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Quasi-optimization of structural design of crude oil tanker

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Quasi-optimization of structural design of crude oil tanker

submitted on 30th July 2021

by

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Master Thesis

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ABSTRACT

Throughout the years, human kind has been looking for ways to improve previous designs. Improvements are made in order to achieve more precise results, increase efficiency, increase productivity, save energy, being greener, save money and staying competitive. In ship design, optimization is also an important procedure to be considered, it can lead to decreasing construction and operational costs, fuel consumption, greenhouse gases emission, increase cargo capacity and overall efficiency.

This work studies the influence of the web frame spacings and longitudinal stiffeners spacings on the weight of the cargo hold of a crude oil tanker. The least weight is desired. In order to analyse the weight of the cargo hold of the vessel, the scantling of five spacings of web frames are calculated. The cargo hold will always have the same length, and the swash bulkhead will remain always in the middle of the cargo hold, in the longitudinal direction. After finding the least weight of the five different spacings of web frames, the spacings of the longitudinal stiffeners are changed five times and the option with the least weight is selected.

The weight of all the scantlings calculated with the help of Nauticus Hull is then compared, considering that the web frames and bulkheads did not suffer any change in weight.

ABSTRACT (Portuguese)

Ao longo dos anos, a humanidade está sempre procurando maneiras de melhorar os projetos anteriores. As melhorias são feitas para obter resultados mais precisos, aumentar a eficiência, aumentar a produtividade, economizar energia, ser mais ecologicamente correto, economizar dinheiro, manter a competitividade e assim por diante. No projeto de navios, a otimização também é um fator importante a ser considerado, pois afeta os custos de construção, custos operacionais, consumo de combustível, emissão de gases de efeito estufa, capacidade de carga e assim por diante.

Este trabalho estuda a influência dos espaçamentos das cavernas e dos reforços longitudinais no peso do porão de um navio petroleiro. O peso mínimo é desejado. Para analisar o peso do porão de carga da embarcação, calcula-se a estrutura de cinco espaçamentos diferentes de cavernas. O porão de carga terá sempre o mesmo comprimento, e a antepara quebra-onda ficará sempre no meio do porão, no sentido longitudinal. Depois de encontrar o menor peso dos cinco espaçamentos diferentes de cavernas, os espaçamentos dos reforços longitudinais são alterados cinco vezes.

Os pesos de todas as possiblidades calculadas com o auxílio do Nauticus Hull, são então comparados, considerando que as cavernas e anteparas não sofreram alteração de peso.

1. INTRODUCTION

Structural ship design is a point of interest for naval architecture considering the constant increase of the overall ship dimensions over the years. Poor ship strength analysis could lead to catastrophic casualties. The structure of a ship is to withstand all the loads due to the cargo, machinery and the sea (local and global loads). The structure of a ship should not have safety factors so high that its weight becomes a cost issue, that is why the classification societies define what is the minimum requirements regarding the ship structural design.

In order to guarantee that the ship has its structure strong enough to resist the load cases that the ship will be subjected to, the ship designer has to strictly follow the design rules imposed by a classification society. In this thesis DNV rules will be used. The class society does not stablish the spacing between frames or stiffeners, this is defined by the structural naval architect, usually in the beginning of the design, in the concept design. Selecting the spacing between the frames and stiffeners of the vessel will determine its weight, this is a crucial task in weight optimization.

The scantling of a ship should be able to carry all the loads whilst the weight is kept to a minimum for cost reasons. The cargo hold of a crude oil tanker is basically composed of stiffened panels. The amount of stiffeners, longitudinal span and material will determine the scantling of the cargo hold and its weight, therefore identifying the best structural arrangement for the least weight, considering constraints such as construction feasibility and construction cost, is a characteristic of the design, that should be analysed in the first steps of the design spiral, during the concept design. There are state of the art codes for ship structural optimization such as NSGA-II, VOP, LBR-5 and in development such as Holiship.

Having a lighter lightship weight represents cost reduction during the operation and might also reduce construction costs, although this is not always true. The construction cost will depend on the difficulty to execute the design, that will impact the amount of man-hours spent on construction, the structural weight and the amount of welding. Having the minimum structural weight will reduce operational cost such as fuel consumption. The lighter the lightship weight is, the smaller the draft, causing less resistance in water, therefore less power and fuel consumption. Ideally the ship owner will operate it as well, if not, it might happen that the ship owner is not so concerned about operation costs, only construction cost.

The objective of this master thesis is to find the scantling of a cargo hold of a crude oil tanker, according to DNV rules, in an optimized way, that is, targeting the least weight. The two variables studied are the spacing of the web frames and the longitudinal stiffeners. Having the least weight will reduce operation costs with fuel, reducing carbon dioxide and other greenhouse gases emission.

2. PROBLEM DESCRIPTION

The crude oil tanker, object of this study, has an overall length of 333 [m] and its other main dimensions given in Table 2.1. The midship section has defined general dimensions as shown in Figure 2.1. The ship has 5 tanks in the longitudinal direction, as shown in Figure 4.3, each one of them have length of 50800 [mm]. The weight of the cargo hold of the ship is a function of the spacing of the frames, spacing of the longitudinal stiffeners, which influence the plate thickness, section modulus of the structural elements, that is web height and thicknesses, flange breadth and thickness. The designer should be looking for the least weight considering the parameters mentioned, and respecting the DNV rules restrictions.

Table 2.1: Principal dimensions of the vessel.

Parameter	Values	Unit
Length O. A.	333.00	[m]
Length B.P.	318.00	[m]
Length Scantling	314.28	[m]
Breadth Moulded	31.25	[m]
Depth Moulded	31.25	[m]
Draft Design	21.00	[m]

Most of the times, the decision about the number of frames and longitudinal stiffeners is not only about finding the least weight. Cost of construction is a source of concern in this decision as well, although is not in the scope of this work. Decreasing the spacing between longitudinal stiffeners reduce the section modulus, but the cost of welding might increase, especially if the profiles are fabricated in the shipyard (welded).

The ship is subjected to a specific loading and sea state. Considering these conditions, it is assumed that the permissible still water bending moment for the third cargo hold is -6,300,000 [kN.m] and the shear force is 204,330 [kN].

It is not in the scope of this work analyse specific loads that might increase the scantling of the cargo holds, such as reaction forces due to docking blocks supporting the ship self-weight on a dry dock, lifting loads during the assembly of the blocks, or loads caused by handling equipment (cranes) on the deck, heavy equipment and so on. This strength analysis should be performed in a more advanced phase of the design.

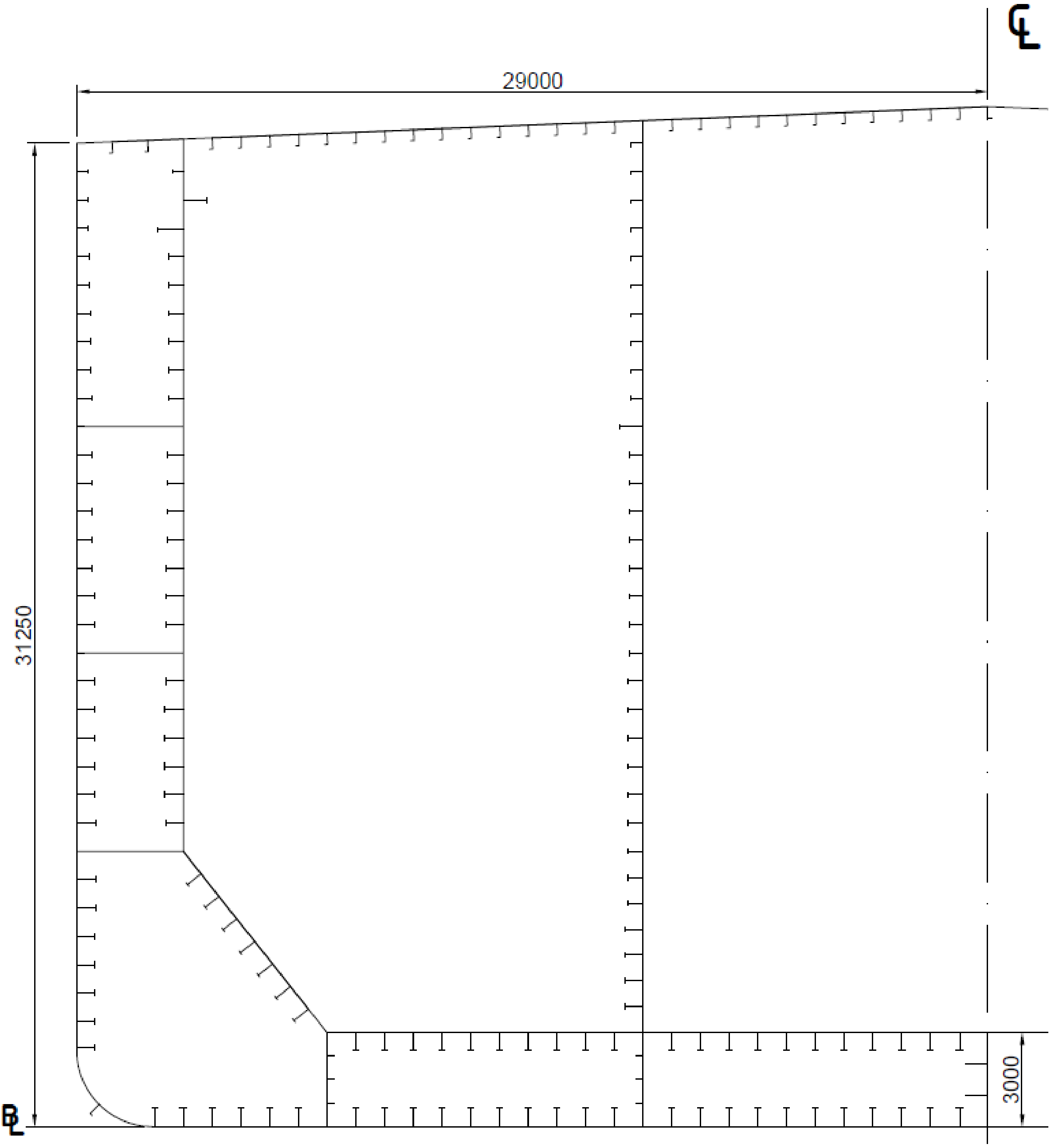


Figure 2.1: Original Midship section scantling. Source: Autor.

3. METHODOLOGY

This chapter outlines the procedure for achieving the objective of this master thesis.

In order to find the structural arrangement of the cargo holds of a crude oil tanker, that is, the number of frames and the longitudinal stiffeners spacing, following the DNV rules, in an optimized way, that is, targeting the least weight, five spacings of web frames are tested and the one with the least weight is selected to define the number of frames that the cargo hold will have. One important constraint is that the number of frames should always be odd numbers, in order to have one in the middle of each cargo hold that will have the function of swash bulkhead. Having selected the best option for the number of frames, five spacings for the longitudinal stiffeners will be tested. Testing five different spacings will allow to check the influence of this variable in the total weight of the cargo hold. The results are then compared and the least weight is the result sought after. This way the longitudinal stiffeners spacings are selected.

The scantling calculation will be made with the tool Nauticus Hull, from DNV. This software checks all the criteria for longitudinal elements described in their rules. For plates it checks the minimum thickness, yielding, bucking and slenderness. For stiffeners it checks the minimum thickness, yielding (section modulus), yielding of the web of the stiffener, buckling and slenderness. The section modulus of the midship section is also checked for the still water bending moment plus the wave bending moment. Finally, the hull girder ultimate bending moment is calculated and checked.

4. SELECTED TOPICS OF SHIP DESIGN THEORY

4.1. SHIP DESIGN

Ship design is an iterative process. It might be divided in four or three phases, such as concept design, preliminary design and contract design. After a client explains the vessel's objective and gives the initial inputs, the designer is going to develop the concept design, the first turn in the design spiral, that is usually done for bidding purposes. In this phase, the minimum technical information of the ship must be available for the economical assessment as well. (Eyres, 2007)
Once the concept design is approved by the client, the preliminary design starts. In this phase the vessel will have every aspect defined, related to hydrostatics, stability, structure, GA and so on.
The information provided in the preliminary design is sufficient for the shipyard to provide the cost of construction. Once the shipyard is chosen, the preliminary design will be used to do the detailed or contract design, also known as shop drawing. This entire process is depicted in Figure 4.1.

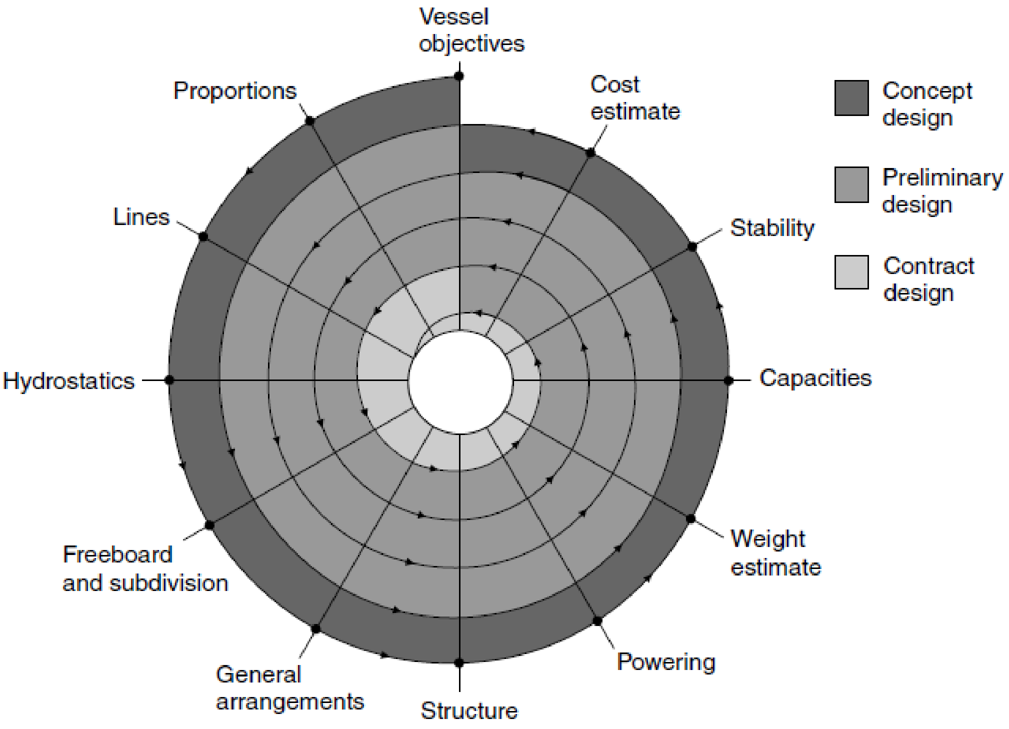


Figure 4.1: Design Spiral. Source: (Eyres, 2007)

4.2. CRUDE OIL TANKER

Crude oil tanker is intended for transporting crude oil, as its name indicates, from the point where it was extracted to the terminals, where the crude oil will be pumped to the refinery (Shama, 2013). This crude oil can be extracted and temporarily stored, say 10 days, in a FPSO (Floating Production Storage and Offloading), then it is offloaded to a Crude oil Tanker for transportation. This vessel is also used to transport oil extracted from shore to another country. In the past the position of the machinery was amidship and the propulsion was with paddle wheel. As the engines developed further to oil fuel, the main engine was shifted to the aft of the ship, together with the bridge and living quarters. This might be a problem when the ship is unloaded. The heavy weight in the aft of the ship cause excessive trim by the stern and must be corrected by adding ballast in the fore part of the vessel causing high hull girder bending moment in hogging. (Eyres, 2007)

Accidents and Incidents such as collision and grounding with oil tankers causing disastrous environment impact as Erika's incident off the coast of France in December 1999, are the reason for single hull oil tankers being phased out. Typical midship section of a double hull oil tanker is shown in Figure 4.2. In fact, "In 1992 MARPOL was amended to make it mandatory for tankers of 5,000 dwt and more ordered after 6 July 1993 to be fitted with double hulls, or an alternative design approved by IMO (regulation 19 in Annex I of MARPOL)". (IMO, 2021)

From Figure 4.2, it is observed that there are Side Ballast Tanks (SBT), and the longitudinal bulkheads of the Centre tank have web frames that connect the middle of its height to the inner bulkhead of the side ballast tank, in order to avoid excessive lateral deflection of the bulkhead during loading.

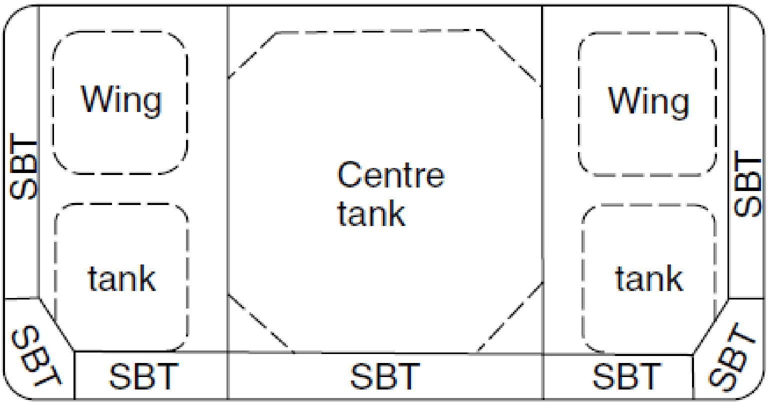


Figure 4.2 : Double hull oil tanker typical midship section. Source: (Eyres, 2007)

Figure 4.3 shows the profile of a double-hull design, note that the double bottom is shown in dashed lines.

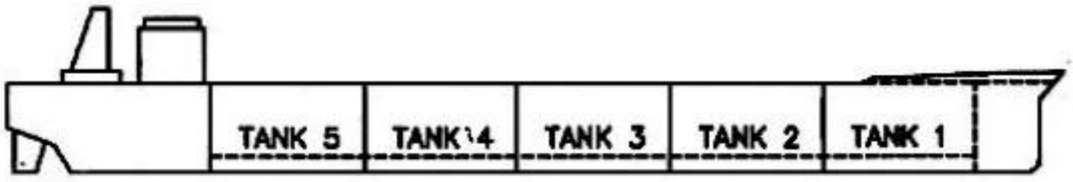


Figure 4.3: A double hull tanker. Source: (Shama, 2013)

Double-hull ships have some advantages, such as increasing safety regarding oil spillage when casualty occur, consequently increasing environmental protection. The spaces between longitudinal bulkheads and side shell can be used as ballast tanks, preventing cargo tanks to be used for ballasting the ship. On the other hand, double-hull ships have higher building cost, larger surface area to be maintained. (Shama, 2013)

4.3. STRUCTURAL ELEMENTS OF A CRUDE OIL TANKER

This chapter briefly describes a few structural elements of ship design and its functions and also outlines the difference between transversally framed and longitudinally framed structures.

The keel of the vessel remembers the backbone of the human body. It is located in the bottom centre line of the vessel. Its main function is to provide longitudinal strength to the hull girder and distribute the load when the vessel is sited in a dry dock. Figure 4.4 shows the flat plate keel, which is the one used in ocean going vessel, such as oil tankers. (Eyres, 2007)

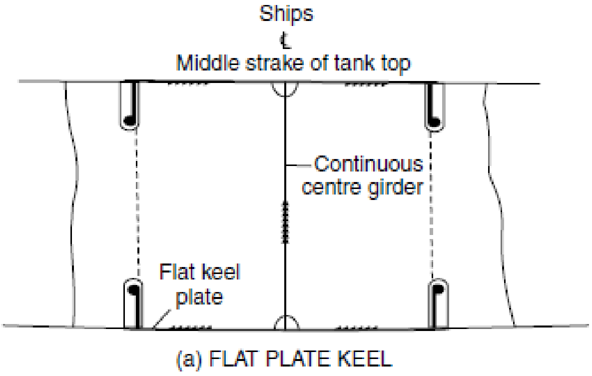


Figure 4.4: Flat plate keel. Source: (Eyres, 2007).

Floors are located in the bottom in the transverse position from centre girder to the bilge. Its main aims are to provide support for the cargo tanks and provide transverse strength. It can also be seen in Figure 4.4 and can be made watertight or oiltight by welding collars.

Primary support members such as the web frames, shown in Figure 4.5, are calculated with finite element analysis. Several types of tank loading conditions (load cases) are checked to avoid failure in this structure. (Mansour & Liu, 2008)

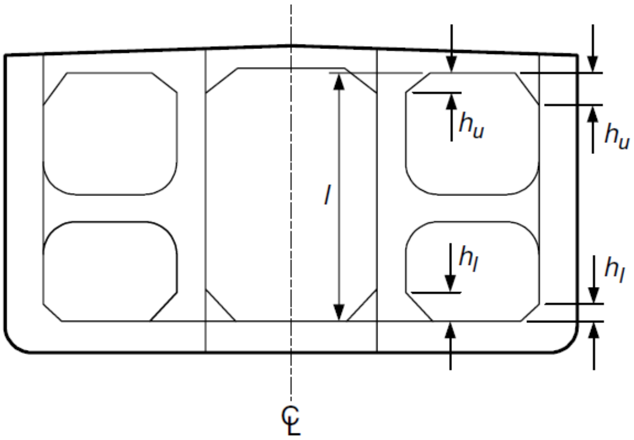


Figure 4.5: Sample of primary support member. (Mansour & Liu, 2008)

4.3.1. Transversally framed cargo hold

In this structural system, the spacing between frames are smaller than in the longitudinally framed structure. The main structure of this system is the same as the longitudinally framed, with keel and side girders. It is known that this system presents better vibration absorption than the longitudinally framed. The drawbacks for this system are that it is heavier and present lower longitudinal resistance. Figure 4.6 show one example of a transversally framed ship and the nomenclature of the structural elements. Note that the frames are closely spaced.

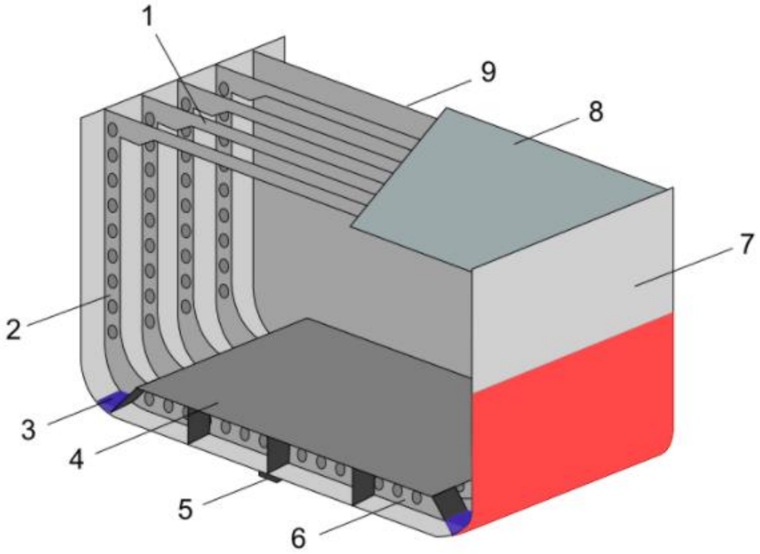


Figure 4.6: Transversely-framed ship. 1. Beam 2. Frame 3. Bilge 4. Inner Bottom 5. Keel 6. Outer bottom 7. Shell plating 8. Deck plating 9. Bulkhead. Source: (Naval Gazing, 2021)

4.3.2. Longitudinally framed cargo hold

Longitudinally framed structures, such as the one shown in Figure 4.7, consists of frames spaced with a distance S from each other and with several longitudinal stiffeners spaced with a b distance between each other. The main structure, such as Tight Bulkheads (TBHD), centre girder and side girders remain the same as in the transversally framed structure. Longitudinally framed structures usually have the interframe spacing greater than in transversally framed structure and receive this name due to the longitudinal disposition of the stiffeners. The L and B stands for the cargo hold length and the breadth, respectively.

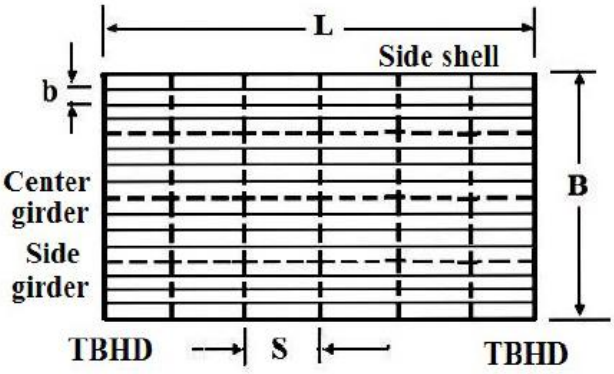


Figure 4.7: Longitudinally framed bottom structure. Source: (Shama, 2013)

Note that as the ship increases in length the second moment of area of the midship section has to withstand the vertical bending moments that the hull girder is subjected to, therefore adding longitudinal elements such as the stiffeners contribute to the increase in the second moment of area of the midship section. “Longitudinal framing was adopted at an early date for the larger ships and revision of the construction rules in the late 1960’s” (Eyres, 2007)

4.4. LOADS

The load cases to be considered in the design process should take into account the load scenarios indicated in (DNV-Chap4, 2021). The strength assessment of the vessel is done, taking into account static and dynamic loads that are present in the form of hull girder loads and local loads.

4.4.1. Hull girder loads

Weight and buoyancy forces along the hull girder cause shear force and vertical bending moment. Figure 4.8 clearly indicates that the buoyancy curve, that follows the curve of sectional areas of the hull, and the weight distributed longitudinally, originated by lightship weight plus the cargo, have resultants indicated with dashed arrows, causing the ship to bend, in this specific case in hogging. When the deformed ship has concave side upwards, it is said to be in sagging. (Rawson & Tupper, 2005)

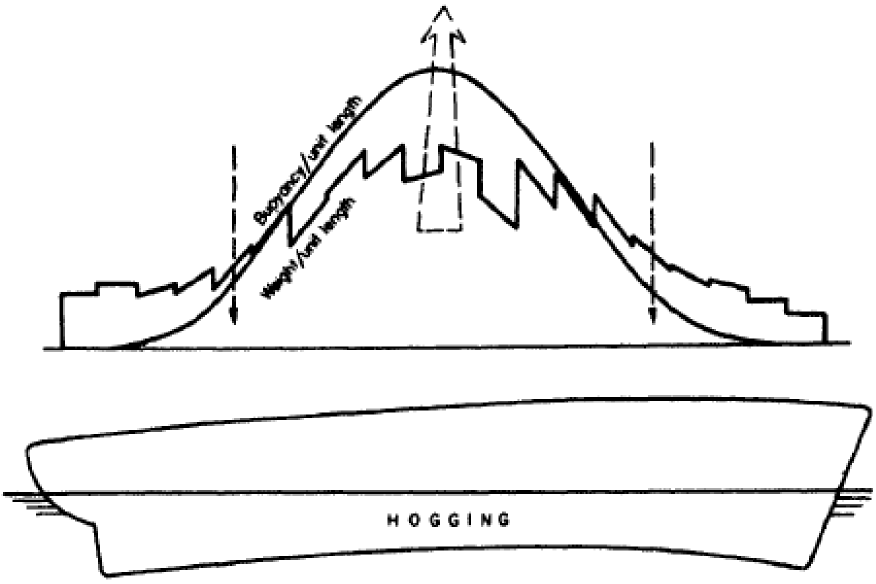


Figure 4.8: Still water hogging. Source: (Rawson & Tupper, 2005)

When a wave of the same length as the ship has its crest amidship causing the ship to have even higher buoyancy amidship than in Figure 4.8, then the ship is subjected to a wave bending moment of hogging. The wave bending moment of sagging is caused by a wave of the same length as the ship with its trough amidship, decreasing the buoyancy in this region. (Okumoto, Takeda, Mano, & Okada, 2009)

The wave bending moment can be calculated according to IACS (International Association of Classification Societies) by Eq. 4.1 and 4.2.

$$M_{w-h} = 0.19 C_1 C_2 L_1^2 B C_b^{`} \qquad \text{Eq. 4.1}$$

$$M_{w-s} = -0.11 C_1 C_2 L_1^2 B (C_b^{`} + 0.7) \qquad \text{Eq. 4.2}$$

Where,

- C_1 is given by Eq. 4.3;
- C_2 is distribution factor along ship length as specified in Figure 4.9;
- L_1 is ship length [m];
- B is ship breadth [m];
- C_b` is block coefficient [-].

$$C_1 = \begin{cases} 10.75 - \left(\dfrac{300 - L_1}{100}\right)^{1.5} & \mathrm{L_1} \leq 300\,\mathrm{m} \\ 10.75 & 300\,\mathrm{m} \leq \mathrm{L_1} \leq 350\,\mathrm{m} \\ 10.75 - \left(\dfrac{L_1 - 350}{100}\right)^{1.5} & 350\,\mathrm{m} \leq \mathrm{L_1} \end{cases} \qquad \text{Eq. 4.3}$$

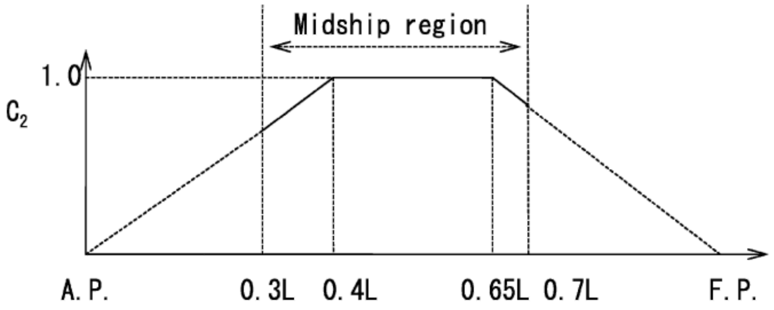


Figure 4.9: Coefficient C_2 : distribution factor. Source: (Okumoto, Takeda, Mano, & Okada, 2009)

Note that the from Eq. 4.1 and 4.2, hogging is indicated as positive and sagging as negative, following the sign convention indicated in (DNV-Chap4, 2021).

The deflection undergone by the ship in hogging and sagging is expressive and can be seen in (Petrov, 2021).

4.4.2. Local loads

Local loads include external loads, such as the one shown in Figure 4.10, which is water pressure, including green see water. Internal loads such as boundaries of ballast water tanks, watertight bulkheads are also local loads. Machinery must also be taken into account as local loads.

Regarding green water, the angle of the bow flare can have an impact on this matter, “The observation of Hong et al. is in line with the observation that increased bow flare reduces the deck wetness (O’Dea & Walden 1984) but increases the relative motion, which apparently is caused by increased dynamic swell-up (Swaan & Vossers 1961; Takagi & Naito, 1993; Watanabe et al. 1989).” (Mansour & Liu, 2008).

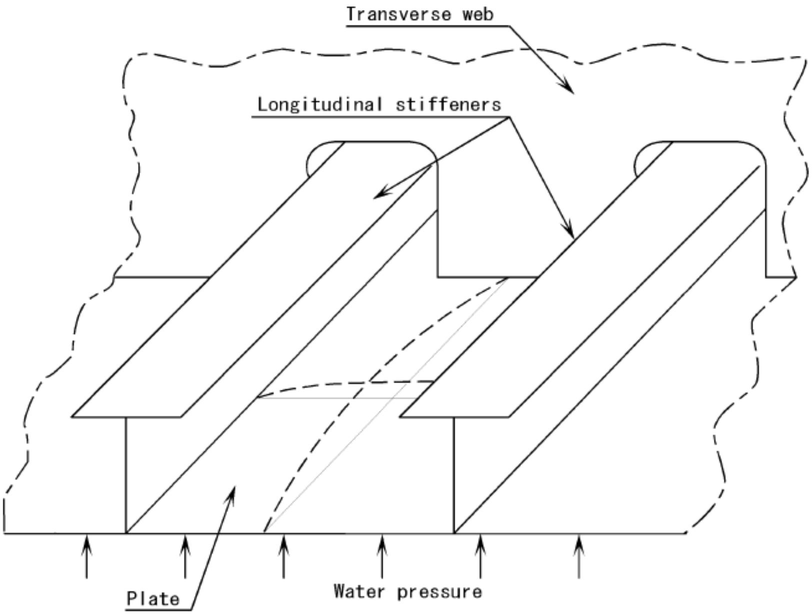


Figure 4.10: Bottom structure under water pressure. Source: (Okumoto, Takeda, Mano, & Okada, 2009)

Note that for vertical loads, the total force should be determined by the summation of static plus dynamic (S + D), in case of this design load case scenario, as shown in Eq. 4.4. (DNV-Chap4, 2021).

$$F_{U\text{-}z} = F_{U\text{-}s} + m_U \, a_{z\text{-}U} \qquad \text{Eq. 4.4}$$

Where $F_{U\text{-}s}$ is the static force equal to the mass of the object times the acceleration of the gravity, and in the second term, $a_{z\text{-}U}$, is given depending on the load combination for envelope accelerations, given in sec 3.3.4 of (DNV-Chap4, 2021).

Using local loads is convenient for designing structural elements, starting from plate thickness, to longitudinal stiffeners, guiders and frames. Formulations involving local loads for scantling are available in (DNV-Chap6, 2021). Special attention should be given to the load scenario described in section 2.1.1 of (DNV-Chap4, 2021).

Liquid cargoes may cause significant pressure due to sloshing in tanks that are partially filled. This load is amplified when the natural vibration of the ship motion is in resonance with the motion of the liquid in the tank. (Mansour & Liu, 2008)

4.5. SCANTLING ACCORDING TO DNV RULES

This section explains how the plate thickness and longitudinal stiffeners are calculated according to DNV rules.

It is important to note that the local scantling proposed by the class society is the minimum acceptable. There are vessel owners that stablishes an extra margin for the scantling, say 10%, due to corrosion (maintenance) and to extend the life of the ship. (Okumoto, Takeda, Mano, & Okada, 2009)

4.5.1. Plating

For selecting the net thickness of the plating subjected to lateral pressure, P, according to (DNV-Chap6, 2021), one can use Eq. 4.5. It is important to note that the net thickness is not the final plate thickness, because a corrosion margin should be applied for each side of the plate. The final plate should have a minimum thickness called gross thickness.

$$t = 0.0158\alpha_p b \sqrt{\frac{|P|}{C_a R_{eH}}} \qquad \text{Eq. 4.5}$$

Where:

- Ca = permissible bending stress coefficient for plates;
- b = breadth of plate panel;
- α_p = correction factor for the panel aspect ratio;
- $C_{a\text{-}max}$ = maximum permissible bending stress coefficient as defined in Table 1 of (DNV-Chap6, 2021).

For bilge plating, there are specifics requirements shown in the standard mentioned above, such as not having its thickness less than the adjacent plates. Plates located in the aft and forebody also have some specific requirements, but the scope of this work is limited to the cargo hold area.

4.5.2. Stiffeners

Plate stiffened with certain profiles act like beans subjected to lateral pressure. There are requirements according to (DNV-Chap6, 2021) for minimum net web thickness and for the minimum net section modulus, in [cm^3], as shown in Eq. 4.6.

$$Z = \frac{f_u |P| s\, \ell_{bdg}^2}{f_{bdg} C_s R_{eH}} \qquad \text{Eq. 4.6}$$

where:

- f_u = factor for unsymmetrical profiles, to be taken as:
  = 1.00 for flat bars and symmetrical profiles (T-profiles)
  = 1.03 for bulb profiles
  = 1.15 for unsymmetrical profiles (L-profiles)
- P = is the lateral pressure [kN/mm^2];
- s = stiffener spacing [mm];
- ℓ_{bdg} = effective bending span [m];
- f_{bdg} = bending moment factor as defined in Table 5 of to (DNV-Chap6, 2021);
- Cs = permissible bending stress coefficient as defined in Table 3 (DNV-Chap6, 2021);
- R_{eH} = specified minimum yield stress [N/mm^2];

Note that parameters such as the stiffener spacing, s, the section modulus, Z, of the longitudinal profile will vary linearly. Whilst varying the frames spacing, ℓ_{bdg}, the section modulus will vary not linearly but quadratically.

Primary support members have similar minimum net section modulus as in Eq. 4.6, the difference is that there is no factor for unsymmetrical profiles, f_u, and the spacing, s, is substituted for S, primary supporting member spacing.

4.6. LONGITUDINAL STRENGH OF HULL GIRDER

The longitudinal strength of a ship is a serious point of concern during the design and the entire life of the vessel. Failing the longitudinal strength check of a hull can cause the ship to break its back and sink. In general, this problem occurs in old vessels, due to corrosion (Okumoto, Takeda, Mano, & Okada, 2009). Several examples of this type of failure are reported in chapter 16 of (Hughes & Paik, 2010). Special attention should be paid for sagging condition in double hull tankers, “Because the sagging condition is the limiting critical ultimate strength condition for double hull tankers” (Mansour & Liu, 2008). Figure 4.11 shows the result of a plastic buckling.

Figure 4.11: Plastic buckling. Source: (DNV-128, 2021)

The required gross section modulus for the hull girder to resist the still water bending moment plus the wave bending moment is given by Eq. 4.7.

$$Z_{gr} = \frac{\left|M_{sw} + M_{wv}\right|}{\sigma_{perm}} 10^{-3} \qquad \text{Eq. 4.7}$$

Where σ_{perm} is the Permissible hull girder bending stress [N/mm^2] and is calculated using Eq. 4.8

$$\sigma_{perm} = \frac{175}{k} \quad \text{for } 0.3 \leq \frac{x}{L} \leq 0.7 \qquad \text{Eq. 4.8}$$

Where k is the material factor [-] equal to 1 for mild steel, and it is defined in item 2.2 of (DNV-Chap3, 2021).

In order to assess the ultimate bending moment of a hull girder, progressive collapse methodology can be used. This methodology takes into account the failure by yielding and buckling of the longitudinal elements until the ultimate vertical bending moment is achieved. Figure 4.12 shows four types of failure. Note that the negative values, according to the convention of signal refer to sagging and its ultimate bending moment is smaller than in hogging (positive bending moment). This happens because the scantling of the deck usually is lighter than in the bottom, because the local loads in the bottom are higher. (Yao, 2002)

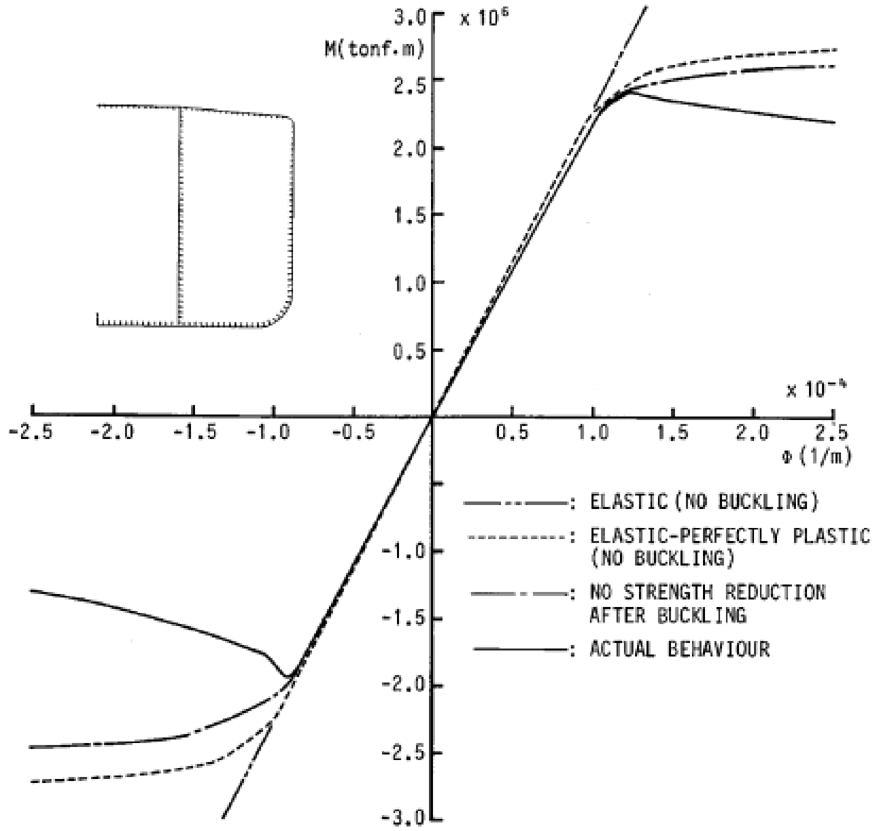


Figure 4.12: Progressive collapse behaviour of hull girder under longitudinal bending. Source: (Yao, 2002).

DNV presents three options for calculating ultimate bending moment, multi-step model, single-step model and direct approach. The multi-step model is an iteration process that adjusts the neutral axis height for every axial load increment. The single-step model achieves the value of the ultimate bending moment by calculating the maximum load of each element and summing them. The direct approach is using non-linear FEM. (DNV-128, 2021).

4.7. OPTIMIZATION

The scantling of a vessel is to provide enough strength with minimum material usage. “Optimum design is often assumed to mean the minimum weight structure capable of performing the required service.” (Rawson & Tupper, 2005)

Having unnecessary lightship weight increased due to poor selection of scantling, increases construction cost, often construction contracts are based in lightship weight. From the economical point of view, this causes unnecessary increase of CapEx and operation cost (OpEx). Throw-out the entire lifecycle of a vessel, operational cost values can be expressive. This philosophy is summarized by Eyres, “Since only cargo weight of the total deadweight is earning capital, other items should be kept to a minimum as long as the vessel fulfils its commitments" (Eyres, 2007)

The goal in structural optimization is to find the minimum weight within the constraints, which are usually mechanical strength, safety and cost. Regarding cost and weight, the design usually "involves a trade-off between weight and fabrication cost" (Hughes & Paik, 2010). In order to find the best solution, variables have to be chosen from the design space. These variables are usually discrete, such as "element size, material type, stiffener spacings." (Guedes Soares & Das, 2009).

Mathematically, structural optimization can be written as a multi-objective problem (for instance, minimum of weight and minimum cost) of M objectives, subjected to J constraints, where x is the design alternatives within the design space X, and is written as shown in Eq. 4.9.

$$\min_{x \in X} \{f_1(\boldsymbol{x}), \ldots, f_M(\boldsymbol{x}) | \boldsymbol{g}_j(\boldsymbol{x}) \geq 0, \quad j \in [1, J]\} \qquad \text{Eq. 4.9}$$

Note that the weight of a cargo hold of a ship is dependent on the overall dimensions, plate thickness, material, stiffener size and spacing, frame size and spacing among others. This function is not elementary and may present discontinuities, for instance the thickness of the plates is available only in discrete way, making Eq. 4.9 not applicable for this investigation.

Optimization codes can be used for optimization of ship structures, such as NSGA-II, VOP (Guedes Soares & Das, 2009), LBR-5. The European Research Council (ERC) provided funding to for the development of a project called Holiship, which "the aim is to develop tools and optimization methodologies for the initial and contract design phase in terms of structure and producibility aspects." (Rigo, et al., 2017)

5. SCANTLING CALCULATION (NAUTICUS HULL)

This chapter summarises the results from Nauticus Hull. Following the methodology presented to approach this study, the number of frames will be altered to assess its influence in the weight of a cargo hold of the crude oil tanker. After that, the influence of the spacing of the longitudinal stiffeners will be evaluated against the weight of the cargo hold.

5.1. DESIGN LOADS

In order to assess the strength of the hull girder, it was supplied for the design office the still water bending moment and the shear force as shown in Table 5.1 and Table 5.3. Wave bending moment and wave shear forces are given in Table 5.2 and Table 5.4 by the rule. Note that in Table 5.1 the user specified values in the last column are approximately 28% and 9% higher than the rules values. The user specified values are more conservative.

One might suggest that the wave bending moment indicated in Table 5.2 for Hogging is smaller than in Stillwater. This happens because the value shown for wave bending moment is only for the wave, and does not include the Stillwater buoyancy, that is shown in Eq. 5.2, the wave bending moment and the Stillwater bending movement are added to calculate the gross section modulus Z_{gr}. Note that these tables follow the sign convention presented in Figure 5.1.

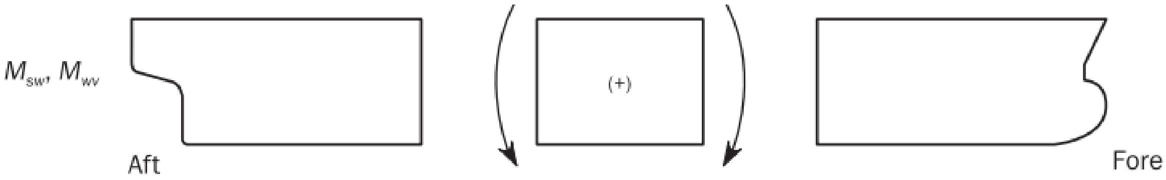


Figure 5.1: Sign conventions for bending moments Msw, Mwv. Source: (DNV-Chap4, 2021)

Table 5.1: Stillwater Bending Moments [kNm]. Source: Nauticus Hull Report.

Condition		**Guidance values**	**User specified**
Seagoing	Sagging	-4910869	-6300000
	Hogging	6385244	7000000

Table 5.2: Wave Bending Moments [kNm]. Source: Nauticus Hull Report.

Condition		**Rule values**
Seagoing	Sagging	-5235853
	Hogging	4931978

Table 5.3: Stillwater Shear Forces [kN]. Source: Nauticus Hull Report.

Condition		User specified
Seagoing	Positive	202801
	Negative	-203108

Table 5.4: Wave Shear Forces [kN]. Source: Nauticus Hull Report.

Condition		Rule values
Seagoing	Positive	31917
	Negative	-31917

Usually, hogging is well understood when the wave crest is amidship. One question that might arise is what causes hogging in Stillwater. This is easily understood considering the loading condition when the cargo holds are empty. The aft part of the ship contains extra loads due to the living quarters, bridge, engine, generators, etc. This extra load would cause the ship to trim by the stern to an unacceptable limit. In order to counter balance this extra load, the ballast tanks in the bow have to be filled causing the ship to be loaded in the two extremities. Combining this load condition to the buoyancy the ship will present hogging.

5.2. MATERIAL

The material used for all the elements of construction (plates, stiffeners and frames) is the VL-32 certified by DNV. This material has a yielding strength of 315 [MPa]. Using the same steel grade for all the elements makes the analysis easier although it is not always practiced by the industry. DNV rules require high tensile steel for some parts of the ship, other parts subjected to less stress can use mild steel, VL-NS with yielding strength of 235 [MPa]. This is specified in item 1.6 of (DNV-Chap5, 2021).

5.3. CHANGING THE NUMBER OF FRAMES

The first structural elements to be altered are the frames. The original cargo hold has 50800mm of length and is divided into 10 spacings, what means that the number of frames is 9. “Tankers with two or more longitudinal bulkheads may have wing and centre tank lengths up to 20% of the ship’s length” (Eyres, 2007). An odd number of frames is required to ensure that one frame will be in the middle of the cargo hold. This frame in the middle is used as swash bulkhead, with the function of reducing sloshing.

Primary supporting members subjected to lateral pressure have the section modulus calculated according to Eq. 5.1, defined by (DNV-Chap6, 2021). It is observed that section modulus is a quadratic function of the effective bending span ℓ_{bdg}. Therefore, as the number of frames is reduced, the section modulus is not going to increase linearly.

$$Z = 1000\frac{\left|P\right| S\,\ell_{bdg}^2}{f_{bdg} C_s R_{eH}} \qquad \text{Eq. 5.1}$$

Analysing the midship section and checking the results in Nauticus Hull, it is clear that the scaling of the original ship is oversized having as reference the rules from DNV. Some details indicated in the original drawings shows the reason for this. The original drawings are from the last stage of the design (detailed), therefore other loads such as reaction forces due to docking blocks supporting the ship self-weight on a dry dock, other deck loads and so on are already considered.

5.3.1. Number of Frames: 9 (Original reduced)

The scope of this work includes only the analyses of the design in its early stages. In order to compare the change in weight of the cargo hold due to the variation of the number of frames, it is necessary to calculate the minimum scantling of the midship section with the same number of frames as the original, according to DNV rules. This would be equivalent from returning from the detailed design to the preliminary design but is important to obtain an accurate comparison of the weight change.

The crude oil tanker has tanks of 50.8 [m] of length and is originally divided longitudinally into 10 spacings of 5080 [mm], that is the spacing between frames. This tank has one oil tight transversal bulkhead in the start and one in the end of the tank. In the longitudinal middle of the tank there is one swash bulkhead. Four frames are placed between the aft oil tight bulkhead and the swash bulkhead. The same concept applies from the swash bulkhead and the forward oil tight bulkhead, that is, more four frames are placed in this space.

Using Nauticus Hull, a software developed by DNV, it is possible to determine the scantling of the longitudinal stiffeners and plates positioned as shown in Figure 5.2. The numbers close to the stiffeners are just the stiffeners identification (ID). Note that the number between square brackets are the thickness of the plates in millimetres and the small triangle shows where the plate starts and ends.

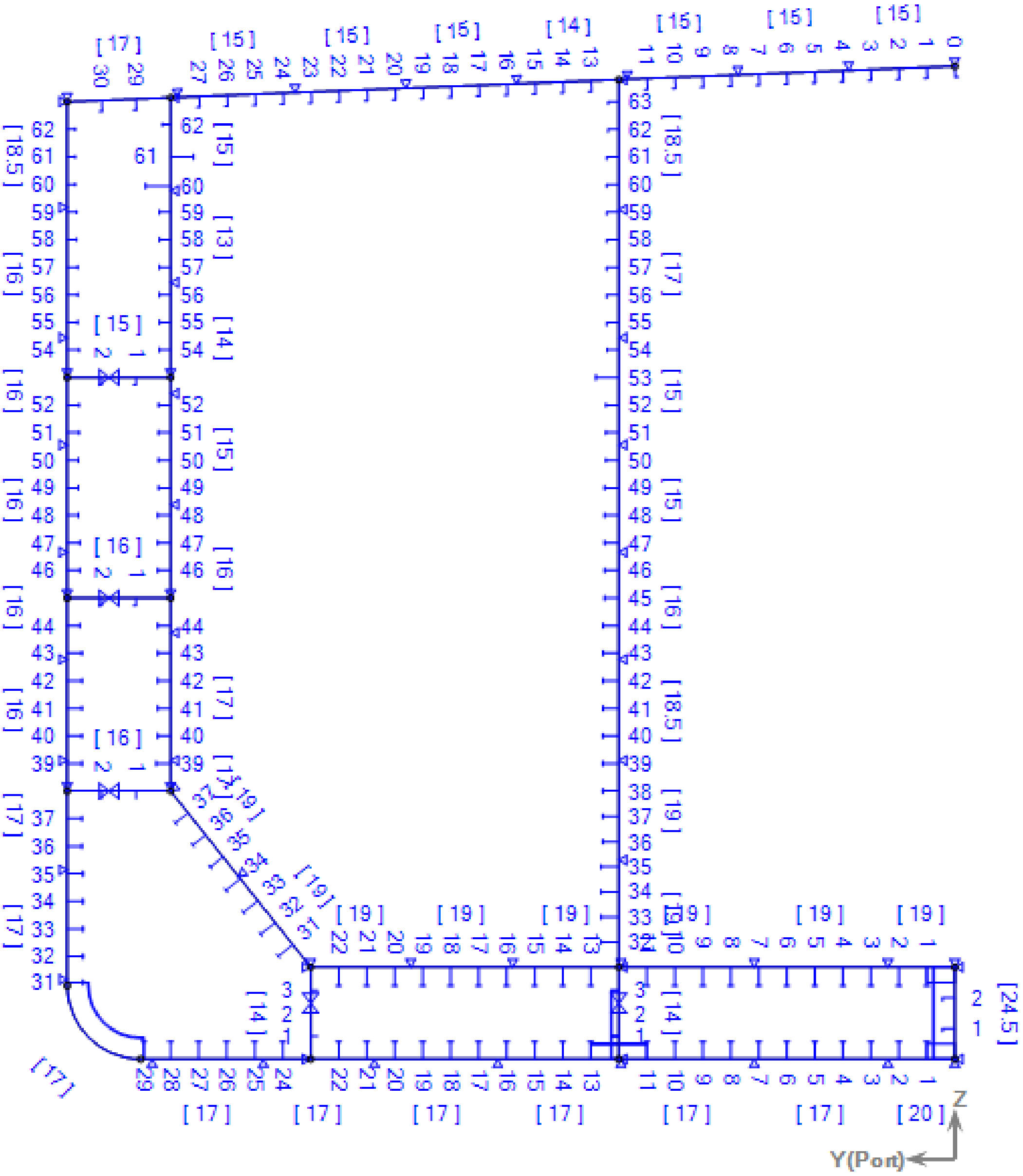
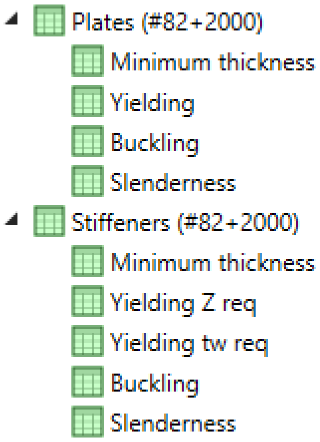


Figure 5.2 : Midship section plot. Source: Report produced by software Nauticus Hull.

The stiffeners and plates dimensions are chosen by trial and error and are checked against several criteria such as Minimum thickness, Yielding, Buckling and Slenderness for plates and Minimum thickness, yielding, section modulus (Z_{req}), Yielding web thickness (tw_{req}), Buckling and Slenderness for stiffeners, as shown in Figure 5.3.



- Plates (#82+2000)
  - Minimum thickness
  - Yielding
  - Buckling
  - Slenderness
- Stiffeners (#82+2000)
  - Minimum thickness
  - Yielding Z req
  - Yielding tw req
  - Buckling
  - Slenderness

Figure 5.3: Criteria for plates and Stiffeners. Source: Nauticus Hull.

Nauticus Hull will display the usage factor of these criteria, as shown in the example of Figure 5.4. In this particular case, the Yielding section modulus (Z_{req}) is shown, as can be seen in the upper left corner of this image. Note that the elements stiffeners in the deck seem to be oversized, but in fact the usage factor for buckling is close to 100%. One must check all the five criteria in order to decide the minimum dimensions of the stiffeners and plates.

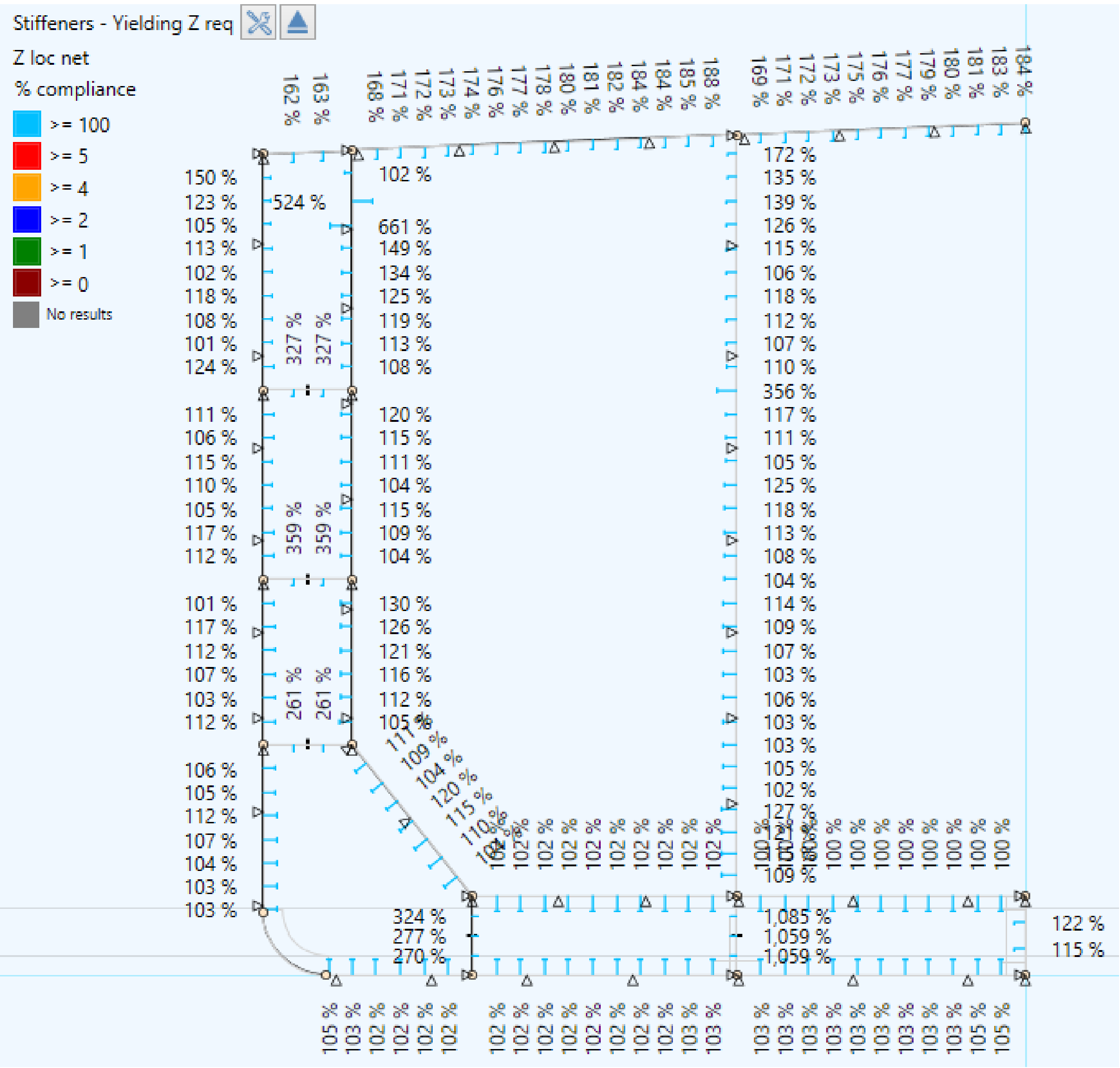


Figure 5.4: Yielding Criterion for Stiffeners. Source: Nauticus Hull.

Nauticus Hull also produce a report from which Table 5.5 was extracted. This feature is important and useful to calculate the volume and the weight of the continuous longitudinal elements, such as plates and stiffeners, from the cross-sectional area as well as to validate the results. The cross-sectional area is used in Table 5.41 to calculate the weight. Note that from Table 5.5 the cut-outs are disregarded, what is a source for error in the weight calculation as well as the welding pass. These weight differences are considered to be negligible here.

Table 5.5 : Cross section properties. Source: Nauticus Hull Report.

		Effective Cut-outs subtracted		**Gross** Cut-outs disregarded	
		as built	net (50% corr)	as built	net (50% corr)
Cross sectional area of the longitudinal elements	cm^2	90559	83715	90559	83715
Horizontal dist. from C.L. to vertical neutral axis, Yn	m	0.000	0.000	0.000	0.000
Vertical distance from B.L. to horizontal neutral axis, Zn	m	13.216	13.194	13.216	13.194
Vertical moment of inertia, Iy	m^4	1230.344	1138.810	1230.345	1138.811
Horizontal moment of inertia , Iz	m^4	3555.807	3288.305	3555.815	3288.313
Product of inertia about the neutral axes, Iyz	m^4	-0.044	-0.040	-0.044	-0.040
Section Modulus, Bottom	m^3	93.097	86.312	93.097	86.312
Section Modulus, Strength deck at side (z = 31250mm)	m^3	68.222	63.071	68.222	63.071
Section Modulus, Equivalent deck line (z = 31250mm)	m^3	68.222	63.071	68.222	63.071
Section Modulus, at Side	m^3	122.616	113.391	122.616	113.392
First moment of the area above the neutral axis, S	m^3	47.259	43.713	47.259	43.713
I/S	m	26.034	26.052	26.034	26.052

A summary of the dimensions, type and yield strength of the stiffeners are shown in Table 5.6. The first column, ID From – to, show the groups of stiffness that have always the same scantling. It is seen that the stiffeners 1 to 29 are equal in the bottom, see Figure 5.2. In the inner bottom the stiffeners 1 to 22 are also equal. These groups are kept equal to ease the construction process. It would be more complicated for the warehouse to store a lot of different plates, for transporting these plates to the shops and finally to assembly the panels. Standardising the stiffeners in groups makes operation easier in the construction process.

Table 5.6 – Cross section stiffeners. Source: Nauticus Hull Report.

ID From - To	**Profile Type**	**Dimensions**	**Yield stress** [N/mm^2]
Outer shell			
1 - 29	Built up T from plates	570 x 180 x 11.5 x 20	315
31 - 35	Built up T from plates	520 x 180 x 11.5 x 20	315
36 - 39	Built up T from plates	474 x 150 x 12 x 24	315
40 - 43	Built up T from plates	474 x 130 x 11.5 x 24	315
44 - 47	Built up T from plates	420 x 150 x 11.5 x 20	315
48 - 50	Built up T from plates	370 x 150 x 11.5 x 20	315
51 - 54	Built up T from plates	398 x 120 x 11.5 x 18	315
55 - 57	Built up T from plates	346 x 120 x 11.5 x 16	315
58 - 59	Built up T from plates	316 x 100 x 11.5 x 16	315
60 - 62	Built up T from plates	266 x 100 x 12 x 16	315
Strength Deck			
0 - 30	WeldedAngle	360 x 100 x 12 x 20	315
Inner bottom & inner side			
1 - 22	Built up T from plates	600 x 180 x 12 x 20	315
31 - 34	Built up T from plates	604 x 150 x 11.5 x 24	315
35 - 37	Built up T from plates	524 x 150 x 11.5 x 24	315
39 - 39	Built up T from plates	474 x 150 x 11.5 x 24	315
40 - 44	Built up T from plates	425 x 180 x 11.5 x 25	315
46 - 48	Built up T from plates	420 x 150 x 11.5 x 20	315
49 - 52	Built up T from plates	398 x 150 x 11.5 x 18	315
54 - 59	Built up T from plates	366 x 150 x 11.5 x 16	315
60 - 60	Built up T from plates	816 x 205 x 15 x 16	315
61 - 61	Built up T from plates	751 x 185 x 15 x 16	315
62 - 62	Built up T from plates	266 x 100 x 12 x 16	315
LongPlaneBulkhead10980_10980			
1 - 3	Flatbar	240 x 15	315
32 - 35	Built up T from plates	574 x 150 x 11.5 x 24	315
36 - 40	Built up T from plates	520 x 150 x 11.5 x 20	315
41 - 44	Built up T from plates	518 x 150 x 11.5 x 18	315
45 - 49	Built up T from plates	468 x 150 x 11.5 x 18	315
50 - 52	Built up T from plates	420 x 120 x 11.5 x 20	315
53 - 53	Built up T from plates	748 x 185 x 14 x 18	315
54 - 54	Built up T from plates	380 x 120 x 11.5 x 20	315
55 - 57	WeldedAngle	400 x 120 x 13 x 18	315
58 - 61	WeldedAngle	400 x 100 x 11.5 x 18	315
62 - 63	WeldedAngle	350 x 100 x 13 x 18	315

The section modulus required is calculated by Nauticus using Eq. 5.2 and is given in Table 5.7.

$$Z_{gr} = \frac{|M_{sw} + M_{wv}|}{\sigma_{perm}} 10^{-3} \qquad \text{Eq. 5.2}$$

Where σ_{perm} is the Permissible hull girder bending stress [N/mm^2] and is calculated using Eq. 5.3.

$$\sigma_{perm} = \frac{175}{k} \quad \text{for } 0.3 \leq \frac{x}{L} \leq 0.7 \qquad \text{Eq. 5.3}$$

Where k is the material factor equal to 0.78 [-] in this case, and it is defined in item 2.2 of (DNV-Chap3, 2021).

Table 5.7: Section Modulus. Source: Nauticus Hull Report.

Operation	**Position**	**Condition**	**M_{sw} [kNm]**	**M_{wv} [kNm]**	**σ_{perm} [MPa]**	**$Z_{requred}$ [m^3]**	**Z_{actual} [m^3]**	**OK?**
Seagoing	Bottom	Sagging	-6300000	-5235853	224.36	51.42	93.10	Yes
		Hogging	7000000	4931978	224.36	53.18	93.10	Yes
	Equivalent deck line	Sagging	-6300000	-5235853	224.36	51.42	68.22	Yes
		Hogging	7000000	4931978	224.36	53.18	68.22	Yes

In order to assess the hull girder longitudinal stress σ_{hg}, shown in Table 5.8, one has to compare it with the permissible longitudinal stress, calculated with Eq. 5.4.

$$\sigma_{hg\text{-}perm} = \frac{205}{k} \qquad \text{Eq. 5.4}$$

The hull girder longitudinal stress σ_{hg}, is calculated by the addition of two components as stated in Eq. 5.5, the longitudinal stress for Stillwater and the longitudinal stress caused by the waves.

$$\sigma_{hg} = \sigma_{hg\text{-}sw} + \sigma_{hg\text{-}dyn} \qquad \text{Eq. 5.5}$$

In Table 5.8, column 3, the weakest plate is indicated as Plate0, as expected this is the highest plate in the midship section shown in Figure 5.2, caused by the camber in the deck. One also notes that the hull girder longitudinal stress is within the acceptable limit.

Table 5.8: Longitudinal normal stress, σ_{hg}

Operation	**Decisive condition**	**Weakest Plate**	**σ_{hg} [N/mm^2]**	**$\sigma_{hg\text{-}perm}$ [N/mm^2]**	**OK?**
Seagoing	ExtremeSea_SD, Full load, HSM_2	Strength Deck: Plate0	201.34	262.82	Yes

The shear stress τ_{hg}, is calculated with item 3.2 of (DNV-Chap5, 2021). The weakest plate, in other words, the plate subjected to highest shear stress on the entire midship section, in this case is located in the longitudinal bulkhead that separates the wing tank from the centre tank, approximately in the middle of the cargo hold height. This is intuitive, since shear stress increases up to the neutral axis, where it is its maximum.

Table 5.9: Shear stress, τ_{hg}

Operation	**Decisive condition**	**Weakest Plate**	τ_{hg} **[N/mm^2]**	$\tau_{hg\text{-}perm}$ **[N/mm^2]**	**OK?**
Seagoing	ExtremeSea_SD, Full load, HSM_1	LongPlaneBulkhead 10980_10980: Plate5	-130.60	153.85	Yes

In section 2.2 of (DNV-Chap5, 2021) is stated that the total vertical hull girder shear capacity Q_R must be greater than the summation of the vertical wave shear force Q_{WV}, and still water shear force Q_{SW}.

Table 5.10: Shear Capacity.

Operation	**Weakest Plate**	f_{har} [-]	Q_{sw} [kN]	Q_{wv} [kN]	Q_R [kN]	**OK?**
Seagoing	LongPlaneBulkhead10980_10980: Plate5	N/A	202801	31917	275944	Yes

Where,

M_{sw}	Permissible hogging and sagging vertical still water bending moment [kNm]
M_{wv}	Vertical wave bending moment [kNm]
σ_{perm}	Permissible hull girder bending stress [N/mm^2]
$Z_{requred}$	Required section modulus at deck or bottom [m^3]
Z_{actual}	Section modulus at deck or bottom [m^3]
Q_{sw}	Permissible positive or negative still water shear force [kN]
Q_{wv}	Vertical wave shear force [kN]
Q_R	Total vertical hull girder shear capacity [kN]

The hull girder ultimate bending capacity, M_U, is calculated using DNVGLCG-0128 Buckling or by non-linear FE. The condition shown in Eq. 5.6 must be satisfied as shown in Table 5.11.

$$M \le \frac{M_U}{\gamma_R} \qquad \text{Eq. 5.6}$$

Where γ_R is the partial safety factor [-], given by the product of γ_w and γ_{DB}.

Table 5.11: Hull Girder Ultimate Strength

H/S	**γ_{DB}**	**γ_W**	**γ_R**	**$M_{sw\text{-}U}$** [kNm]	**M_{wv}** [kNm]	**M** [kNm]	**M_U** [kNm]	**US** [%]	**OK?**
Hog	1.10	1.20	1.21	7000000	4931978	12918374	23296301	149	Yes
Sag	1.00	1.20	1.10	-6300000	-5235853	-12583024	-17339028	125	Yes

Abbreviations are shown in Table 5.12.

Table 5.12: Abreviation of Table 5.11

γ_M	Partial safety factor for the vertical hull girder ultimate bending capacity, covering material, geometric and strength prediction uncertainties
γ_S	Partial safety factor for the still water bending moment
DLS	Design load scenario (S+D): A = Msw-h or Msw-s, B = Maximum sagging still water bending moment for operational seagoing homogeneous full load condition
H/S	Hogging or Sagging
γ_{DB}	Partial safety factor for the vertical hull girder ultimate bending capacity, covering the effect of double bottom bending,
γ_W	Partial safety factor for the vertical wave bending moment
γ_R	Partial safety factor for the vertical hull girder ultimate bending capacity
$M_{sw\text{-}U}$	Permissible still water bending moment, in kNm, in hogging and sagging conditions at the hull transverse section
M_{wv}	Vertical wave bending moment, in kNm, in hogging and sagging conditions at the hull transverse section
M	The vertical hull girder bending moment, M in hogging and sagging conditions, to be considered in the ultimate strength check
M_U	Vertical hull girder ultimate bending capacity
US	100 MU / (M γR)
OK?	No! if US < 100, else Yes

5.3.2. Number of Frames: 11

In this section two frames are added to the original cargo hold, one each side of the swash bulkhead. This means that the length of the cargo hold (50.8m) will be divided by 12 spaces, what gives an interframe space of 4233.3 [mm]. By adding these 2 frames, consequently reducing the interframe spacing it will decrease the dimensions of the longitudinal stiffeners, consequently its weight. But, the weight of these 2 frames should also be taken into account, that is what is done in the section Summary.

The midship section of the cargo hold with 11 frames has the same overall dimensions (breadth and height) what is changed is the thickness of the elements, such as plates and longitudinal stiffeners. This means that the midship section looks like Figure 5.2, with the same number of longitudinal elements stiffeners.

Altering the stiffeners and plates dimensions affects the midship section properties, such as cross section area and section modulus, as shown in Table 5.13.

Table 5.13: Cross section data. Source: Nauticus Hull Report.

		Effective Cut-outs subtracted		**Gross** Cut-outs disregarded	
		as built	net (50% corr)	as built	net (50% corr)
Cross sectional area of the longitudinal elements	cm^2	86025	79380	86025	79380
Horizontal dist. from C.L. to vertical neutral axis, Yn	m	0.000	0.000	0.000	0.000
Vertical distance fom B.L. to horizontal neutral axis, Zn	m	13.356	13.332	13.356	13.332
Vertical moment of inertia, Iy	m^4	1177.539	1087.803	1177.540	1087.804
Horizontal moment of inertia , Iz	m^4	3414.431	3154.360	3414.439	3154.367
Product of inertia about the neutral axes, Iyz	m^4	-0.045	-0.041	-0.045	-0.041
Section Modulus, Bottom	m^3	88.165	81.591	88.166	81.591
Section Modulus, Strength deck at side (z = 31250mm)	m^3	65.806	60.711	65.807	60.711
Section Modulus, Equivalent deck line (z = 31250mm)	m^3	65.806	60.711	65.807	60.711
Section Modulus, at Side	m^3	117.741	108.772	117.741	108.773
First moment of the area above the neutral axis, S	m^3	45.113	41.647	45.113	41.648
I/S	m	26.102	26.119	26.102	26.119

The new scantling of the longitudinal stiffeners are shown in Table 5.14. Note that the stiffeners are grouped in the same ways as previously.

Table 5.14 : Cross section stiffeners. Source: Nauticus Hull Report.

ID **From - To**	**Profile Type**	**Dimensions**	**Yield stress** [N/mm^2]
Outer shell			
1 - 29	Built up T from plates	517 x 150 x 11.5 x 17	315
31 - 31	Built up T from plates	468 x 150 x 11.5 x 18	315
32 - 35	Built up T from plates	468 x 150 x 12 x 18	315
36 - 39	Built up T from plates	438 x 150 x 12 x 18	315
40 - 43	Built up T from plates	416 x 150 x 11.5 x 16	315
44 - 47	Built up T from plates	418 x 120 x 11.5 x 18	315
48 - 50	Built up T from plates	368 x 100 x 11.5 x 18	315
51 - 54	Built up T from plates	338 x 100 x 12 x 18	315
55 - 57	Built up T from plates	314 x 100 x 11.5 x 14	315
58 - 59	Built up T from plates	283 x 100 x 11.5 x 13	315
60 - 62	Built up T from plates	253 x 100 x 12 x 13	315
Strength Deck			
0 - 30	WeldedAngle	350 x 120 x 12 x 18	315
Inner bottom & inner side			
1 - 22	Built up T from plates	567 x 150 x 11.5 x 17	315
31 - 31	Built up T from plates	566 x 150 x 11.5 x 16	315
32 - 32	Built up T from plates	567 x 150 x 11.5 x 17	315
33 - 34	Built up T from plates	566 x 150 x 11.5 x 16	315
35 - 37	Built up T from plates	467 x 150 x 11.5 x 17	315
39 - 44	Built up T from plates	418 x 150 x 11.5 x 18	315
46 - 48	Built up T from plates	416 x 120 x 11.5 x 16	315
49 - 52	Built up T from plates	368 x 100 x 11.5 x 18	315
54 - 59	Built up T from plates	336 x 100 x 12 x 16	315
60 - 60	Built up T from plates	816 x 205 x 15 x 16	315
61 - 61	Built up T from plates	751 x 185 x 15 x 16	315
62 - 62	Built up T from plates	366 x 100 x 11.5 x 16	315
LongPlaneBulkhead10980_10980			
1 - 3	Flatbar	240 x 15	315
32 - 35	Built up T from plates	516 x 150 x 11.5 x 16	315
36 - 40	Built up T from plates	418 x 150 x 11.5 x 18	315
41 - 44	Built up T from plates	416 x 150 x 11.5 x 16	315
45 - 49	Built up T from plates	416 x 120 x 13 x 16	315
50 - 52	Built up T from plates	415 x 120 x 11.5 x 15	315
53 - 53	Built up T from plates	748 x 185 x 14 x 18	315
54 - 54	Built up T from plates	413 x 120 x 11.5 x 13	315
55 - 57	WeldedAngle	370 x 100 x 11.5 x 16	315
58 - 61	WeldedAngle	350 x 100 x 11.5 x 16	315
62 - 63	WeldedAngle	350 x 100 x 13 x 18	315

Regarding the load conditions, such as hull girder bending moments for Stillwater or in waves in hogging and sagging, shear forces, they are the same as in Number of Frames: 9 (Original reduced), and Table 5.1-5 are still valid.

The required section modulus $Z_{requred}$ is still identical to the previous sections, because the moments and permissible stress σ_{perm}, are unchanged. Nevertheless, the Z_{actual} is recalculated and shown in Table 5.15, meeting the requirement.

Table 5.15: Section modulus

Position	**Condition**	**M_{sw} [kNm]**	**M_{wv} [kNm]**	**σ_{perm} [N/mm^2]**	**$Z_{requred}$ [m^3]**	**Z_{actual} [m^3]**	**OK?**
Bottom	Sagging	-6300000	-5235853	224.36	51.42	88.17	Yes
	Hogging	7000000	4931978	224.36	53.18	88.17	Yes
Equivalent deck line	Sagging	-6300000	-5235853	224.36	51.42	65.81	Yes
	Hogging	7000000	4931978	224.36	53.18	65.81	Yes

The longitudinal normal stress σ_{hg}, is calculated and shown in Table 5.16. The permissible longitudinal stress, calculated with Eq. 5.4 remains the same. The weakest plate is still the Plate0 in the highest position of the main deck, due to the camber.

Table 5.16: Longitudinal normal stress, σ_{hg}

Operation	**Decisive condition**	**Weakest Plate**	**σ_{hg} [N/mm^2]**	**$\sigma_{hg-perm}$ [N/mm^2]**	**OK?**
Seagoing	ExtremeSea_SD, Full load, HSM_2	Strength Deck: Plate0	209.26	262.82	Yes

Shear stress and shear capacity is calculated and shown in Table 5.17 and Table 5.18, and meets the requirements as shown in the last column.

Table 5.17: Shear stress, τ_{hg}

Operation	**Decisive condition**	**Weakest Plate**	**τ_{hg} [N/mm^2]**	**$\tau_{hg-perm}$ [N/mm^2]**	**OK?**
Seagoing	ExtremeSea_SD, Full load, HSM_2	LongPlaneBulkhead 10980_10980: Plate5	-124.42	153.85	Yes

Table 5.18: Shear capacity

Operation	**Weakest Plate**	f_{har} [-]	Q_{sw} [kN]	Q_{wv} [kN]	Q_R [kN]	**OK?**
Seagoing	LongPlaneBulkhead10980_10980: Plate5	N/A	201158	31917	287006	Yes

Hull Girder Ultimate Strength, calculated by Nauticus Hull and shown in Table 5.19.

Table 5.19: Hull Girder Ultimate Strength

Cond	**H/S**	γ_R	$M_{sw\text{-}U}$ [kNm]	M_{wv} [kNm]	**M** [kNm]	M_U [kNm]	**US** [%]	**OK?**
Seagoing	Hog	1.21	7000000	4931978	12918374	22101529	141	Yes
Seagoing	Sag	1.10	-6300000	-5235853	-12583024	-16750558	121	Yes

It is observed that the US (usage) decreased compared to Table 5.11. This is an important factor that can be used to support a final decision if the weights of the proposed options are too close.

5.3.3. Number of Frames: 13

In this section, 4 frames will be added to the original cargo hold, two each side of the swash bulkhead, that is located in the middle of the cargo hold. With this modification, the total length of the cargo hold (50.8m) will be divided by 14 interframe spaces, what results in an interframe space of 3628.6 [mm].

The cross section of this arrangement will look like Figure 5.2, with the same number of longitudinal stiffeners. The only modification is the dimensions of the longitudinal stiffeners that might decrease, due to the increase of number of transversal frames. Table 5.20 shows the resultant cross section properties of the arrangement with 13 frames. The cross-section area of the longitudinal elements is the parameter used to calculate the weight. Note that this is the smallest area found so far.

Table 5.20: Cross section properties.

		Effective Cut-outs subtracted		**Gross** Cut-outs disregarded	
		as built	net (50% corr)	as built	net (50% corr)
Cross sectional area of the longitudinal elements	cm^2	82592	76278	82592	76278
Horizontal dist. from C.L. to vertical neutral axis, Yn	m	0.000	0.000	0.000	0.000
Vertical distance fom B.L. to horizontal neutral axis, Zn	m	13.426	13.399	13.426	13.399
Vertical moment of inertia, Iy	m^4	1141.240	1055.464	1141.241	1055.465
Horizontal moment of inertia , Iz	m^4	3272.236	3025.029	3272.244	3025.036
Product of inertia about the neutral axes, Iyz	m^4	-0.044	-0.040	-0.044	-0.040
Section Modulus, Bottom	m^3	85.005	78.771	85.005	78.772
Section Modulus, Strength deck at side (z = 31250mm)	m^3	64.026	59.127	64.027	59.127
Section Modulus, Equivalent deck line (z = 31250mm)	m^3	64.026	59.127	64.027	59.127
Section Modulus, at Side	m^3	112.837	104.313	112.838	104.313
First moment of the area above the neutral axis, S	m^3	43.591	40.285	43.591	40.285
I/S	m	26.180	26.200	26.180	26.200

Table 5.21 shows the dimensions of the groups of stiffeners.

Table 5.21: Cross section stiffeners.

ID From - To	Profile Type	Dimensions	Yield stress [N/mm^2]
Outer shell			
1 - 29	Built up T from plates	417 x 150 x 11.5 x 17	315
31 - 31	Built up T from plates	397 x 120 x 11.5 x 17	315
32 - 35	Built up T from plates	396 x 120 x 12 x 16	315
36 - 39	Built up T from plates	337 x 100 x 11.5 x 17	315
40 - 43	Built up T from plates	336 x 80 x 11.5 x 16	315
44 - 47	Built up T from plates	296 x 80 x 11.5 x 16	315
48 - 50	Built up T from plates	295 x 80 x 11.5 x 15	315
51 - 54	Built up T from plates	295 x 80 x 12 x 15	315
55 - 57	Built up T from plates	293 x 100 x 11.5 x 13	315
58 - 59	Built up T from plates	233 x 80 x 11.5 x 13	315
60 - 62	Built up T from plates	213 x 80 x 12 x 13	315
Strength Deck			
0 - 30	WeldedAngle	330 x 100 x 12 x 16	315
Inner bottom & inner side			
1 - 34	Built up T from plates	466 x 150 x 11.5 x 16	315
35 - 37	Built up T from plates	396 x 150 x 11.5 x 16	315
39 - 39	Built up T from plates	396 x 120 x 11.5 x 16	315
40 - 44	Built up T from plates	396 x 100 x 11.5 x 16	315
46 - 48	Built up T from plates	336 x 100 x 11.5 x 16	315
49 - 52	Built up T from plates	316 x 100 x 11.5 x 16	315
54 - 59	Built up T from plates	313 x 80 x 12 x 13	315
60 - 60	Built up T from plates	816 x 205 x 15 x 16	315
61 - 61	Built up T from plates	751 x 185 x 15 x 16	315
62 - 62	Built up T from plates	312 x 80 x 11.5 x 12	315
LongPlaneBulkhead10980_10980			
1 - 3	Flatbar	240 x 15	315
32 - 35	Built up T from plates	416 x 150 x 11.5 x 16	315
36 - 40	Built up T from plates	396 x 120 x 11.5 x 16	315
41 - 44	Built up T from plates	396 x 100 x 11.5 x 16	315
45 - 49	Built up T from plates	366 x 100 x 11.5 x 16	315
50 - 52	Built up T from plates	314 x 100 x 11.5 x 14	315
53 - 53	Built up T from plates	748 x 185 x 14 x 18	315
54 - 54	Built up T from plates	313 x 80 x 11.5 x 13	315
55 - 57	WeldedAngle	280 x 100 x 11.5 x 16	315
58 - 61	WeldedAngle	300 x 80 x 11.5 x 12	315
62 - 63	WeldedAngle	280 x 80 x 11.5 x 12	315

The section modulus Z_{actual}, is calculated and shown in Table 5.15. Its value is higher than the required section modulus, what makes it pass the criterion.

Table 5.22: Section modulus.

Position	**Condition**	**M_{sw} [kNm]**	**M_{wv} [kNm]**	**σ_{perm} [N/mm^2]**	**$Z_{requred}$ [m^3]**	**Z_{actual} [m^3]**	**OK?**
Bottom	Sagging	-6300000	-5235853	224.36	51.42	85.01	Yes
	Hogging	7000000	4931978	224.36	53.18	85.01	Yes
Equivalent deck line	Sagging	-6300000	-5235853	224.36	51.42	64.03	Yes
	Hogging	7000000	4931978	224.36	53.18	64.03	Yes

The longitudinal normal stress is one point of concern in the design, mistakes in this area can lead the vessel to catastrophic failures. The permissible longitudinal stress depends on the material factor k [-], used in the deck and it is constant for all the cases calculated in this work. The area subjected to the highest longitudinal stress is the most distant from the neutral axis and is the deck. Since the deck has a camber, the uppermost plate is located in the centre line, that is why the weakest plate is Plate0, as shown in Table 5.23.

Table 5.23: Longitudinal normal stress, σ_{hg}

Operation	**Decisive condition**	**Weakest Plate**	**σ_{hg} [N/mm^2]**	**$\sigma_{hg-perm}$ [N/mm^2]**	**OK?**
Seagoing	ExtremeSea_SD, Full load, HSM_2	Strength Deck: Plate0	214.92	262.82	Yes

The highest shear flow is located in the neutral axis, but the plate in the neutral axis is thicker than the plate above, what causes the highest shear stress to be in Plate5, as shown in Table 5.24.

Table 5.24: Shear stress, τ_{hg}

Operation	**Decisive condition**	**Weakest Plate**	**τ_{hg} [N/mm^2]**	**$\tau_{hg-perm}$ [N/mm^2]**	**OK?**
Seagoing	ExtremeSea_SD, Full load, HSM_2	LongPlaneBulkhead10980_10980: Plate5	-123.36	153.85	Yes

The shear capacity criterion is met, as shown in Table 5.25.

Table 5.25: Shear capacity

Operation	**Weakest Plate**	**f_{har}** [-]	**Q_{sw}** [kN]	**Q_{wv}** [kN]	**Q_R** [kN]	**OK?**
Seagoing	LongPlaneBulkhead10980_10980: Plate5	N/A	199201	31917	287600	Yes

Comparing the Hull Girder Ultimate Strength Usage factor (US), from the previous 2 section with this one in Table 5.26, it is possible to conclude that increasing the number of frames, decreases the overall strength of the hull girder. This is not an elementary conclusion, because although the dimensions of the longitudinal stiffeners decrease, the length of this elements decrease.

Furthermore, it was observed that increasing from 11 frames to 13 frames, the plate thickness did not change.

Table 5.26: Hull Girder Ultimate Strength

H/S	**γ_{DB}**	**γ_W**	**γ_R**	**M_{sw-U}** [kNm]	**M_{wv}** [kNm]	**M** [kNm]	**M_U** [kNm]	**US** [%]	**OK?**
Hog	1.10	1.20	1.21	7000000	4931978	12918374	21644465	138	Yes
Sag	1.00	1.20	1.10	-6300000	-5235853	-12583024	-16159020	117	Yes

5.3.4. Number of Frames: 7

In this section, instead of adding frames, two frames will be deduced from the original arrangement. The length of the cargo hold will be divided by 8 interframe spaces, resulting in an interframe spacing (ΔF) of 6350 [mm].

Altering the scantling of the cargo hold produces different midship section properties, as seen in Table 5.27. Only the dimensions of the longitudinal stiffeners were changed, the amount and spacing were not, resulting in a midship section similar to Figure 5.2.

Table 5.27: Cross section properties

		Effective Cut-outs subtracted		**Gross** Cut-outs disregarded	
		as built	net (50% corr)	as built	net (50% corr)
Cross sectional area of the longitudinal elements	cm^2	96039	88711	96039	88711
Horizontal dist. from C.L. to vertical neutral axis, Yn	m	0.000	0.000	0.000	0.000
Vertical distance fom B.L. to horizontal neutral axis, Zn	m	12.954	12.902	12.954	12.902
Vertical moment of inertia, Iy	m^4	1284.714	1186.633	1284.715	1186.634
Horizontal moment of inertia , Iz	m^4	3769.481	3481.664	3769.490	3481.672
Product of inertia about the neutral axes, Iyz	m^4	-0.046	-0.042	-0.046	-0.042
Section Modulus, Bottom	m^3	99.174	91.976	99.174	91.976
Section Modulus, Strength deck at side (z = 31250mm)	m^3	70.219	64.672	70.219	64.672
Section Modulus, Equivalent deck line (z = 31250mm)	m^3	70.219	64.672	70.219	64.672
Section Modulus, at Side	m^3	129.984	120.059	129.984	120.059
First moment of the area above the neutral axis, S	m^3	49.555	45.753	49.555	45.753
I/S	m	25.925	25.935	25.925	25.935

Table 5.28 shows the dimensions of the groups of longitudinal stiffeners per part such as outer shell (Bottom and side shell), upper deck, inner bottom and side and longitudinal bulkhead.

Table 5.28: Cross section Stiffeners.

ID **From - To**	**Profile Type**	**Dimensions**	**Yield stress** [N/mm^2]
Outer shell			
1 - 29	Built up T from plates	603 x 250 x 12 x 23	315
31 - 35	Built up T from plates	603 x 180 x 11.5 x 23	315
36 - 39	Built up T from plates	625 x 180 x 12 x 25	315
40 - 43	Built up T from plates	605 x 180 x 11.5 x 25	315
44 - 47	Built up T from plates	573 x 180 x 11.5 x 23	315
48 - 50	Built up T from plates	523 x 180 x 11.5 x 23	315
51 - 54	Built up T from plates	518 x 150 x 11.5 x 18	315
55 - 57	Built up T from plates	466 x 150 x 11.5 x 16	315
58 - 59	Built up T from plates	416 x 150 x 11.5 x 16	315
60 - 62	Built up T from plates	366 x 120 x 12 x 16	315
Strength Deck			
0 - 30	WeldedAngle	425 x 150 x 13 x 18	315
Inner bottom & inner side			
1 - 22	Built up T from plates	625 x 250 x 12.5 x 25	315
31 - 34	Built up T from plates	625 x 250 x 12 x 25	315
35 - 39	Built up T from plates	604 x 200 x 12 x 24	315
40 - 44	Built up T from plates	605 x 180 x 11.5 x 25	315
46 - 48	Built up T from plates	570 x 150 x 11.5 x 20	315
49 - 52	Built up T from plates	518 x 150 x 12 x 18	315
54 - 59	Built up T from plates	466 x 150 x 12 x 16	315
60 - 60	Built up T from plates	816 x 205 x 15 x 16	315
61 - 61	Built up T from plates	751 x 185 x 15 x 16	315
62 - 62	Built up T from plates	366 x 120 x 12 x 16	315
LongPlaneBulkhead10980_10980			
1 - 3	Flatbar	240 x 15	315
32 - 35	Built up T from plates	625 x 200 x 12 x 25	315
36 - 44	Built up T from plates	573 x 200 x 12 x 23	315
45 - 49	Built up T from plates	568 x 180 x 12 x 18	315
50 - 52	Built up T from plates	518 x 150 x 12 x 18	315
53 - 53	Built up T from plates	748 x 185 x 14 x 18	315
54 - 54	Built up T from plates	468 x 150 x 12 x 18	315
55 - 57	WeldedAngle	500 x 180 x 13 x 18	315
58 - 61	WeldedAngle	460 x 120 x 12 x 17	315
62 - 63	WeldedAngle	400 x 100 x 13 x 18	315

The actual section modulus calculated is greater than the required, as shown in Table 5.29, what passes this requirement.

Table 5.29: Section modulus.

Position	**Condition**	**M_{sw} [kNm]**	**M_{wv} [kNm]**	**σ_{perm} [N/mm^2]**	**$Z_{requred}$ [m^3]**	**Z_{actual} [m^3]**	**OK?**
Bottom	Sagging	-6300000	-5235853	224.36	51.42	99.17	Yes
	Hogging	7000000	4931978	224.36	53.18	99.17	Yes
Equivalent deck line	Sagging	-6300000	-5235853	224.36	51.42	70.22	Yes
	Hogging	7000000	4931978	224.36	53.18	70.22	Yes

The longitudinal normal stress, what takes into account the warping stress, has its criterion also met as shown in Table 5.30.

Table 5.30: Longitudinal normal stress, σ_{hg}

Operation	**Decisive condition**	**Weakest Plate**	**σ_{hg} [N/mm^2]**	**$\sigma_{hg\text{-}perm}$ [N/mm^2]**	**OK?**
Seagoing	ExtremeSea_SD, Full load, HSM_2	Strength Deck: Plate0	196.16	262.82	Yes

The shear stress and shear capacity, shown in Table 5.31 and 5.32, have their criteria satisfied.

Table 5.31: Shear stress, τ_{hg}

Operation	**Decisive condition**	**Weakest Plate**	**τ_{hg} [N/mm^2]**	**$\tau_{hg\text{-}perm}$ [N/mm^2]**	**OK?**
Seagoing	ExtremeSea_SD, Full load, HSM_2	LongPlaneBulkhead10980_10980: Plate6	-129.66	153.85	Yes

Table 5.32: Shear capacity

Operation	**Weakest Plate**	**f_{har}** [-]	**Q_{sw}** [kN]	**Q_{wv}** [kN]	**Q_R** [kN]	**OK?**
Seagoing	LongPlaneBulkhead10980_10980: Plate6	N/A	202527	31917	278710	Yes

Hull Girder Ultimate Strength can be seen in Table 5.33. Note that the Usage Factor (US) has increased a little, compared to the original, that is, although the interframe spacing has increased, the dimensions of the longitudinal stiffeners have increased, granting a more resistant beam column.

Table 5.33: Hull Girder Ultimate Strength

H/S	γ_{DB}	γ_W	γ_R	M_{sw-U} [kNm]	M_{wv} [kNm]	**M** [kNm]	M_U [kNm]	**US** [%]	**OK?**
Hog	1.10	1.20	1.21	7000000	4931978	12918374	24560183	157	Yes
Sag	1.00	1.20	1.10	-6300000	-5235853	-12583024	-17637408	127	Yes

5.3.5. Number of Frames: 5

In this section, four frames will be deduced from the original arrangement. The length of the cargo hold will be divided by 6 interframe spaces, resulting in an interframe spacing (ΔF) of 8466.7 [mm].

Altering the scantling of the cargo hold produces different cross-section properties, as seen in Table 5.34. Only the dimensions of the longitudinal stiffeners were changed, the spacing were not, resulting in a midship section similar to Figure 5.2.

Table 5.34: Cross section properties.

		Effective Cut-outs subtracted		**Gross** Cut-outs disregarded	
		as built	net (50% corr)	as built	net (50% corr)
Cross sectional area of the longitudinal elements	cm^2	113275	105278	113275	105278
Horizontal dist. from C.L. to vertical neutral axis, Yn	m	0.000	0.000	0.000	0.000
Vertical distance fom B.L. to horizontal neutral axis, Zn	m	12.549	12.483	12.549	12.483
Vertical moment of inertia, Iy	m^4	1470.820	1364.676	1470.821	1364.677
Horizontal moment of inertia , Iz	m^4	4373.090	4061.021	4373.099	4061.030
Product of inertia about the neutral axes, Iyz	m^4	-0.021	-0.019	-0.021	-0.019
Section Modulus, Bottom	m^3	117.201	109.326	117.202	109.326
Section Modulus, Strength deck at side (z = 31250mm)	m^3	78.651	72.715	78.651	72.715
Section Modulus, Equivalent deck line (z = 31250mm)	m^3	78.651	72.715	78.651	72.715
Section Modulus, at Side	m^3	150.797	140.036	150.797	140.036
First moment of the area above the neutral axis, S	m^3	57.228	53.104	57.228	53.104
I/S	m	25.701	25.698	25.701	25.698

Table 5.35 shows the dimensions of the stiffeners divided in groups.

Table 5.35: Cross section Stiffeners.

ID From - To	Profile Type	Dimensions	Yield stress [N/mm^2]
Outer shell			
1 - 29	Built up T from plates	775 x 280 x 15 x 25	315
31 - 39	Built up T from plates	775 x 250 x 15 x 25	315
40 - 43	Built up T from plates	775 x 280 x 15 x 25	315
44 - 47	Built up T from plates	625 x 180 x 12 x 25	315
48 - 50	Built up T from plates	523 x 180 x 11.5 x 23	315
51 - 54	Built up T from plates	518 x 150 x 11.5 x 18	315
55 - 57	Built up T from plates	466 x 150 x 11.5 x 16	315
58 - 59	Built up T from plates	416 x 150 x 11.5 x 16	315
60 - 62	Built up T from plates	366 x 120 x 12 x 16	315
Strength Deck			
0 - 30	WeldedAngle	500 x 180 x 12 x 20	315
Inner bottom & inner side			
1 - 34	Built up T from plates	785 x 250 x 15 x 35	315
35 - 48	Built up T from plates	775 x 250 x 15 x 25	315
49 - 52	Built up T from plates	625 x 180 x 12 x 25	315
54 - 59	Built up T from plates	574 x 150 x 11.5 x 24	315
60 - 60	Built up T from plates	816 x 205 x 15 x 16	315
61 - 61	Built up T from plates	751 x 185 x 15 x 16	315
62 - 62	Built up T from plates	418 x 150 x 11.5 x 18	315
LongPlaneBulkhead10980_10980			
1 - 3	Flatbar	250 x 16	315
32 - 35	Built up T from plates	780 x 250 x 15 x 30	315
36 - 49	Built up T from plates	775 x 250 x 15 x 25	315
50 - 52	Built up T from plates	625 x 180 x 12 x 25	315
53 - 53	Built up T from plates	748 x 185 x 14 x 18	315
54 - 57	Built up T from plates	625 x 180 x 12 x 25	315
58 - 61	Built up T from plates	573 x 180 x 11.5 x 23	315
62 - 63	WeldedAngle	500 x 180 x 12 x 20	315
Stringer No38			
1 - 2	Built up T from plates	262 x 150 x 14 x 12	315
Stringer No45			
1 - 2	Built up T from plates	262 x 150 x 14 x 12	315
Stringer No53			
1 - 2	Built up T from plates	262 x 150 x 14 x 12	315
Keel0			
1 - 2	Flatbar	250 x 16	315
Girder21045			
1 - 3	WeldedAngle	250 x 90 x 12 x 16	315

The section modulus Z_{actual}, is shown in Table 5.36. Note that its values are higher than the required section modulus.

Table 5.36: Section modulus.

Condition	**M_{sw} [kNm]**	**M_{wv} [kNm]**	**σ_{perm} [N/mm^2]**	**$Z_{required}$ [m^3]**	**Z_{actual} [m^3]**	**OK?**
Sagging	-6300000	-5235853	224.36	51.42	117.20	Yes
Hogging	7000000	4931978	224.36	53.18	117.20	Yes
Sagging	-6300000	-5235853	224.36	51.42	78.65	Yes
Hogging	7000000	4931978	224.36	53.18	78.65	Yes

The permissible longitudinal stress and the actual longitudinal stress is shown in Table 5.37. The weakest plate is Plate0, that is, the plate subjected to the highest longitudinal stress.

Table 5.37: Longitudinal normal stress, σ_{hg}

Operation	**Decisive condition**	**Weakest Plate**	**σ_{hg} [N/mm^2]**	**$\sigma_{hg\text{-}perm}$ [N/mm^2]**	**OK?**
Seagoing	ExtremeSea_SD, Full load, HSM_2	Strength Deck: Plate0	174.23	262.82	Yes

Table 5.38 shows the highest Shear stress, τ_{hg} and the location where it occurs, which is Plate5.

Table 5.38: Shear stress, τ_{hg}

Operation	**Decisive condition**	**Weakest Plate**	**τ_{hg} [N/mm^2]**	**$\tau_{hg\text{-}perm}$ [N/mm^2]**	**OK?**
Seagoing	ExtremeSea_SD, Full load, HSM_2	LongPlaneBulkhead 10980_10980: Plate5	-127.09	153.85	Yes

The shear capacity criterion is shown in Table 5.39.

Table 5.39: Shear capacity

Weakest Plate	**f_{har}** [-]	**Q_{sw}** [kN]	**Q_{wv}** [kN]	**Q_R** [kN]	**OK?**
LongPlaneBulkhead10980_10980: Plate5	N/A	198415	31917	278855	Yes

Ultimate Hull Girder Bending Moment is calculated and shown in Table 5.40.

Table 5.40: Hull Girder Ultimate Strength

H/S	γ_{DB}	γ_W	γ_R	M_{sw-U} [kNm]	M_{wv} [kNm]	**M** [kNm]	M_U [kNm]	**US** [%]	**OK?**
Hog	1.1	1.2	1.21	7000000	4931978	12918374	28495155	182.3	Yes
Sag	1.0	1.2	1.10	-6300000	-5235853	-12583024	-19977756	144.3	Yes

Note that the highest value for Hull Girder Ultimate Strength Usage factor (US) is found. The longitudinal stiffeners in this case have very large section modulus, producing the heaviest structure calculated so far.

5.3.6. Summary – Number of frames variation

Table 5.41 shows the weight of the original cargo hold and more five options. It was observed that varying the number of frames, considering the weight of the frames the same for all the variations the lighter option is the cargo hold with 7 frames, spaced 6350mm from each other. This structure produces a reduction in weight of approximately 0.8% compared to the reference Original (rule).

Table 5.41: Weight comparison of one cargo hold varying number of frames.

Reference	# ΔF	ΔF [mm]	# Frames	A (cm^2)	W [ton]	%
ORIGINAL	10	5080	9	101832	5221.1	109.4%
ORIGINAL (rule)	10	5080	9	90598	4772.5	100.0%
2+ FRAMES	12	4233.3	11	86025	4846.6	101.6%
4+ FRAMES	14	3628.6	13	82592	4966.2	104.1%
2- FRAMES	8	6350	7	96039	4733.1	99.2%
4- FRAMES	6	8466.7	5	113275	5164.6	108.2%

5.4. FIVE LONGITUDINAL STIFFENERS SCANTLING

Having selected the number of frames as indicated in Summary (7 frames), it is possible to vary the number of longitudinal stiffeners. Note that due to the fixed overall dimensions of the midship section, it is not always possible to have exact values for the spacings of the longitudinal stiffeners. In Table 5.77 the column Reference shows the approximate value of the spacing between longitudinal stiffeners. The following sub-sections will show the effect of varying the stiffeners spacing. Five different nominal spacings will be checked with Nauticus Hull and a summary will be done to show the results.

5.4.1. Stiffeners spacing of 1100mm

In this section, the scantling of the crude oil tanker cargo hold will be performed with 7 frames, that is 8 interframe spacings of 6350mm and a nominal spacing between stiffeners of 1100mm. The term nominal here is used because it is not always possible to divide the sections exactly in 1100mm. Illustrating that, the stiffeners spacing in the hopper is1050mm and the stiffeners spacing from the longitudinal bulkhead 10980mm and the hopper is 1120mm.

Figure 5.5 shows the midship section with a nominal stiffener spacing of 1100mm. Note that in the bottom the last stiffener has the ID 25, instead of 29 as shown in Figure 5.2.

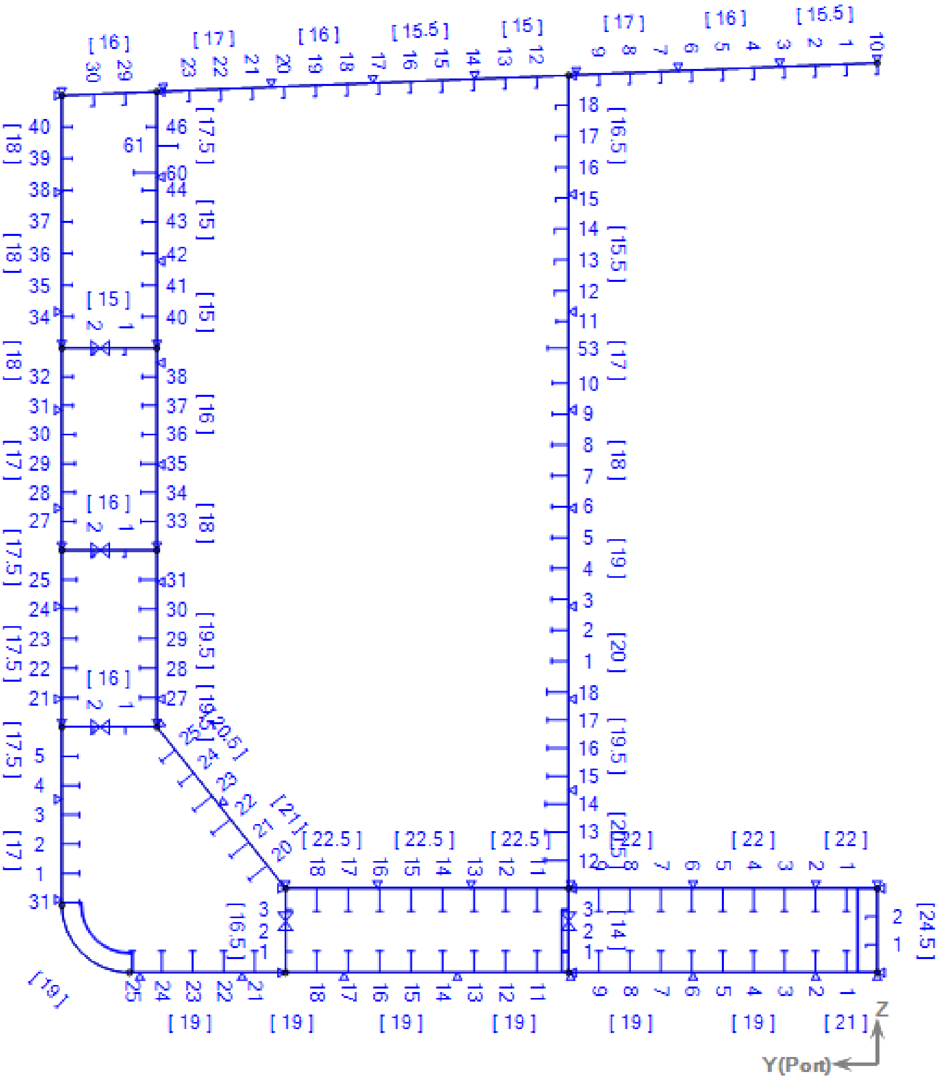


Figure 5.5: Midship section.

Table 5.42 shows the cross-section properties of the selected dimensions of the stiffeners. The gross as built cross section area of the longitudinal elements is used to calculate the volume and the weight of the cargo hold in the section 5.4.6 Summary - Stiffeners spacing .

Table 5.42: Cross Section Properties.

		Effective Cut-outs subtracted		**Gross** Cut-outs disregarded	
		as built	net (50% corr)	as built	net (50% corr)
Cross sectional area of the longitudinal elements	cm^2	98995	92025	98995	92025
Horizontal dist. from C.L. to vertical neutral axis, Yn	m	0.000	0.000	0.000	0.000
Vertical distance fom B.L. to horizontal neutral axis, Zn	m	12.614	12.570	12.614	12.570
Vertical moment of inertia, Iy	m^4	1309.051	1216.681	1309.052	1216.682
Horizontal moment of inertia , Iz	m^4	3834.419	3563.184	3834.427	3563.193
Product of inertia about the neutral axes, Iyz	m^4	-0.039	-0.035	-0.039	-0.035
Section Modulus, Bottom	m^3	103.775	96.791	103.776	96.791
Section Modulus, Strength deck at side (z = 31250mm)	m^3	70.244	65.134	70.244	65.134
Section Modulus, Equivalent deck line (z = 31250mm)	m^3	70.244	65.134	70.244	65.134
Section Modulus, at Side	m^3	132.223	122.870	132.223	122.870
First moment of the area above the neutral axis, S	m^3	50.689	47.096	50.689	47.096
I/S	m	25.825	25.834	25.825	25.834

Table 5.43 shows all the stiffeners used in this cross section.

Table 5.43: Cross section - Stiffeners

ID From - To	Profile Type	Dimensions	Yield stress [N/mm^2]
Outer shell			
1 - 25	Built up T from plates	766 x 250 x 14 x 16	315
31 - 31	Built up T from plates	624 x 200 x 12 x 24	315
1 - 4	Built up T from plates	623 x 200 x 12 x 23	315
5 - 21	Built up T from plates	574 x 150 x 11.5 x 24	315
22 - 25	Built up T from plates	523 x 180 x 11.5 x 23	315
27 - 30	Built up T from plates	468 x 150 x 12 x 18	315
31 - 34	Built up T from plates	391 x 150 x 11.5 x 16	315
35 - 37	Built up T from plates	366 x 120 x 12 x 16	315
38 - 40	Built up T from plates	367 x 100 x 12 x 17	315
Strength Deck			
10 - 23	WeldedAngle	400 x 100 x 11.5 x 16	315
29 - 30	WeldedAngle	425 x 150 x 13 x 18	315
Inner bottom & inner side			
1 - 18	Built up T from plates	816 x 250 x 16 x 16	315
20 - 23	Built up T from plates	816 x 205 x 15 x 16	315
24 - 25	Built up T from plates	625 x 250 x 12 x 25	315
27 - 27	Built up T from plates	604 x 200 x 12 x 24	315
28 - 31	Built up T from plates	605 x 180 x 11.5 x 25	315
33 - 35	Built up T from plates	574 x 150 x 11.5 x 24	315
36 - 38	Built up T from plates	518 x 180 x 12 x 18	315
40 - 44	Built up T from plates	518 x 150 x 11.5 x 18	315
60 - 60	Built up T from plates	816 x 205 x 15 x 16	315
61 - 61	Built up T from plates	751 x 185 x 15 x 16	315
46 - 46	Built up T from plates	367 x 100 x 12 x 17	315
LongPlaneBulkhead10980_10980			
1 - 3	Flatbar	240 x 15	315
12 - 14	Built up T from plates	816 x 205 x 15 x 16	315
15 - 17	Built up T from plates	751 x 185 x 15 x 16	315
18 - 18	Built up T from plates	766 x 250 x 14 x 16	315
1 - 4	Built up T from plates	604 x 200 x 12 x 24	315
5 - 8	Built up T from plates	600 x 180 x 11.5 x 20	315
9 - 10	Built up T from plates	570 x 150 x 11.5 x 20	315
53 - 53	Built up T from plates	748 x 185 x 14 x 18	315
11 - 11	Built up T from plates	425 x 150 x 11.5 x 25	315
12 - 14	WeldedAngle	500 x 180 x 13 x 18	315
15 - 18	WeldedAngle	460 x 150 x 13 x 18	315

Regarding global loads, required by (DNV-Chap5, 2021), the section modulus Z_{actual} is over the required, as seen in Table 5.44.

Table 5.44: Section Modulus.

Position	**Condition**	**M_{sw} [kNm]**	**M_{wv} [kNm]**	**σ_{perm} [N/mm^2]**	**$Z_{requred}$ [m^3]**	**Z_{actual} [m^3]**	**OK?**
Bottom	Sagging	-6300000	-5235853	224.36	51.42	103.78	Yes
	Hogging	7000000	4931978	224.36	53.18	103.78	Yes
Equivalent deck line	Sagging	-6300000	-5235853	224.36	51.42	70.24	Yes
	Hogging	7000000	4931978	224.36	53.18	70.24	Yes

The longitudinal normal stress, presented in Table 5.45, is verified and pass the minimum criterion.

Table 5.45: Longitudinal normal stress, σ_{hg}

Operation	**Decisive condition**	**Weakest Plate**	**σ_{hg} [N/mm^2]**	**$\sigma_{hg\text{-}perm}$ [N/mm^2]**	**OK?**
Seagoing	ExtremeSea_SD, Full load, HSM_2	Strength Deck: Plate0	194.57	262.82	Yes

Shear stress and shear capacity are shown in Table 5.46 and Table 5.47, respectively and they are approved.

Table 5.46: Shear stress, τ_{hg}

Operation	**Decisive condition**	**Weakest Plate**	**τ_{hg} [N/mm^2]**	**$\tau_{hg\text{-}perm}$ [N/mm^2]**	**OK?**
Seagoing	ExtremeSea_SD, Full load, HSM_2	LongPlaneBulkhead10980_10980: Plate7	-105.70	153.85	Yes

Table 5.47: Shear capacity

Operation	**Weakest Plate**	**f_{har}** [-]	**Q_{sw}** [kN]	**Q_{wv}** [kN]	**Q_R** [kN]	**OK?**
Seagoing	LongPlaneBulkhead10980_10980: Plate5	N/A	202527	31917	336940	Yes

Table 5.48 shows that in hogging, when the bottom is under compression, the usage is higher than the original scantling with 9 frames. This happens because the stiffeners have lower slenderness. On the other hand, in sagging, the Usage Factor (US) is very similar to the original

scantling. It can be explained based on the small change of the stiffeners on the deck, they are subjected to small local loads.

Table 5.48: Hull Girder Ultimate Strength

H/S	γ_{DB}	γ_{W}	γ_{R}	**M_{sw-U}** [kNm]	**M_{wv}** [kNm]	**M** [kNm]	**M_U** [kNm]	**US** [%]	**OK?**
Hog	1.10	1.20	1.21	7000000	4931978	12918374	24962299	160	Yes
Sag	1.00	1.20	1.10	-6300000	-5235853	-12583024	-16958064	123	Yes

5.4.2. Stiffeners spacing of 1000mm

In this section, the scantling for frame spacing of 6350 [mm] is used and the nominal spacing of the longitudinal stiffeners is 1000 [mm]. Nominal spacing is used here because the midship section has fixed overall dimensions, what makes difficult to have exactly 1000 [mm] of spacing between longitudinal elements.

When changing the longitudinal stiffeners spacing, the plates dimensions are affected as well as the stiffener itself. The midship section properties, such as cross section area and section modulus, as shown in Table 5.49. Note that the comparison of the lightest midship section is now done just comparing the cross-sectional area of longitudinal elements (as built), because the number of frames is now already selected.

Table 5.49: Cross section properties

		Effective Cut-outs subtracted		**Gross** Cut-outs disregarded	
		as built	net (50% corr)	as built	net (50% corr)
Cross sectional area of the longitudinal elements	cm^2	96521	89528	96521	89528
Horizontal dist. from C.L. to vertical neutral axis, Yn	m	0.000	0.000	0.000	0.000
Vertical distance fom B.L. to horizontal neutral axis, Zn	m	12.662	12.606	12.662	12.606
Vertical moment of inertia, Iy	m^4	1268.180	1174.869	1268.181	1174.870
Horizontal moment of inertia , Iz	m^4	3770.016	3497.326	3770.024	3497.334
Product of inertia about the neutral axes, Iyz	m^4	-0.039	-0.035	-0.039	-0.035
Section Modulus, Bottom	m^3	100.153	93.200	100.153	93.201
Section Modulus, Strength deck at side (z = 31250mm)	m^3	68.227	63.015	68.227	63.015
Section Modulus, Equivalent deck line (z = 31250mm)	m^3	68.227	63.015	68.227	63.015
Section Modulus, at Side	m^3	130.002	120.599	130.002	120.599
First moment of the area above the neutral axis, S	m^3	49.240	45.619	49.240	45.619
I/S	m	25.755	25.754	25.755	25.754

The scantling of the longitudinal stiffeners is shown in Table 5.50. The stiffeners are no longer grouped in the same ways as previously because the number of stiffeners changed.

Table 5.50: Cross section stiffeners

ID From - To	**Profile Type**	**Dimensions**	**Yield stress** [N/mm^2]
Outer shell			
1 - 20	Built up T from plates	604 x 250 x 12 x 24	315
21 - 26	Built up T from plates	625 x 250 x 12 x 25	315
31 - 31	Built up T from plates	603 x 250 x 12 x 23	315
28 - 31	Built up T from plates	604 x 200 x 12 x 24	315
32 - 34	Built up T from plates	568 x 200 x 12 x 18	315
35 - 38	Built up T from plates	523 x 180 x 11.5 x 23	315
40 - 43	Built up T from plates	512 x 150 x 14 x 12	315
44 - 55	Built up T from plates	416 x 150 x 11.5 x 16	315
56 - 58	Built up T from plates	366 x 120 x 12 x 16	315
59 - 62	Built up T from plates	262 x 150 x 14 x 12	315
Strength Deck			
28 - 30	WeldedAngle	400 x 100 x 11.5 x 16	315
Inner bottom & inner side			
1 - 20	Built up T from plates	675 x 250 x 13.5 x 25	315
31 - 34	Built up T from plates	625 x 250 x 12 x 25	315
35 - 37	Built up T from plates	604 x 200 x 12 x 24	315
28 - 28	Built up T from plates	603 x 250 x 12 x 23	315
29 - 32	Built up T from plates	605 x 180 x 11.5 x 25	315
34 - 36	Built up T from plates	574 x 150 x 11.5 x 24	315
37 - 39	Built up T from plates	570 x 150 x 11.5 x 20	315
41 - 45	Built up T from plates	468 x 150 x 12 x 18	315
60 - 60	Built up T from plates	816 x 205 x 15 x 16	315
61 - 61	Built up T from plates	751 x 185 x 15 x 16	315
62 - 62	Built up T from plates	367 x 100 x 12 x 17	315
LongPlaneBulkhead10980_10980			
1 - 3	Flatbar	240 x 15	315
5 - 7	Built up T from plates	675 x 250 x 13.5 x 25	315
8 - 10	Built up T from plates	625 x 250 x 12.5 x 25	315
11 - 14	Built up T from plates	604 x 200 x 11.5 x 24	315
15 - 18	Built up T from plates	570 x 200 x 12 x 20	315
19 - 22	Built up T from plates	570 x 150 x 11.5 x 20	315
53 - 53	Built up T from plates	748 x 185 x 14 x 18	315
24 - 24	Built up T from plates	468 x 150 x 12 x 18	315
25 - 28	WeldedAngle	500 x 180 x 13 x 18	315
29 - 32	WeldedAngle	460 x 120 x 12 x 17	315

The required section modulus $Z_{requred}$ is still identical to the previous sections, because the moments and permissible stress σ_{perm}, are unchanged. However, the Z_{actual} is recalculated and shown in Table 5.51. The result is that the actual section modulus is above the required.

Table 5.51: Section modulus.

Position	**Condition**	**M_{sw} [kNm]**	**M_{wv} [kNm]**	**σ_{perm} [N/mm^2]**	**$Z_{requred}$ [m^3]**	**Z_{actual} [m^3]**	**OK?**
Bottom	Sagging	-6300000	-5235853	224.36	51.42	100.15	Yes
	Hogging	7000000	4931978	224.36	53.18	100.15	Yes
Equivalent deck line	Sagging	-6300000	-5235853	224.36	51.42	68.23	Yes
	Hogging	7000000	4931978	224.36	53.18	68.23	Yes

The longitudinal normal stress σ_{hg}, is calculated and shown in Table 5.52. The permissible longitudinal stress, calculated with Eq. 5.4 remains the same. The weakest plate is still the Plate0 in the highest position of the main deck, due to the camber.

Table 5.52: Longitudinal normal stress, σ_{hg}

Operation	**Decisive condition**	**Weakest Plate**	**σ_{hg} [N/mm^2]**	**$\sigma_{hg\text{-}perm}$ [N/mm^2]**	**OK?**
Seagoing	ExtremeSea_SD, Full load, HSM_2	Strength Deck: Plate0	201.13	262.82	Yes

Shear stress and shear capacity is calculated and shown in Table 5.53 and Table 5.54, and meets the requirements as shown in the last column. Hull Girder Ultimate Strength, calculated by Nauticus Hull and shown in Table 5.19.

Table 5.53: Shear stress, τ_{hg}

Operation	**Decisive condition**	**Weakest Plate**	**τ_{hg} [N/mm^2]**	**$\tau_{hg\text{-}perm}$ [N/mm^2]**	**OK?**
Seagoing	ExtremeSea_SD, Full load, HSM_2	LongPlaneBulkhead10980_10980: Plate5	-119.51	153.85	Yes

Table 5.54: Shear capacity

Operation	**Weakest Plate**	**f_{har}** [-]	**Q_{sw}** [kN]	**Q_{wv}** [kN]	**Q_R** [kN]	**OK?**
Seagoing	LongPlaneBulkhead10980 _10980: Plate5	N/A	202527	31917	299147	Yes

Hull Girder Ultimate Strength, calculated by Nauticus Hull and shown in Table 5.55.

Table 5.55: Hull Girder Ultimate Strength

H/S	**γ_{DB}**	**γ_W**	**γ_R**	**M_{sw-U}** [kNm]	**M_{wv}** [kNm]	**M** [kNm]	**M_U** [kNm]	**US** [%]	**OK?**
Hog	1.10	1.20	1.21	7000000	4931978	12918374	24506696	157	Yes
Sag	1.00	1.20	1.10	-6300000	-5235853	-12583024	-16545747	120	Yes

5.4.3. Stiffeners spacing of 800mm

In this section, 7 frames will be divided equally the cargo hold, and the nominal spacing of the stiffeners will be 800 [mm].

The cross section of this arrangement will not have the same number of longitudinal stiffeners. But the same idea of grouping equal longitudinal elements will be used. Table 5.56 shows the resultant cross section properties of this arrangement. The cross-section area of the longitudinal elements multiplied by the cargo hold length and the steel density is the weight of the longitudinal elements. The total weight will add the weight of the frames.

Table 5.56: Cross section properties

		Effective Cut-outs subtracted		**Gross** Cut-outs disregarded	
		as built	net (50% corr)	as built	net (50% corr)
Cross sectional area of the longitudinal elements	cm^2	91728	84218	91728	84218
Horizontal dist. from C.L. to vertical neutral axis, Yn	m	0.000	0.000	0.000	0.000
Vertical distance fom B.L. to horizontal neutral axis, Zn	m	12.606	12.547	12.606	12.547
Vertical moment of inertia, Iy	m^4	1214.021	1113.856	1214.021	1113.856
Horizontal moment of inertia , Iz	m^4	3568.652	3278.328	3568.658	3278.333
Product of inertia about the neutral axes, Iyz	m^4	-0.023	-0.021	-0.023	-0.021
Section Modulus, Bottom	m^3	96.302	88.778	96.302	88.778
Section Modulus, Strength deck at side (z = 31250mm)	m^3	65.117	59.554	65.117	59.554
Section Modulus, Equivalent deck line (z = 31250mm)	m^3	65.117	59.554	65.117	59.554
Section Modulus, at Side	m^3	123.058	113.047	123.058	113.047
First moment of the area above the neutral axis, S	m^3	47.030	43.147	47.030	43.147
I/S	m	25.814	25.815	25.814	25.815

Table 5.57 shows the dimensions of the groups of stiffeners.

Table 5.57: Cross section stiffeners

ID From - To	Profile Type	Dimensions	Yield stress [N/mm^2]
Outer shell			
1 - 46	Built up T from plates	603 x 200 x 11.5 x 23	315
31 - 31	Built up T from plates	603 x 180 x 11.5 x 23	315
47 - 50	Built up T from plates	570 x 200 x 12 x 20	315
51 - 53	Built up T from plates	518 x 180 x 12 x 18	315
55 - 56	Built up T from plates	518 x 150 x 11.5 x 18	315
57 - 60	Built up T from plates	516 x 150 x 11.5 x 16	315
61 - 64	Built up T from plates	466 x 150 x 11.5 x 16	315
65 - 67	Built up T from plates	416 x 150 x 11.5 x 16	315
68 - 72	Built up T from plates	367 x 120 x 12 x 17	315
73 - 74	Built up T from plates	366 x 120 x 12 x 16	315
75 - 76	Built up T from plates	264 x 120 x 12 x 14	315
77 - 81	Built up T from plates	262 x 100 x 12 x 12	315
Strength Deck			
14 - 36	WeldedAngle	380 x 100 x 11.5 x 16	315
Inner bottom & inner side			
1 - 62	Built up T from plates	625 x 250 x 12 x 25	315
63 - 66	Built up T from plates	604 x 200 x 11.5 x 24	315
29 - 29	Built up T from plates	570 x 200 x 12 x 20	315
30 - 35	Built up T from plates	568 x 200 x 12 x 18	315
37 - 40	Built up T from plates	520 x 150 x 11.5 x 20	315
41 - 44	Built up T from plates	470 x 150 x 12 x 20	315
46 - 52	Built up T from plates	466 x 150 x 11.5 x 16	315
60 - 60	Built up T from plates	816 x 205 x 15 x 16	315
61 - 61	Built up T from plates	751 x 185 x 15 x 16	315
55 - 55	Built up T from plates	317 x 100 x 12 x 17	315
LongPlaneBulkhead10980_10980			
1 - 3	Flatbar	240 x 15	315
5 - 8	Built up T from plates	625 x 200 x 12 x 25	315
9 - 12	Built up T from plates	603 x 180 x 11.5 x 23	315
13 - 16	Built up T from plates	570 x 200 x 12 x 20	315
17 - 20	Built up T from plates	571 x 150 x 11.5 x 21	315
21 - 24	Built up T from plates	518 x 180 x 12 x 18	315
25 - 27	Built up T from plates	518 x 150 x 12 x 18	315
53 - 53	Built up T from plates	748 x 185 x 14 x 18	315
29 - 29	Built up T from plates	468 x 150 x 12 x 18	315
30 - 32	WeldedAngle	500 x 150 x 13 x 18	315
33 - 36	WeldedAngle	460 x 120 x 12 x 17	315
37 - 39	WeldedAngle	400 x 100 x 11.5 x 16	315

The section modulus Z_{actual}, is calculated and shown in Table 5.58. Its passes the criteria as shown in the last column.

Table 5.58: Section modulus

Position	**Condition**	**M_{sw} [kNm]**	**M_{wv} [kNm]**	**σ_{perm} [N/mm^2]**	**$Z_{requred}$ [m^3]**	**Z_{actual} [m^3]**	**OK?**
Bottom	Sagging	-6300000	-5235853	224.36	51.42	96.30	Yes
	Hogging	7000000	4931978	224.36	53.18	96.30	Yes
Equivalent deck line	Sagging	-6300000	-5235853	224.36	51.42	65.12	Yes
	Hogging	7000000	4931978	224.36	53.18	65.12	Yes

The permissible longitudinal stress has its higher value smaller than the actual longitudinal stress, passing this criterion as shown in Table 5.59. The weakest plate is the one subjected to the highest longitudinal stress. The furthest plate from the horizontal neutral axis is Plate0.

Table 5.59: Longitudinal normal stress, σ_{hg}

Operation	**Decisive condition**	**Weakest Plate**	**σ_{hg} [N/mm^2]**	**$\sigma_{hg\text{-}perm}$ [N/mm^2]**	**OK?**
Seagoing	ExtremeSea_SD, Full load, HSM_2	Strength Deck: Plate0	212.78	262.82	Yes

Regarding shear stress and shear capacity, Table 5.60 and Table 5.61 shows the results. The highest shear flow is located in the neutral axis, but the plate in the neutral axis is thicker than the plate above, what causes the highest shear stress to be in Plate5, as shown in Table 5.24.

Table 5.60: Shear stress, τ_{hg}

Operation	**Decisive condition**	**Weakest Plate**	**τ_{hg} [N/mm^2]**	**$\tau_{hg\text{-}perm}$ [N/mm^2]**	**OK?**
Seagoing	ExtremeSea_SD, Full load, HSM_2	LongPlaneBulkhead10980_10980: Plate5	-137.54	153.85	Yes

Table 5.61: Shear capacity

Operation	**Weakest Plate**	**f_{har}** [-]	**Q_{sw}** [kN]	**Q_{wv}** [kN]	**Q_R** [kN]	**OK?**
Seagoing	LongPlaneBulkhead10980_10980: Plate5	N/A	202527	31917	262788	Yes

The Hull Girder Ultimate Strength Usage factor (US), from the previous 2 section and one in Table 5.62, decreased the overall strength of the hull girder with the decrease of the longitudinal stiffeners spacing.

Table 5.62: Hull Girder Ultimate Strength

H/S	γ_{DB}	γ_{W}	γ_{R}	M_{sw-U} [kNm]	M_{wv} [kNm]	**M** [kNm]	M_{U} [kNm]	**US** [%]	**OK?**
Hog	1.10	1.20	1.21	7000000	4931978	12918374	23262343	149	Yes
Sag	1.00	1.20	1.10	-6300000	-5235853	-12583024	-15968042	115	Yes

5.4.4. Stiffeners spacing of 700mm

The objective of this section is to calculate the scantling of the cargo hold area. The interframe spacing (ΔF) is 6350 [mm] and the nominal longitudinal stiffener spacing is 700 [mm].

Table 5.63 shows the midship section properties. Note that the smallest cross-sectional area calculated so far is for this arrangement.

Table 5.63: Cross section properties.

		Effective Cut-outs subtracted		**Gross** Cut-outs disregarded	
		as built	net (50% corr)	as built	net (50% corr)
Cross sectional area of the longitudinal elements	cm^2	91667	83966	91667	83966
Horizontal dist. from C.L. to vertical neutral axis, Yn	m	0.000	0.000	0.000	0.000
Vertical distance fom B.L. to horizontal neutral axis, Zn	m	12.616	12.565	12.616	12.565
Vertical moment of inertia, Iy	m^4	1211.606	1110.298	1211.607	1110.298
Horizontal moment of inertia , Iz	m^4	3610.502	3310.721	3610.508	3310.726
Product of inertia about the neutral axes, Iyz	m^4	-0.023	-0.021	-0.023	-0.021
Section Modulus, Bottom	m^3	96.034	88.365	96.034	88.365
Section Modulus, Strength deck at side (z = 31250mm)	m^3	65.023	59.422	65.023	59.422
Section Modulus, Equivalent deck line (z = 31250mm)	m^3	65.023	59.422	65.023	59.422
Section Modulus, at Side	m^3	124.501	114.164	124.501	114.164
First moment of the area above the neutral axis, S	m^3	46.978	43.034	46.978	43.034
I/S	m	25.791	25.800	25.791	25.800

Table 5.64: Cross section stiffeners.

ID **From - To**	**Profile Type**	**Dimensions**	**Yield stress** [N/mm^2]
Outer shell			
1 - 37	Built up T from plates	603 x 180 x 11.5 x 23	315
31 - 31	Built up T from plates	604 x 150 x 11.5 x 24	315
1 - 4	Built up T from plates	568 x 200 x 12 x 18	315
5 - 8	Built up T from plates	520 x 150 x 11.5 x 20	315
10 - 13	Built up T from plates	468 x 150 x 12 x 18	315
14 - 17	Built up T from plates	466 x 150 x 11.5 x 16	315
19 - 22	Built up T from plates	416 x 150 x 11.5 x 16	315
23 - 32	Built up T from plates	367 x 120 x 12 x 17	315
33 - 40	Built up T from plates	262 x 150 x 14 x 12	315
Strength Deck			
1 - 26	WeldedAngle	310 x 100 x 12 x 17	315
Inner bottom & inner side			
1 - 28	Built up T from plates	625 x 200 x 12 x 25	315
65 - 68	Built up T from plates	625 x 180 x 12 x 25	315
69 - 73	Built up T from plates	603 x 180 x 11.5 x 23	315
31 - 34	Built up T from plates	568 x 180 x 12 x 18	315
35 - 38	Built up T from plates	570 x 150 x 11.5 x 20	315
40 - 42	Built up T from plates	518 x 150 x 11.5 x 18	315
43 - 48	Built up T from plates	470 x 150 x 12 x 20	315
50 - 53	Built up T from plates	416 x 150 x 11.5 x 16	315
54 - 57	Built up T from plates	368 x 120 x 12 x 18	315
60 - 60	Built up T from plates	816 x 205 x 15 x 16	315
61 - 61	Built up T from plates	751 x 185 x 15 x 16	315
60 - 61	Built up T from plates	262 x 150 x 14 x 12	315
LongPlaneBulkhead10980_10980			
1 - 3	Flatbar	240 x 15	315
5 - 8	Built up T from plates	624 x 200 x 12 x 24	315
9 - 12	Built up T from plates	570 x 200 x 12 x 20	315
13 - 16	Built up T from plates	568 x 200 x 12 x 18	315
17 - 20	Built up T from plates	570 x 150 x 11.5 x 20	315
21 - 24	Built up T from plates	518 x 180 x 12 x 18	315
25 - 28	Built up T from plates	516 x 150 x 11.5 x 16	315
29 - 30	Built up T from plates	470 x 150 x 12 x 20	315
53 - 53	Built up T from plates	748 x 185 x 14 x 18	315
32 - 32	Built up T from plates	418 x 150 x 11.5 x 18	315
33 - 35	WeldedAngle	460 x 150 x 12 x 17	315
36 - 36	WeldedAngle	450 x 120 x 12 x 16	315
37 - 39	WeldedAngle	425 x 150 x 13 x 18	315
40 - 44	WeldedAngle	400 x 100 x 11.5 x 16	315

The actual section modulus calculated is greater than the required, as shown in Table 5.65, what passes this requirement.

Table 5.65: Section modulus.

Position	Condition	M_{sw} [kNm]	M_{wv} [kNm]	σ_{perm} [N/mm^2]	$Z_{requred}$ [m^3]	Z_{actual} [m^3]	OK?
Bottom	Sagging	-6300000	-5235853	224.36	51.42	96.03	Yes
	Hogging	7000000	4931978	224.36	53.18	96.03	Yes
Equivalent deck line	Sagging	-6300000	-5235853	224.36	51.42	65.02	Yes
	Hogging	7000000	4931978	224.36	53.18	65.02	Yes

The longitudinal normal stress, what takes into account the warping stress, has its criterion also checked as shown in Table 5.66. This is crucial in ship structures. If this criterion is not met the ship might break its back.

Table 5.66: Longitudinal normal stress, σ_{hg}

Decisive condition	Weakest Plate	σ_{hg} [N/mm^2]	$\sigma_{hg\text{-}perm}$ [N/mm^2]	OK?
ExtremeSea_SD, Full load, HSM_2	Strength Deck: Plate0	213.27	262.82	Yes

The shear stress and shear capacity, shown in Table 5.67 and Table 5.68, and have their criteria satisfied.

Table 5.67: Shear stress, τ_{hg}

Decisive condition	Weakest Plate	τ_{hg} [N/mm^2]	$\tau_{hg\text{-}perm}$ [N/mm^2]	OK?
ExtremeSea_SD, Full load, HSM_2	LongPlaneBulkhead10980_10980: Plate4	-149.84	153.85	Yes

Table 5.68: Shear capacity

Operation	Weakest Plate	f_{har} [-]	Q_{sw} [kN]	Q_{wv} [kN]	Q_R [kN]	OK?
Seagoing	LongPlaneBulkhead10980_10980: Plate4	N/A	202527	31917	242564	Yes

Hull Girder Ultimate Strength can be seen in Table 5.69. Note that the Usage Factor (US) has been decreasing, with the decrease of the spacing of the longitudinal stiffeners.

Table 5.69: Hull Girder Ultimate Strength

H/S	γ_{DB}	γ_W	γ_R	$M_{sw\text{-}U}$ [kNm]	M_{wv} [kNm]	**M** [kNm]	M_U [kNm]	**US** [%]	**OK?**
Hog	1.10	1.20	1.21	7000000	4931978	12918374	23120843	148	Yes
Sag	1.00	1.20	1.10	-6300000	-5235853	-12583024	-16103755	116	Yes

5.4.5. Stiffeners spacing of 600mm

In this section, the nominal spacing of the longitudinal elements will be 600 [mm] and the interframe spacing will remain the same, that is 6350 [mm]. The scantling is calculated with Nauticus Hull and the results are presented in this section.

Table 5.70 shows the cross-section properties.

Table 5.70: Cross section properties

		Effective Cut-outs subtracted		**Gross** Cut-outs disregarded	
		as built	net (50% corr)	as built	net (50% corr)
Cross sectional area of the longitudinal elements	cm^2	93160	85073	93160	85073
Horizontal dist. from C.L. to vertical neutral axis, Yn	m	0.000	0.000	0.000	0.000
Vertical distance fom B.L. to horizontal neutral axis, Zn	m	12.596	12.557	12.596	12.557
Vertical moment of inertia, Iy	m^4	1232.686	1126.413	1232.687	1126.413
Horizontal moment of inertia , Iz	m^4	3660.036	3348.850	3660.043	3348.856
Product of inertia about the neutral axes, Iyz	m^4	-0.023	-0.021	-0.023	-0.021
Section Modulus, Bottom	m^3	97.862	89.706	97.862	89.706
Section Modulus, Strength deck at side (z = 31250mm)	m^3	66.082	60.258	66.082	60.258
Section Modulus, Equivalent deck line (z = 31250mm)	m^3	66.082	60.258	66.082	60.258
Section Modulus, at Side	m^3	126.209	115.478	126.209	115.479
First moment of the area above the neutral axis, S	m^3	47.745	43.610	47.745	43.610
I/S	m	25.818	25.829	25.818	25.829

The scantling of the longitudinal stiffeners is shown in Table 5.71. Note that the stiffeners are grouped but has increased since the spacing between them decreased.

Table 5.71: Cross section stiffeners

ID **From - To**	**Profile Type**	**Dimensions**	**Yield stress** [N/mm^2]
Outer shell			
46 - 88	Built up T from plates	568 x 200 x 12 x 18	315
31 - 4	Built up T from plates	523 x 180 x 11.5 x 23	315
5 - 9	Built up T from plates	518 x 150 x 11.5 x 18	315
1 - 4	Built up T from plates	466 x 150 x 12 x 16	315
5 - 9	Built up T from plates	416 x 150 x 11.5 x 16	315
1 - 11	Built up T from plates	367 x 120 x 12 x 17	315
13 - 16	Built up T from plates	366 x 120 x 12 x 16	315
17 - 25	Built up T from plates	264 x 120 x 12 x 14	315
Strength Deck			
18 - 42	WeldedAngle	280 x 100 x 12 x 16	315
23 - 26	WeldedAngle	300 x 100 x 12 x 17	315
Inner bottom & inner side			
76 - 108	Built up T from plates	603 x 200 x 11.5 x 23	315
1 - 7	Built up T from plates	603 x 180 x 11.5 x 23	315
8 - 11	Built up T from plates	568 x 200 x 12 x 18	315
1 - 4	Built up T from plates	570 x 150 x 11.5 x 20	315
5 - 9	Built up T from plates	520 x 150 x 11.5 x 20	315
1 - 4	Built up T from plates	468 x 150 x 12 x 18	315
5 - 8	Built up T from plates	418 x 150 x 11.5 x 18	315
9 - 16	Built up T from plates	416 x 150 x 11.5 x 16	315
17 - 21	Built up T from plates	368 x 120 x 12 x 18	315
60 - 60	Built up T from plates	816 x 205 x 15 x 16	315
61 - 61	Built up T from plates	751 x 185 x 15 x 16	315
24 - 25	Built up T from plates	368 x 120 x 12 x 18	315
LongPlaneBulkhead10980_10980			
1 - 3	Flatbar	240 x 15	315
1 - 4	Built up T from plates	603 x 180 x 11.5 x 23	315
5 - 8	Built up T from plates	568 x 200 x 12 x 18	315
9 - 12	Built up T from plates	568 x 180 x 12 x 18	315
13 - 16	Built up T from plates	570 x 150 x 11.5 x 20	315
17 - 20	Built up T from plates	518 x 150 x 11.5 x 18	315
21 - 24	Built up T from plates	516 x 150 x 11.5 x 16	315
25 - 30	Built up T from plates	468 x 150 x 12 x 18	315
53 - 53	Built up T from plates	748 x 185 x 14 x 18	315
32 - 32	Built up T from plates	368 x 120 x 12 x 18	315
33 - 35	WeldedAngle	425 x 150 x 13 x 18	315
36 - 40	WeldedAngle	400 x 120 x 13 x 18	315
41 - 46	WeldedAngle	380 x 100 x 11.5 x 16	315

The section modulus Z_{actual}, was calculated and is in Table 5.72. Its passes the criteria as the last column indicates.

Table 5.72: Section modulus

Position	**Condition**	**M_{sw} [kNm]**	**M_{wv} [kNm]**	**σ_{perm} [N/mm^2]**	**$Z_{requred}$ [m^3]**	**Z_{actual} [m^3]**	**OK?**
Bottom	Sagging	-6300000	-5235853	224.36	51.42	97.86	Yes
	Hogging	7000000	4931978	224.36	53.18	97.86	Yes
Equivalent deck line	Sagging	-6300000	-5235853	224.36	51.42	66.08	Yes
	Hogging	7000000	4931978	224.36	53.18	66.08	Yes

The longitudinal normal stress, presented in Table 5.73, is checked and pass the minimum criterion.

Table 5.73: Longitudinal normal stress, σ_{hg}

Operation	**Decisive condition**	**Weakest Plate**	**σ_{hg} [N/mm^2]**	**$\sigma_{hg\text{-}perm}$ [N/mm^2]**	**OK?**
Seagoing	ExtremeSea_SD, Full load, HSM_2	Strength Deck: Plate0	210.30	262.82	Yes

Shear stress and shear capacity is calculated and shown in Table 5.74 and Table 5.75. They have the minimum criteria met as shown in the last column.

Table 5.74: Shear stress, τ_{hg}

Decisive condition	**Weakest Plate**	**τ_{hg} [N/mm^2]**	**$\tau_{hg\text{-}perm}$ [N/mm^2]**	**OK?**
ExtremeSea_SD, Full load, HSM_2	LongPlaneBulkhead 10980_10980: Plate2	-147.77	153.85	Yes

Table 5.75: Shear capacity

Operation	**Weakest Plate**	**f_{har}** [-]	**Q_{sw}** [kN]	**Q_{wv}** [kN]	**Q_R** [kN]	**OK?**
Seagoing	LongPlaneBulkhead10980_10980: Plate2	N/A	202527	31917	245785	Yes

The Hull Girder Ultimate Strength, calculated by Nauticus is shown in Table 5.76.

Table 5.76: Hull Girder Ultimate Strength

Cond	H/S	γ_{DB}	γ_W	γ_R	M_{sw-U} [kNm]	M_{wv} [kNm]	M [kNm]	M_U [kNm]	US [%]	OK?
Seagoing	Hog	1.10	1.20	1.21	7000000	4931978	12918374	23825622	152	Yes
Seagoing	Sag	1.00	1.20	1.10	-6300000	-5235853	-12583024	-16673669	120	Yes

5.4.6. Summary - Stiffeners spacing variation

Using 7 frames in the cargo hold, what results in 8 interframe spaces of 6350mm, and varying the nominal spacing between stiffeners from 1100mm to 600mm, one can calculate the scantlings of the cargo hold region using Nauticus Hull. Then, the Cross-sectional area of the longitudinal elements, A, shown in column 4 of Table 5.77, is used to calculate the weight by multiplying the length of one cargo hold, and after multiply by the density of steel to obtain the weight of the longitudinal elements. The frame has the weight calculated separately and added to the weight of longitudinal elements accordingly.

The last column of Table 5.77, W [%], has the percentage of weight compared to the original arrangement of interframe spacing and stiffeners spacing, which is 9 frames spaced 5080mm and nominal 900mm, respectively. Note that the least weight for the cargo hold is obtained with an interframe spacing of 6350mm and a nominal longitudinal stiffener spacing of 700mm.

Table 5.77: Weight comparison of one cargo hold varying the spacing of longitudinal stiffeners.

Reference	ΔF [mm]	# Frames	A [cm^2]	W [ton]	W [%]
ΔS-1100mm	6350	7	98995	4851.1	101.6%
ΔS-1000mm	6350	7	96521	4752.4	99.6%
ΔS-800mm	6350	7	91728	4561.0	95.6%
ΔS-700mm	6350	7	91667	4558.5	95.5%
ΔS-600mm	6350	7	93160	4618.2	96.8%

5.5. RESULTS DISCUSSION

5.5.1. Plates and longitudinal stiffeners

Table 5.78 shows the weight of longitudinal elements such as plates (W_PL), longitudinal stiffeners (W_SIFF), all longitudinal elements without the frames (W_long) and the total weight with frames (W).

Table 5.78: Weight of plates, longitudinal stiffeners and total weight when varying interframe spacing.

TYPE	**# ΔF**	**W_PL [ton]**	**W_STIFF [ton]**	**W_ long [ton]**	**W [ton]**	**W %**
4+ FRAMES (13 Fr)	14	1239	2059	3298	4966.2	104.1%
2+ FRAMES (11 Fr)	12	1231	2204	3435	4846.6	101.6%
ORIGINAL (9 Fr)	10	1254	2362	3616	4771.0	100.0%
2- FRAMES (7 Fr)	8	1212	2622	3835	4733.1	99.2%
4- FRAMES (5 Fr)	6	1278	3245	4523	5164.6	108.3%

Figure 5.6 depicts the variation of the weight of the plates and the weight of the longitudinal stiffeners in function of the number of interframe spacing. Note that the weight of the plates (in blue) did not have a significant change when altering the span of the frames and keeping the longitudinal stiffener spacing constant. Although Eq. 4.5, that defines the plate thickness, is dependent on a correction factor for the panel aspect ratio, α_p, this coefficient is not sensitive or does not vary much with large aspect ratios, as seen in Eq. 5.7.

$$\alpha_p = 1.2 - \frac{b}{2.1\, a} \qquad \text{Eq. 5.7}$$

Where,

- a = length of plate panel;
- b = breadth of plate panel.

Looking at the weight of longitudinal stiffeners, (in orange) in Figure 5.6, it is seen that it decreases as the interframe spacing is decreased, this was expected having Eq. 4.6 in mind, because the section modulus of the longitudinal stiffeners is quadratically dependent on the effective bending span, ℓ_{bdg}, therefore decreasing the bending span (interframe spacing) will decrease the weight of the longitudinal stiffeners.

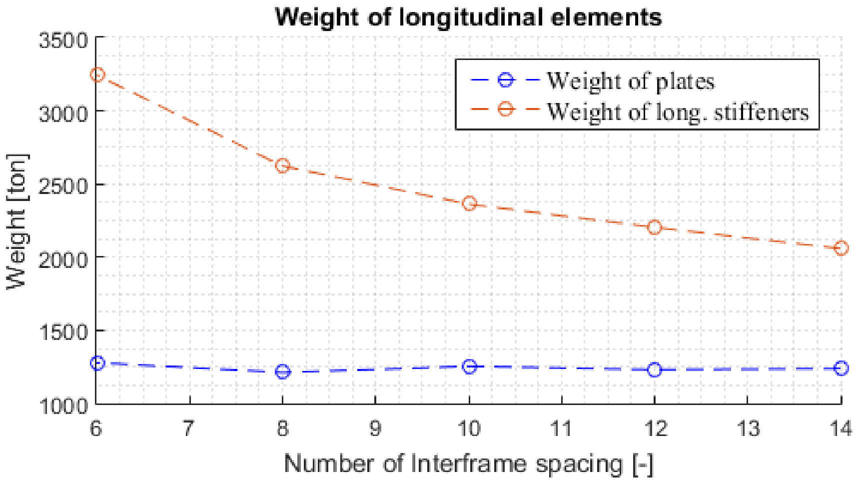


Figure 5.6: Weight of longitudinal elements when varying the interframe spacing.

Table 5.79 shows the weight of the longitudinal elements when varying the stiffeners spacing.

Table 5.79: Weight of plates, longitudinal stiffeners and total weight when varying longitudinal stiffener spacing.

TYPE	**# ΔF**	**W_PL [ton]**	**W_STIFF [ton]**	**W_ long [ton]**	**W [ton]**	**W %**
7 Frames - ΔS-1100mm	8	1361	2591	3953	4851	101.7%
7 Frames - ΔS-1000mm	8	1296	2557	3854	4752	99.6%
7 Frames - ΔS-800mm	8	1101	2561	3663	4561	95.6%
7 Frames - ΔS-700mm	8	1058	2603	3660	4559	95.5%
7 Frames - ΔS-600mm	8	1019	2701	3720	4618	96.8%

Figure 5.7 shows the weight of the plates and longitudinal stiffeners in function of the nominal longitudinal stiffener spacing, extracted from Table 5.79. Note that the weight of the plates (in blue) decreases as the longitudinal stiffener spacing decreases. This result is expected having the minimum plate thickness equation, Eq. 4.5, in mind, because the breadth of plate panel, b, is directly proportional to the minimum plate thickness. Therefore, increasing the spacing of the longitudinal elements will increase the thickness of the plates, consequently increasing the weight.

The weight of the longitudinal stiffeners (in orange) in Figure 5.7, did not present severe changes as in Figure 5.6. This effect is comprehensible because although the only parameter varying in the section modulus equation, Eq. 4.6, is the stiffener spacing, s, when decreasing it, the section modulus decreases (consequently its individual weight decreases), but the weight decrease is compensated by some other longitudinal stiffeners that must be added, resulting is slightly changes in the overall weight of the longitudinal stiffeners (W_STIFF).

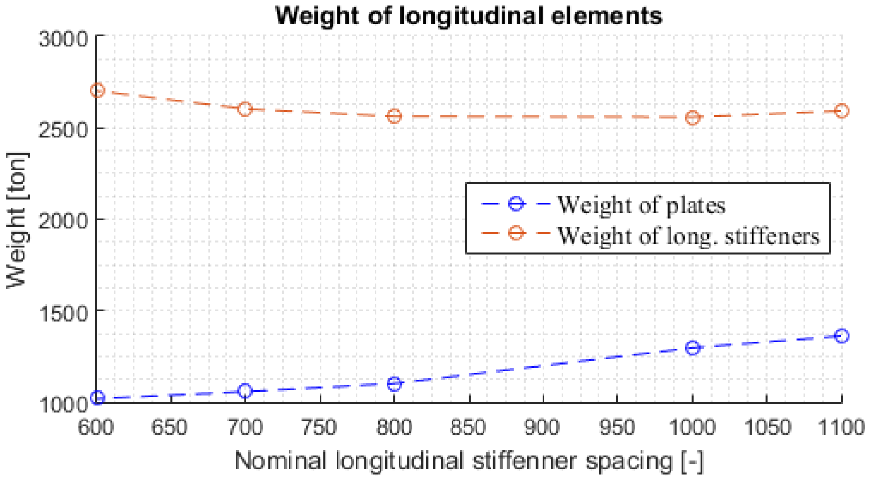


Figure 5.7: Weight of longitudinal elements when varying nomial logitudinal stiffener spacing.

5.5.2. Overall weight

The values displayed in Table 5.41 and 5.77, can be plotted in a 3D graph, where the Y-axis is the number of frames, the X-axis is the nominal spacing of frames and the Z-axis is the Weight ratio, having as 100% the original scantling. The result is shown in Figure 5.8.

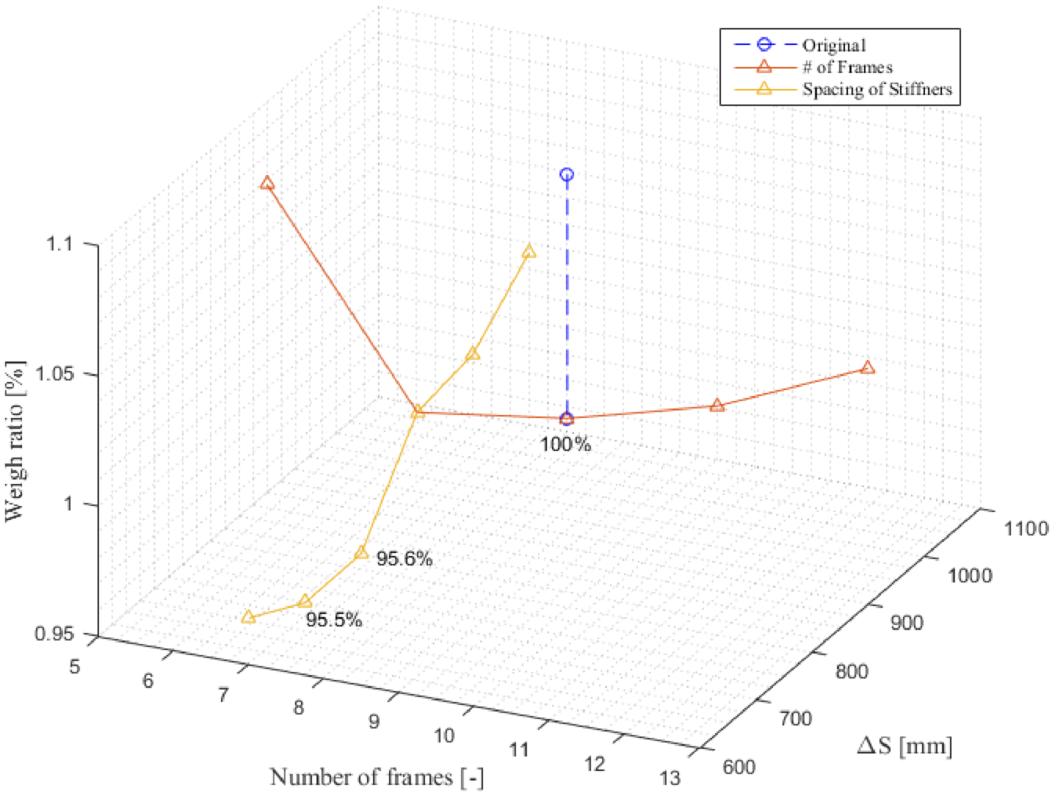


Figure 5.8 : Distribution of the weight varying the number of frames and spacing of stiffeners.

One can notice that decreasing the number of frames from 13 to 7 decreased the weight of the entire cargo hold. This conclusion could not be withdrawn just by looking at the section modulus equation of the longitudinal stiffeners, Eq. 4.6, because the section modulus varies quadratically in function of the span. It is seen that the weight of the web frames makes a major contribution to the final weight of the cargo hold. There is also a high jump in weight from 7 to 5 frames, in this case the span of the stiffeners is so big that their section modulus has to be very large as well to resist the local loads.

Decreasing the spacing of the longitudinal stiffeners from 1100mm to 700mm decreased the weight of the cargo hold. In region of the graph the weight of the plates govern the total weight of the cargo hold, since the number of frames are constant and the weight of the longitudinal elements does not vary too much. Finally, decreasing too much the spacing between the stiffeners, 600mm for instance, caused the total weight to increase again, due to the weight of several longitudinal stiffeners added.

Therefore, the lightest arrangement has 7 frames, and a nominal stiffener spacing of 700mm, resulting in a weight saving of over 4%.

6. CONCLUSION

The conclusions from the investigation performed in this master thesis are:

- The weight of the cargo hold is greatly influenced by the weight of the web frames, therefore reducing the number of web frames up to a limit decreases the cargo hold weight. For the structural arrangement with least weight selected, with interframe spacing of 6350mm and nominal longitudinal stiffeners spacing of 700mm, the web frame mass is over 24%. Decreasing too much the number of web frames leads to very large section modulus for the longitudinal stiffeners, what also increase the weight of the cargo hold drastically.
- The spacing of the longitudinal stiffeners plays a significant role in the final weight of the cargo hold. It was observed that decreasing the spacing between stiffeners decreased the final weight of the cargo hold, although more stiffeners needed to be added. This effect has also a limit, decreasing too much the spacing of the longitudinal stiffeners causes too many of them to be added, increasing the weigh. The plating weigh combined with the number of longitudinal stiffeners added were the determinant factors. For the least weight structural arrangement, mentioned above, the weight of the plating represents over 23% of the cargo hold weight.
- The weight of the plating such as the plating on the hull, inner bottom, inner side, longitudinal bulkheads represent 21 to 28% of the cargo hold weight. This parameter is greatly influenced by the longitudinal stiffeners spacing and not very much influenced by the aspect ratio of the panel (interframe spacing);
- Adding two frames or reducing two frames from the original arrangement of the cargo hold structure did not influence the overall weight too much, but decreasing the longitudinal stiffeners spacing 100 or 200mm produce relevant weight saving of over 4%.
- The plates that are not subjected to large lateral pressure, such as deck plates, usually are limited by buckling. This is the main constraint in the weight reduction for this area.
- For plates subjected to large lateral pressure, such as bottom plates, or inner bottom plates the checking criteria that limits the weight reduction is yielding.

7. SUGGESTIONS FOR FUTURE WORKS

For future works, the following actions and suggestions could enlarge the scope of this work:

- Development of a code in MATLAB for selecting the dimensions of the profiles;
- Instead of calculating only 10 scantlings for the cargo hold, a matrix of 5 frames options and 5 longitudinal spacings could be calculated;
- Calculate the construction cost of the options;
- Calculate overall percentage of weight saving;
- Calculate the fuel saving;
- Develop a new profile with different scantling for every stiffener (without groups).

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