29099.19	120009.5	202154.9	183766.5	274622.7	228864.4

The cross-section with maximal obtained equivalent stresses is plotted shown in Figure 47.

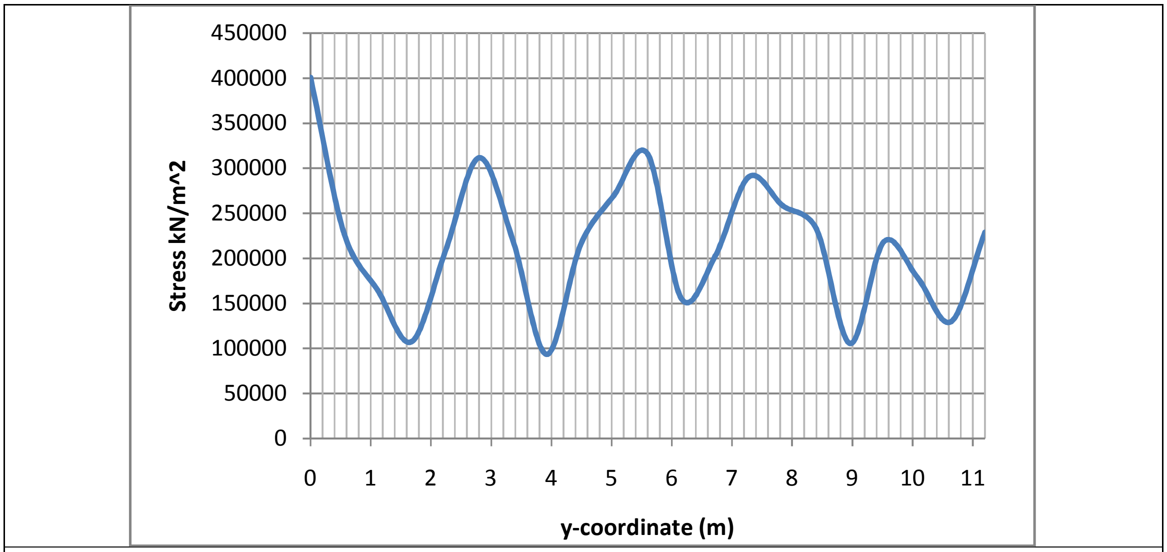


Figure 47: Von Mises equivalent stress distribution for internal structure, section h7

The position of this cross section is directly on the connection between stool structure and equivalent plate. According to obtained results, the maximal value of equivalent stress equals 400 MPa and exceeds the permitted values of 307 MPa. This problem requires additional observation in form of additional local structural analysis. Apart from stress concentrations obtained in several structural points, overall distribution of equivalent stresses across the plate structure is under the acceptable limits, as the obtained values across the observed points do not exceed 200 MPa.

5.5.2. Stress Analysis of the Entire Bulkhead Structure

The analysis of remaining parts in absence of equivalent plate structure will be performed. This is done to investigate structural response of entire structure, submitted to static distributed loads. The imposed loads are hydrostatical and cargo load. Boundary conditions are applied on highlighted elements as clamped. FE model, loads and boundary conditions are shown in Figure 48.

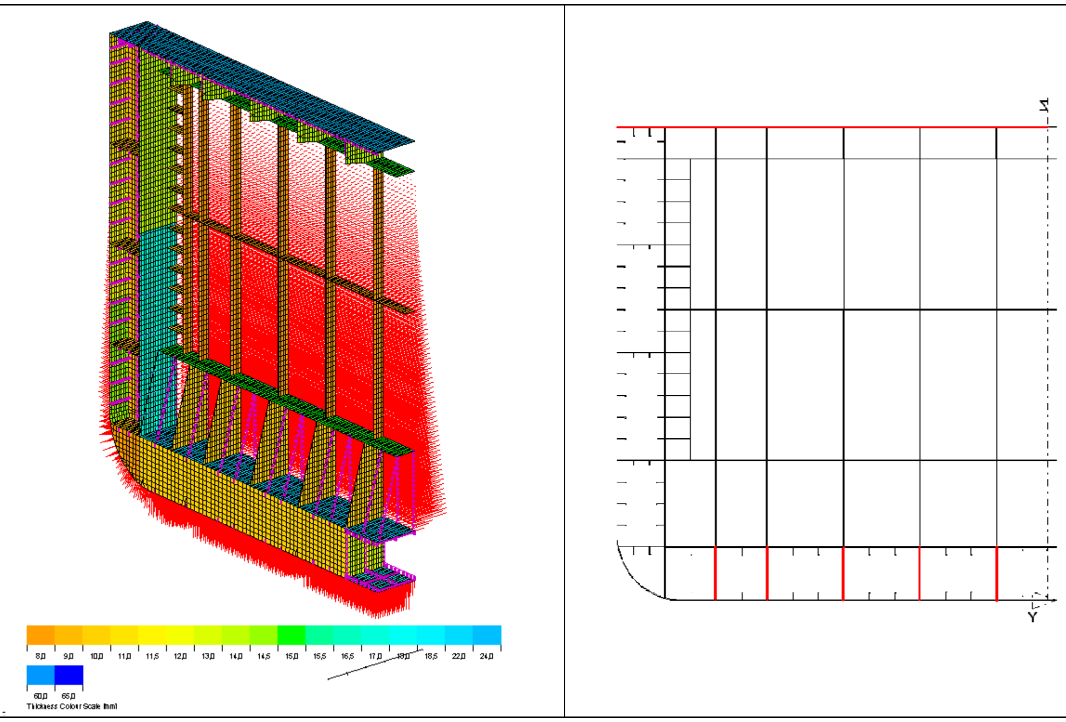


Figure 48: Left: FE model of entire bulkhead structure with imposed loads, Right: Denoted positions of boundary conditions

Having applied loads and boundary conditions as shown; obtained results are presented in following figures.

Total nodal displacement for entire bulkhead structure is shown in Figure 49.

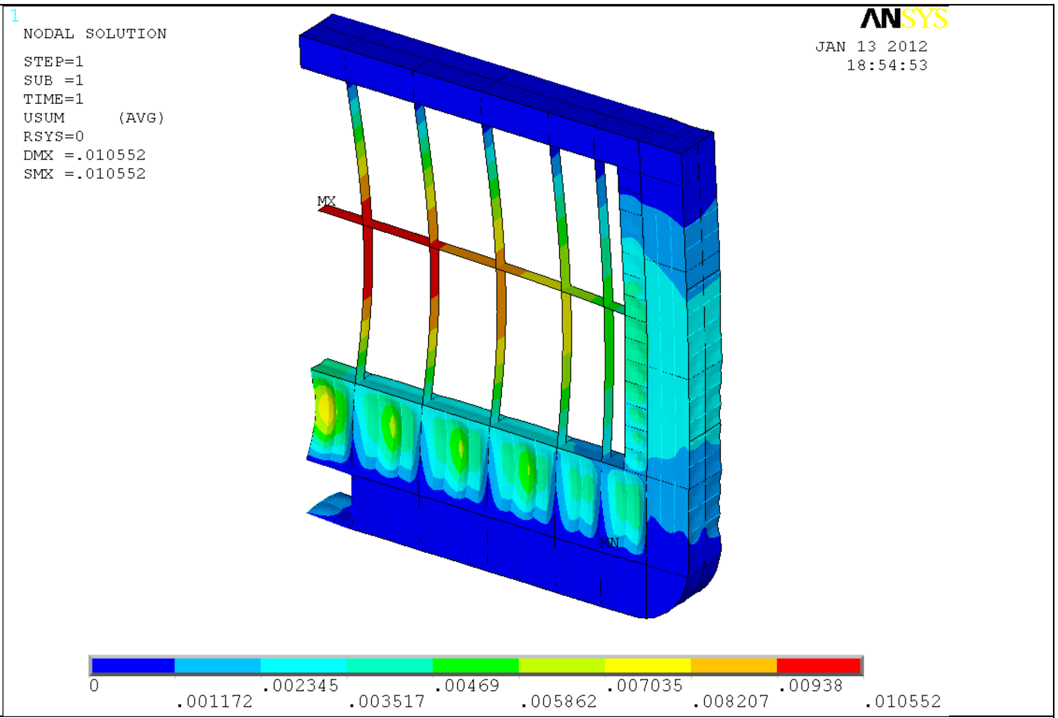


Figure 49: Total nodal displacement

Distribution of transversal stresses for entire bulkhead structure is shown in Figure 50.

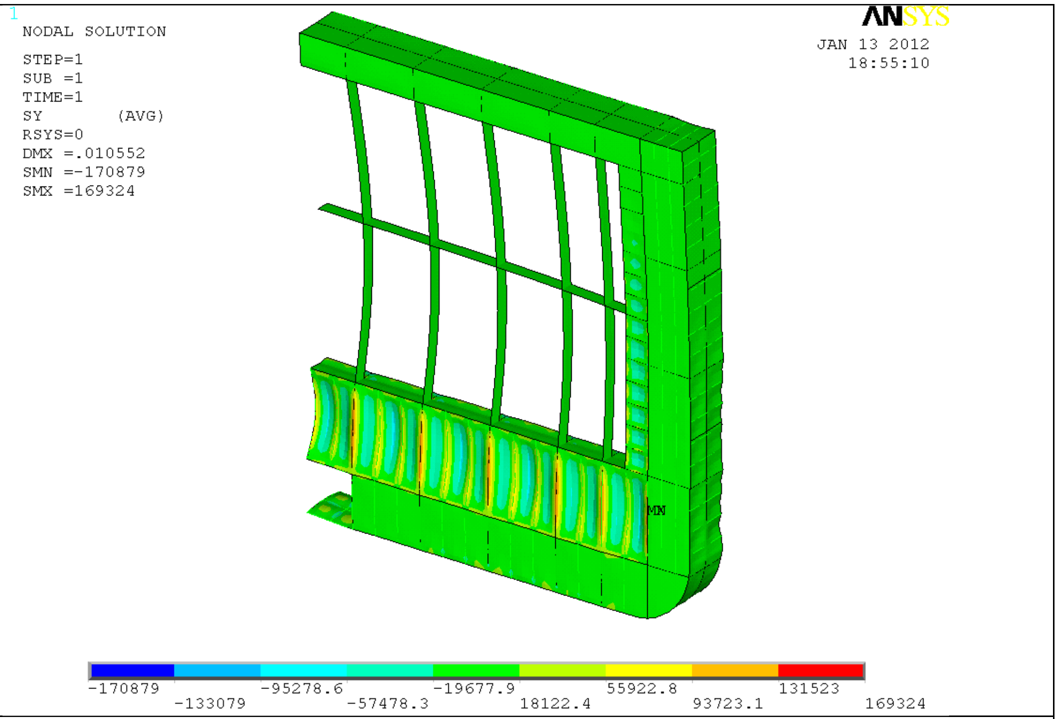


Figure 50: Distribution of transversal stresses

Distribution of vertical stresses for entire bulkhead structure is shown in Figure 51.

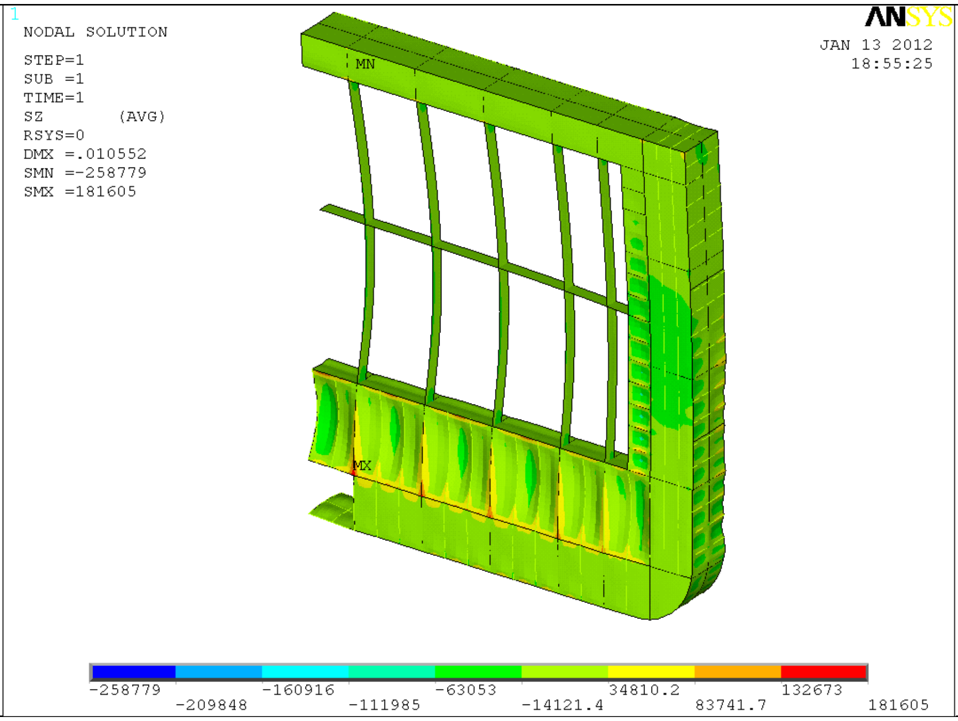


Figure 51: Distribution of vertical stresses

Distribution of equivalent stresses for entire bulkhead structure is shown in Figure 52.

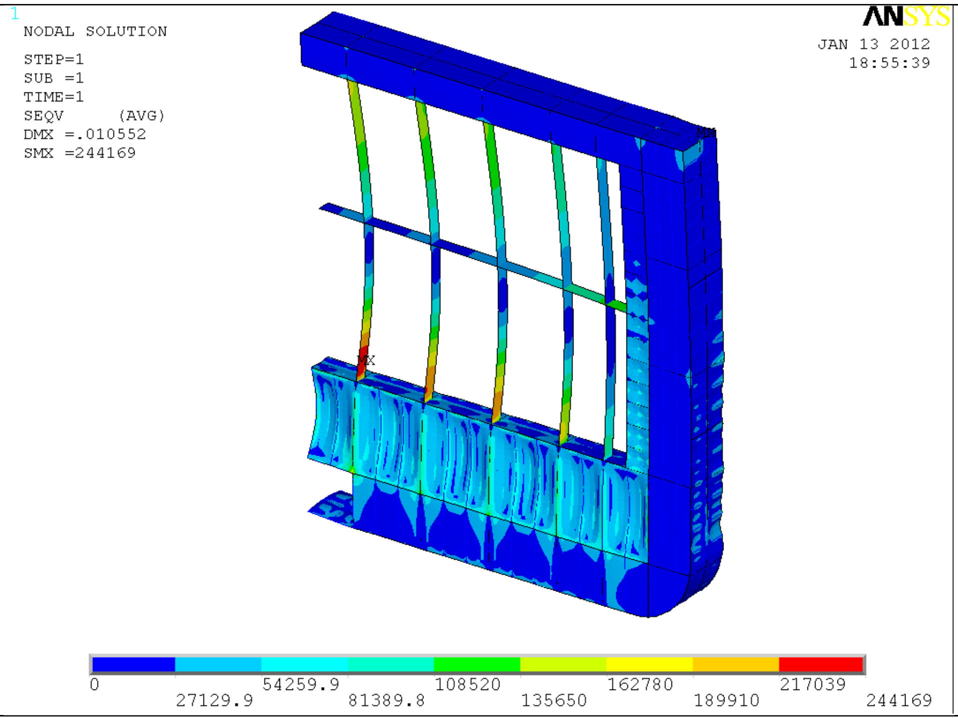


Figure 52: Distribution of von Mises equivalent stresses

This brief structural examination of entire bulkhead structure is performed to investigate the overall behaviour of the structure on the imposed external static loads. The high values of stresses were obtained mostly on the structural connections; the values of horizontal and vertical stresses on the most loaded part of the structure i.e. the vertical wall of stool structure do not exceed permitted values.

Peak of shear stresses and von Mises equivalent stresses is obtained on the same position in internal bulkhead structure, on vertical spacing element. This could maybe be avoided by inserting additional bracket element on outer connecting point between sandwich panel and stool structure. That would enable better stress transfer between the elements, insignificantly influencing overall mass of the structure.

6. CONCLUSION

6.1. Afterword

This work presents an example of structural design and analysis of a structure which relies on innovative design materials and philosophy. By its essence it presents a step forward from the design of classical structures commonly used in the shipbuilding industry, having a number of advantages and disadvantages. A designer should be aware of the possibilities and constraints of structural applicability and feasibility of a structure – in other words this can also be called as a compromise. This work can be considered as a preliminary design; as the dimensions, locations, spacing and scantlings of the principal structural members were determined.

6.2. Project Retrospection

There are no rules which actually deal with steel sandwich structures, so the combinations with present rules needed to be done. Preliminary design of the double bulkhead structure is performed according to the same Rules required for section moduli of the corrugated structures. The fact is that this requirement transfer needs to be additionally approved, despite the fact that the final dimensions of the sandwich structure in this case have proven the structural capacity to the applied loads.

As there was no available data for the classical bulkhead structure, several different proposals for corrugated bulkhead structure were presented. Furthermore, different structural double bulkhead candidates were offered as an altered to the classical structure and comparison between all corrugated bulkheads and double sandwich bulkhead proposals was performed. The suitable solution was chosen among the candidate solutions, but on the end the simplest possible solution was chosen. It was done for several reasons; mostly as a measure of caution; as the project is being developed without any pre-existing structural reference of a similar kind. Selected structure is then being examined for the most probable loads acting on the structure.

In order to reduce the number of finite elements required to describe the sandwich panel behaviour, homogenisation process was performed. This process was done by developing equivalent orthotropic plates using *Lok and Cheng 2000* formulation. Conclusion was that this formulation is not offering acceptable results for completely clamped panel in terms of displacements and stresses, so several improvements were introduced. The improvements consist of developing correction factors which lead to resemblance of results of stress and displacement distribution for real sandwich panel and equivalent plate. Later on, these factors were used in structural analysis to obtain more realistic stress values for equivalent plates.

First, only the double bulkhead as an isolated structure was examined with static structural loads applied. The results are the acceptable values of the stresses on the majority of the elements with appearance of the stress concentrations on several locations, as described locally in text.

Under the scope of this thesis, basic design of an innovative structure is made, having on mind the simplifications and assumptions which were made to make this project placed in the context of logical and rational academic solution of an engineering problem.

To conclude the work and to clear the general image on the ideal project as a whole, the disadvantages will shortly be presented.

6.3. Drawbacks

Presented double sandwich bulkhead structure design was proven to be weight effective, offering a considerable weight reduction over the classical corrugated bulkhead structure. The main disadvantage is the presented double bulkhead design occupies considerably more space than classical corrugated structure. From the aspect of a ship owner, this affects total volume of the cargo space decreasing the cargo hold capacity – very important parameter in ship’s economical bilance.

Several simplifications of the double bulkhead structure led to some disadvantages in the aspect of the production and fitting technology. The design was guided by the general idea of increasing the quality of desirable design parameters such as weight reduction, cost reductions, energy saving, assembly simplification etc. From the technological point of view the possibility of assembly and fitting the bulkhead should be seriously considered. Due to small structural dimensions there is a problem of difficult and limited access to certain welds and locations for a worker or an inspector. Small structural dimension make the workmanship, maintenance and inspection difficult. These parameters need to be additionally checked and approved in possible additional and detailed analysis in the future.

6.4. Future Analysis

All the disadvantages were mentioned in order to make the recommendations for any possible project continuation in the field of double bulkhead design.

Using of homogenisation of sandwich panel using proposed formulation should, theoretically, be verified by a series of experiments.

Slightly over dimensioning of the sandwich double bulkhead structure offers a good basis for structural optimisation and analysis. Detailed analysis of overall watertight should be performed including structural details, joints and connections.

Computer codes used for verification of structural design are unfortunately not offering the possibility of presenting the structural suitability of individual structural elements. It would be interesting to see the distribution of these properties over the structure.

Stress concentrations were found on different critical spots of the structure, presenting the critical points in fatigue analysis. There are structural design possibilities to avoid the stress concentration on certain members, but in general the stress concentration points are difficult to avoid.

Joints and connections are very important structural locations and it is not possible to have a good structure without extensive structural analysis of these locations. The joints are mostly considered as the connections between two adjacent sandwich panel elements inserting the joining element. The connections are the locations of connection other structural elements

Analysis of vibrations should be performed as well. On the end, extensive cost analysis should be carried out to completely verify the fact that the double sandwich structure is really more affordable than the classical structure.

7. ACKNOWLEDGEMENTS

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Professors and researchers quoted in the references, quotations of their work is highly appreciated and adequately acknowledged

Finally, special and most important thank to my family for the endless support, especially to my beloved Maja and my daughter Eva, to whom I dedicate this work.

Szczecin, 15 January 2011

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9. APPENDIX 1 – GENERAL ARRANGEMENT

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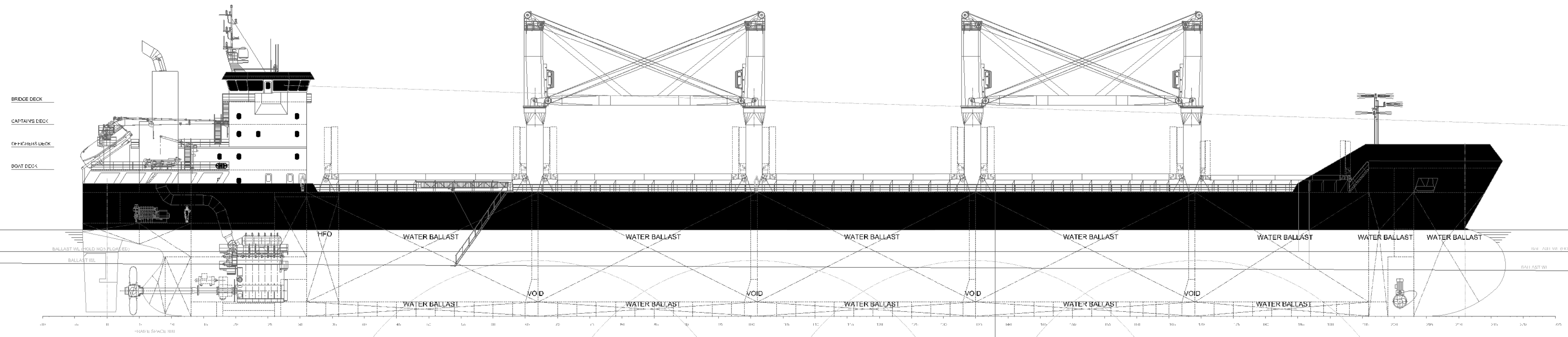
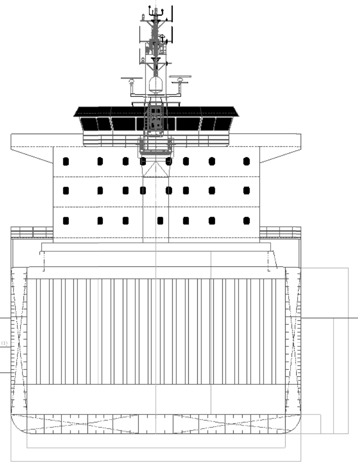
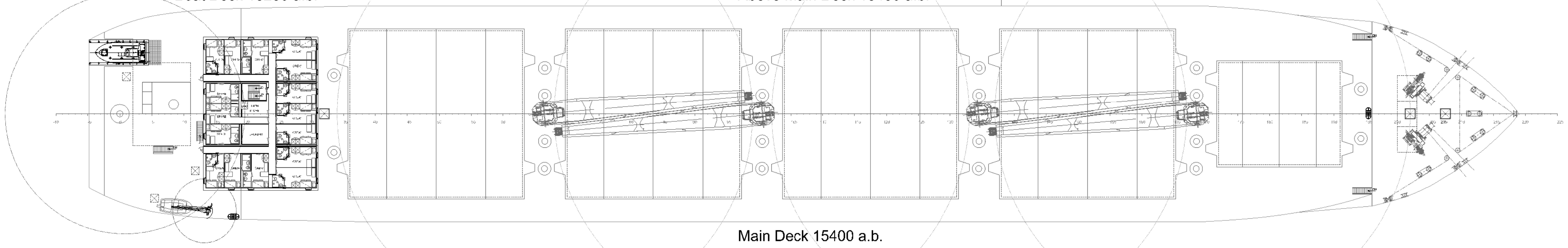


Cross-section



Boat Deck 18200 a.b. Above Main Deck 15400 a.b.



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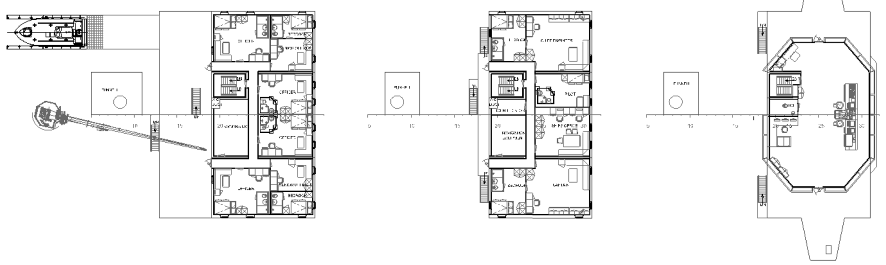
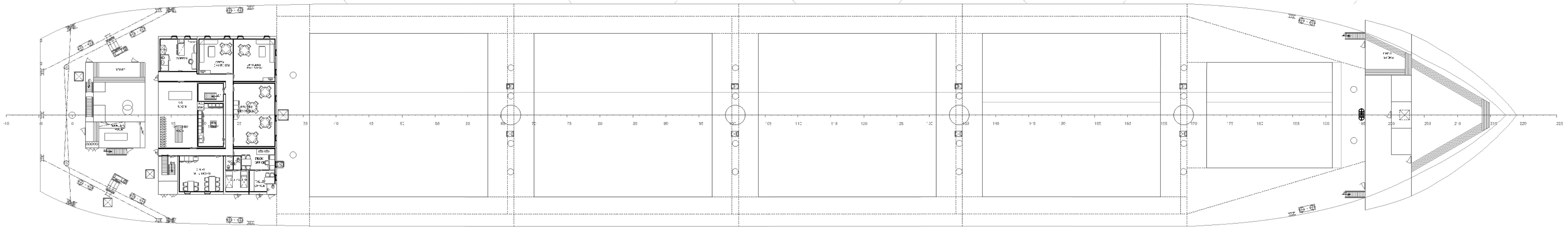
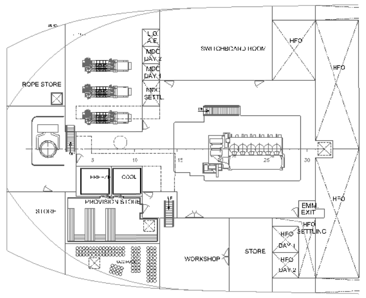
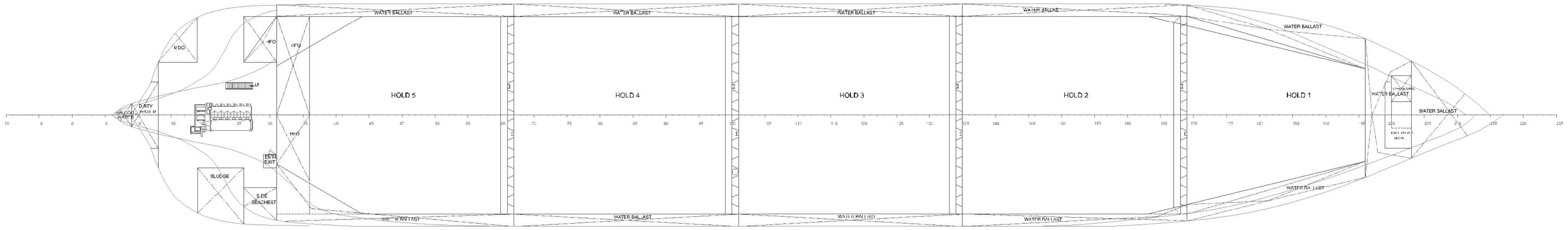


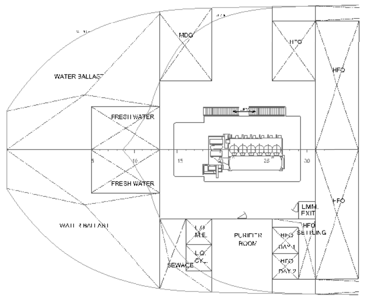
Main Deck 15400 a.b.



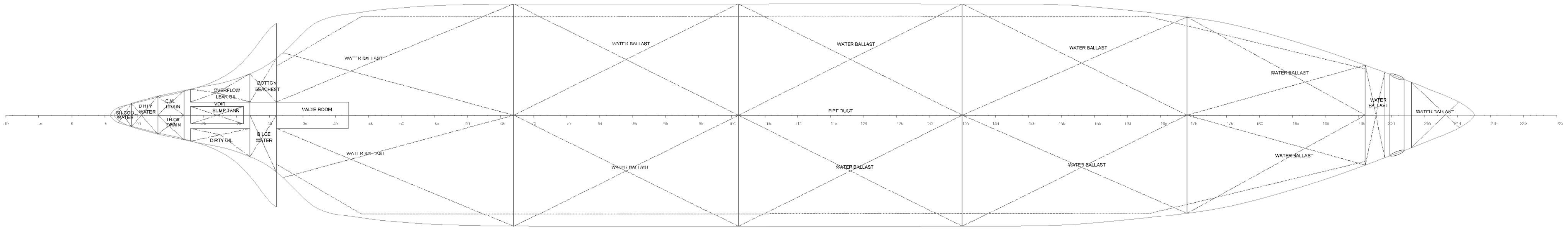


PS- Below Main Deck 15400 a.b. SB- Above Tank Top 1750 a.b.





Below Tank Top 1750 a.b.



Dimensions

Length o.a.	: 177.00 m.
Length b.p.	: 168.80 m.
Beam mld.	: 27.00 m.
Depth	: 15.40 m.
Design draft, approx.	: 10.75 m.
Deadweight, approx.	: 32 000 ton
Gross tonnage, approx.	: 21 000
Nett tonnage, approx.	: 10 820

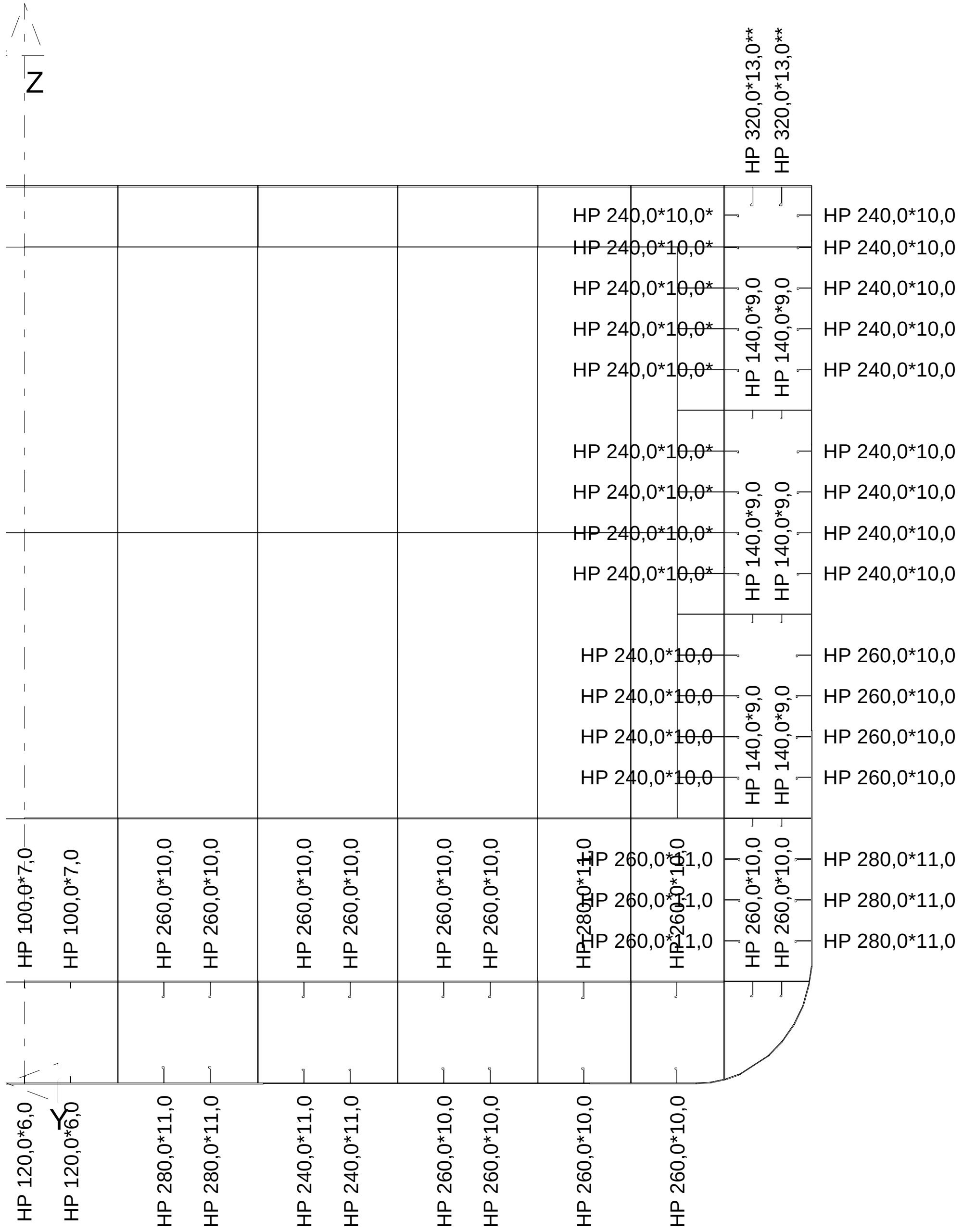
Capacities approx.

Hold	: 42475 m3
HFO	: 1550 m3.
MDO	: 130 m3.
Freshwater	: 175 m3.
Ballastwater	: 1350 m3 + 9455 m3 in Hold 3.

REV	ALTERATION	BY	DATE

10. APPENDIX 2 – CROSS SECTION SCANTLINGS

Frame No.: 66 +380 (F) Longitudinal Profiles



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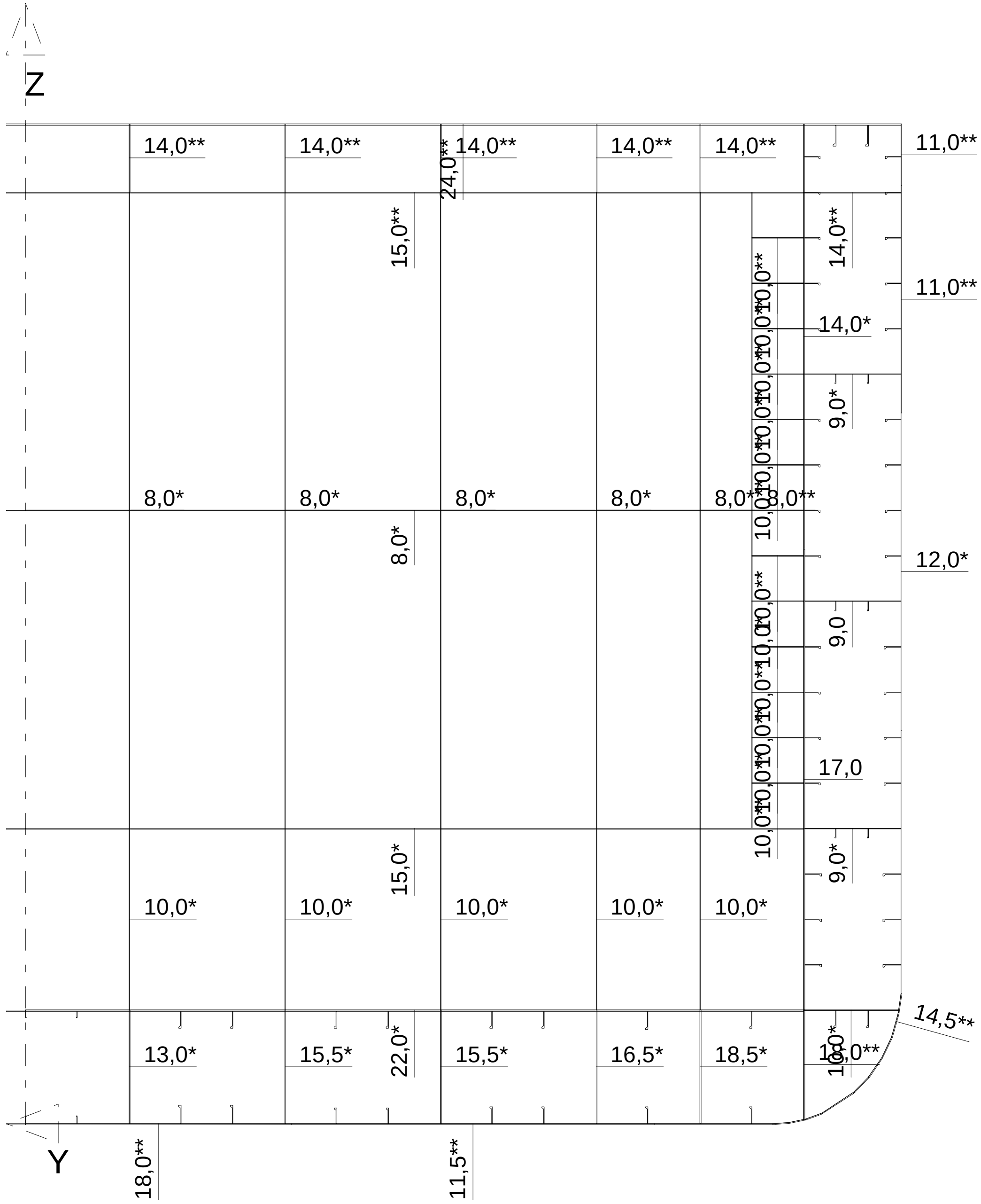
Frame No.: 66 +380 (F) Longitudinal Plates



Project : **by** martinmarkulin (1584)

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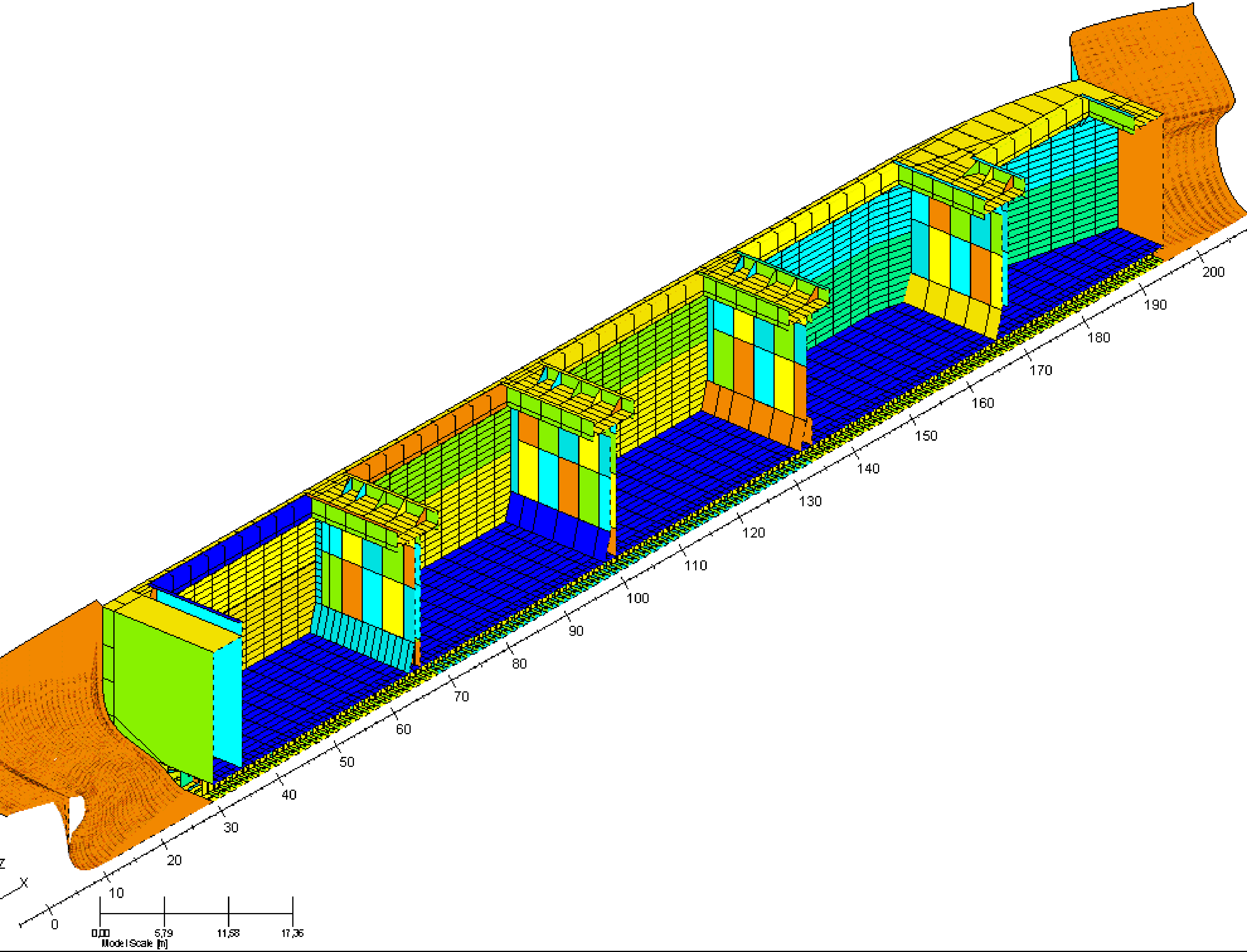
11. APPENDIX 3 – GLOBAL STRUCTURE MODEL (GL-Poseidon 3D Model)



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