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Master Thesis / Proyecto Fin de Carrera:

ANALYTICAL AND NUMERICAL DETERMINATION OF THE HULL GIRDER DEFLECTION OF INLAND NAVIGATION VESSELS

DETERMINACIÓN ANALÍTICA Y NUMÉRICA DE LA DEFLEXIÓN DEL BUQUE-VIGA DE BUQUES DE NAVEGACIÓN INTERIOR

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1. ABSTRACT

In this project, the analytical and numerical determination of the hull girder deflection of inland navigation vessels is carried out.

This means that this project joins together different knowledge related to shipbuilding, strength of materials, ship design, rules and regulations, drawing applied to shipbuilding and advanced Finite Element Analysis of structures.

The structure of a ship suffers different types of deformations from the building stage to the end of its service. These deformations have different sources like local buckling, thermal influences, global bending moment or even weldings during workmanship.

The hull girder deflection occurs when a vessel undergoes vertical bending moment, which can be caused by the lightship weight distribution, the load distribution and the wave induced global loads.

The value of the hull girder deflection should be maintained within a range compatible with a proper operation of machinery and equipment onboard. For instance, some difficulties may occur in shafting but also piping. Concerning the main shaft, it can experience higher torsional moments due to the eccentricity and inefficiency because of the bigger efforts of the shaft between the bearings. When deflection occurs, piping can meet some problems like stuck liquids and important efforts in the supports.

According to International Standards, hull girder deflection is limited to 1 mm per meter of ship length. As per the classification rules, no specific limits on hull girder deflections are given explicitly, but the L/D ratio is related to the criteria which allows safeguarding against excessive deflection.

Studying this phenomenon is essential for the definition of the criteria allowing safeguarding against excessive deflection.

This investigation deals with the determination of the response of the ship complying with *Bureau Veritas Rules for the Classification of Inland Navigation Vessels*, in the form of deflection, to the applied loads.

The study is carried out according to the following steps:

1. The structure strength of a chemical tanker is checked according to the *BV Rules for Inland Navigation Vessels* using *Mars Inland* and the FEA software *FEMAP with NX Nastran*.

2. Analytical determination of the hull girder deflection of the chemical tanker
3. Numerical determination of the hull girder deflection of the chemical tanker
4. Analytical determination of the hull girder deflection of standard inland navigation vessels

The analytical method consists of the calculation of the deflection of the ship due to bending, which is similar to that for a beam. The ship is considered free-free supported and has a varying moment of inertia (I), and the deflection is obtained by the second integration of the M_B/EI curve.

The numerical method refers to direct calculations by using Finite Element Analysis. The main aim of using FEA in structures is to obtain an accurate calculation of the hull structure response so that the analytical method can be validated.

2. INTRODUCTION

2.1. Naval architecture's terms and definitions

The naval architecture's terms that are related to this project and other definitions are included in this section:

Ship geometry and parts

Fore: is the front part of the vessel.

Aft: it is the rear or back part of the ship.

Stem: is the most forward part of a boat or ship's bow (front of the ship) and is an extension of the keel itself.

Aft Perpendicular (AP): is the vertical line that coincides with the aft end of the length between perpendiculars.

Length overall (LOA): is the maximum length of a vessel's hull measured parallel to the waterline.

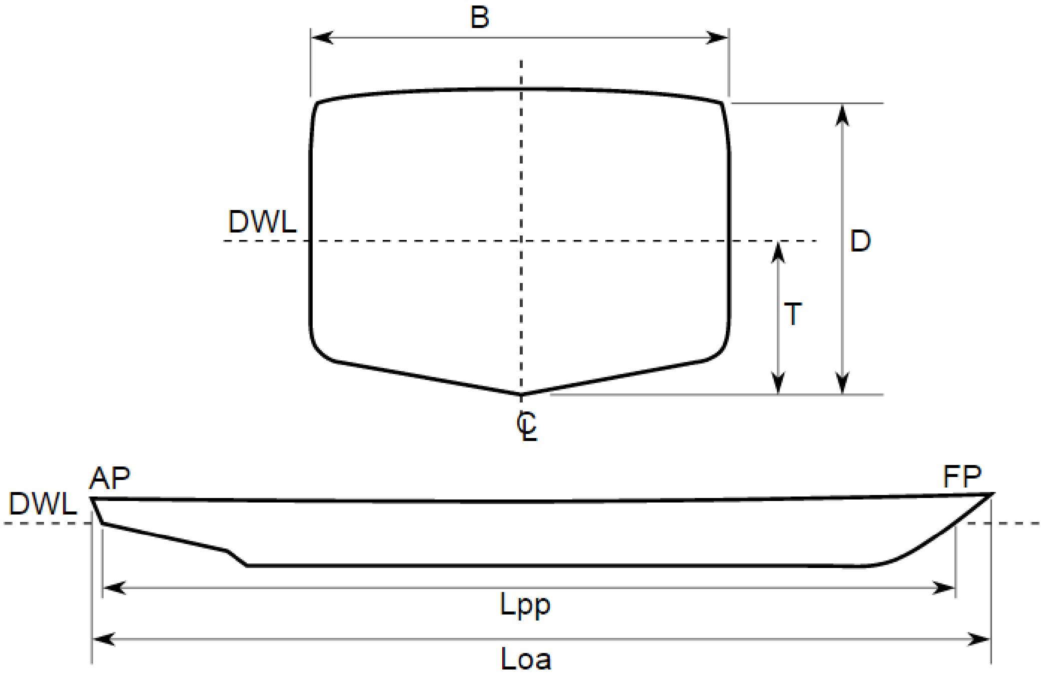


Figure 2.1.1. Main dimensions of a ship (Wikipedia)

Length between Perpendiculars (L_{PP}): refers to the length of a vessel along the waterline from the forward surface of the stem, or main bow perpendicular member, to the after surface of the sternpost, or main stern perpendicular member. When there is no sternpost, the centerline axis of the rudder stock is used as the aft end of the length between perpendiculars.

Length at the waterline (LWL): is the length of a ship or boat at the point where it sits in the water.

Breadth or beam (B): is the width of the hull.

Depth (D): is the vertical distance measured from the top of the keel (central structural basis of the hull) to the underside of the upper deck at side.

Draught or draft (T): is the vertical distance between the waterline and the bottom of the hull (keel), with the thickness of the hull included.

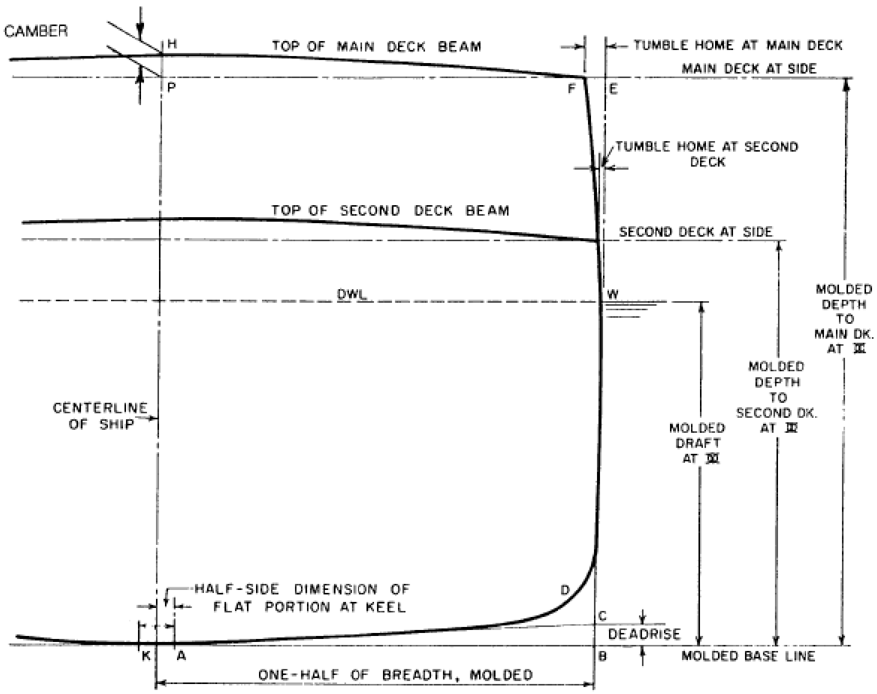


Figure 2.1.2. Midship section, molded form (Lewis, 1988)

Block coefficient (C_B): is the volume (V) divided by the LWL x B x T. If you draw a box around the submerged part of the ship, it is the ratio of the box volume occupied by the ship. It gives a sense of how much of the box is filled by the hull.

Full forms such as oil tankers will have a high C_b where fine shapes such as sailboats will have a low C_b.

$$C_b = \frac{V}{L_{WL} \cdot B \cdot T}$$

Midship: The middle section of a vessel with reference to the longitudinal plane, as distinguished from fore or aft.

Centerline: An imaginary line down the center of a vessel lengthwise. Any structure or anything mounted or carried on a vessel that straddles this line and is equidistant from either side of the vessel is *on the centerline* (or *centreline*).

Bilge: is the curved plate between the bottom and the side shell of the hull.

Bulkhead: A bulkhead is an upright wall within the hull of a ship. Other kinds of partition elements within a ship are decks and deckheads. One of its purposes is to increase structural rigidity of the vessel or divide functional areas into rooms, like the cargo holds.

Double hull: A double hull is a ship hull design and construction method where the bottom and sides of the ship have two complete layers of watertight hull surface: one outer layer forming the normal hull of the ship, and a second inner hull which is some distance inboard, typically by a few feet, which forms a redundant barrier to seawater in case the outer hull is damaged and leaks. The space between the two hulls is sometimes used for storage of fuel or ballast water.

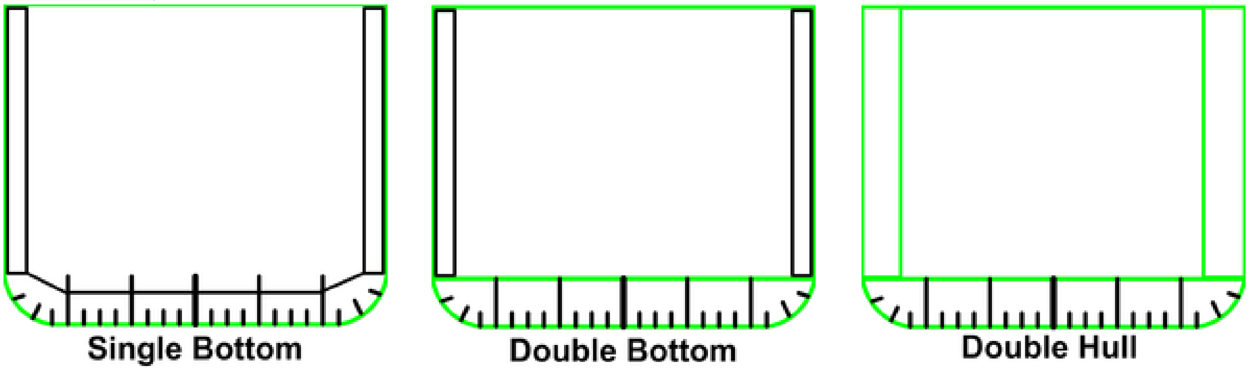


Figure 2.1.3. Single bottom, double bottom and double hull (Wikipedia)

Deck: The top of the ship. Unlike flats, they are a structural part of the ship. The under-side of the deck above is called deckhead.

Engine Room: one of the machinery spaces of a vessel, usually the largest one, containing the ship's prime mover (usually a diesel engine). Larger vessels may have more than one engine room, like the fore part engine room for the fore propellers or thrusters.

Frame: a transverse structural member in the side which gives the hull strength and shape.

Hold: in earlier use, below the orlop deck, the lower part of the interior of a ship's hull, especially when considered as storage space, as for cargo. In later merchant vessels it extended up through the decks to the underside of the weather deck.

Superstructure: the parts of the ship or a boat, including sailboats, fishing boats, passenger ships, and submarines, that project above her main deck. This does not usually include its masts or any armament turrets.

Other definitions:

Buoyancy: is an upward force exerted by a fluid that opposes the weight of an immersed object. An object whose density is greater than that of the fluid in which it is submerged tends to sink. If the object is either less dense than the liquid or is shaped appropriately (as in a ship), the force can keep the object afloat. In a situation of fluid statics, the net upward buoyancy force is equal to the magnitude of the weight of fluid displaced by the body, which is the weight of the body for a floating object.

Classification Society: is a non-governmental organization that establishes and maintains technical standards for the construction and operation of ships and offshore structures. The society will also validate that construction is according to these standards and carry out regular surveys in service to ensure compliance with the standards.

Classification societies set technical rules, confirm that designs and calculations meet these rules, survey ships and structures during the process of construction and commissioning, and periodically survey vessels to ensure that they continue to meet the rules. Classification societies are also responsible for classing oil platforms, other offshore structures, and submarines. This survey process covers diesel engines, important shipboard pumps and other vital machinery.

Classification surveyors inspect ships to make sure that the ship, its components and machinery are built and maintained according to the standards required for their class.

Displacement: is the weight of water that a ship displaces when it is floating, which in turn is the weight of a ship (Lightship) and its contents (Deadweight). Units are usually in tons.

Displacement = Lightship weight + Deadweight

Grounding: when a ship (while afloat) touches the bed of the sea, or goes "aground".

Hogging: when the peak of a wave is amidships, causing the hull to bend so the ends of the keel are lower than the middle. The opposite phenomenon is called **sagging**. Also refers to a distortion of the hull in the same manner caused by the bow and stern of a ship being less buoyant than the midship section.

International Association of Classification Societies (IACS): technically based organization consisting of twelve marine classification societies headquartered in London. Marine classification is a system for promoting the safety of life, property and the environment primarily through the establishment and verification of compliance with technical and engineering standards for the design, construction and life-cycle maintenance of ships, offshore units and other marine-related facilities. These standards are contained in rules established by each Society. IACS provides a forum within which the member societies can discuss, research and adopt technical criteria that enhance maritime safety.

Lines Plan: The Lines Plan defines the exterior form of a ship’s hull. The Lines Plan can be either a drawing or a numerical table where every point of the hull’s surface can be obtained.

Scantlings: dimensions of ships structural members, e.g., frame, beam, girder, etc.

Tanker: a ship designed to transport liquids in bulk. For example, an oil tanker, also known as a petroleum tanker, is a merchant ship designed for the bulk transport of oil.

Trim (t): is the measurement of the longitudinal inclination of the vessel.

2.2. Description of the study

2.2.1. Beam theory, deflection and the L/D ratio

Elementary beam theory is usually utilized in computing the component of primary stress or deflection due to vertical or lateral hull bending loads. In assessing the applicability of this beam theory to ship structures, it is useful to restate the underlying assumptions:

- The beam is prismatic, i.e., all cross sections are the same,
- Plane cross sections remain plane, and merely rotate as the beam deflects,
- Transverse (Poisson) effects on strain are neglected,
- The material behaves elastically, the modulus of elasticity in tension and compression being equal,
- Shear effects (stresses, strains) can be separated from and do not influence bending stresses or strains.

Many experiments have been conducted to investigate the bending behaviour of ships or ship-like structures. The results, in many cases, agree quite well with the predictions of simple beam theory.

The derivation of the equations for stress and deflection under the assumptions of elementary beam theory is related to the strength of materials. The elastic curve equation for a beam is obtained by equating the resisting moment to the bending moment, *M*, at section *x*, all in consistent units,

$$EI\frac{d^2y}{dx^2} = M(x)$$

Where:

y : is the deflection,

E : is the modulus of elasticity of the material,

I : is the moment of inertia of the beam cross section about an horizontal axis through its centroid.

This may be written in terms of the load per unit length, *q(x)*, as

$$EI\frac{d^4y}{dx^4} = q(x)$$

The deflection of the ship's hull as a beam is obtained by the second integration of the M_B/EI curve or by the multiple integration of the previous formula. It may be seen that the deflection, hence stiffness against bending, depends upon both geometry (moment of inertia, I) and elasticity (E). Hence, a reduction in hull depth or a change to a material such as aluminium (E approximately 1/3 that of steel) will reduce hull stiffness.

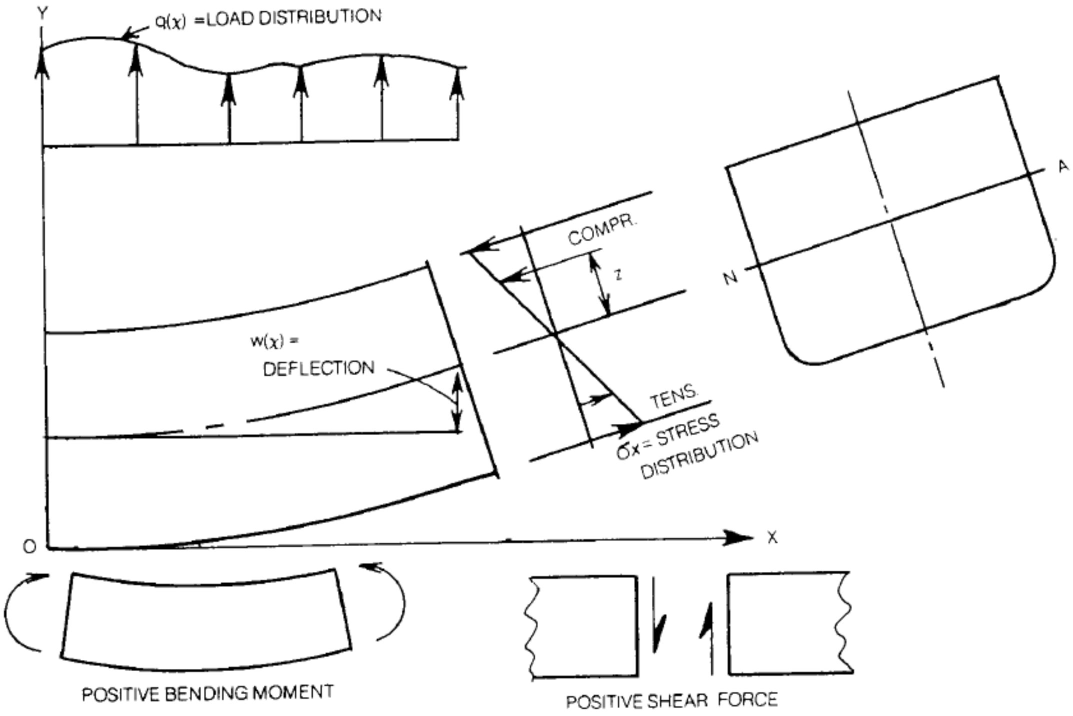


Figure 2.2.1. Loading, shear and deflection of elementary beam (Lewis, 1988)

Excessive deflection may limit the structural effectiveness of a member, even though material failure does not occur, if that deflections results in a misalignment or other geometric displacement of vital components of the ship's machinery, navigational equipments, or weapons systems, thus rendering system ineffective.

The present thesis is concerned with the determination of the response, in the form of stress and deflection, of structural members to the applied loads. Once the responses are known, it is necessary to determine whether the structure is adequate to withstand the demands placed upon it, and this requires consideration of several possible failure modes.

One of the most important characteristics of the ship structure is its composition of an assemblage of plate-stiffener panels. The loading applied to any such panel may contain components in the plane of the plating and components normal to the plane of the plating. The normal components of load originate in the secondary loading resulting from fluid pressures of the water surrounding the ship or from internal liquids, and in the weights of supported material such as the distributed bulk cargo and the structural members themselves.

The in-plane loading of the longitudinal members originates mainly the primary external bending and twisting of the hull. The most obvious example of an in-plane load is the tensile or compressive stress induced in the deck or bottom by the bending of the hull girder in response to the distribution of weight and water pressure over the ship length.

Since flexibility is seldom a problem for hulls of normal proportions constructed of mild steel, primary structure is usually designed on the basis of strength consideration rather than deflection. However, classification society rules deal indirectly with the problem by specifying a limit on L/D ratio of:

- 15 for oceangoing vessels,
- 21 for Great Lakes bulk carriers (which experience less severe wave bending moments),
- 25 for inland navigation vessels for a range of navigation of IN($1{,}2 \leq x \leq 2$),
- 35 for inland navigation vessels for IN(0,6), which means that the maximum wave height is 0,6 meters.

Designs in which L/D exceeds these values must be "specially considered". There is also a lower limit on hull girder moment of inertia, which likewise has the effect of limiting deflection, especially if high-strength steels are used. An all-aluminium alloy hull would show considerably less stiffness than a steel hull having the same strength. Therefore, classification societies agree on the need for some limitation on deflection, although opinions differ as to how much.

2.2.2. Rule-based versus direct analysis and design

There are basically two ways to perform analysis and design of a ship structure. The first one, the oldest, is called *rule-based design*. It is mainly based on the rules defined by the classification societies.

In the past, ship structural design has been largely empirical, based on accumulated experience and ship performance, and expressed in the form of structural design codes or rules published by the various ship classification societies. These rules concern the loads, the strength and the design criteria and provide simplified and easy-to-use formulas for the structural dimensions, or "scantlings" of a ship. This approach saves time in the design office and, since the ship must obtain the approval of a classification society, it also saves time in the approval process.

The second way is the *Rationally Based Structural Design*, that is based on direct analysis. There are several disadvantages to a completely "rulebook" approach to design. First, the modes of structural failure are numerous, complex, and interdependent. With such simplified formulas the margin against failure remains unknown; thus one cannot distinguish between structural adequacy and over-adequacy. Second, and most important, these formulas involve a number of simplifying assumptions and can be used only within certain limits. Outside of this range they may be inaccurate. For these reasons there is a general trend toward direct structural analysis.

Even if direct calculation has always been performed, design based on direct analysis only became popular when numerical analysis methods became available and were certified. Direct analysis has become the standard procedure in aerospace, civil engineering and partly offshore industries. In ship design, classification societies preferred to offer updated rules resulting from numerical analysis calibration. For the designer, ever if the rules were continuously changing, the design remained *rule-based*.

Hopefully, in 2002, this was no longer true. The advantages of direct analysis are so obvious that classification societies include, usually as an alternative, a direct analysis procedure (numerical packages based on finite element method). In addition, for new vessel types or non-standard dimension, such direct procedure is the only way to assess the structural safety.

When carrying out direct strength analysis in order to verify the equivalence of structural strength with rule requirements, it is necessary for the classification society to clarify the strength that a hull structure should have with respect to each of the various steps taken in the analysis process, from load estimation through to strength evaluation. In addition, in order to make this a practical and effective method of analysis, it is necessary to give careful consideration to more rational and accurate methods of direct strength analysis.

2.2.3. Development and procedure of the study

The current thesis is part of a long-term study considering that it requires an extensive research. As stated previously, the definition of the criteria allowing safeguarding against excessive deflection is a phenomenon that has to be study along with the L/D ratio since they are related to each other.

The determination of the deflection of a wide range of conventional inland navigation vessels, with different structural configurations, has to be studied so as to check that the condition of 1 mm per meter of vessel's length is complied with.

In order to complete this task, the study is divided into two parts, the first of which is carried out in this project:

1. The analytical and numerical determination of the hull girder deflection of a standard inland navigation vessel in order to validate the analytical deflection.
2. The analytical determination of the hull girder deflection of standard inland navigation vessels for the purpose of updating the L/D ratio in the Rules.

Therefore, **the main objective of this thesis is the analytical and numerical determination of the hull girder deflection of a chemical tanker** so as to validate the deflection obtained analytically.

The procedure to develop this project follows the next steps:

1. Strength check

To begin with, the scantlings and strength of the structure are checked by using the software *Mars Inland*, which is a software that verifies the structure and is based on the *Bureau Veritas Rules for Inland Navigation Vessels* (or simply, the *Rules*).

The strength of primary supporting members is also checked with the finite element software *FEMAP with NX Nastran*. Hence, the hull girder strength of the tanker is checked, in way of stresses, analytically and numerically.

If the scantlings do not comply with the *Rules*, a structure optimization must be carried out.

2. Analytical determination of the hull girder deflection

Once the check is performed, the maximum bending moment using direct calculations must be obtained in order to determine the highest value of deflection. That bending moment can be found when studying all the loading conditions according to the *Rules*.

The distribution of the moment of inertia along the length must also be obtained and, then, the analytical method is used to get the hull girder deflection.

3. Numerical determination of the hull girder deflection

The next step deals with the numerical method and it refers to direct calculations by using the FEA software *Femap with NX Nastran*. This part is the core of the thesis.

The modelling and analysis of a complete hull girder using finite elements is performed so as to determine its deflection precisely. The result obtained in this part is used for the validation of the analytical determination of the hull girder deflection.

4. Validation of the results

Analytical and numerical results are compared. In addition, and as an example, four more conventional inland navigation vessels are analyzed for the purpose of obtaining analytically their deflections.

Therefore, the objective of this thesis, the analytical and numerical deflection of a standard inland navigation vessel, is achieved, according to the procedure explained.

2.3. The Finite Element Method

It is possible, using a computer-based method of analysis known as the finite element method, to analyze the entire hull at one time. The finite element procedure is a powerful tool that is widely and routinely used in most aspects of modern structural analysis, and standard computer programs are available from computer service bureaus and a number of other sources.

The aim of using finite element method (FEM) in structural analysis is to obtain an accurate calculation of the stress response in the hull structure. Several types or levels of FE-models may be used in the analyses:

- Global stiffness model,
- Cargo hold model,
- Frame and girder models,
- Local structure models,
- Stress concentration models.

The model or sets of models applied is to give a proper representation of the following structure:

- Longitudinal plating,
- Transverse bulkheads/frames,
- Stringers/Girders,
- Longitudinals or other structural stiffeners.

The finer mesh models are usually referred to as sub-models. These models may be solved separately by transfer of boundary deformations/ boundary forces from the coarser model.

This requires that the various mesh models are compatible, meaning that the coarser models have meshes producing deformations and/or forces applicable as boundary conditions for the finer mesh models.

In this project, the FE-model is a *global stiffness model* which means that it should be a relatively coarse mesh which is used to represent the overall stiffness and global stress distribution of the primary members of the total hull length. A typical global finite element model is shown in Figure 2.3.1.

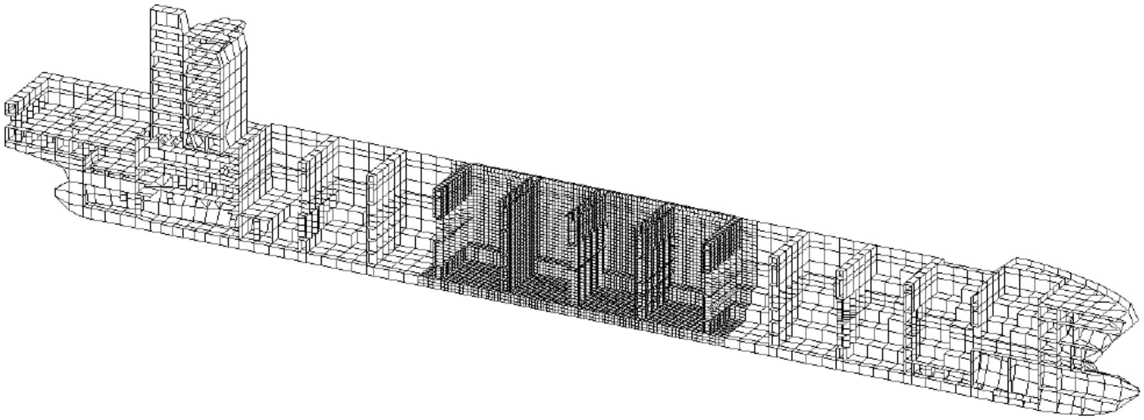


Figure 2.3.1. Global Finite Element Model of Container Vessel including 4 Cargo Holds Sub-model (Rigo and Rizzuto, 2010)

The mesh density of the model has to be sufficient to describe deformations and nominal stresses from the following effects:

- Vertical hull girder bending including shear lag effects,
- Vertical shear distribution between ship side and bulkheads,
- Horizontal hull girder bending including shear lag effects, torsion of the hull girder,
- Transverse shear and bending.

Stiffened panels may be modelled by means of layered elements, anisotropic elements or frequently by a combination of plate and beam elements. It is important to have a good representation of the overall membrane panel stiffness in the longitunal/transverse directions.

Structure not contributing to the global strength of the vessel may be disregarded; the mass of these elements shall nevertheless be included (for vibration). The scantling is to be modelled with *reduced scantling*, that is, corrosion addition is to be deducted from the actual scantling.

All girder webs should be modelled with shell elements. Flanges may be modelled using beam and truss elements. Web and flange properties are to be according to the real geometry.

The performance of the model is closely linked to the type of elements and the mesh topology that is used. As a standard practice, it is recommended to use 4-node shell or membrane elements in combination with 2-node beam or truss elements are used. The shape of 4-node elements should be as rectangular as possible as skew elements will lead to inaccurate element stiffness properties. The element formulation of the 4-node element requires all four nodes to be in the same plane. Double curved surfaces should therefore not be modelled with 4-node elements. 3-node elements should be used instead.

The minimum element sizes to be used in a global structural model (coarse mesh) for 4-node elements (finer mesh divisions may of course be used and is welcomed, especially with regard to sub-models):

- Main model: 1 element between transverse frames/girders; 1 element between structural deck levels and minimum 3 elements between longitudinal bulkheads,
- Girders: 3 elements over the height,
- Plating: 1 element between 2 longitunals.

When a *cargo hold model* is carried out, the model is used to analyze the deformation response and nominal stresses of the primary members of the midship area. The model will normally cover ½ + 1 + ½ cargo hold/tank length in the midship region. Typical models are shown in Figure 2.3.2.

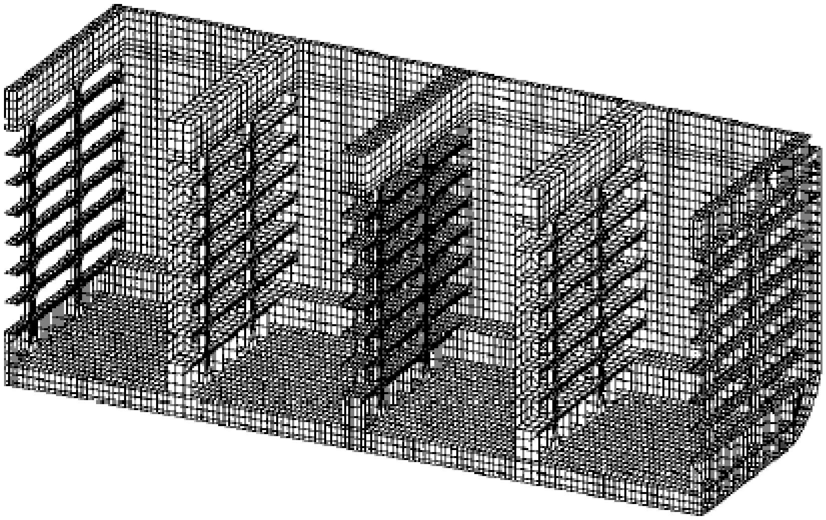


Figure 2.3.2. Cargo Hold Model Example (Based on the Fine Mesh of the Frame Model) (Rigo and Rizzuto, 2010)

The *frame and girder models* are used to analyze nominal stresses in the main framing/girder system (Figure 2.3.3). The element mesh is to be fine enough to describe stress increase in critical areas (such as bracket with continuous flange). This model may be included in the cargo hold model, or run separately with prescribed boundary deformations/forces. However, if sufficient computer capacity is available, it will normally be convenient to combine the two analyses into one model.

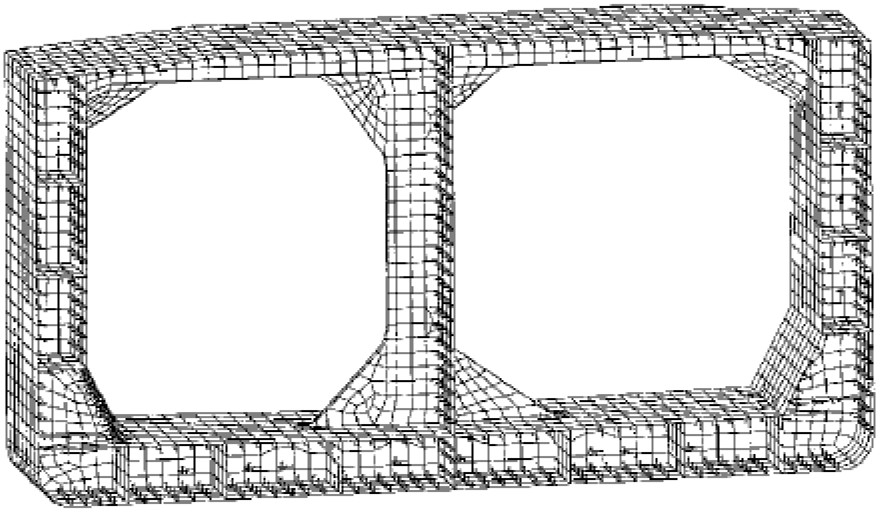


Figure 2.3.3. Frame and Girder Model Example (Web Frame) (Rigo and Rizzuto, 2010)

Local structure analyses are used to analyze stresses in local areas. Stresses in laterally loaded local plates and stiffeners subjected to large relative deformations between girders/frames and bulkheads may be necessary to investigate along with stress increase in critical areas, such as brackets with continuous flanges.

As an example, the areas to model are normally the following for a tanker:

- Longitudinal in double bottom and adjoining vertical bulkhead members,
- Deck longitudinal and adjoining vertical bulkhead members,
- Double side longitudinal and adjoining horizontal bulkhead members,
- Hatch corner openings,
- Corrugations and supporting structure.

Stress concentration models are used for fatigue analyses of details where the geometrical stress concentration is unknown.

2.3.1. Uncertainties related to FEA

An important issue in structural analysis is the verification of the analysis. The FEM is basically reliable but many sources of errors can appear, mainly induced by inappropriate modelling and wrong data. For this reason, different levels of verification of the analysis should be performed in order to ensure trustworthiness of the analysis results. Verification must be achieved at the following steps:

- Basic input,
- Assumptions and simplifications made in modelling/analysis,
- Models,
- Loads and load transfer,
- Analysis,
- Results,
- Strength calculations.

One important step in the verification is the understanding of the physics and check of deformations and stress flow against expected patterns/levels. However, all levels of verification are important in order to verify the results.

Assumptions and simplifications will have to be made for most structural models when verifying them. These should be listed such that an evaluation of their influence on the results can be made.

The *boundary conditions* for the global structural model should reflect simple supporting to avoid built-in stresses. The fixation points should be located away from areas where stresses are of interest. Fixation points are often applied in the centreline close to the aft and the forward ends of the vessel.

When verifying loads, inaccuracy in the load transfer from the hydrodynamic analysis to the structural model is among the main error sources in this type of analysis. The load transfer can be checked on basis of the structural response or on basis on the load transfer itself.

The response should be verified at several levels to ensure correctness of the analysis:

- Global displacement patterns/magnitude,
- Local displacement patterns/magnitude,
- Global sectional forces,
- Stress levels and distribution,
- Sub-model boundary displacement/forces,
- Reaction forces and moments.

2.3.2. Static analysis

Static analysis represents the traditional way to perform stress and strength analyses of a ship structure. Loads are assessed separately of the strength structure and, even if their origins are dynamic (flow induced), they are assumed to be static (do not change with the time). This assumption may be correct for the hydrostatic pressure but not when the dynamic wave loads are changed to static loads applied on the side plates of the hull.

In the future, even if the assumption of static loads is not verified, static analysis will continue to be performed, as it is easier and faster to do it. In addition, tens of experience years have shown that they provide accurate results when stresses and deflections assessments are the main target.

Such analysis is also the standard procedure for fatigue assessment to determine the hot spot stress through fine mesh FEA.

3. SHIP STRUCTURES. DEFORMATIONS AND SERVICEABILITY

3.1. Nature of ship structures

The size and principal characteristics of a new ship are determined primarily by its mission or intended service. In addition to basic functional considerations there are requirements such as stability, low resistance and high propulsive efficiency, and navigational limitations on draft or beam, all of which influence the choice of dimensions and form.

The ship's structure must be designed, within these and other basic constraints, to sustain all of the loads expected to arise in its environment. As a result, a ship's structure possesses certain distinctive features not found on other man-made structures.

Among the most important distinguishing characteristics of ship structures are the size, complexity, and multiplicity of function of structural components, the random or probabilistic nature of the loads imposed and the uncertainties inherent in our ability to predict the response of the structure to those loads. In contrast to land-based structures, the ship does not rest on a fixed foundation but derives its entire support from buoyant pressures exerted by a dynamic and ever-changing fluid environment.

3.1.1. Structural configurations

A ship is composed of plates and beams. The first components of a ship are the cargo holds since they make the ship resistant against twisting, which is due to moments. The second elements are panels or stiffened panels (deck, sides, bottom). Inside the panels, the below elements can be found:

- Unstiffened plates: it does not have stiffeners and they are related to resistance,
- Girders: longitudinal primary members,
- Stiffeners: longitudinal secondary members,
- Frames: transversal primary members.

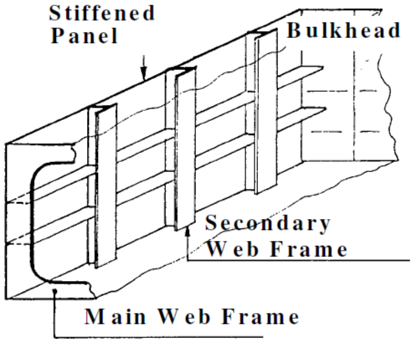


Figure 3.1.1. A standard stiffened panel (Rigo and Rizzuto, 2010)

Stiffening systems

A ship structure has to be arranged in function of its purpose and operations or services. The cylindrical body fixes the stiffening system because its main purpose is the resistance of the ship. Fore and aft bodies are more related to security and support of systems like propulsion or mooring.

The reinforcements are transverse or longitudinal, but the stiffening systems set up resistant rings, either longitudinal or transversal.

When an unstiffened plate has its longitudinal dimension bigger than the transverse one, we deal with a longitudinal stiffening system. Otherwise it is a transverse framing system.

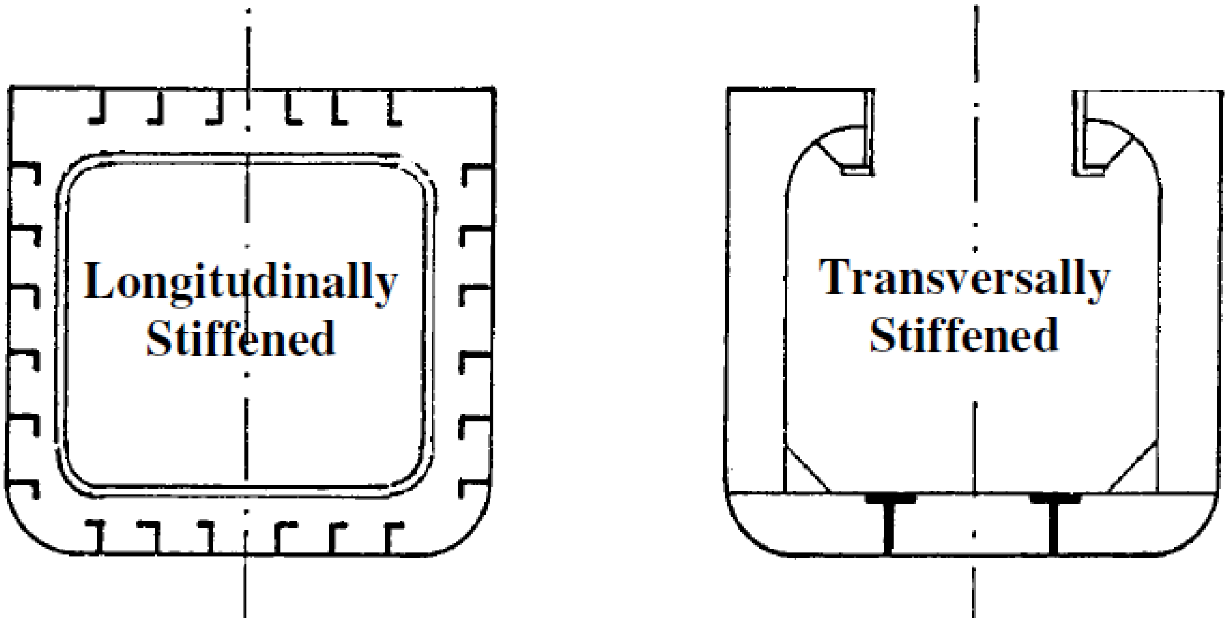


Figure 3.1.2. Types of stiffening (Longitudinal and Transverse) (Rigo and Rizzuto, 2010)

Longitudinal framing system

It is composed of girders, stiffeners and frames. Secondary members are fitted in the longitudinal direction and are known as longitudinals. The system consists of many small, closely spaced longitudinals supporting the plating and also by a few large, widely spaced longitudinals called girders. The deep, heavy transverse structures called frames support the longitudinals.

This framing system is used for larger ships where longitudinal strength is a major consideration. The primary function of longitudinals is to resist the longitudinal bending stress due to sagging and hogging.

The keel girder is extra large and heavy in order to carry the loads imposed during dry docking. This system is desirable to be adopted for lengths bigger than 120 meters. In tankers with lengths bigger than 200 meters this system is a must.

Some advantages of this system are:

+ Plating is more resistant to buckling,
+ Each longitudinal can be sized to withstand the maximum pressure associated with its depth in the ship, thus achieving an efficient use of material

Some drawbacks are:

- Deep webs for ships carrying packaged cargo,
- Difficulties of structural arrangements near both ends of the ship,
- Difficulties during construction when they converge so closely that some longitudinals have to be eliminated.

Transverse framing system

It is composed of girders, frames and secondary frames. Instead of stiffeners, there is a secondary framing system so, there are more frames than in the longitudinal system.

This system is used for small ships where the main loads are local loads, which do not come from the bending moment. For instance, the hydrostatic pressure or the green water (the water which gets on board). Local loads are the key issue to design a small ship.

Some advantages of this stiffening system are:

+ It is easier to build than the longitudinal system,
+ There is more space in the cargo holds so it is easier to load/unload the cargo.

Some disadvantages are:

- It is heavier because of the plate thickness.

Mixed framing system

This system mixes the two main systems. Deck, bottom and double bottom are arranged according to the longitudinal system and both sides are arranged with the transverse framing system (secondary frames end at the first stiffeners at deck and bottom).

This arrangement takes advantage of each of the other two systems, depending upon the loads and resistance conditions that the ship will support.

For instance, this system is used in bulkcarriers since it is easier to clean the cargo when it is unloaded, due to the fact that there are no side longitudinals (although this system is disappearing in this kind of ship lately because there are corrosion problems in the side shells).

3.1.2. Limit states

The goal of structural designers is to avoid structural failures. To achieve this objective, it is necessary for the designer to be aware of the potential limit states, failure modes and methods of predicting their occurrence.

A limit state is any condition in which a structure or a structural element becomes unsuitable to perform its structural function due to effects caused by a load or a combination of loads.

Ship structural failure may occur as a result of a variety of causes, and the degree of severity of the failure may vary from a minor aesthetic degradation to catastrophic failure resulting in loss of the ship. Three major failure modes are defined:

1. Tensile or compressive yield of the material (plasticity),
2. Compressive instability (buckling),
3. Fracture that includes ductile tensile rupture, low-cycle fatigue and brittle fracture.

Yielding: Let’s assume that a tensile load is gradually applied to a structure, then some elongation might be induced and be proportional to the load increment as long as the load is small. Once the load exceeds a certain critical value, then elongation would increase rapidly. That failure mode is called yielding. The designer usually takes care to maintain the strength of the structure so as not to exceed the yield point.

Buckling: In the case of a structure under compression load, the structure may suddenly be deflected when the load reaches a critical value. Such a failure mode is called buckling. Once a large deflection takes place, the structure may not recover its original shape even when the load is removed.

Fatigue: The structure may be fractured by small loads when the loads are provided repeatedly to the structure. That failure mode is called fatigue. Fatigue is very dangerous, because it may result even from substantially lower loads than yielding strength, especially when the number of cycles is very large. That type of fracture is sometimes caused by vibration, because its frequency is very high.

From the viewpoint of steel structural design, there are four types of limit states:

1. Service or serviceability limit state,
2. Ultimate limit state,
3. Fatigue limit state,
4. Accidental limit state.

A *service limit state* corresponds to the situation where the structure can no longer provide the service for which it was conceived, for example: excessive deck deflection, elastic buckling in a plate and local cracking due to fatigue. Typically they are related to aesthetic, functional or maintenance problems, but do not lead to collapse.

Figure 3.1.3. Collapse of the hull girder (Marineinsight.com)

An *ultimate limit state* corresponds to collapse or failure, including collision and grounding. A classic example of ultimate limit state is the ultimate hull bending moment. The ultimate limit state is symbolized by the higher point (C) of the moment-curvature curve (M-ϕ), Figure 3.1.4.

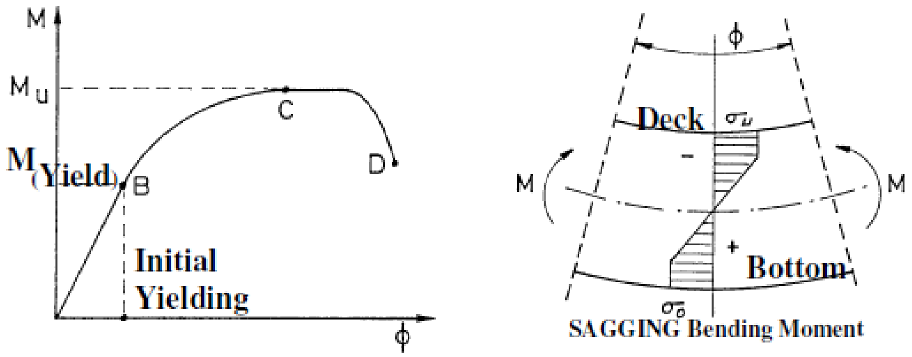


Figure 3.1.4. The Moment-Curvature Curve (M-ϕ) (Rigo and Rizzuto, 2010)

Fatigue can be either considered as a third limit state or, classically, considered as a service limit state. Even if it is also a matter of discussion, *yielding* should be considered as a service limit state. First yield is sometimes used to assess the ultimate state, for instance for the ultimate hull bending moment, but basically, collapse occurs later. Most of the time, *vibration* relates to service limit states.

In practice, it is important to differentiate *service*, *ultimate*, *fatigue* and *accidental limit states* because the partial safety factors associated with these limit states are generally different.

3.1.3. Partial safety factors

Almost every design requires restrictions, that is, requirements or conditions that have to be satisfied. In structural design the most important restrictions are the strength restrictions, which are oriented to provide suitable safety and service.

Structural safety is probabilistic since there is a failure risk from the loads and their effects but, apart from dealing with statistical uncertainties, a rational design procedure must provide some means to control the other uncertainties by the designer or the class society.

This is done by specifying a minimum value of the margin between the value of the limit state $Q_L(X)$ of the considered variable and the extreme characteristic value $Q_C(X)$. In practise, this margin is the safety factor γ_0, which is the minimum value for which Q_L must exceed Q_C. The restriction, in terms of γ_0, is:

$$\gamma_0 \, Q_C(X) \leq Q_L(X)$$

Besides taking into consideration the uncertainties, it is necessary to use more safety factors so as to take into account the degree of importance of each and every type of failure, not only with respect to safety (loss of lives) but also to service (economic loss or operation capacity loss). Furthermore, it is also necessary to apply factors that take into account the type of ship and the cost and the importance of the type of ship operation. These diverse factors are known as partial safety factors.

The required safety level is given by the total safety factor, which is the product of all the partial safety factors. Therefore, γ_0 is the total safety factor.

3.1.3. Safeguard against excessive deflection

In general, design criteria based on allowable deflection requires much heavier scantlings for structural members, relative to that based on allowable stress. For instance, the stern must be designed so as not to allow excessive deflection which would disturb the smooth rotation of propeller and rudder, as well as keeping the stress in the stern within allowable limits.

Stern structure and engine room structure have several rotating machines inside them, therefore, they must be designed from the viewpoint of allowable stress and also from allowable deflection. It was already mentioned that it is important in the design of an engine room that the structure is designed so as not to cause misalignment of machines or pumps, due to large deflection in the structure. In the same manner, much attention must be paid to restrict excessive deflection in the stern structure.

If we calculate the stress of the stern or stern frame by assuming proper external load, we find that the stress level of these members is almost one tenth those of the other structures. That is because the scantlings of these members are decided not by allowable stress criteria but by allowable deflection.

In order to progress a design based on allowable deflection, allowable limits must be clarified first, and then the stiffness of structural members is determined so that the defection of the member is lower than the critical limit. However, for the stern, stern frame and rudder, it is regretted that the allowable criteria of deflection cannot be completely established at initial stages of a project.

Establishment of the following criteria is essential in designing more reasonable and more sophisticated structures:

- Allowable stress to prevent cracking or buckling
- Allowable amplitude to prevent vibration
- Allowable deflection to prevent machinery damage

3.2. Types of deformations

3.2.1. Local

Deformations can be created by either secondary or tertiary responses of the hull girder. Secondary response relates to the global bending of stiffened panels or to the behaviour of the double bottom and double sides.

Tertiary response describes the out-of-plane deflection and associated stress of an individual unstiffened plate panel included between 2 longitudinals and 2 transverse web frames. The boundaries are formed by these components (Figure 3.2.1).

3.2.2. Hull girder

Is the response of the entire hull, which is called primary response. As explained throughout this thesis, the ship bends as a beam under the longitudinal distribution of load.

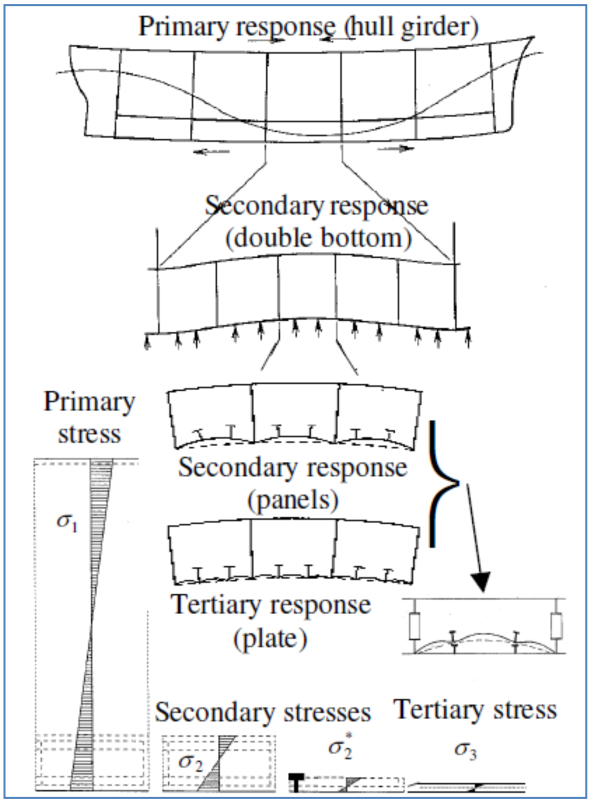


Figure 3.2.1. Primary, secondary and tertiary structural responses (Rigo and Rizzuto, 2010)

The associated primary stresses, σ_1, are those, which are usually called the longitudinal bending stresses, but the general category of primary does not imply a direction.

3.2.3. At building stage

As shipbuilding is one of those areas of metal-working industry, where large scale products have to be manufactured and assembled, these products are subjected to high levels of loading because of forces, moments and temperature differences, the latter caused by welding in particular.

Because of all these factors, the stress and deformation caused by the combined action of material, geometry and loading create problems particularly with regard to precision of manufacture.

3.2.4. During the ship service

The steel plating often experiences permanent plastic deformation from in-service loads and this deformation is greatest between stiffeners and frames.

Such plate deformations may be caused by various loads such as ice pressure, green water, wave slamming, docking, and wheel loading on decks. Design guidelines are available that permit a level of permanent set or inelastic deformation in certain locations on the ship and under specified conditions. These design guidelines are often expressed in terms of maximum plate deflection based on location in the hull.

3.3. Serviceability

3.3.1. Limit tolerances

Regarding local deflections, classification society rules may contain requirements to ensure that local deflections are not excessive. Special requirements also apply to stiffeners. Special attention must be given to rigidity of members under compressive loads to avoid buckling. This is done by providing a minimum moment of inertia at the stiffener and associated plating.

In actual service, a ship may be subjected to bending in the inclined position and to other forces, such as those which induce torsion or side bending in the hull girder, not to mention the dynamic effects resulting from the motions of the ship itself. Heretofore it has been difficult to arrive at the minimum scantlings for a large ship’s hull by first principles alone, since the forces that the structure might be required to withstand in service conditions are uncertain.

Accordingly, it must be assumed that the allowable stress includes an adequate factor of safety, or margin, for these uncertain loading factors. In practice, the margin against yield failure of the structure is obtained by a comparison of the structure's von Mises stress, σ_e, against the permissible stress (or allowable stress), σ_0, giving the result:

$$\sigma_e \leq \sigma_0 = s_1 \times \sigma_y$$

Where:

s_1 : partial safety factor defined by the classification society, which depends on the loading condition and method of analysis.

σ_y : minimum yield point of the considered steel

For different ship types, different permissible stresses may be specified for different parts of the hull structure.

3.3.2. Typical potential problems

In shafting

The shaft alignment problem is related to the propulsion shafting sensitivity to small disturbances in the supporting bearing offsets. The primary contributor to the bearing offset disturbances on the vessel in operation is from the hull girder deflections as the result of a change of the loading condition of the vessel.

The ability to predict hull deflections with sufficient accuracy is of the foremost importance in order to ensure robust alignment design, and consequently, less alignment-related casualties.

The alignment procedure itself starts at a very early stage of ship production and finishes only after the vessel is waterborne. The accuracy of the alignment procedure will depend on the ability to account for those hull deflections in alignment design. The main problem is that hull deflections are quite difficult and expensive to obtain.

In piping

Piping systems also can meet some problems like stuck liquids and important efforts in the supports due to high values of deflection. These systems count on specific devices to avoid any inconvenience.

Classification Societies take into consideration all these problems and create rules so as to require a safe design, construction and testing.

4. HULL GIRDER DEFLECTION

The reactions of structural components of the ship hull to external loads are usually measured by either *stresses* or *deflections*. Structural performance criteria and the associated analyses involving stresses are referred to under the general term of *strength* while deflection-based considerations are referred to under the term *stiffness*.

The ability of a structure to fulfil its purpose may be measured by either or both strength and stiffness considerations. The strength of a structural component may be termed inadequate and structural failure would be deemed to have occurred if the material of which the component is constructed experiences a loss of load-carrying ability through fracture, yield, buckling, or some other failure mechanism in response to the applied loading.

4.1. Causes

The hull girder deflection occurs when a vessel undergoes vertical bending moment, which can be caused by the lightship weight distribution, the load distribution and the wave induced global loads.

Actual deflection in service is affected also by thermal influences, rigidity of structural components and workmanship. Furthermore, deflection due to shear is additive to the bending deflection, though its amount is usually relatively small.

The same influences, which gradually increase nominal stress levels, also increase flexibility. Additionally, draft limitations and stability requirements may force the L/D ratio up, as ships get larger. In general, therefore, modern design requires that more attention should be focused on flexibility than formerly.

No specific limits on hull girder deflections are given in the classification rules. The required minimum scantlings, however, as well as general design practices, are based on the limitation of the L/D ratio range.

4.2. Vertical and horizontal bending

Principally, attention has been focused upon the vertical longitudinal bending response of a vessel. As the ship moves through a seaway encountering waves from directions other than directly ahead or astern, it will experience lateral bending loads and twisting moments in addition to the vertical loads.

The former may be dealt with by methods that are similar to those used for treating the vertical bending loads, noting that there will be no component of stillwater bending moment or shear in the lateral direction. The twisting or torsional loads will require some special consideration. Note that the response of the ship to the overall hull twisting loading should be considered a primary response.

The combination of vertical and horizontal bending moment has a major effect to increase the stress at the extreme corners of the structure:

$$\sigma = \frac{\mathrm{M_v}}{\mathrm{I_v}/\mathrm{c_v}} + \frac{\mathrm{M_h}}{\mathrm{I_h}/\mathrm{c_h}}$$

Where:

M : bending moment

I : sectional moment of Inertia about the neutral axis

c : distance from the neutral axis to the extreme member

For, respectively, the vertical bending and the horizontal bending.

For a given vertical bending moment, the periodical wave induced horizontal bending moment increases stress, alternatively, on the upper starboard (right side of the vessel) and lower portside (left side of the vessel), and on the upper portside and lower starboard. This explains why these areas are usually reinforced.

In this project, when mentioning bending moment, it is the vertical bending moment the one that is considered because it affects the vertical response of the vessel. Hence, the second addend of the previous formula is not considered since horizontal bending does not interact with the vertical bending as for the hull girder deflection.

4.3. Calculation

Bending deflection

The calculation of the deflection of a ship due to bending is similar for that for a beam. A ship is free-free supported and has a varying moment of inertia, and the deflection is obtained by the second integration of an intermediate M_B/I curve. The basic relation is:

$$\frac{M_B}{EI} = \frac{d^2y}{dx^2}$$

$$\frac{dy}{dx} = \frac{1}{E}\left[\int \frac{M_B}{I} dx\right] + a$$

$$y = \frac{1}{E}\left[\iint \frac{M_B}{I} dx\, dx\right] + ax + b$$

Where:

y is the deflection,

a is the first constant of integration of the M_B/I curve,

b is the second constant of integration of the M_B/I curve.

The slope curve

The first integration of the M_B/I curve gives the change in slope and the ordinates of the curve are equal to the areas under the M_B/I curve represented by:

$$\frac{dy}{dx} = \frac{1}{E}\left[\int \frac{M_B}{I} dx\right] + a$$

Since the ends of the hull girder are free, the end slope is the constant of integration a and not zero. The axis of the slope curve is a line parallel to the baseline and the sum of the end ordinates is equal to the total slope. The point at which the slope curve crosses the axis is the point of maximum deflection, and is generally near the maximum ordinate of the M_B/I curve.

The loading may be such that the bending moment crosses its baseline in one or more points. In this case, the M_B/I curve would have points of zero value and the slope curve would have corresponding points of maximum or minimum slope, depending upon the magnitude of the areas on the opposite side of the baseline.

Deflection curve

The deflection curve is the second integral of the M_B/I curve and is expressed by:

$$y = \frac{1}{E}\left[\iint \frac{M_B}{I} dx\, dx\right] + ax + b$$

Since the ends of the hull girder are free, the constant of integration b of the deflection curve is equal to zero. If the slope curve is integrated about the axis of the curve, the deflection curve will close at the ends about the baseline.

From the deflection, the constant of integration a of the slope curve is determined by the fact that when x equals the length L, y is equal to zero and:

$$a = \frac{-\frac{1}{E}\iint_0^L \frac{M_B}{I}\,dx\,dx}{L}$$

The deflections resulting from built-in bending moments or from dynamic bending moments would theoretically be calculated in a similar manner, but in practice the indefinite nature of such bending moments makes the application of these principles extremely difficult and, in general, impracticable.

In general, the shear deflection is much smaller than the bending-moment deflection and it usually may be neglected. The deflection is of a significant value only when the unsupported length of the ship girder is short in comparison to its depth. If, for instance, it is desired to determine the deflection of that part of a ship which overhangs the keel blocks in drydock, the shear deflection should be included.

Differences in temperature between different parts of a ship's structure generally result in a condition intermediate between the two extremes of completely unrestrained expansion or contraction, with no thermal stress, and complete restraint, with thermal stress but no expansion or contraction.

The ship as a whole, when floating freely, is of course not restrained, and a condition in which the upper portion of the ship is as a whole warmer or colder than the bottom portion will result in deflection of the hull girder. If the upper portion is warmer than the bottom, as might occur under a hot sun, the ship will "hog"; if colder, as might occur in subzero weather, the ship will "sag".

The deflection resulting from a difference in temperature between the top and bottom of a steel ship can also be estimated.

4.4. Measurement

The hull girder longitudinal deflection can be determined from multiple draft readings, similar to a lightship survey. Freeboard measurements are taken along the length of a vessel at multiple locations. When plotted against the vessel's lines plan, the direction and magnitude of deflection can be visually observed by the resulting curvature in the waterline.

For a lightship survey, all tanks need to first be sounded to determine their volume. A manifest of the non-lightship weights onboard must be conducted, with the individual weights mass and location noted. The draught marks are recorded as a check. Then, at numerous points along the vessel, the distance from the water to the moulded deck edge is measured and recorded (freeboard measurements).

5. STRENGTH CHECK

In this current Section, the hull girder strength of the tanker is checked, in way of stresses, analytically and numerically.

This strength review is carried out since the vessel has to comply with the Bureau Veritas Rules and, even though this vessel is already classed with BV and is currently in service, it is useful to reassure that the ship is in accordance with the Rules and, besides, to collect structural information of the vessel for its use throughout this project.

The purpose of the strength review is also to compare the analytical and numerical results so as to check the finite element model.

The structural members involved in the computation of primary stress are, for the most part, the longitudinally continuous members such as deck, side, bottom shell, longitudinal bulkheads, and continuous or fully effective longitudinal primary or secondary stiffening members. However, primary stress also refers to the in-plane stress in transverse bulkheads due to the weights and shear loads transmitted into the bulkhead by the adjacent decks, bottom and side shell.

5.1. Procedure

In order to check the hull girder strength, the *Bureau Veritas Rules for the Classification of Inland Navigation Vessels* have been followed.

The procedure consists of, first, modelling plates, ordinary stiffeners and primary structure and, then, check that the scantlings comply with the rules. Second, check the scantlings of plating, ordinary stiffeners and primary supporting members numerically provided that the finite element model is already finished.

Normally, the details of the structure have to comply with:

- Minimum net thickness requirements, regardless of applicable loads
- Thickness and modulus calculations based on the loading service conditions and test conditions, if applicable.

Primary supporting members are checked by direct calculation, using the finite element model, because the vessel’s length is bigger than 120 meters.

5.1.1. Net scantling approach

“Net scantlings” are the scantlings of the hull structure necessary to sustain the acting loads, without any implicit margin for corrosion. The corrosion additions are defined in the Rules and are added to the net scantlings to obtain the scantlings with which the vessel is to be built.

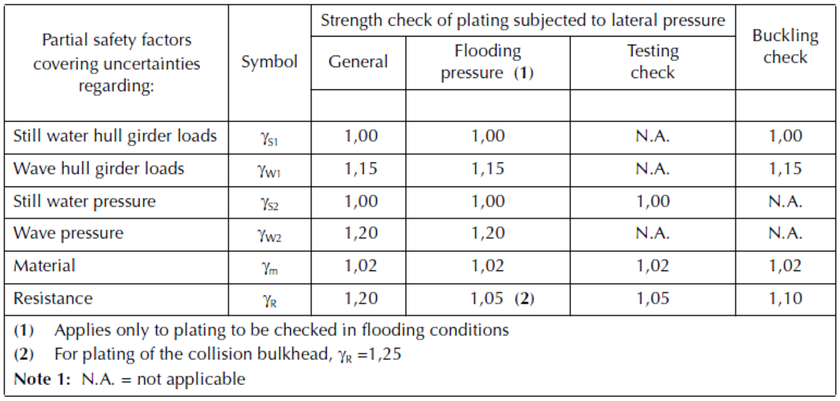
The “net scantling concept” enables the strength criteria for the various limit states to be explicitly defined with respect to the net thickness, without any implicit safety margins to account for corrosion. The corrosion additions can be defined in the Rules depending on the severity of the environment which surrounds each structural element.

This formulation allows a more rational calculation of class renewal thicknesses and a more rational reassessment of vessels in service.

5.1.2. Partial safety factors

The values of resistance partial safety factor covering uncertainties on resistance to be considered for checking structural members, according to the *Rules*, are specified in the following tables for different structural members.

Table 1 : Plating - Partial safety factors



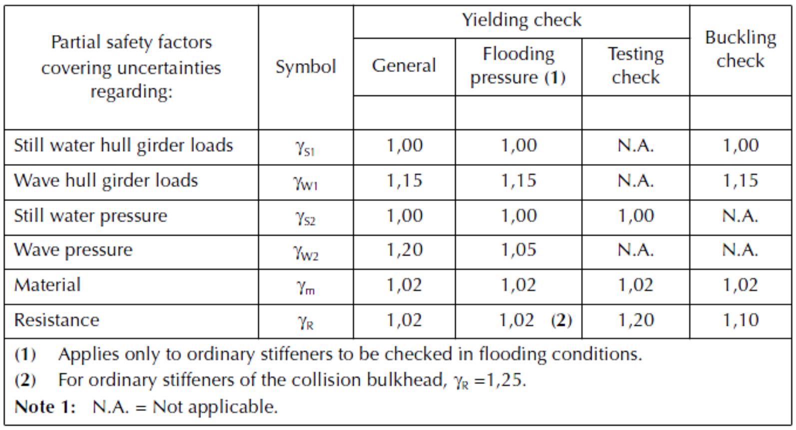
Partial safety factors covering uncertainties regarding:	Symbol	Strength check of plating subjected to lateral pressure			Buckling check
		General	Flooding pressure (1)	Testing check	
Still water hull girder loads	γ_{S1}	1,00	1,00	N.A.	1,00
Wave hull girder loads	γ_{W1}	1,15	1,15	N.A.	1,15
Still water pressure	γ_{S2}	1,00	1,00	1,00	N.A.
Wave pressure	γ_{W2}	1,20	1,20	N.A.	N.A.
Material	γ_m	1,02	1,02	1,02	1,02
Resistance	γ_R	1,20	1,05 (2)	1,05	1,10

(1) Applies only to plating to be checked in flooding conditions

(2) For plating of the collision bulkhead, γ_R =1,25

Note 1: N.A. = not applicable

Table 2 : Ordinary stiffeners - Partial safety factors



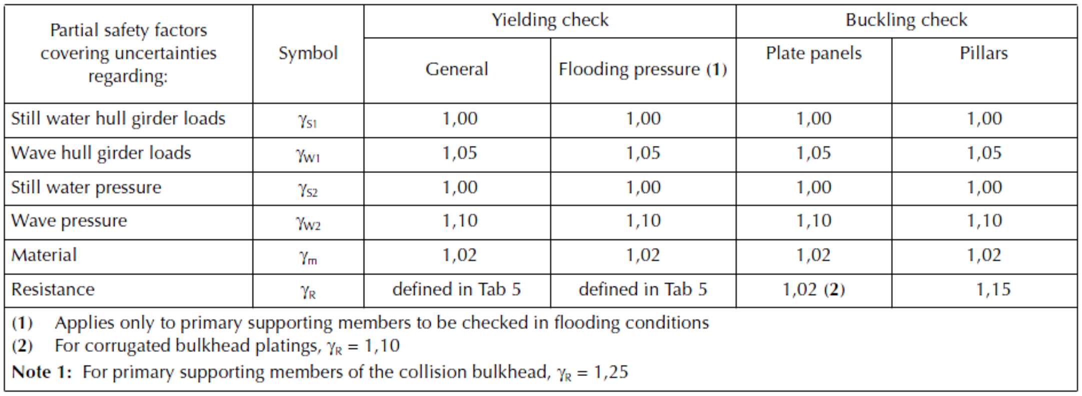
Partial safety factors covering uncertainties regarding:	Symbol	Yielding check			Buckling check
		General	Flooding pressure (1)	Testing check	
Still water hull girder loads	γ_{S1}	1,00	1,00	N.A.	1,00
Wave hull girder loads	γ_{W1}	1,15	1,15	N.A.	1,15
Still water pressure	γ_{S2}	1,00	1,00	1,00	N.A.
Wave pressure	γ_{W2}	1,20	1,05	N.A.	N.A.
Material	γ_m	1,02	1,02	1,02	1,02
Resistance	γ_R	1,02	1,02 (2)	1,20	1,10

(1) Applies only to ordinary stiffeners to be checked in flooding conditions.

(2) For ordinary stiffeners of the collision bulkhead, γ_R =1,25.

Note 1: N.A. = Not applicable.

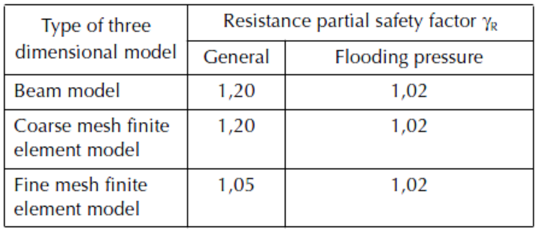
Table 3 : Primary supporting members analysed through three dimensional models - Partial safety factors



Partial safety factors covering uncertainties regarding:	Symbol	Yielding check		Buckling check	
		General	Flooding pressure (1)	Plate panels	Pillars
Still water hull girder loads	γ_{S1}	1,00	1,00	1,00	1,00
Wave hull girder loads	γ_{W1}	1,05	1,05	1,05	1,05
Still water pressure	γ_{S2}	1,00	1,00	1,00	1,00
Wave pressure	γ_{W2}	1,10	1,10	1,10	1,10
Material	γ_m	1,02	1,02	1,02	1,02
Resistance	γ_R	defined in Tab 5	defined in Tab 5	1,02 (2)	1,15

(1) Applies only to primary supporting members to be checked in flooding conditions
(2) For corrugated bulkhead platings, $\gamma_R = 1{,}10$
Note 1: For primary supporting members of the collision bulkhead, $\gamma_R = 1{,}25$

Table 4 : Primary supporting members analysed through three dimensional or complete ship models Resistance partial safety factor



Type of three dimensional model	Resistance partial safety factor γ_R	
	General	Flooding pressure
Beam model	1,20	1,02
Coarse mesh finite element model	1,20	1,02
Fine mesh finite element model	1,05	1,02

5.1.3. Strength criteria and limit states considered

The *serviceability limit states* adopted for the hull structure, i.e., hull girder, primary supporting members, plating and ordinary stiffeners are summarized in Table 5.

Table 5 : Serviceability limit states

	Yielding	strength of plating under lateral loads	Buckling
Hull girder	x		
Primary supporting members	x		x
plating		x	x
Stiffeners	x		x

The *yielding limit state* is reached when excessive deformation occurs in the hull structure due to first yielding formation under serviceability loads. This general concept is expressed by the relationship:

$$\sigma \leq \frac{R_y}{\gamma_R \gamma_m}$$

The scantling of plating is carried out with reference to each elementary plate panel. In this check, each plate panel is considered as being subjected to lateral pressure, induced by the cargo or the external sea pressure. For plating which contributes to the hull girder longitudinal strength, the in-plane normal and shear stresses induced by hull girder loads are also taken into account.

The basic assumption is that a limit state is reached when, under contemporary actions of these loads and stresses, plastic hinges originate in the panel so as to impede it to sustain further loads without excessive deformation. Plastic hinges originate in the factious beam, which connects the mid-span of the longer side of the panel.

Ultimate strength is reached when the number of hinges indicated in Table 6 occurs.

Table 6 : Ultimate strength - number of hinges

Plating	contributing to HGS	not contributing to HGS
Transversely framed	2 hinges	3 hinges
longitudinally framed	3 hinges	
HGS: hull girder strength		

The *buckling limit state* is reached when excessive deformation occurs in slender hull structures due to the buckling under compressive serviceability loads. This general concept is expressed by the following relation:

$$\frac{\sigma_C}{\gamma_R \gamma_m} \geq \sigma$$

Where:

σ_C : critical buckling stress
σ : actual stress

5.2. Strength Check: Hull scantling

5.2.1. Tool: Mars Inland

Mars Inland is a computer tool developed by the Inland Navigation Department of Bureau Veritas for rule-based scantling of plating and ordinary stiffeners of any transverse section located along the vessel's central part.

The geometry and the scantlings are defined using a user-friendly process and the program is updated each time the Rules are modified.

The software is organized around the following main modules:

- Shell: it allows to create a new database or to choose from an existing database
- Basic vessel data: it allows the input of general data common for all the cross sections. It also performs calculations that may be carried out from these data
- Section input: allows the input of any section along the vessel
- Section check

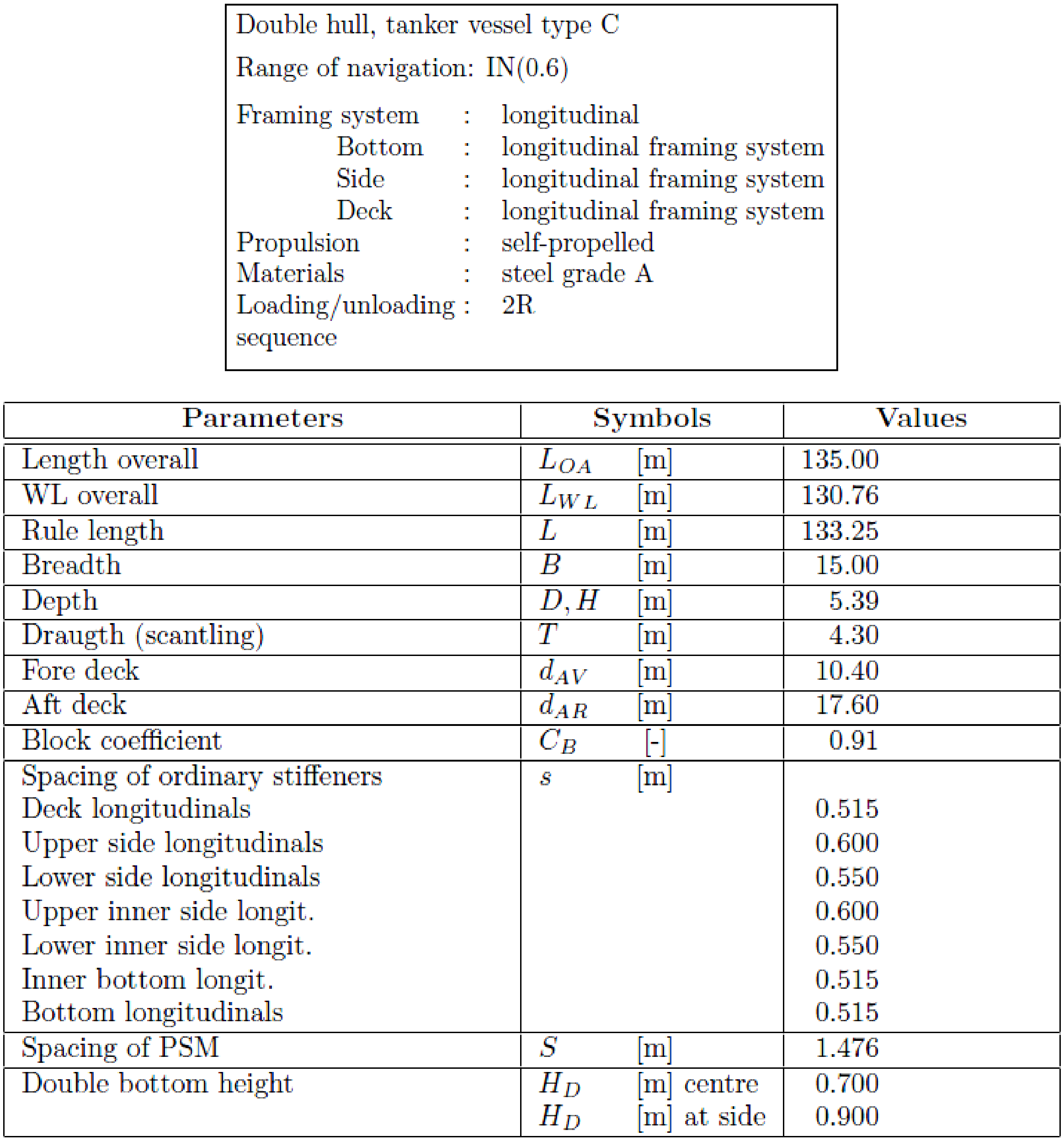
The scope of calculations includes scantling check of strakes and stiffeners for any cross section in the central part of the vessel, with regard to the following limit states:

- Hull girder yielding
- Strength of plating under lateral loads
- Structural member yielding
- Buckling strength

Mars-Inland is intended to become a daily tool for plan review as well as a support for designers.

5.2.2. Scantlings

First of all, the main characteristics of the vessel are defined:



Double hull, tanker vessel type C

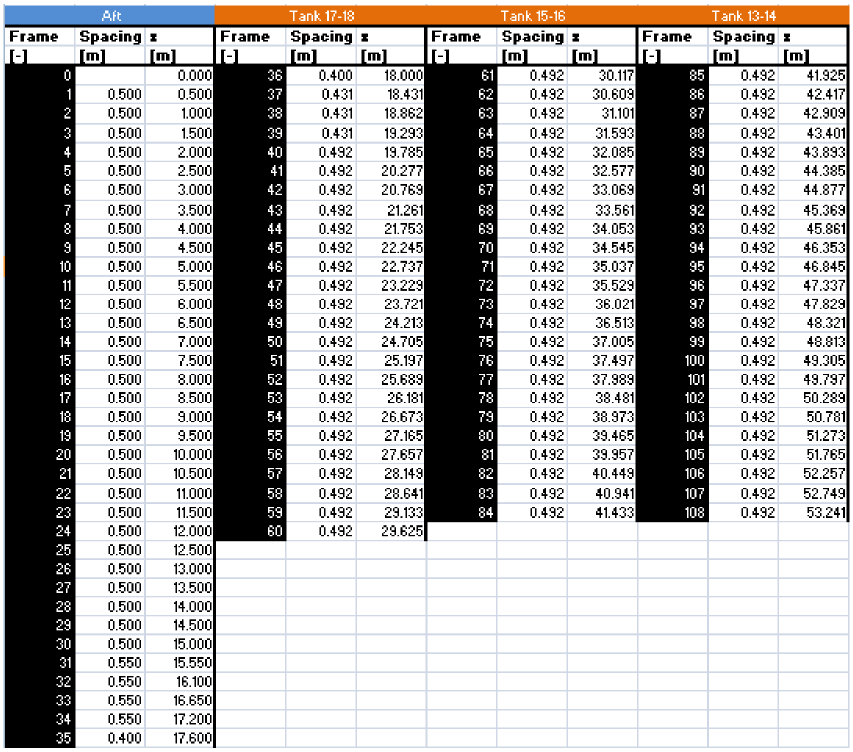
Range of navigation: IN(0.6)

Framing system : longitudinal
Bottom : longitudinal framing system
Side : longitudinal framing system
Deck : longitudinal framing system
Propulsion : self-propelled
Materials : steel grade A
Loading/unloading sequence : 2R

Parameters	Symbols	Values
Length overall	L_{OA} [m]	135.00
WL overall	L_{WL} [m]	130.76
Rule length	L [m]	133.25
Breadth	B [m]	15.00
Depth	D, H [m]	5.39
Draugth (scantling)	T [m]	4.30
Fore deck	d_{AV} [m]	10.40
Aft deck	d_{AR} [m]	17.60
Block coefficient	C_B [-]	0.91
Spacing of ordinary stiffeners	s [m]	
Deck longitudinals		0.515
Upper side longitudinals		0.600
Lower side longitudinals		0.550
Upper inner side longit.		0.600
Lower inner side longit.		0.550
Inner bottom longit.		0.515
Bottom longitudinals		0.515
Spacing of PSM	S [m]	1.476
Double bottom height	H_D [m] centre	0.700
	H_D [m] at side	0.900

Figure 5.2.1. Tanker characteristics

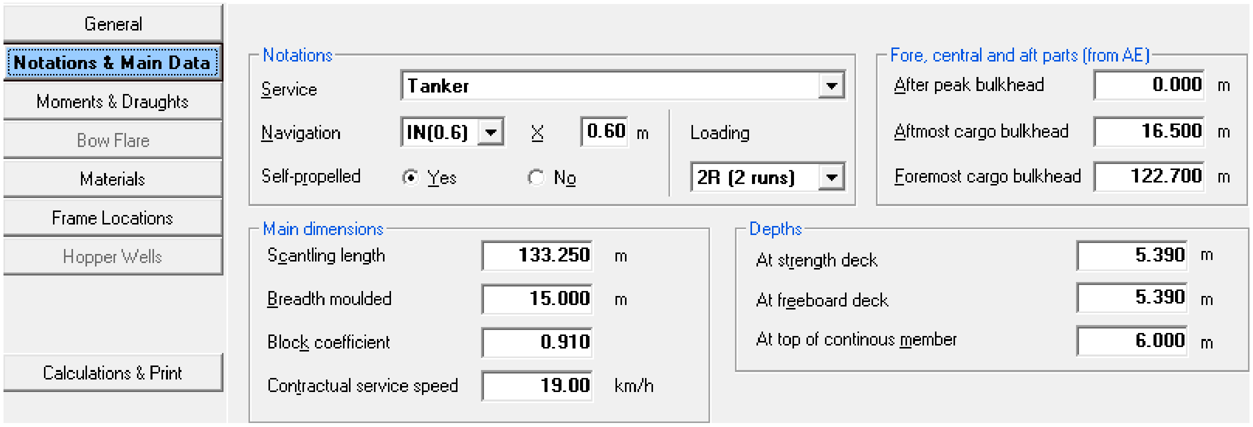
Secondly, an *Excel* table with the frame locations is created. This calculation can be done by following the General Arrangement of the tanker. With this table, the input data in *Mars Inland* can be easily obtained.



Aft			Tank 17-18			Tank 15-16			Tank 13-14		
Frame	Spacing	z	Frame	Spacing	z	Frame	Spacing	z	Frame	Spacing	z
[-]	[m]	[m]	[-]	[m]	[m]	[-]	[m]	[m]	[-]	[m]	[m]
0		0.000	36	0.400	18.000	61	0.492	30.117	85	0.492	41.925
1	0.500	0.500	37	0.431	18.431	62	0.492	30.609	86	0.492	42.417
2	0.500	1.000	38	0.431	18.862	63	0.492	31.101	87	0.492	42.909
3	0.500	1.500	39	0.431	19.293	64	0.492	31.593	88	0.492	43.401
4	0.500	2.000	40	0.492	19.785	65	0.492	32.085	89	0.492	43.893
5	0.500	2.500	41	0.492	20.277	66	0.492	32.577	90	0.492	44.385
6	0.500	3.000	42	0.492	20.769	67	0.492	33.069	91	0.492	44.877
7	0.500	3.500	43	0.492	21.261	68	0.492	33.561	92	0.492	45.369
8	0.500	4.000	44	0.492	21.753	69	0.492	34.053	93	0.492	45.861
9	0.500	4.500	45	0.492	22.245	70	0.492	34.545	94	0.492	46.353
10	0.500	5.000	46	0.492	22.737	71	0.492	35.037	95	0.492	46.845
11	0.500	5.500	47	0.492	23.229	72	0.492	35.529	96	0.492	47.337
12	0.500	6.000	48	0.492	23.721	73	0.492	36.021	97	0.492	47.829
13	0.500	6.500	49	0.492	24.213	74	0.492	36.513	98	0.492	48.321
14	0.500	7.000	50	0.492	24.705	75	0.492	37.005	99	0.492	48.813
15	0.500	7.500	51	0.492	25.197	76	0.492	37.497	100	0.492	49.305
16	0.500	8.000	52	0.492	25.689	77	0.492	37.989	101	0.492	49.797
17	0.500	8.500	53	0.492	26.181	78	0.492	38.481	102	0.492	50.289
18	0.500	9.000	54	0.492	26.673	79	0.492	38.973	103	0.492	50.781
19	0.500	9.500	55	0.492	27.165	80	0.492	39.465	104	0.492	51.273
20	0.500	10.000	56	0.492	27.657	81	0.492	39.957	105	0.492	51.765
21	0.500	10.500	57	0.492	28.149	82	0.492	40.449	106	0.492	52.257
22	0.500	11.000	58	0.492	28.641	83	0.492	40.941	107	0.492	52.749
23	0.500	11.500	59	0.492	29.133	84	0.492	41.433	108	0.492	53.241
24	0.500	12.000	60	0.492	29.625						
25	0.500	12.500									
26	0.500	13.000									
27	0.500	13.500									
28	0.500	14.000									
29	0.500	14.500									
30	0.500	15.000									
31	0.550	15.550									
32	0.550	16.100									
33	0.550	16.650									
34	0.550	17.200									
35	0.400	17.600									

Figure 5.2.2. Frame locations' example

The basic data which is mandatory in *Mars Inland* is shown in the following plots. Within the Notation & Main Data menu, some inputs must be introduced like the type of ship, the range of navigation or the main dimensions, among other data.



Notations
Service: Tanker
Navigation: IN(0.6) X 0.60 m
Loading: 2R (2 runs)
Self-propelled: ● Yes ○ No

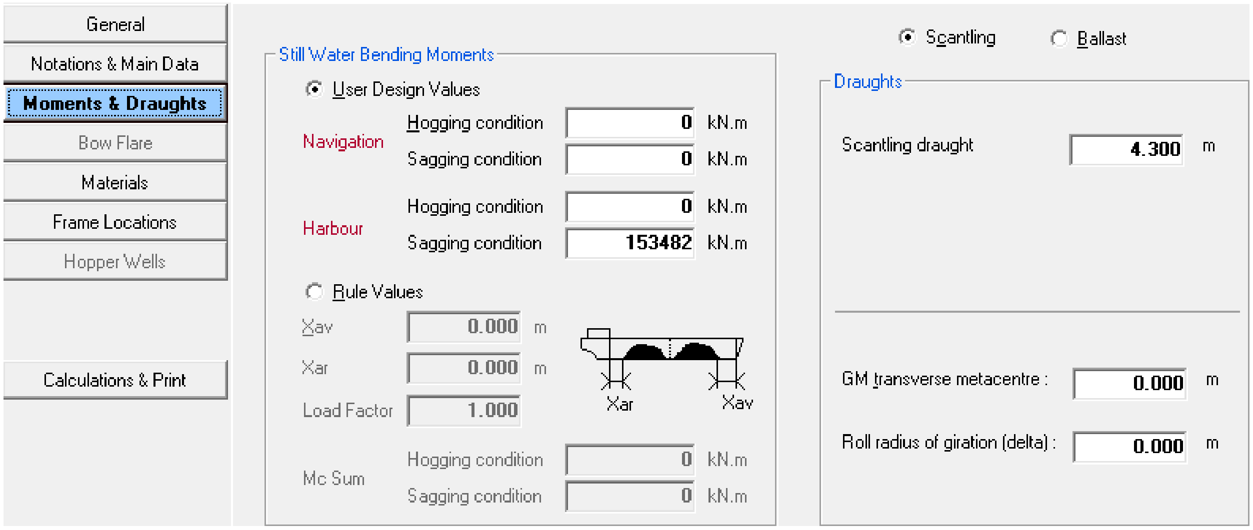
Fore, central and aft parts (from AE)
After peak bulkhead: 0.000 m
Aftmost cargo bulkhead: 16.500 m
Foremost cargo bulkhead: 122.700 m

Main dimensions
Scantling length: 133.250 m
Breadth moulded: 15.000 m
Block coefficient: 0.910
Contractual service speed: 19.00 km/h

Depths
At strength deck: 5.390 m
At freeboard deck: 5.390 m
At top of continous member: 6.000 m

Figure 5.2.3. Mars Inland's basic data: Notations & Main Data

In the basic data, the design values have to be introduced. For instance, the bending moments can be manually indicated, as shown in the next Figure, or they can be automatically obtained if the Rule Values' option is selected.



● Scantling ○ Ballast

Still Water Bending Moments

● User Design Values

Navigation
Hogging condition 0 kN.m
Sagging condition 0 kN.m

Harbour
Hogging condition 0 kN.m
Sagging condition 153482 kN.m

○ Rule Values

Xav 0.000 m
Xar 0.000 m
Load Factor 1.000

Mc Sum
Hogging condition 0 kN.m
Sagging condition 0 kN.m

Draughts

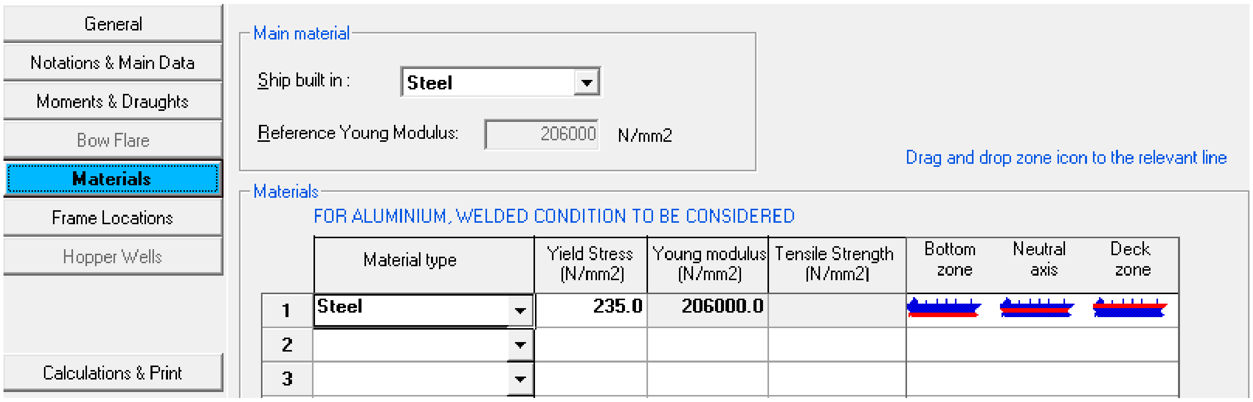
Scantling draught 4.300 m

GM transverse metacentre : 0.000 m

Roll radius of giration (delta) : 0.000 m

Figure 5.2.4. Mars Inland's basic data: Moments & Draughts

The materials at the bottom, neutral axis and deck zone are also defined in this step. Steel is the material of this vessel. Yield stress and Young modulus are automatically attached to the material.



Main material

Ship built in : Steel

Reference Young Modulus: 206000 N/mm2

Drag and drop zone icon to the relevant line

Materials

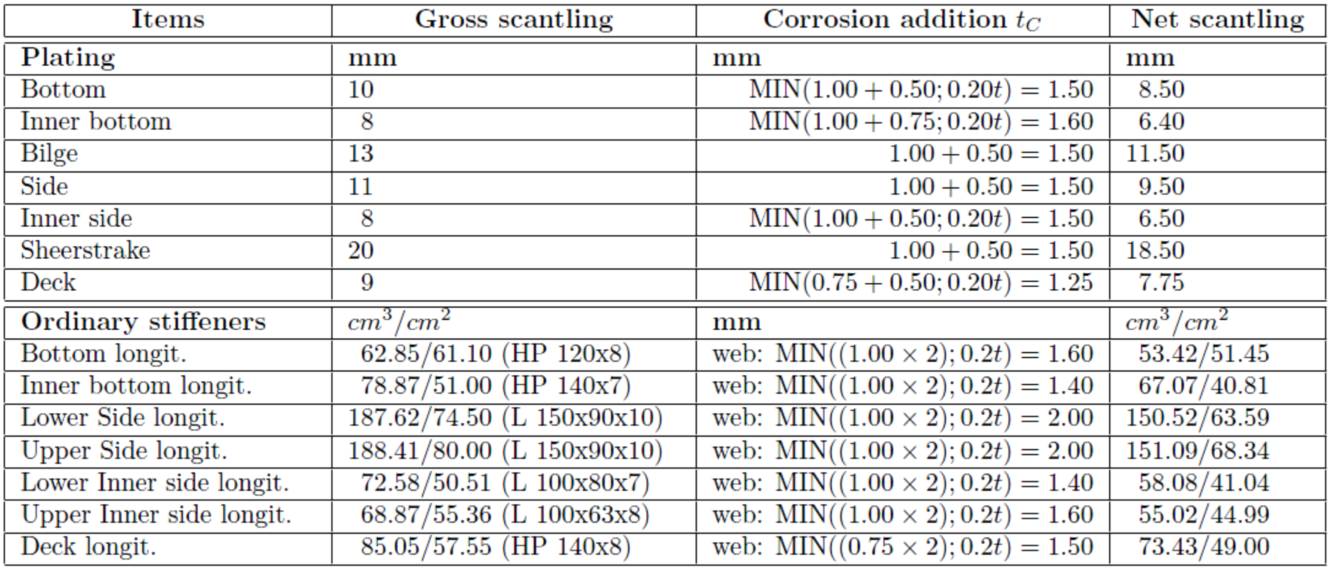
FOR ALUMINIUM, WELDED CONDITION TO BE CONSIDERED

	Material type	Yield Stress (N/mm2)	Young modulus (N/mm2)	Tensile Strength (N/mm2)	Bottom zone	Neutral axis	Deck zone
1	Steel	235.0	206000.0		🚢	🚢	🚢
2							
3							

Figure 5.2.5. Mars Inland's basic data: Materials

The next step consists of editing a section from the central body of the vessel, i.e., the midship section. This task is carried out by following the midship section drawings of the tanker, which provide plate thicknesses, stiffeners dimensions and all the necessary data.

Any hull girder transverse section is to be considered as being constituted by the members contributing to the hull girder longitudinal strength, i.e., all continuous longitudinal members below the strength deck (uppermost continuous deck). Large openings are always to be deducted from the sectional area included in the section.



Items	Gross scantling	Corrosion addition t_C	Net scantling
Plating	mm	mm	mm
Bottom	10	$\mathrm{MIN}(1.00 + 0.50; 0.20t) = 1.50$	8.50
Inner bottom	8	$\mathrm{MIN}(1.00 + 0.75; 0.20t) = 1.60$	6.40
Bilge	13	$1.00 + 0.50 = 1.50$	11.50
Side	11	$1.00 + 0.50 = 1.50$	9.50
Inner side	8	$\mathrm{MIN}(1.00 + 0.50; 0.20t) = 1.50$	6.50
Sheerstrake	20	$1.00 + 0.50 = 1.50$	18.50
Deck	9	$\mathrm{MIN}(0.75 + 0.50; 0.20t) = 1.25$	7.75
Ordinary stiffeners	cm^3/cm^2	mm	cm^3/cm^2
Bottom longit.	62.85/61.10 (HP 120x8)	web: $\mathrm{MIN}((1.00 \times 2); 0.2t) = 1.60$	53.42/51.45
Inner bottom longit.	78.87/51.00 (HP 140x7)	web: $\mathrm{MIN}((1.00 \times 2); 0.2t) = 1.40$	67.07/40.81
Lower Side longit.	187.62/74.50 (L 150x90x10)	web: $\mathrm{MIN}((1.00 \times 2); 0.2t) = 2.00$	150.52/63.59
Upper Side longit.	188.41/80.00 (L 150x90x10)	web: $\mathrm{MIN}((1.00 \times 2); 0.2t) = 2.00$	151.09/68.34
Lower Inner side longit.	72.58/50.51 (L 100x80x7)	web: $\mathrm{MIN}((1.00 \times 2); 0.2t) = 1.40$	58.08/41.04
Upper Inner side longit.	68.87/55.36 (L 100x63x8)	web: $\mathrm{MIN}((1.00 \times 2); 0.2t) = 1.60$	55.02/44.99
Deck longit.	85.05/57.55 (HP 140x8)	web: $\mathrm{MIN}((0.75 \times 2); 0.2t) = 1.50$	73.43/49.00

Figure 5.2.6. Contributing members

The section is drawn by, first, introducing the points where the plates are situated, taking into consideration every change of thickness. Then, the plates are drawn, considering their bending efficiency.

Every longitudinal element has a bending efficiency of 100% but, as the longitudinal corrugated bulkhead is vertically corrugated, it does not contribute to the hull girder strength, so the bending efficiency is 0% (As per Part B, Chapter 4, Sec 1, [2.1.2] from the Rules). As a simile, a vertically corrugated bulkhead works as an accordion.

Transverse elements like the transversal corrugated bulkheads neither affect the hull girder strength since they do not contribute to it. In general, only members that are effective in both tension and compression are assumed to act as part of the hull girder.

Once the plates are modelled, the stiffeners are introduced according to their position at each plate. Then, the transverse stiffening is also set and, finally, the compartments are defined because they are the key for the Rules to estimate the net scantlings.

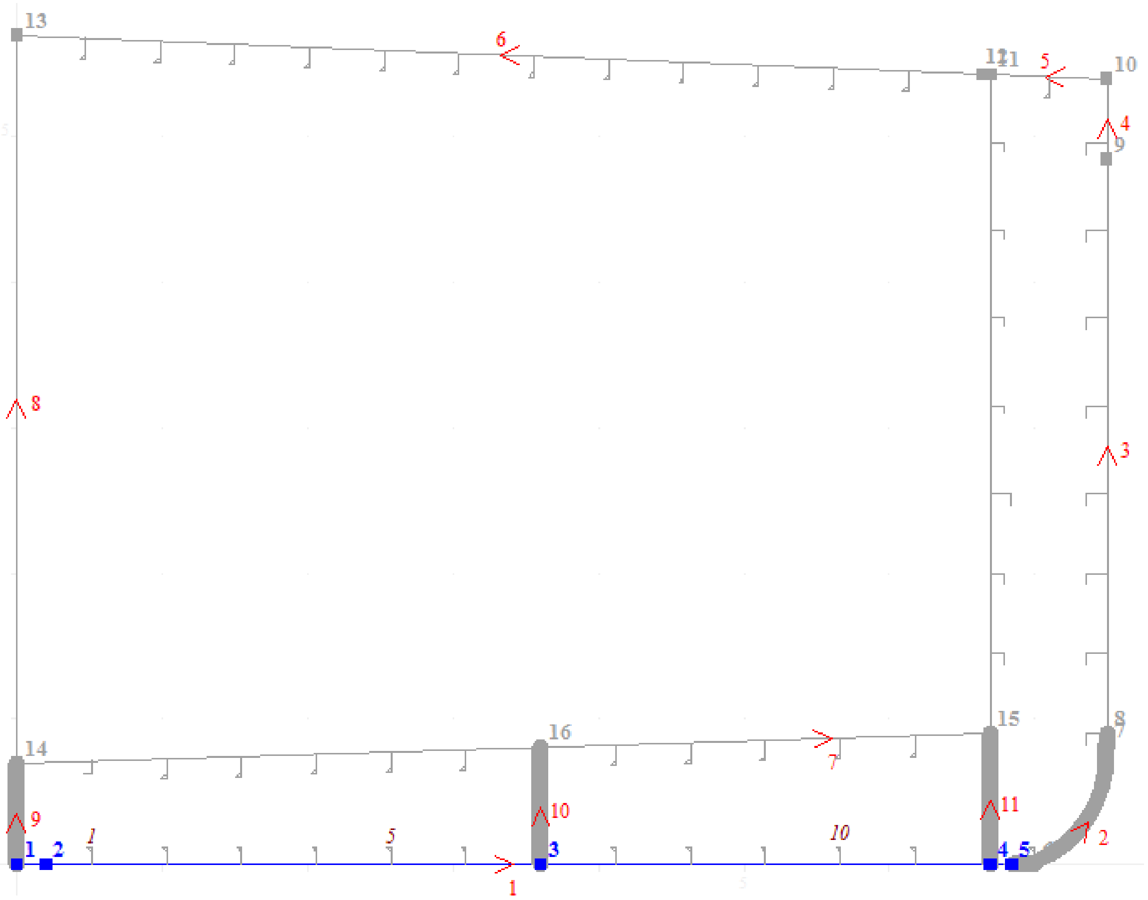
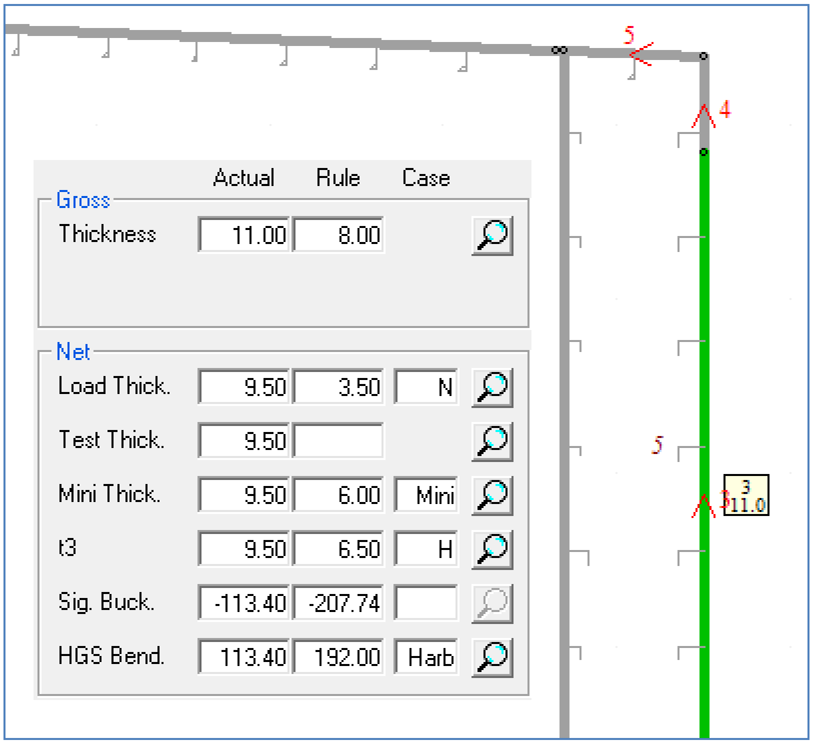


Figure 5.2.7. Midship section in *Mars Inland*

In the last step the scantlings of the structure are checked so as to be sure that the Rules are complied. The way to review the scantlings consists of selecting the plates and the stiffeners one by one. Then, the software calculates the rule-based thicknesses and compares them with the net thickness of the selected element. If any red color is shown, the scantling of the selected element is wrong.

For instance, as shown in the below figure, the verification of the results related to the side plate's thickness is carried out.



	Actual	Rule	Case
Gross			
Thickness	11.00	8.00	
Net			
Load Thick.	9.50	3.50	N
Test Thick.	9.50		
Mini Thick.	9.50	6.00	Mini
t3	9.50	6.50	H
Sig. Buck.	-113.40	-207.74	
HGS Bend.	113.40	192.00	Harb

Figure 5.2.8. Midship section's check in *Mars Inland*

As shown in the previous plot, *Mars Inland* calculates three different rule-based thicknesses. These thicknesses are:

t_1 or t_{Minimum}	:	takes into account the global strength of the vessel
t_2 or t_{Load}	:	takes into account local pressures due to loads
t_3 or t_{Buckling}	:	takes into account the buckling strength check

Apart from checking the thicknesses, *Mars Inland* also calculates the buckling stress (Sigma Buckling) and the Von Misses stress (Hull Girder Stress). According to the Rules, Pt B, Ch 4, Sec 2, it is to be checked that the normal hull girder stresses, in *MPa*, at any point of the net hull girder transverse section are in compliance with the following:

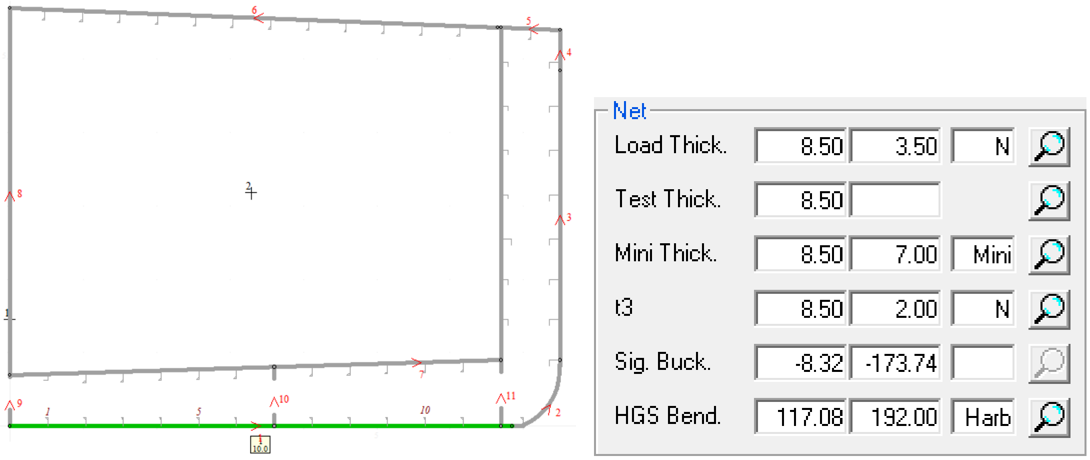
$$\sigma_1 \leq \frac{192}{k} = \frac{192}{1} = 192\ MPa$$

Where k is the material factor, which is 1 for steel with a yield stress of 235 MPa. Therefore:

Checking criterion for the Hull Girder Stress: $\sigma_1 \leq 192\ MPa$

As per the previous image, the rule-based Von Misses stress is 192 MPa whereas the actual stress, corresponding to the net scantlings, is smaller than the limit. No red colors are shown so therefore the side plate's scantlings are right.

The analytical or rule-based **strength check** is done by getting the Hull Girder Stress at the bottom and at the deck of the midship section.



Load Thick.	8.50	3.50	N
Test Thick.	8.50		
Mini Thick.	8.50	7.00	Mini
t3	8.50	2.00	N
Sig. Buck.	-8.32	-173.74	
HGS Bend.	117.08	192.00	Harb

Figure 5.2.9. Midship section's check in *Mars Inland*

As per the Figure 5.2.9, the bottom plate is selected on *Mars Inland* and the hull girder stress is:

$$\boldsymbol{\sigma_{Bottom} = 117.08\ MPa}$$

The encountered hull girder stress in the deck on *Mars Inland* is:

$$\boldsymbol{\sigma_{Deck} = 153.87\ MPa}$$

Therefore, the maximum hull girder stress appears in the deck and, considering that it is smaller than the limit of 192 MPa, the checking criterion is met, being the scantlings correct.

5.3. Strength check of primary supporting members

Not only must be the strength and the scantlings checked with the Rules but also with a finite element model. In *Mars Inland*, transverse elements are not considered and local stresses are not shown.

Following the Rules, Pt B, Ch 5, App 1, [2.1.1], all primary supporting members in the midship region are normally to be included in the three dimensional model, with the purpose of calculating their stress level and verifying their scantlings.

The analysis of primary supporting members is to be carried out on fine mesh models and all the elements are to be modelled with their net scantlings.

When the primary supporting member arrangement is such that the Society can accept that the results obtained for the midship region are extrapolated to other regions, no additional analyses are required. Otherwise, analyses of the other regions are to be carried out.

Primary supporting members in simple beam form can be analyzed as per ordinary stiffeners, for example a longitudinal stringer between two transverse bulkheads, assuming that the supporting structure is rigid.

However for many cases of structure, the crossing of primary structural members are complex and the size of the structures not necessarily that much different. It is not easy to clearly see how much one member is supporting the other.

According to Pt B, Ch 5, Sec 1, [5.6.3] from the Rules, the checking criteria for analyses based on fine mesh finite element models, it is to be checked, for all the elements, that the normal stresses are in compliance with the following formulae:

$$\textbf{Checking criterion for fine mesh models: } \boldsymbol{\sigma_1 \leq \frac{0.98\, R_{eH}}{\gamma_R} = 219\ MPa}$$

Where:

R_{eH} : Minimum yield stress, 235 MPa for steel

γ_R : Resistance partial safety factor, 1.05 as per Section 5.1.2

5.3.1. Tool: Femap with NX Nastran v10.3.1

Femap (*Finite Element Modeling And Postprocessing*) is an engineering analysis program sold by *Siemens PLM Software* that is used to build finite element models of complex engineering problems ("pre-processing") and view solution results ("post-processing").

It runs on *Microsoft Windows* and provides CAD import, modeling and meshing tools to create a finite element model, as well as post-processing functionality that allows naval engineers to interpret analysis results.

The finite element method allows engineers to virtually model components, assemblies, or systems to determine behavior under a given set of boundary conditions, and is typically used in the design process to reduce costly prototyping and testing, evaluate differing designs and materials, and for structural optimization to reduce weight.

Product simulation applications include basic strength analysis, frequency and transient dynamic simulation, system-level performance evaluation and advanced response, fluid flow and multi-physics engineering analysis for simulation of functional performance.

Femap is used by engineering organizations and consultants to model complex products, systems and processes including satellites, aircraft, defense electronics, heavy construction equipment, lift cranes, marine vessels and process equipment.

5.3.2. Procedure

Primary supporting members' strength has to be checked with a finite element model. In order to carry out this task, the vessel has been modelled in *Femap* as explained in Section 7.1. Then, a transverse ring (several sections) of the vessel's central body is selected and the rest of the structure is removed. This ring is analyzed by clamping one extreme and applying the bending moment in the other extreme.

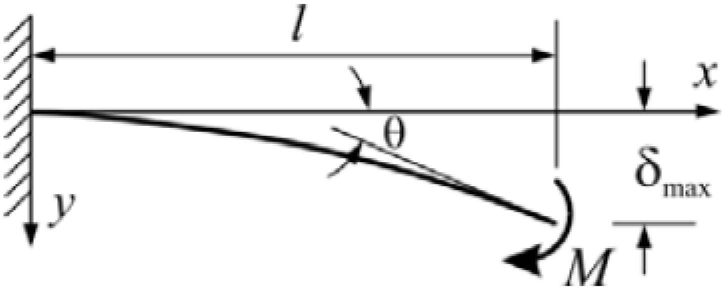


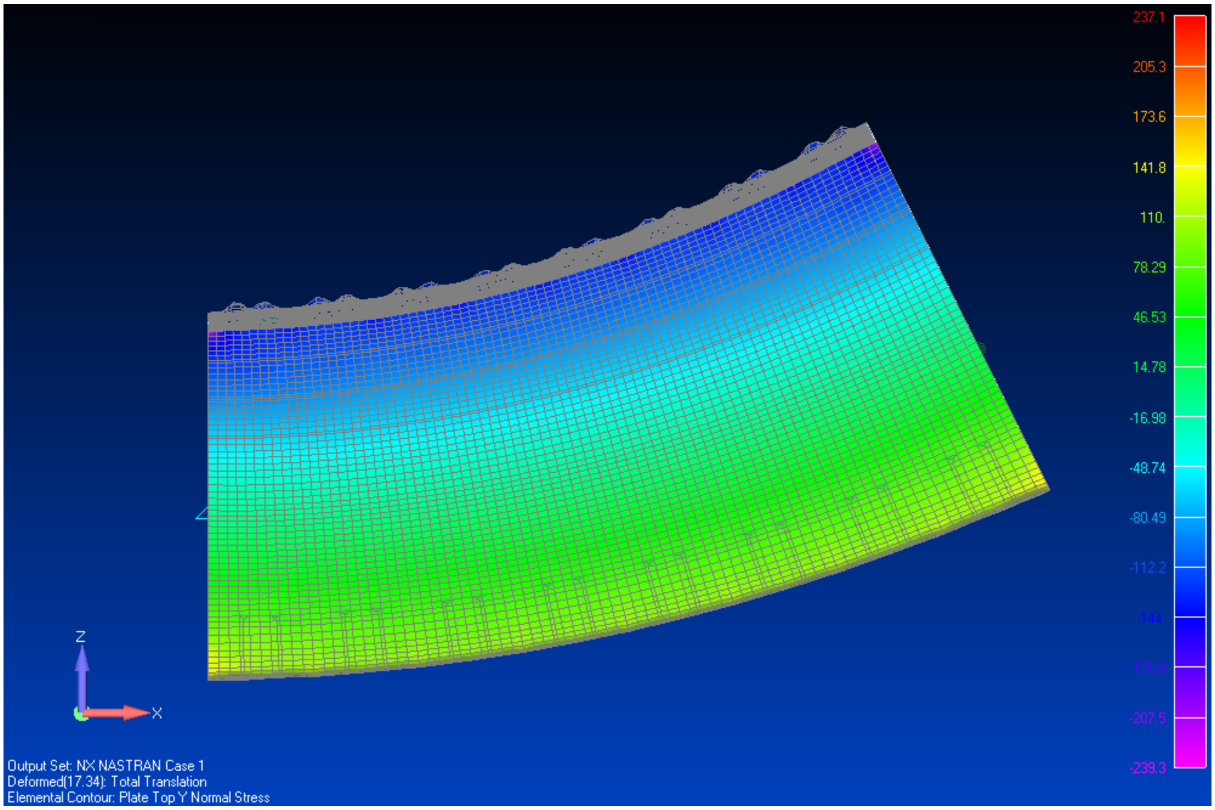
Figure 5.3.1. Cantilever beam with an applied moment at the free end

There is no need to add any load in this analysis since the bending moment is directly applied, but the steel properties like the Young modulus and Poisson's ratio have to be defined ($E = 2.06x10^5$ *MPa* and $\nu = 0.33$).

As per the Rules, Pt B, Ch 5, App 1, [3.6.1], the three dimensional model is assumed to be fixed at one end, while the bending moment is applied at the other end to ensure equilibrium. At the free end section, rigid constraint conditions are to be applied to all nodes located on longitudinal members, in such a way that the transverse section remains plane after deformation.

To sum up, there are two rigid elements. One has the displacements and rotations fixed (clamped) whereas in the other, the bending moment is applied. Therefore, the transverse ring is set as a cantilever beam and the sagging bending moment is applied at the free end.

Note that the bending moment's direction that corresponds to the sagging condition is in the other way around of the direction shown in the Figure 5.3.1. In this way, I'll have compression on the deck and tension on the bottom.



Output Set: NX NASTRAN Case 1
Deformed(17.34): Total Translation
Elemental Contour: Plate Top Y Normal Stress

Figure 5.3.2. Numerically strength check: Boundary conditions

Before setting the ring as a cantilever beam, the first approach was to analyze a ring of the vessel's central part by applying all the loads as per Section 7, having the complete model of the vessel. But there was a problem: the stresses did not distribute very well along the deck since there are openings that absorb them (obtaining smaller stresses in the midship area). Therefore, the simplest solution is just to model a ring of a cargo hold and analyze it.

5.3.3. Analysis and results

Once the model, boundary conditions and the moment are established, the analysis is carried out. Then, the results can be measured in way of stresses. Note that the stresses are measured near the extreme that is not clamped and that the elements are oriented according to the Y global axis.

The next plot shows half of the ring so as to compare it to the midship section modelled in *Mars Inland*. Considering that, according to the checking criteria, stresses must be under the limit of 219 MPa, the maximum encountered stress in the ring is 234.4 MPa.

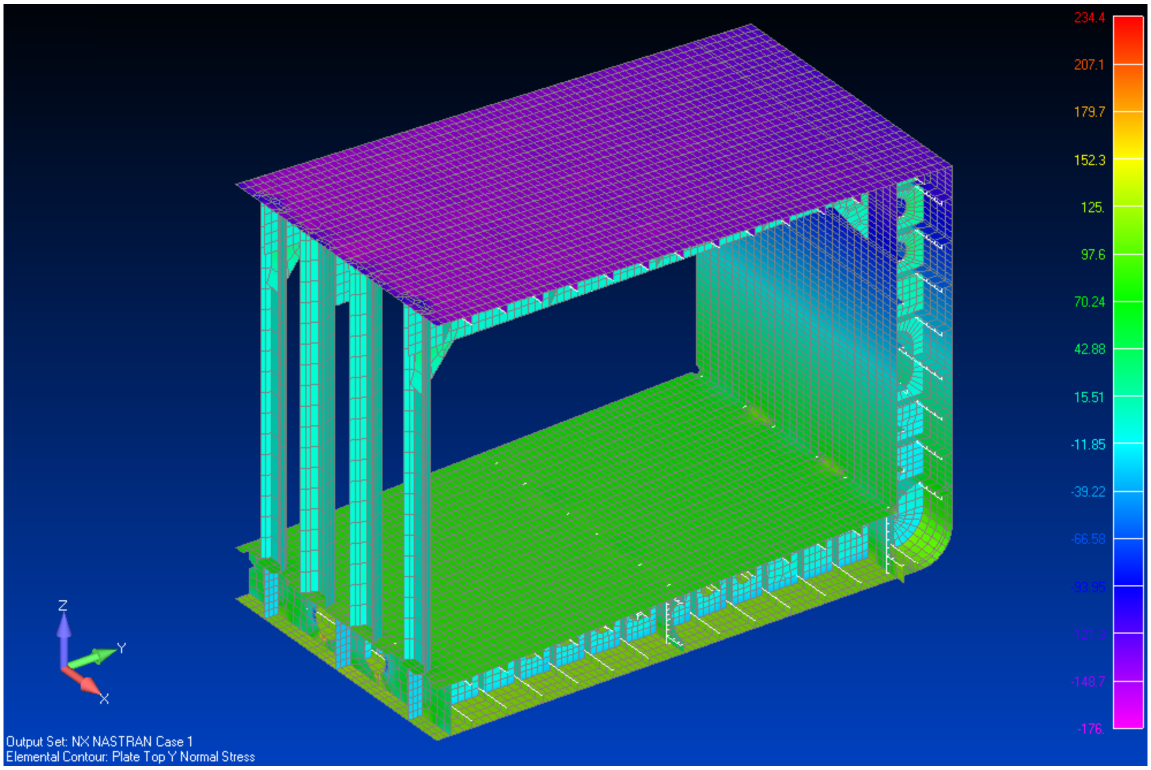


Figure 5.3.3. Numerically strength check: Midship Section

The areas where high values of stress appear are neglected because they correspond to peak stresses which are not realistic since the structure is not modelled in detail. For instance, the stress concentrations appear near transversal manholes, where some reinforcements have not been modelled besides the fact that these holes are not smooth enough because of the mesh size.

The resultant stresses that are measured in this Section correspond to the primary response of the components of the structure. Primary stresses are uniform (or nearly uniform) through the plate thickness.

Taking into consideration that the higher values of stress are in the deck and in the bottom, these panels are selected as a group for the purpose of visualizing them clearly. As per the below figure, the maximum stress is 175.2 MPa, hence complying with the checking criteria.

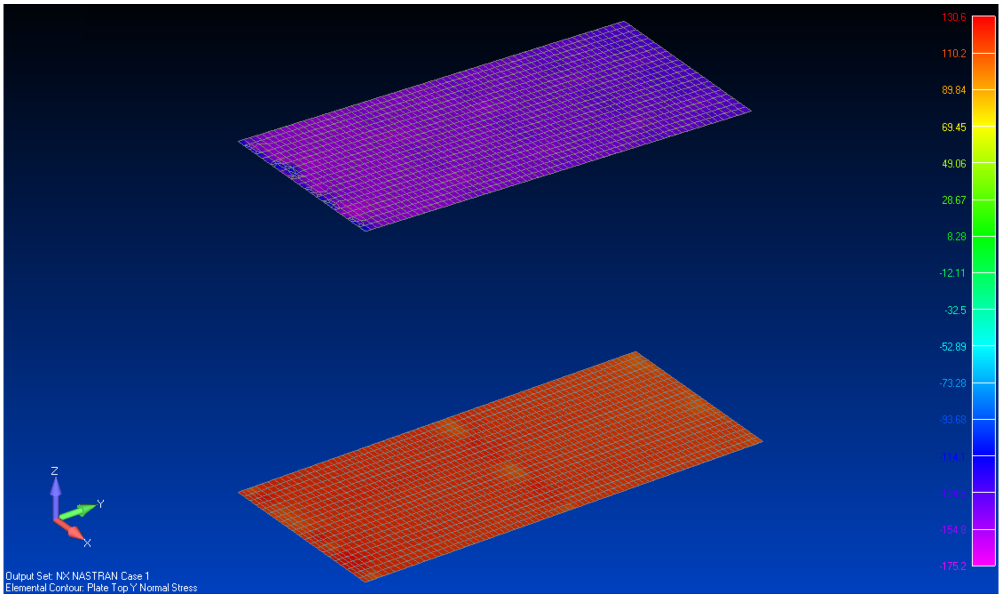


Figure 5.3.4. Numerically strength check: Bottom and Deck

In order to get the stresses at the deck and the bottom, each panel is selected individually.

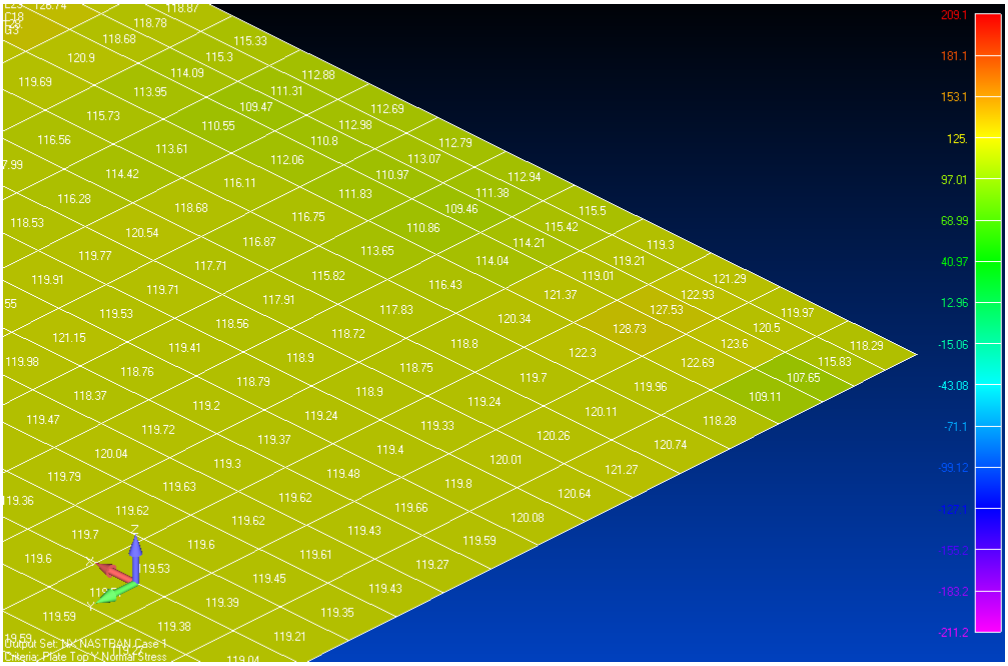


Figure 5.3.5. Numerically strength check: Bottom

Taking five elements in the same row, transversally, the stresses are obtained so as to get their average:

point 1:	110.16	MPa
point 2:	116.75	MPa
point 3:	118.72	MPa
point 4:	119.29	MPa
point 5:	118.28	MPa
sum	583.2	
Average	**116.64**	**MPa**

Note that the bottom is in tension so that the values are positive. Therefore, the deck is in compression due to the sagging condition and hence the values of stress are negative.

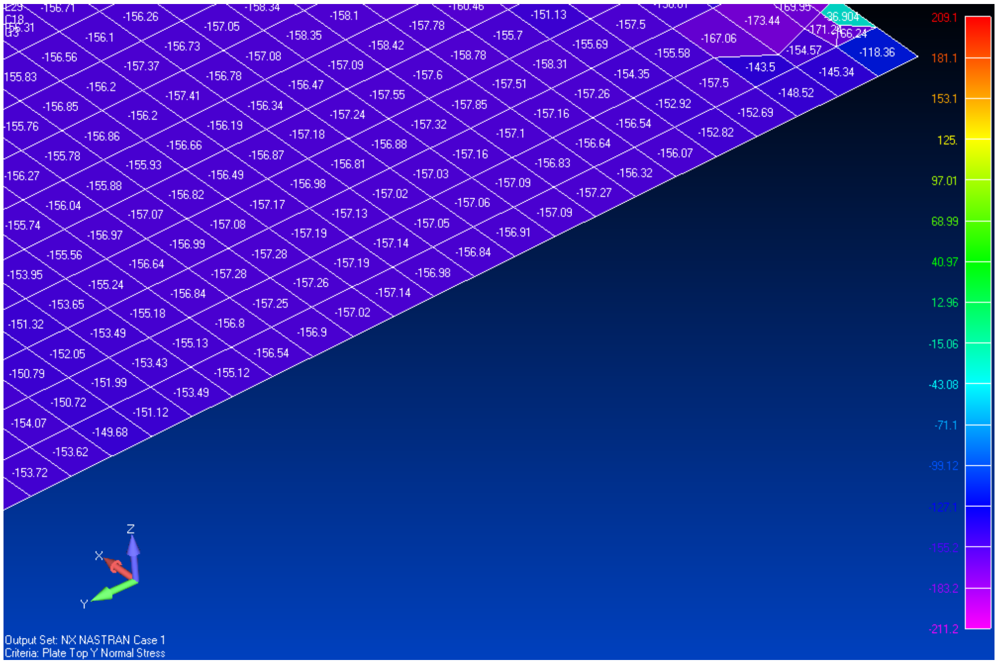


Figure 5.3.6. Numerically strength check: Deck

point 1:	-148.07	MPa
point 2:	-148.95	MPa
point 3:	-153.24	MPa
point 4:	-157.02	MPa
point 5:	-156.07	MPa
sum	-763.35	
Average	**-152.67**	**MPa**

In summary, these are the results along with the results from *Mars Inland*:

$$\sigma_{Bottom|Femap} = \mathbf{116.64}\ \boldsymbol{MPa}$$

$$\sigma_{Deck|Femap} = -\mathbf{152.67}\ \boldsymbol{MPa}$$

$$\sigma_{Bottom|Rules} = \mathbf{117.08}\ \boldsymbol{MPa}$$

$$\sigma_{Deck|Rules} = -\mathbf{153.87}\ \boldsymbol{MPa}$$

So in order to conclude, the strength is checked and validated since the values which come from *Mars Inland* and *Femap* are very close.

6. ANALYTICAL DETERMINATION OF THE HULL GIRDER DEFLECTION

The maximum bending moment using direct calculations must be obtained in order to determine the highest value of deflection analytically. That bending moment can be found when studying all the loading conditions according to the *Rules*.

6.1. Standard loading conditions for tank vessels

According to Part B, Chapter 3, Section 1, [3] from the Rules, the loading conditions can be divided into the next categories for self-propelled tank vessels:

1. **Lightship**
   The light standard loading conditions are:
   - Supplies: 100%
   - Ballast: 50%
2. **Fully loaded vessel**
   The vessel is considered to be homogeneously loaded at its maximum draught with 10% of supplies, without ballast.
3. **Transitory conditions**
   The vessel, without ballast, is assumed to carry the following amount of supplies:
   - In hogging condition: 100% of supplies
   - In sagging condition: 10% of supplies
4. **Loading/unloading in two runs (2R)**
   Loading and unloading are performed uniformly in two runs of almost equal masses, starting from one end of the cargo space and progressing towards the opposite end.
5. **Loading/unloading in one run (1R)**
   Loading and unloading are performed uniformly in one run, starting from one end of the cargo space, progressing towards the opposite end.
6. **Loading/unloading for liquid cargoes**
   Loading and unloading for liquid cargoes are assumed to be performed in two runs, unless otherwise specified.

The rule-based loading conditions for which this vessel has been designed are:

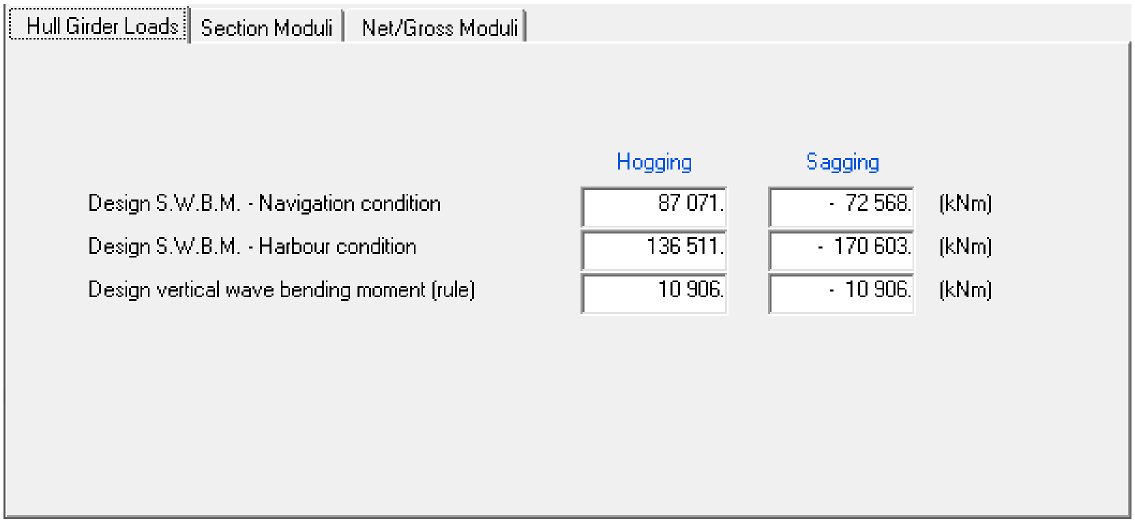
Load case	Hogging	Sagging
Navigation	X	X
Harbour 2R	X	X
Harbour 1R		

So the mentioned loading conditions are the ones which are studied in this project.

6.2. Stillwater bending moment according to the Rules

Using the rule-based software *Mars Inland*, the Stillwater bending moments can be easily obtained for each condition. The way to obtain these bending moments consists of introducing the input data that the software requires along with the scantlings of the vessel's central part and then, check them as explained the Section 5.2.

Finally, the hull girder loads (or bending moments) are automatically obtained by selecting the *Global Strength Criteria* option in the *View* menu.



	Hogging	Sagging	
Design S.W.B.M. - Navigation condition	87 071.	- 72 568.	(kNm)
Design S.W.B.M. - Harbour condition	136 511.	- 170 603.	(kNm)
Design vertical wave bending moment (rule)	10 906.	- 10 906.	(kNm)

Figure 6.2.1. Rule-based bending moments for 1R (*Mars Inland*)

Note that, for the Figure 6.2.1, the bending moments have been obtained considering the 1R loading condition. This is done because classification society always takes the most conservative solution into account.

6.3. Wave-induced bending moment according to the rules

An additional wave-induced bending moment has to be calculated since it takes into consideration the stream and water conditions in the navigation zone, which is an inland waterway with a maximum wave height of 0,6 meters (IN(0.6)). According to Bureau Veritas' Rules:

$$M_W = 0.045 \times L^2 \times B \times C_B = 0.045 \times 133.25^2 \times 15 \times 0.91 = 10906.35 \text{ kN m}$$

As expected, this result is the same as the one obtained in the previous section with *Mars Inland*.

This bending moment is only added to both hogging and sagging bending moments calculated for the navigation condition. In the harbour condition, waves are not taken into account.

6.4. Stillwater bending moment according to *Argos*

Tool: Argos

Argos is a software used to obtain strength and stability calculations from the ship. Input data for this software is the ship's definition, by means of Lines Plan, Compartments Definition, Opening Points, Capacity Plans and Lightship Weight Distribution.

Figure 6.4.1. Main window in *Argos*

According to the loading conditions explained in the Section 6.1 (Loading Conditions are defined in *Argos* as explained in the Appendix C), the maximum stillwater bending moments and their distributions have been obtained, for gross and net scantlings, using *Argos.* Note that, for the navigation conditions, the wave-induced bending moment from the previous section has to be added since the software does not consider the waves.

The values of the maximum bending moments for each condition are:

- **For gross scantlings:**
  Navigation
  - Lightship condition. Hogging:
    - M_{hog} = 89996.63 kN m
  - Fully loaded vessel. Sagging:
    - M_{sag} = -101771.22 kN m

  Harbour. 2 Runs
  - Loading 50% of the tanks from the aft to the fore part. First layer.
    - M_{hog} = 92132.93 kN m
    - M_{sag} = -63736.13 kN m
  - Loading 50% of the tanks from the fore to the aft part. First layer.
    - M_{hog} = 108607.86 kN m
    - M_{sag} = -36605.11 kN m
  - Loading 100% of the tanks from the aft to the fore part. Second layer.
    - M_{hog} = 10077.92 kN m
    - **M_{sag} = -153482.02 kN m**

  - Loading 100% of the tanks from the fore to the aft part. Second layer.
    - M_{hog} = 38658.47 kN m
    - M_{sag} = -121953.46 kN m

- **For net scantlings:**
  Navigation
  - Lightship condition. Hogging:
    - M_{hog} = 87210.24 kN m
  - Fully loaded vessel. Sagging:
    - M_{sag} = -101475.27 kN m

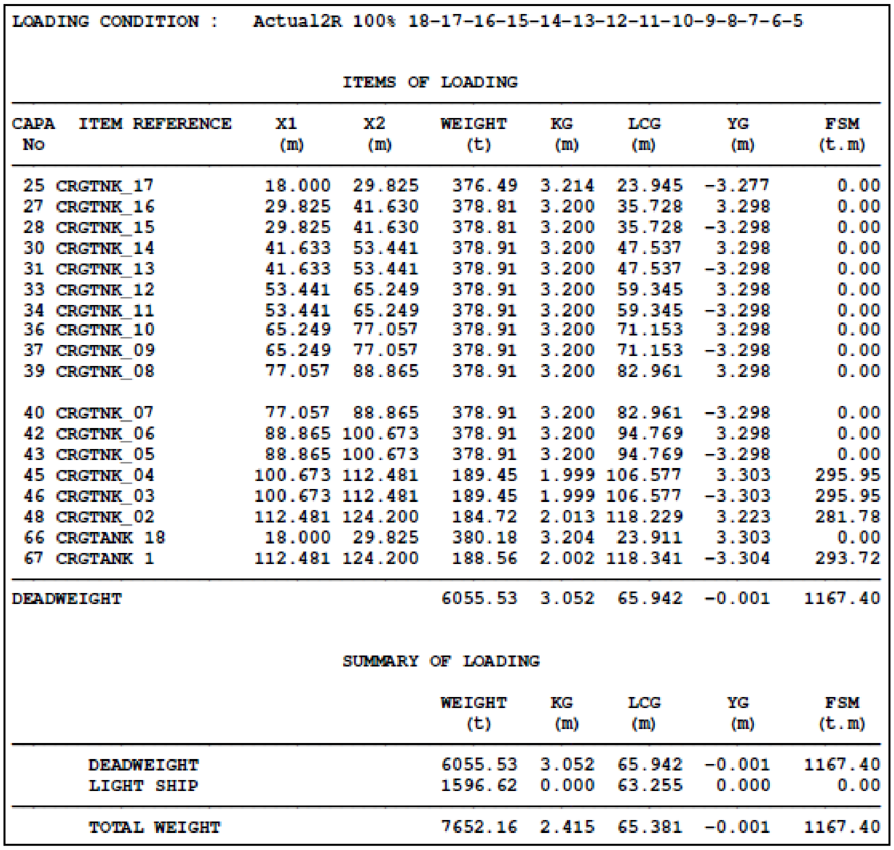
  Harbour. 2 Runs
  - Loading 50% of the tanks from the aft to the fore part. First layer.
    - M_{hog} = 90253.78 kN m
    - M_{sag} = -64457.06 kN m
  - Loading 50% of the tanks from the fore to the aft part. First layer.
    - M_{hog} = 104664.20 kN m (*See Appendix A*)
    - M_{sag} = -38216.87 kN m
  - Loading 100% of the tanks from the aft to the fore part. Second layer.
    - M_{hog} = 9754 kN m
    - M_{sag} = -153458.31 kN m (*See Appendix A*)
  - Loading 100% of the tanks from the fore to the aft part. Second layer.

- $M_{hog} = 37701.26$ kN m
- $M_{sag} = -121757.03$ kN m

From these results, three conclusions are obtained:

1. When comparing each one of the results between the net and gross scantlings, the values are very close. This is expected since the value of the bending moment does not depend on the inertia of the cross section.
2. The maximum bending moment comes from the harbour condition, when the tanks of the vessel are being loaded completely from the aft to the fore part or when the tanks are being unloaded in the other way around. During this process, the vessel is in sagging condition.
3. There is no need to add the wave-induced bending moment because the results will neither reach nor exceed the bending moment encountered in the harbour condition.

The following table is the summary of the lightship weight and the specific deadweight applied in this loading case. The total weight is called displacement of the vessel.



```
LOADING CONDITION :   Actual2R 100% 18-17-16-15-14-13-12-11-10-9-8-7-6-5

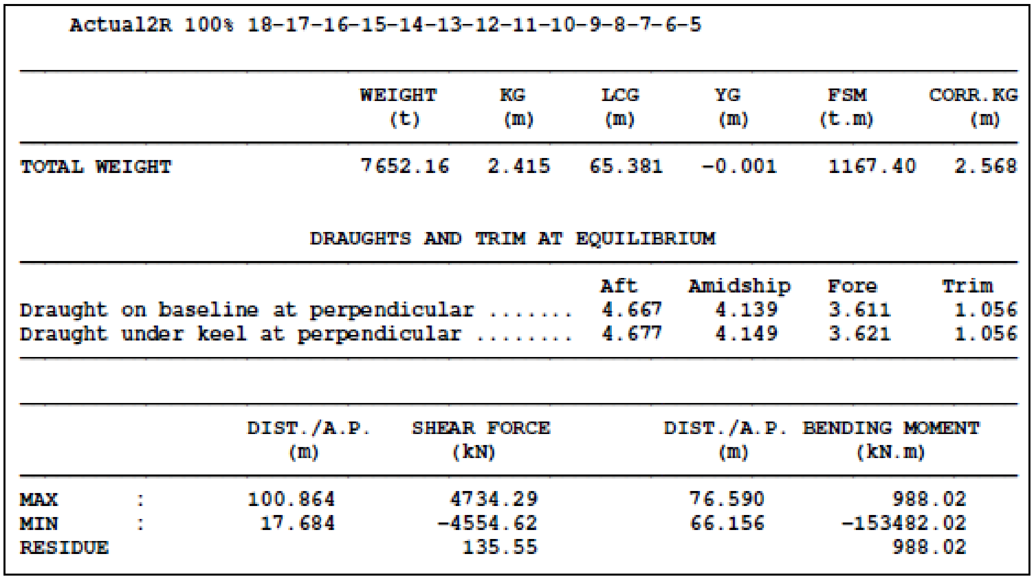

                                  ITEMS OF LOADING
-----------------------------------------------------------------------------------
CAPA   ITEM REFERENCE        X1       X2     WEIGHT     KG      LCG       YG      FSM
 No                         (m)      (m)       (t)      (m)     (m)      (m)    (t.m)
-----------------------------------------------------------------------------------
 25 CRGTNK_17            18.000   29.825    376.49   3.214  23.945   -3.277     0.00
 27 CRGTNK_16            29.825   41.630    378.81   3.200  35.728    3.298     0.00
 28 CRGTNK_15            29.825   41.630    378.81   3.200  35.728   -3.298     0.00
 30 CRGTNK_14            41.633   53.441    378.91   3.200  47.537    3.298     0.00
 31 CRGTNK_13            41.633   53.441    378.91   3.200  47.537   -3.298     0.00
 33 CRGTNK_12            53.441   65.249    378.91   3.200  59.345    3.298     0.00
 34 CRGTNK_11            53.441   65.249    378.91   3.200  59.345   -3.298     0.00
 36 CRGTNK_10            65.249   77.057    378.91   3.200  71.153    3.298     0.00
 37 CRGTNK_09            65.249   77.057    378.91   3.200  71.153   -3.298     0.00
 39 CRGTNK_08            77.057   88.865    378.91   3.200  82.961    3.298     0.00

 40 CRGTNK_07            77.057   88.865    378.91   3.200  82.961   -3.298     0.00
 42 CRGTNK_06            88.865  100.673    378.91   3.200  94.769    3.298     0.00
 43 CRGTNK_05            88.865  100.673    378.91   3.200  94.769   -3.298     0.00
 45 CRGTNK_04           100.673  112.481    189.45   1.999 106.577    3.303   295.95
 46 CRGTNK_03           100.673  112.481    189.45   1.999 106.577   -3.303   295.95
 48 CRGTNK_02           112.481  124.200    184.72   2.013 118.229    3.223   281.78
 66 CRGTANK 18           18.000   29.825    380.18   3.204  23.911    3.303     0.00
 67 CRGTANK 1           112.481  124.200    188.56   2.002 118.341   -3.304   293.72
-----------------------------------------------------------------------------------
DEADWEIGHT                                 6055.53   3.052  65.942   -0.001  1167.40


                                  SUMMARY OF LOADING

                                            WEIGHT     KG      LCG       YG      FSM
                                              (t)      (m)     (m)      (m)    (t.m)
-----------------------------------------------------------------------------------
       DEADWEIGHT                          6055.53   3.052  65.942   -0.001  1167.40
       LIGHT SHIP                          1596.62   0.000  63.255    0.000     0.00
-----------------------------------------------------------------------------------
       TOTAL WEIGHT                        7652.16   2.415  65.381   -0.001  1167.40
```

The drafts and the trim for the worst scenario are shown in the following table. In addition, the maximum shear force and bending moment with their distances from the aft perpendicular appear in the second part of the table.



```
   Actual2R 100% 18-17-16-15-14-13-12-11-10-9-8-7-6-5

                                WEIGHT     KG      LCG       YG       FSM     CORR.KG
                                 (t)      (m)      (m)      (m)      (t.m)      (m)

TOTAL WEIGHT                   7652.16   2.415   65.381   -0.001   1167.40    2.568

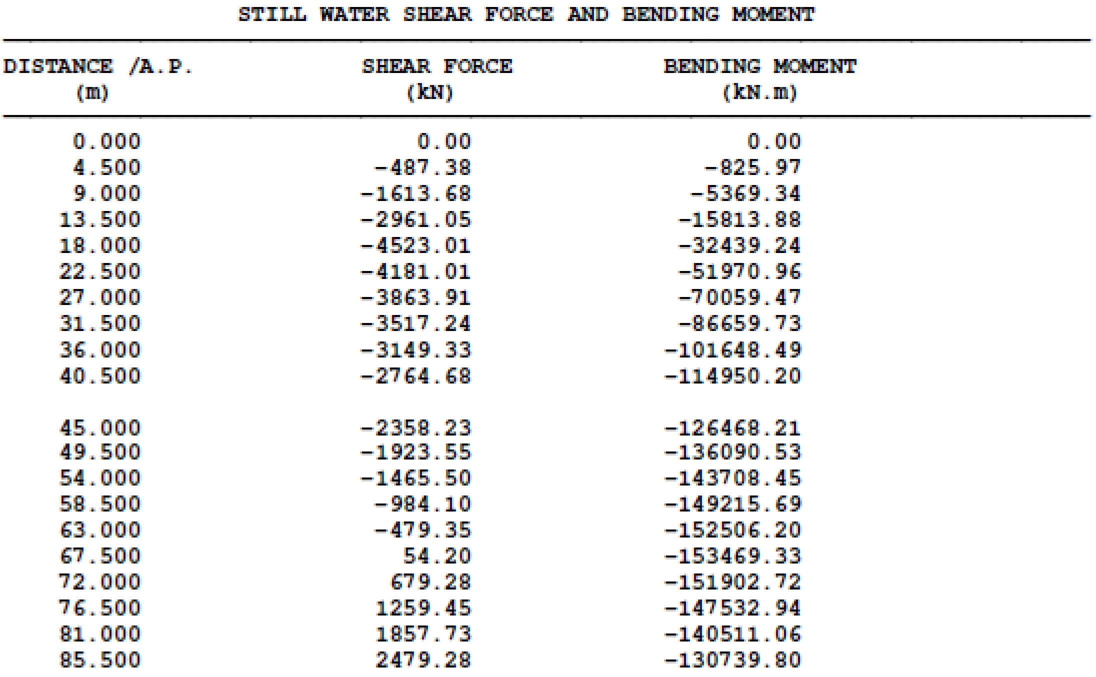
                        DRAUGHTS AND TRIM AT EQUILIBRIUM

                                              Aft    Amidship   Fore      Trim
Draught on baseline at perpendicular .......  4.667    4.139    3.611     1.056
Draught under keel at perpendicular ........  4.677    4.149    3.621     1.056


                     DIST./A.P.    SHEAR FORCE          DIST./A.P. BENDING MOMENT
                        (m)           (kN)                  (m)        (kN.m)

MAX        :         100.864         4734.29             76.590          988.02
MIN        :          17.684        -4554.62             66.156      -153482.02
RESIDUE                               135.55                              988.02
```

The next table is very important since it includes the distributions of the shear force and the bending moment along the length of the vessel.



```
                       STILL WATER SHEAR FORCE AND BENDING MOMENT

DISTANCE /A.P.               SHEAR FORCE            BENDING MOMENT
    (m)                         (kN)                    (kN.m)

     0.000                      0.00                     0.00
     4.500                   -487.38                  -825.97
     9.000                  -1613.68                 -5369.34
    13.500                  -2961.05                -15813.88
    18.000                  -4523.01                -32439.24
    22.500                  -4181.01                -51970.96
    27.000                  -3863.91                -70059.47
    31.500                  -3517.24                -86659.73
    36.000                  -3149.33               -101648.49
    40.500                  -2764.68               -114950.20

    45.000                  -2358.23               -126468.21
    49.500                  -1923.55               -136090.53
    54.000                  -1465.50               -143708.45
    58.500                   -984.10               -149215.69
    63.000                   -479.35               -152506.20
    67.500                     54.20               -153469.33
    72.000                    679.28               -151902.72
    76.500                   1259.45               -147532.94
    81.000                   1857.73               -140511.06
    85.500                   2479.28               -130739.80
```

```
  90.000            3124.19           -118113.13
  94.500            3795.40           -102524.70
  99.000            4489.97            -83867.70
 103.500            4318.09            -63312.35
 108.000            3642.97            -45422.57
 112.500            2988.17            -30518.60
 117.000            2373.75            -18449.37
 121.500            1755.37             -9166.46
 126.000             999.33             -2787.54
 130.500             305.06               177.13

 135.000             135.55               988.02
```

These distributions and the weight and buoyancy distributions can be visualized clearly in the following two plots, which are also generated automatically in the software *Argos*.

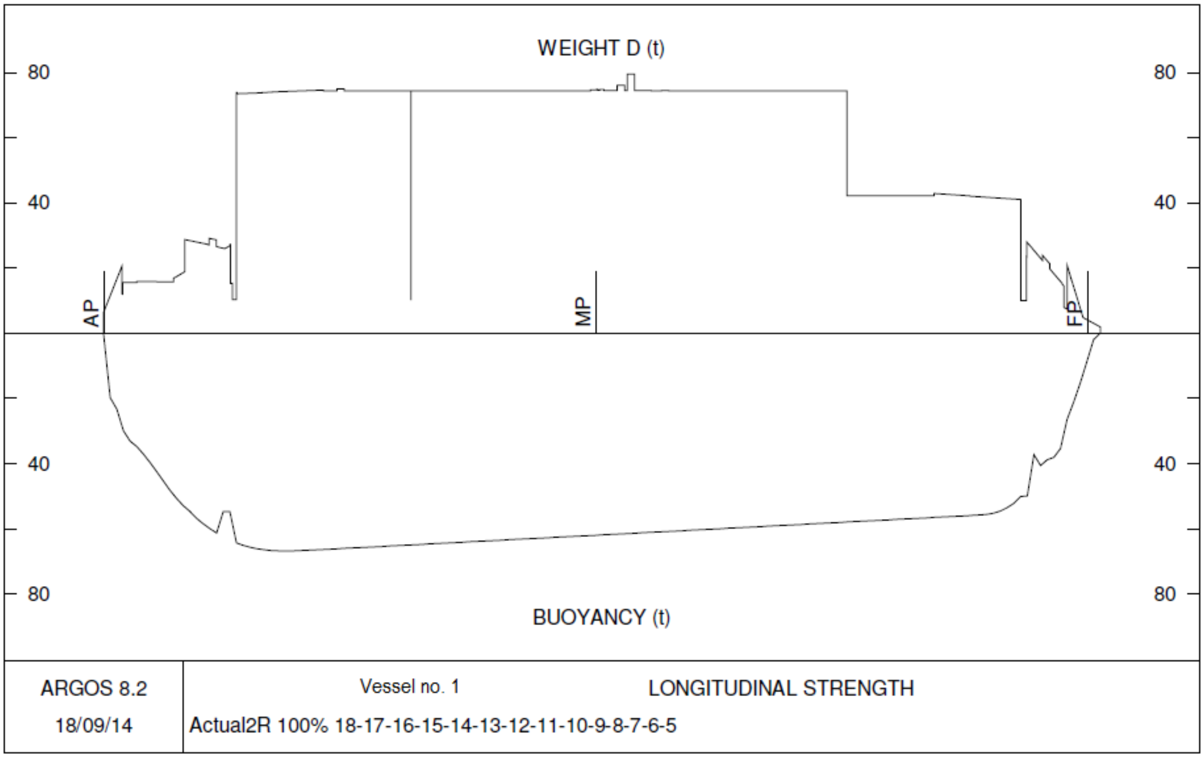


Figure 6.4.2. Weight and buoyancy distributions of the tanker

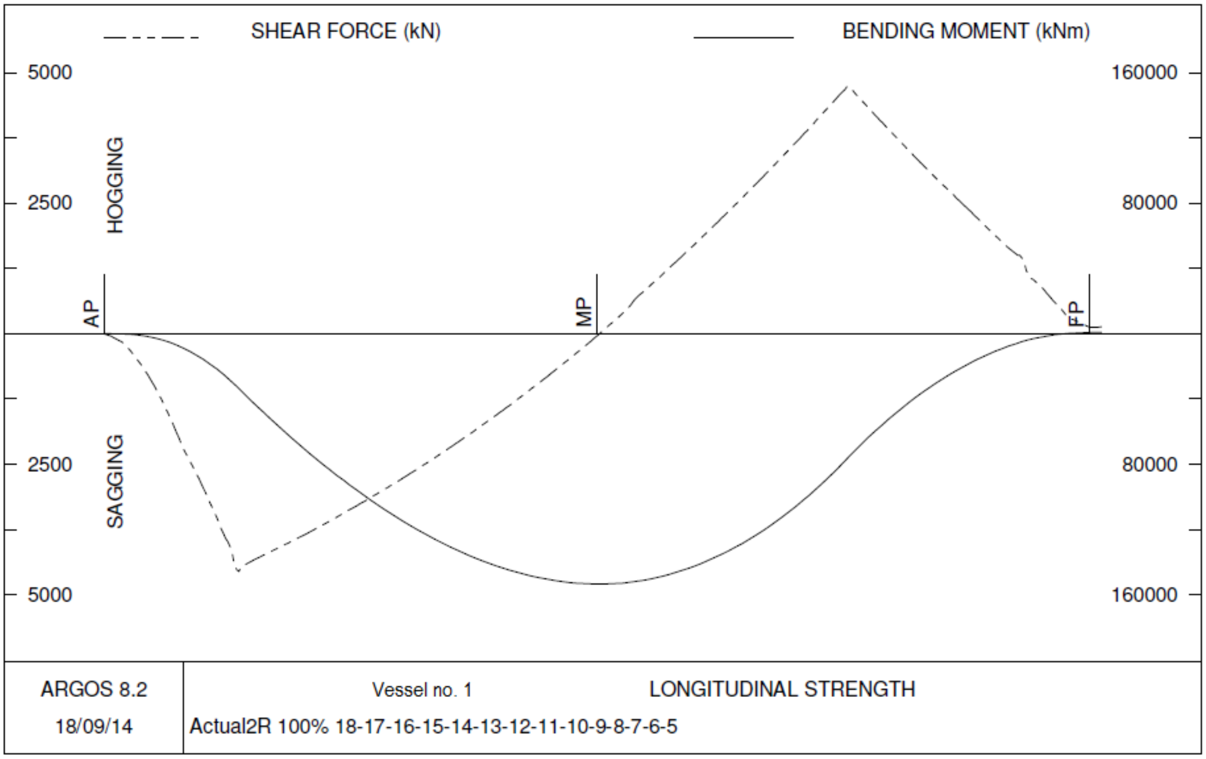


Figure 6.4.3. Shear force and bending moment distributions of the tanker

6.5. Analytical determination of the deflection

The deflection is analytically determined by following the next formula, as explained in Section 4.3:

$$y = \frac{1}{E}\left[\iint \frac{M_B}{I}\,dx\,dx\right] + ax + b$$

Since the ends of the hull girder are free, the constant of integration *b* of the deflection curve is equal to zero. From the deflection, the constant of integration *a* of the slope curve is determined by the fact that when *x* equals the length *L*, *y* is equal to zero and:

$$a = \frac{-\frac{1}{E}\iint_0^L \frac{M_B}{I}\,dx\,dx}{L}$$

Therefore, the distributions of the maximum bending moment and the moment of inertia have to be determined so as to get the deflection analytically with the formula.

6.5.1. Maximum bending moments

Maximum bending moments have been obtained both from the Rules and from *Argos*. Their values are:

M_{Rules} =	- 170603	kN m
M_{Argos} =	- 153482	kN m

Both bending moments are encountered in the harbour condition, loading or unloading the cargo in 2 Runs, being the vessel in sagging.

The maximum bending moment comes from the Rules. This is logical because the Rules are more conservative than any other method so that safety always prevails over any other design variable. This bending moment has also been used to design the tanker which is studied in this project.

In any case, for the sake of the accuracy of this study, the bending moment which has been obtained with *Argos* is the one used to get the deflection because of 2 reasons:

1. Even though the rule-based bending moment is bigger, it is not realistic since it is obtained from a statistical method which involves a wide range of types of ships and

cargo. This is explained in the Section 2.2.2 of this project since the direct analysis has more advantages than the rule-based approach.

2. Selecting the bending moment obtained with the software means a real approach and precision to the analysis of this vessel because *Argos* generates the distribution of the bending moment along the length, following the variation of the hull form and the loads' distribution (See Figures 6.4.2 and 6.4.3).

The distribution of the bending moment along the vessel's length is shown in the next plot and its numerical values can be found in the Section 6.4.

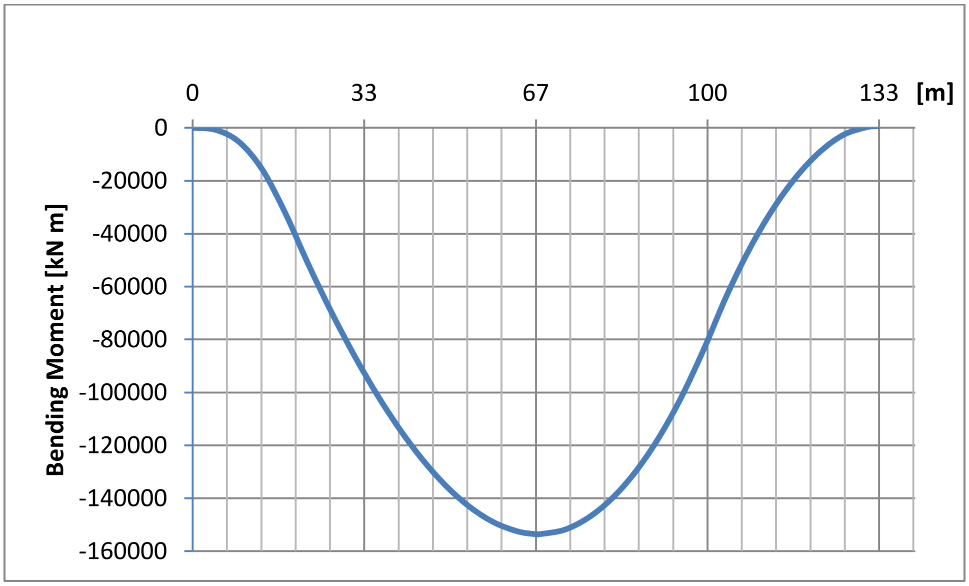


Figure 6.5.1. Distribution of the bending moment along the length

6.5.2. Moment of inertia

The next step is to determine the moment of inertia (I) in several transversal sections of the vessel along all its length for the purpose of obtaining its distribution. The selected cross sections or frames are those which are coincident with the distribution of the bending moment so as to be more precise.

The moment of inertia is automatically determined by the software *Mars Inland* when the scantling of a cross section is drawn. Therefore, the way the inertia is obtained in this study is by modelling the scantlings of some frames.

The scantlings are drawn by following the structural plans of the vessel, exactly in the same way as per the Section 5.2.2, where the frame of the midship section is also modeled.

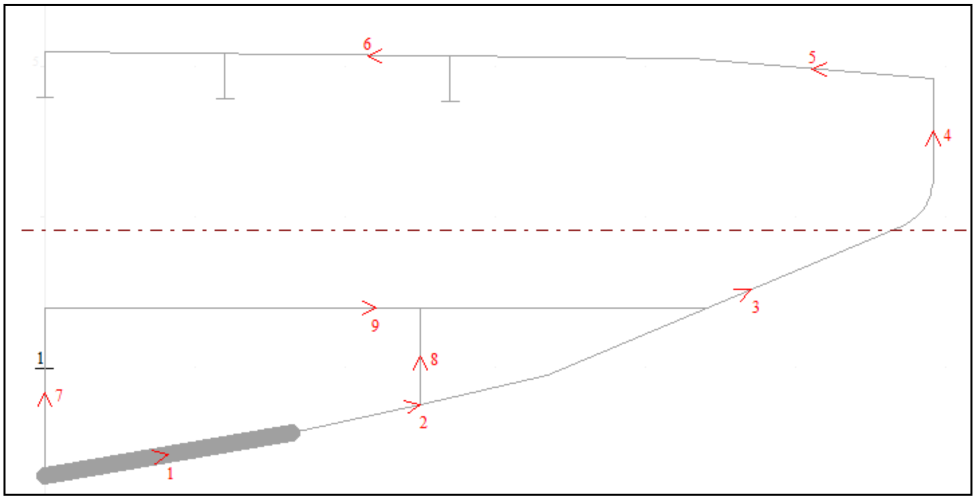
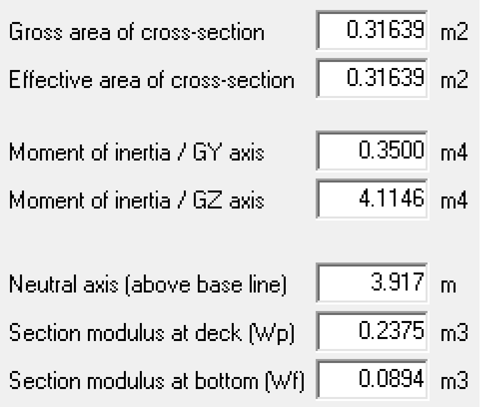


Figure 6.5.2. Frame 2

In the Figure 6.5.3, some outputs from the software for the frame 2, like the moment of inertia and the height of the neutral axis are shown.



Gross area of cross-section	0.31639	m2
Effective area of cross-section	0.31639	m2
Moment of inertia / GY axis	0.3500	m4
Moment of inertia / GZ axis	4.1146	m4
Neutral axis (above base line)	3.917	m
Section modulus at deck (Wp)	0.2375	m3
Section modulus at bottom (Wf)	0.0894	m3

Figure 6.5.3. Output of the Frame 2 in *Mars Inland*

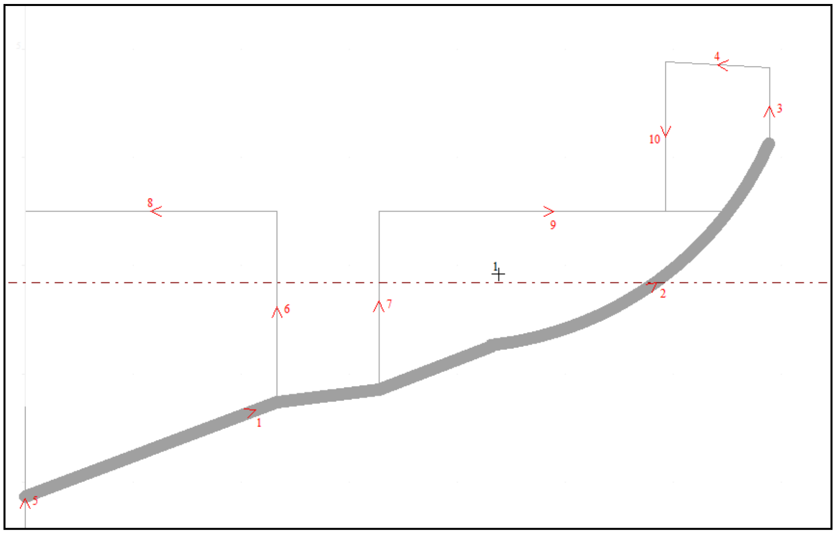


Figure 6.5.4. Frame 10

As the sections get nearer both ends of the vessel, the cross sectional areas decrease due to the hull form and therefore, the moments of inertia decrease as well.

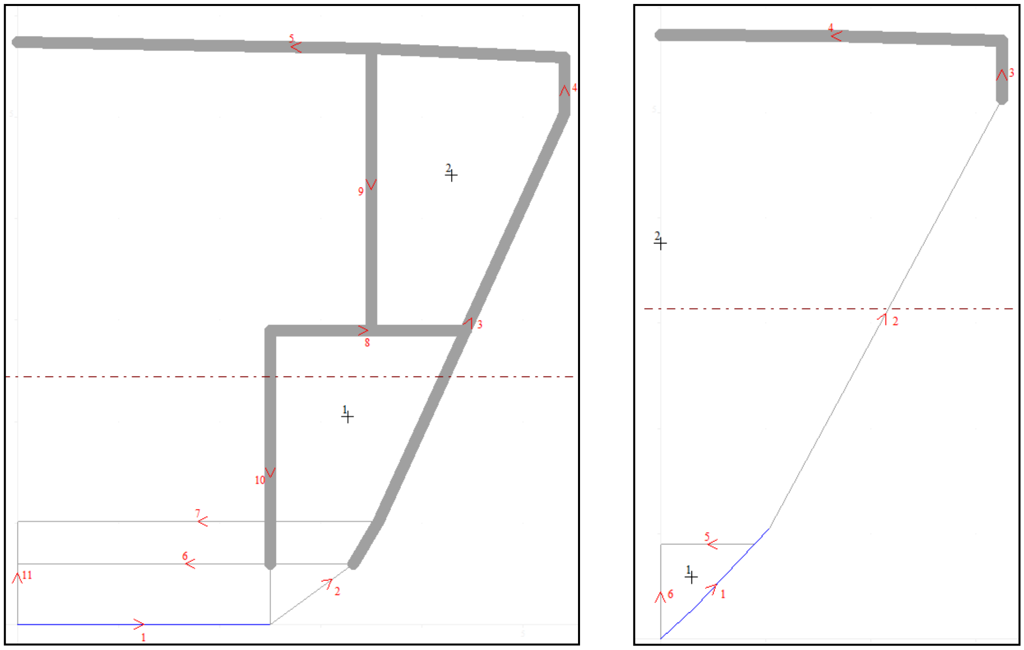


Figure 6.5.5. Frames 264 and 270

The previous figures show a few frames as an example. The different values of inertia for all the frames which have been modelled are introduced in an *Excel* table so as to get the distribution, which is shown below:

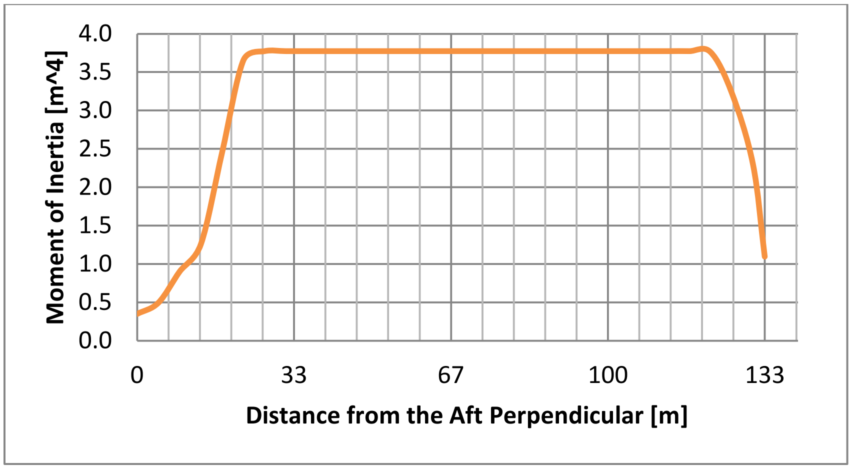


Figure 6.5.6. Distribution of the moment of Inertia along the length

As mentioned, the values of the inertia decrease when the extremes of the vessel are approached. Note that the openings have been taken into account when drawing the frames so that the worst case is studied.

6.5.3. Deflection

The analytical way of getting the deflection is summarized in the following table:

Distance from AP [m]	Bending Moment [kN m]	Moment of Inertia [m^4]	Inertia Equation	M/I	M/I Equation	∫∫ M/I	Deflection
							y [m]
0.0	0.0	0.3500	0.3953	0.00	-1847.50	0.00	0.000
4.5	-826.0	0.4961	0.4435	-1862.60	-2904.61	-21242.56	0.033
9.0	-5369.3	0.9021	0.7913	-6785.47	-5039.30	-103120.22	0.065
13.5	-15813.9	1.2596	1.4389	-10990.64	-7993.55	-288424.99	0.097
18.0	-32439.2	2.4569	2.3861	-13595.09	-11529.04	-636578.34	0.128
22.5	-51971.0	3.6541	3.6331	-14305.05	-15427.12	-1218804.98	0.158
27.0	-70059.5	3.7741	3.7741	-18563.23	-19488.84	-2113705.37	0.187
31.5	-86659.7	3.7741	3.7741	-22961.69	-23534.90	-3403226.66	0.213
36.0	-101648.5	3.7741	3.7741	-26933.17	-27405.72	-5169032.34	0.237
40.5	-114950.2	3.7741	3.7741	-30457.65	-30961.38	-7489270.39	0.259
45.0	-126468.2	3.7741	3.7741	-33509.50	-34081.65	-10435740.05	0.277
49.5	-136090.5	3.7741	3.7741	-36059.07	-36665.99	-14071457.11	0.293
54.0	-143708.5	3.7741	3.7741	-38077.54	-38633.52	-18448617.89	0.304
58.5	-149215.7	3.7741	3.7741	-39536.76	-39923.07	-23606961.71	0.312
63.0	-152506.2	3.7741	3.7741	-40408.63	-40493.14	-29572531.94	0.316
66.2	-153482.0	3.7741	3.7741	-40667.18	-40451.63	-34235492.40	**0.316**
67.5	-153469.3	3.7741	3.7741	-40663.82	-40321.92	-36356835.72	0.316
72.0	-151902.7	3.7741	3.7741	-40248.73	-39407.26	-43956402.14	0.312
76.5	-147532.9	3.7741	3.7741	-39090.89	-37766.73	-52352739.09	0.304
81.0	-140511.1	3.7741	3.7741	-37230.35	-35437.56	-61512688.67	0.292
85.5	-130739.8	3.7741	3.7741	-34641.32	-32476.66	-71389181.13	0.277
90.0	-118113.1	3.7741	3.7741	-31295.71	-28960.63	-81922387.50	0.259
94.5	-102524.7	3.7741	3.7741	-27165.34	-24985.76	-93041270.66	0.237
99.0	-83867.7	3.7741	3.7741	-22221.91	-20668.00	-104665535.13	0.214
103.5	-63312.4	3.7741	3.7741	-16775.48	-16143.02	-116707975.31	0.188
108.0	-45422.6	3.7741	3.7741	-12035.34	-11566.14	-129077222.42	0.161
112.5	-30518.6	3.7741	3.7741	-8086.33	-7112.37	-141680889.95	0.133
117.0	-18449.4	3.7741	3.7741	-4888.42	-2976.42	-154429117.70	0.104
121.5	-9166.5	3.7624	3.2701	-2803.13	627.34	-167238514.39	0.074
126.0	-2787.5	3.2337	2.8392	-981.80	3464.84	-180036498.91	0.045
130.5	177.1	2.3011	1.6267	108.89	5282.33	-192766040.10	0.016
133.0	627.6	1.0964	0.6153	1020.03	5751.47	-199794051.55	0.000

The bending moment and the moment of inertia have been obtained in the Sections 6.5.1 and 6.5.2, respectively, along with their distribution's plots (see Figures 6.5.1 and 6.5.6). In order to obtain a mathematical approach of the distribution of the moment of inertia near the ends of the vessel, a parabolic equation has been obtained.

As explained in the Introduction, the deflection is obtained by the second integration of the M_B/I curve. This mathematical operation can easily be done by integrating twice the function obtained in the software *Excel* when adding a trendline to the M_B/I curve. This function is shown in the next figure.

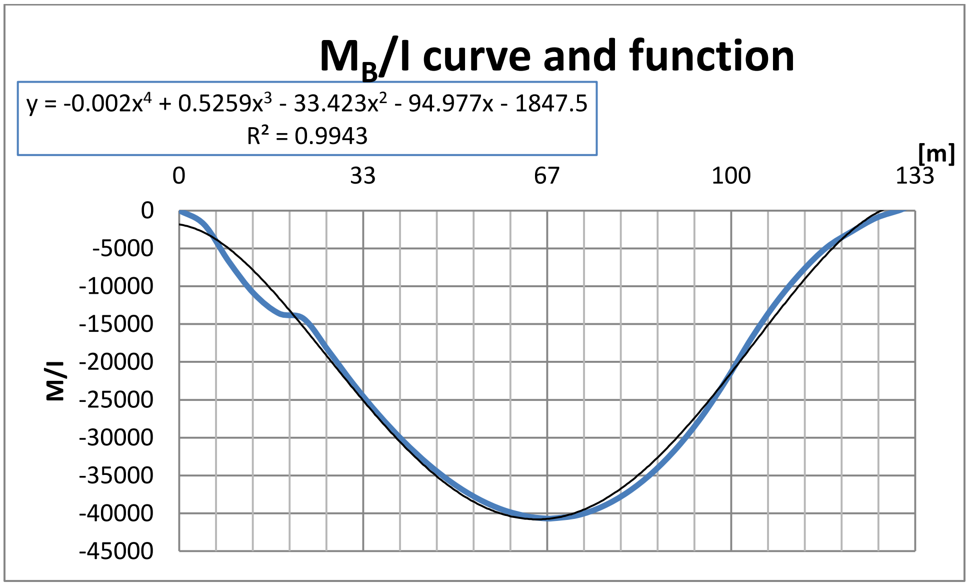


Figure 6.5.7. M_B/I curve and function

The M_B/I function is an approximation to the original curve with an R-squared value of 0,9943. The R-squared value or coefficient of determination indicates how well data fit the curve. The second integration of the function is the following:

$$\iint \frac{M_B}{I}\,dx\,dx = \frac{-0.002}{30}x^6 + \frac{0.5259}{20}x^5 - \frac{33.423}{12}x^4 - \frac{94.977}{6}x^3 - \frac{1847.5}{2}x^2$$

This mathematical function is applied in *Excel* for each one of the cross sections (x). Then, the constant of integration a is calculated for the length (L) of 133 meters:

$$a = \frac{-\frac{1}{E} \times \iint_0^L \frac{M_B}{I}\,dx\,dx}{L} = \frac{-\frac{1}{3.06 \times 10^8} \times (-199794051.55)}{133} = 0.00729229$$

Where E is the Young modulus in kN/m^2.

As per the values of the *Excel* table, the maximum deflection is 316 mm and its distribution can also be plotted.

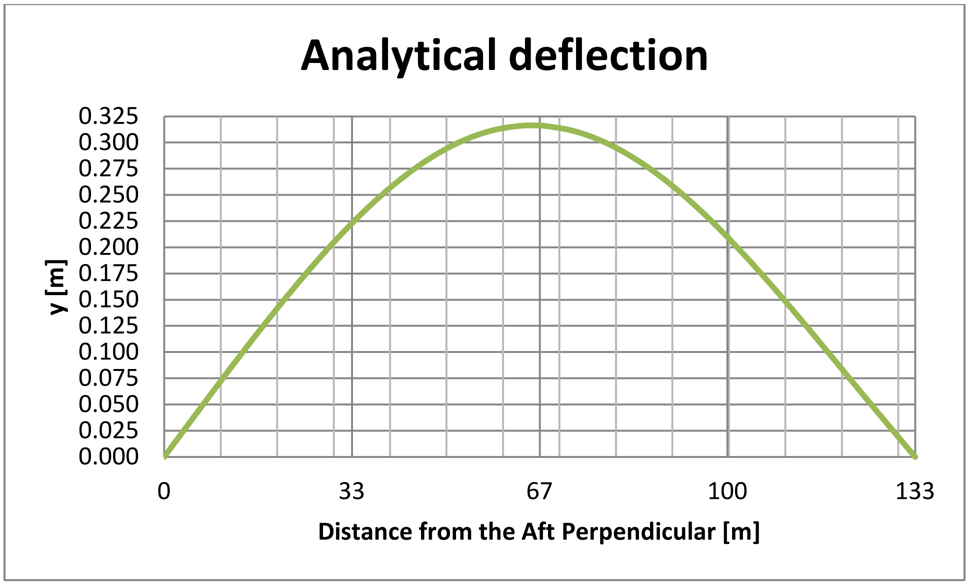


Figure 6.5.8. Deflection of the tanker vessel

As expected, the maximum value of the deflection corresponds to the maximum value of the bending moment at the cross section of *'x = 66,15 m'*.

7. NUMERICAL DETERMINATION OF THE HULL GIRDER DEFLECTION

This current section is the main core of the project. Most of the time necessary to complete this study has been spent in this part, in which the modelling and analysis of a complete hull girder using FEM has been performed so as to determine its deflection numerically. The result of this part is used for the validation of the analytical determination of the hull girder deflection.

The hull of the tanker vessel has been modelled following the drawings which are available at Bureau Veritas and, once the model is finished, the constraints are set and the loads which come from the worst scenario are applied. Then, the analysis is carried out for the purpose of obtaining eventually the deflection, which is the main objective of this project.

7.1. Model

Reference coordinate system

The vessel's geometry is defined with respect to the following right-hand coordinate system:

- Origin: at the intersection among the longitudinal plane of symmetry of the vessel, the aft end and the baseline
- X axis: longitudinal axis, positive forwards
- Y axis: transverse axis, positive towards portside
- Z axis: vertical axis, positive upwards

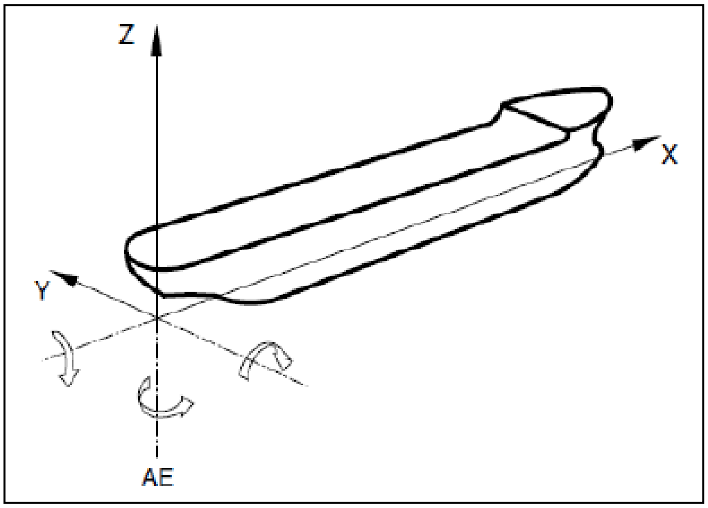


Figure 7.1.1. Reference coordinate system

Description

The vessel has been modelled by using the specialized software *FEMAP with NX Nastran*. In order to perform the modelling, all the structural plans of the tanker have been followed. These plans are available at the Classification Society Bureau Veritas while developing this study and two of them are accessible in the appendix section of this project. The software *Argos* includes some parts definitions and the lines plan so it has been used also to model several parts of the vessel which are difficult to draw like, for instance, the inner bottom or the curvature of the hull as they get near both ends.

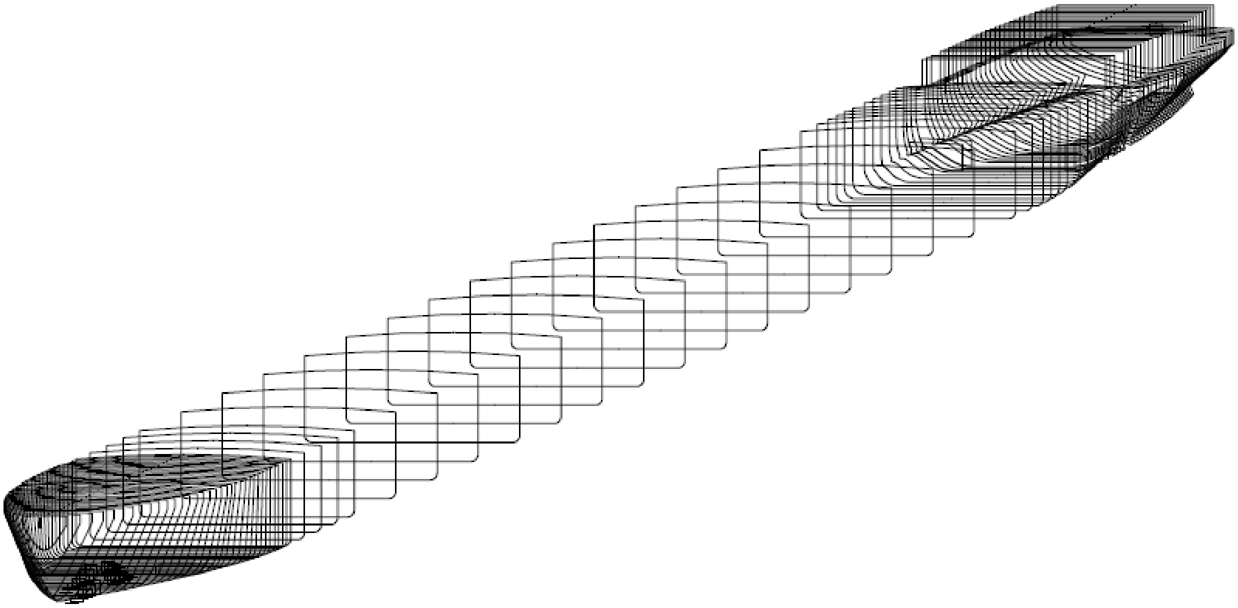


Figure 7.1.2. Perspective view of the tanker in *Argos*

The way to model the vessel has been made by following the next order (copying, extruding and reflecting elements when necessary): ordinary frame, web frame, transversal corrugated bulkhead, cargo hold, longitudinal corrugated bulkhead, aftmost cargo hold, engine room, aft peak, foremost cargo hold, fore part engine room and fore peak.

The primary plate panels of the hull structure, such as bottom, bilges, sides, deck, longitudinal and transverse corrugated bulkheads are modelled using 4-node and 3-node plate elements. Webs of girders and stiffeners are also modelled with plate elements. Flanges of girders and stiffeners are modelled using beam elements. These kinds of elements are normally the common elements used in the shipbuilding industry when carrying out a FEA project.

According to the Rules, Pt B, Ch 5, App 1, [3.4.1], in general, for some of the most common elements, the quadrilateral elements are to be such that the ratio between the longer side length and the shorter side length does not exceed 4 and, in any case, is less than 2 for most elements. Their angles are to be greater than 60º and less than 120º. The triangular element angles are to be greater than 30º and less than 120º.

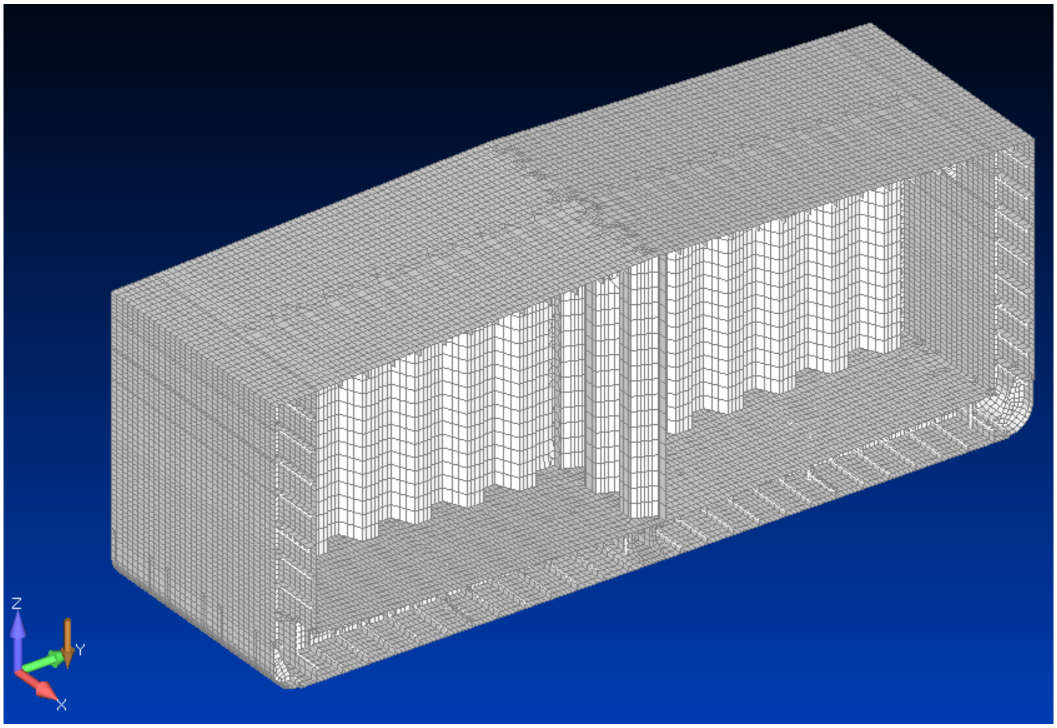


Figure 7.1.3. Elements size in the cylindrical body

The model has been built on the basis of the following criteria, among others:

- Webs of primary supporting members are modelled with only one element on their height
- Holes for the passage of ordinary stiffeners or small pipes are disregarded
- Manholes in the webs of primary supporting members are not disregarded (If had been disregarded, the element thickness is to be reduced in proportion to the hole height and the web height ratio)

Special attention has been paid to the properties of the model, in which the thickness of the plates and stiffeners are defined. Since this study is made according to the worst possible scenario, the net scantlings have to be used in the model but, in order to model the vessel with no complexities, the gross scantlings are followed in a first approach because they are the ones in the structural plans. Finally, a new file is copied from the original one and the properties are changed, reducing the thickness in all of them, according to the net scantlings.

Mesh size

The average element size is set to 150 mm in the cylindrical body whereas in the fore and aft part the size is enlarged to 500 mm in order to reduce the amount of elements throughout the model. Due to the element size, the model has a fine mesh generally.

For analyses of this kind, where the outcome is a global calculation, the model should have a coarse mesh with a minimum average size equal the stiffener spacing, which is 515 mm. For the purpose of checking the strength of the primary supporting members, the specific sections to be analyzed must have a fine mesh. The Figures 7.1.3 and 7.1.4 give an impression of the element size of the model.

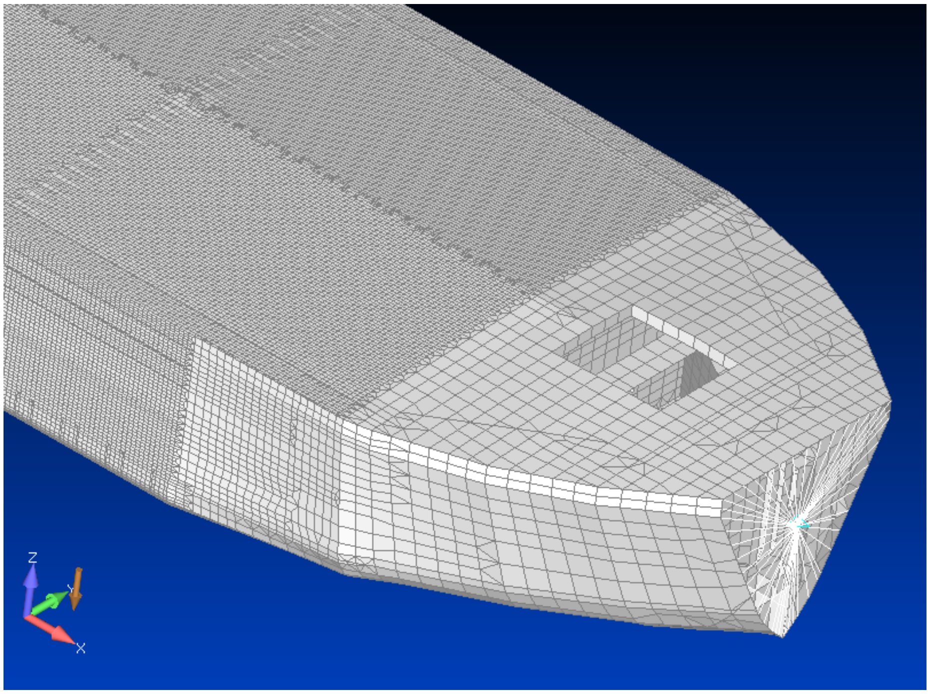


Figure 7.1.4. Fore part of the vessel

7.2. Constraints

A vessel behaves like a simply supported beam when studying its general response, hence that is the boundary condition in this case.

The model is constrained at two master nodes, set at the centre of each of the two rigid elements created especially for this purpose and which are situated at the aft edge (X = 0 m) and at the fore edge (X = 133 m). The rigid element which is set at the fore part and its master node can be seen in the previous figure. The overall ship length has been reduced in order to put the fore constraint in a relatively big section. If the total ship length had been used, the rigid element would cover only a small section, blocking a proper transfer of the forces.

As shown in Figure 7.2.1, the model is constrained as a free-free or simply supported beam, fixing the displacements in the three directions of space and the rotations around the Z and X axes, allowing therefore only the rotation around the Y axis.

Figure 7.2.1. Model constrained as a simply supported beam.

All applied loads must be in static equilibrium, obtaining zero reaction forces at the constrained master nodes.

Figure 7.2.2. Simply supported beam. Plan view

7.3. Applied loads

In this section, the applied loads are described. As mentioned in the previous section, all the applied loads must be in equilibrium, obtaining zero reaction forces at the constraints. To achieve this condition, all the loads or forces going downwards (due to the gravity) must equal the ones going upwards (due to the buoyancy).

Loads going downwards are divided into three parts: **structural loads, local loads and cargo loads**. Loads going upwards are represented by the **hydrostatic pressure**.

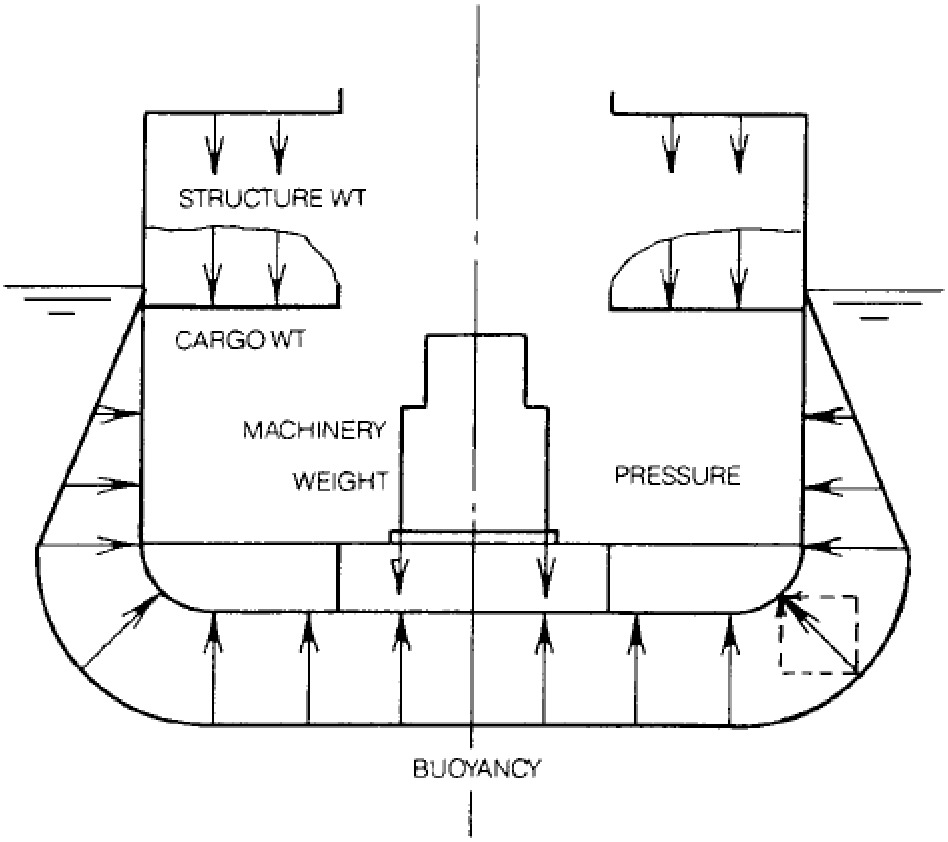


Figure 7.3.1. Static load components on hull (Lewis, 1988)

To begin with, and before applying all these loads (or forces) which the vessel undergoes, the worst scenario has to be taken into account so that the maximum deflection can be obtained. The worst scenario can be found studying all the **loading conditions** and getting the maximum bending moment directly. This has been made in the Section 6.4.

7.3.1. Structural loads

Structural loads refer to the own weight of the vessel's structure, that can be obtained from the technical specifications received from the shipyard or from the technical office. In order to be accurate, the weight has to be distributed accordingly along the structure of the vessel. In addition, this weight is the one according to the gross scantling of the vessel since the maximum bending moment appears in this condition.

The vessel is divided into three parts from the structural weight point of view. These three parts are:

- Aft part: from the aftmost frame, *'x = 0 m'*, to *'x = 17.2 m'*
- Central body: from *'x = 17.2 m'* to *'x = 125 m'*
- Fore part: from *'x = 125 m'* to the foremost frame at *'x= 133 m'*.

As reported before, the main aim of this project is to obtain a general response of the vessel and therefore the structure has not been modelled in detail. Consequently, the weight of the vessel which is obtained from the model, in the software *Femap*, is different from the actual weight of the vessel.

The way to proceed, in order to apply the structural weight, is to **assign a new value of density** at each one of the three parts of the vessel which have been defined from the structural point of view. This kind of technique is widely used when performing finite element analyses and it is called **weight calibration**.

In order to calculate the new densities, the actual weight of the structure and the model's weight have to be obtained. The actual weight is provided in the technical specifications and the weight of the model is obtained by getting the volume in Femap.

$$\Delta_{model} = \rho_{steel} \times \nabla_{model}$$

$$\rho_{calibration} = \rho_{steel} \frac{\Delta_{actual}}{\Delta_{model}}$$

Where:

Δ_{model} : Weight of the model

ρ_{steel} : Density of steel

∇_{model} : Volume of the model obtained in *Femap*

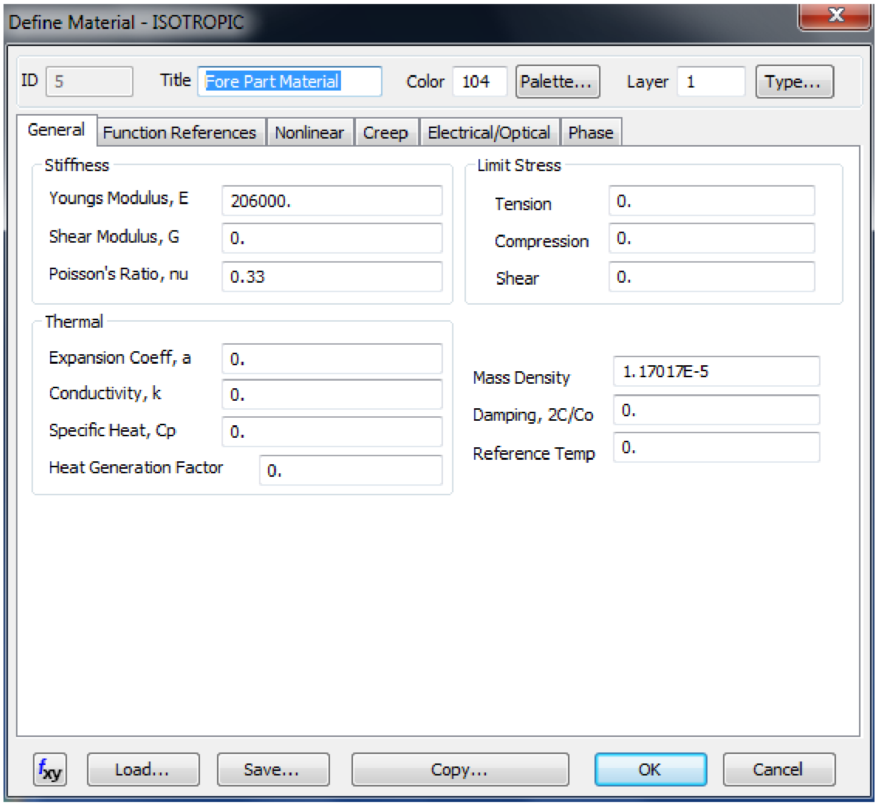
$\rho_{calibration}$: New value of density at each part of the vessel

Δ_{actual} : Weight of the model obtained from the specifications of the vessel

The results of the calculations are summarized in the following table.

Vessel's part	ρ_{steel} [kg/mm^3]	Δ_{actual} [t]	∇_{model} [mm^3]	Δ_{model} [t]	**$\rho_{calibration}$ [kg/mm^3]**
Aft Part	7,85E-06	130,58	1,0663E+10	83,70	1,22461E-05
Central Body	7,85E-06	1006,70	1,2308E+11	966,18	8,17923E-06
Fore Part	7,85E-06	73,99	6,3230E+09	49,64	1,17017E-05

Therefore, three materials have been defined in *Femap* and every structural element in the software is related to one of these materials, through each element's property, depending upon the situation along the length of the vessel.


Define Material - ISOTROPIC

ID 5
Title Fore Part Material
Color 104
Layer 1

Stiffness
Youngs Modulus, E 206000.
Shear Modulus, G 0.
Poisson's Ratio, nu 0.33

Limit Stress
Tension 0.
Compression 0.
Shear 0.

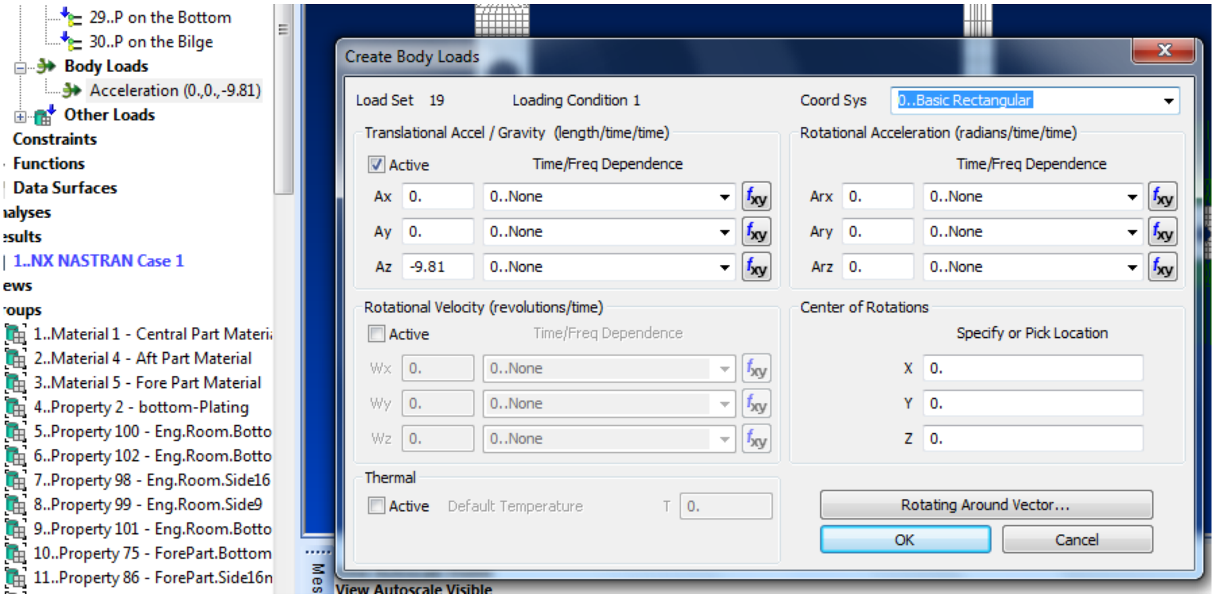
Thermal
Expansion Coeff, a 0.
Conductivity, k 0.
Specific Heat, Cp 0.
Heat Generation Factor 0.

Mass Density 1.17017E-5
Damping, 2C/Co 0.
Reference Temp 0.

Figure 7.3.2. Define Material Window in *Femap*

As noted, the weight which is applied comes from the gross scantlings but the scantlings of the model follow the net condition (considering the corrosion margin). This is due to the fact that the Classification Society considers the most conservative analysis, even if it is unrealistic.

Eventually, body loads are defined by applying the gravity in the whole model so that the structural loads are completely determined and applied during the analysis.



29..P on the Bottom
30..P on the Bilge
Body Loads
Acceleration (0.,0.,-9.81)
Other Loads
Constraints
Functions
Data Surfaces
ıalyses
ɛsults
1..NX NASTRAN Case 1
ews
'oups
1..Material 1 - Central Part Materi
2..Material 4 - Aft Part Material
3..Material 5 - Fore Part Material
4..Property 2 - bottom-Plating
5..Property 100 - Eng.Room.Botto
6..Property 102 - Eng.Room.Botto
7..Property 98 - Eng.Room.Side16
8..Property 99 - Eng.Room.Side9
9..Property 101 - Eng.Room.Botto
10..Property 75 - ForePart.Bottom
11..Property 86 - ForePart.Side16n

Create Body Loads

Load Set 19 Loading Condition 1 Coord Sys 0..Basic Rectangular

Translational Accel / Gravity (length/time/time)

☑ Active Time/Freq Dependence

		Time/Freq Dependence
Ax	0.	0..None
Ay	0.	0..None
Az	-9.81	0..None

Rotational Acceleration (radians/time/time)

		Time/Freq Dependence
Arx	0.	0..None
Ary	0.	0..None
Arz	0.	0..None

Rotational Velocity (revolutions/time)

☐ Active Time/Freq Dependence

		Time/Freq Dependence
Wx	0.	0..None
Wy	0.	0..None
Wz	0.	0..None

Center of Rotations

Specify or Pick Location

X 0.
Y 0.
Z 0.

Thermal

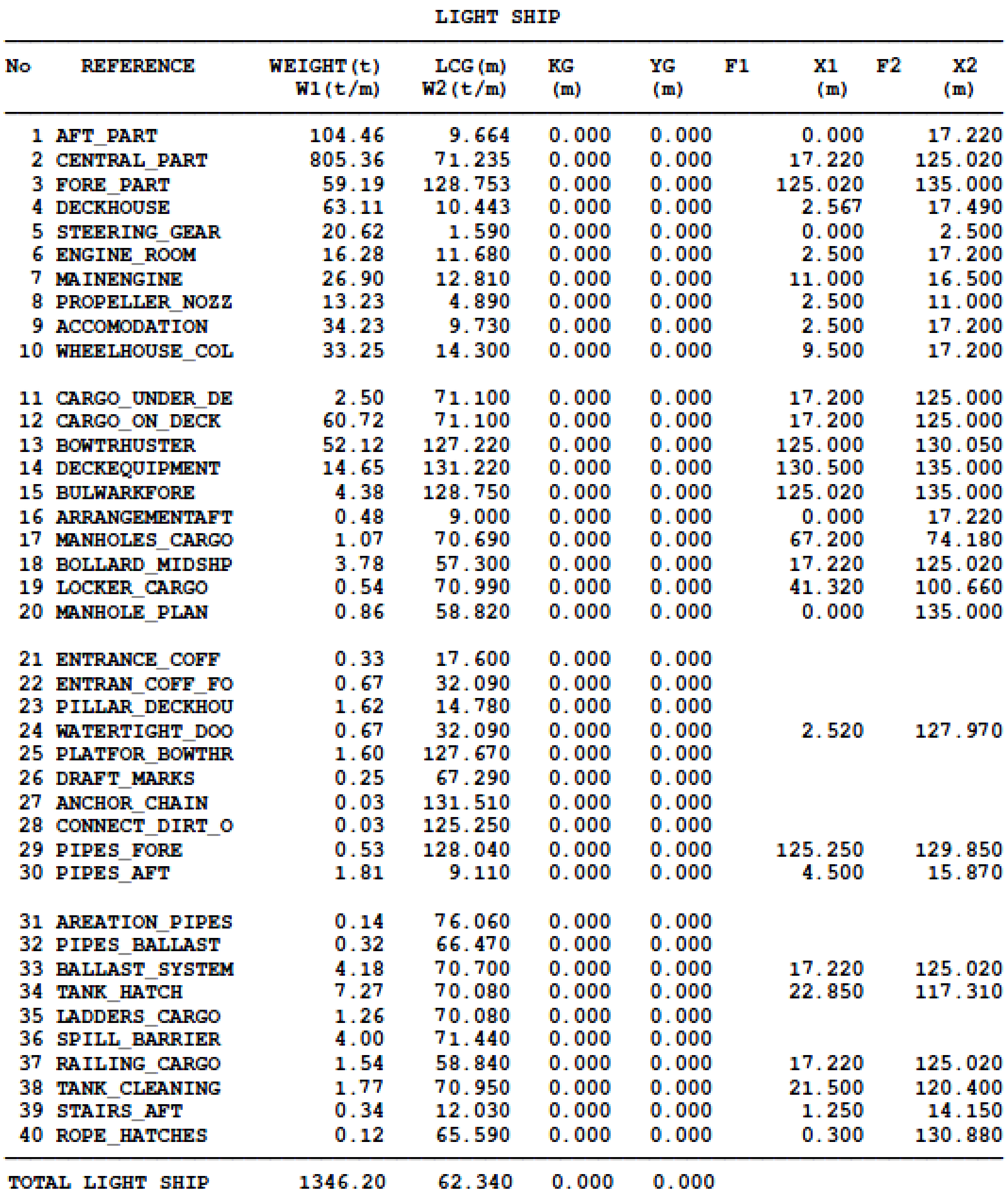
☐ Active Default Temperature T 0.

Figure 7.3.3. Body Loads in Femap

7.3.2. Local Loads

Local loads are the ones which come from the weight of fixed elements like machinery, parts of the structure that can be dismounted or structures which do not contribute to the overall strength of the vessel.

These loads, along with the weight of the structure, come from the specifications of the vessel and are defined in the software *Argos*, as shown in the following table:



```
                                 LIGHT SHIP
--------------------------------------------------------------------------------
No     REFERENCE        WEIGHT(t)    LCG(m)    KG       YG     F1      X1    F2      X2
                          W1(t/m)   W2(t/m)    (m)      (m)            (m)           (m)
--------------------------------------------------------------------------------
  1 AFT_PART              104.46     9.664   0.000    0.000          0.000         17.220
  2 CENTRAL_PART          805.36    71.235   0.000    0.000         17.220        125.020
  3 FORE_PART              59.19   128.753   0.000    0.000        125.020        135.000
  4 DECKHOUSE              63.11    10.443   0.000    0.000          2.567         17.490
  5 STEERING_GEAR          20.62     1.590   0.000    0.000          0.000          2.500
  6 ENGINE_ROOM            16.28    11.680   0.000    0.000          2.500         17.200
  7 MAINENGINE             26.90    12.810   0.000    0.000         11.000         16.500
  8 PROPELLER_NOZZ         13.23     4.890   0.000    0.000          2.500         11.000
  9 ACCOMODATION           34.23     9.730   0.000    0.000          2.500         17.200
 10 WHEELHOUSE_COL         33.25    14.300   0.000    0.000          9.500         17.200

 11 CARGO_UNDER_DE          2.50    71.100   0.000    0.000         17.200        125.000
 12 CARGO_ON_DECK          60.72    71.100   0.000    0.000         17.200        125.000
 13 BOWTRHUSTER            52.12   127.220   0.000    0.000        125.000        130.050
 14 DECKEQUIPMENT          14.65   131.220   0.000    0.000        130.500        135.000
 15 BULWARKFORE             4.38   128.750   0.000    0.000        125.020        135.000
 16 ARRANGEMENTAFT          0.48     9.000   0.000    0.000          0.000         17.220
 17 MANHOLES_CARGO          1.07    70.690   0.000    0.000         67.200         74.180
 18 BOLLARD_MIDSHP          3.78    57.300   0.000    0.000         17.220        125.020
 19 LOCKER_CARGO            0.54    70.990   0.000    0.000         41.320        100.660
 20 MANHOLE_PLAN            0.86    58.820   0.000    0.000          0.000        135.000

 21 ENTRANCE_COFF           0.33    17.600   0.000    0.000
 22 ENTRAN_COFF_FO          0.67    32.090   0.000    0.000
 23 PILLAR_DECKHOU          1.62    14.780   0.000    0.000
 24 WATERTIGHT_DOO          0.67    32.090   0.000    0.000          2.520        127.970
 25 PLATFOR_BOWTHR          1.60   127.670   0.000    0.000
 26 DRAFT_MARKS             0.25    67.290   0.000    0.000
 27 ANCHOR_CHAIN            0.03   131.510   0.000    0.000
 28 CONNECT_DIRT_O          0.03   125.250   0.000    0.000
 29 PIPES_FORE              0.53   128.040   0.000    0.000        125.250        129.850
 30 PIPES_AFT               1.81     9.110   0.000    0.000          4.500         15.870

 31 AREATION_PIPES          0.14    76.060   0.000    0.000
 32 PIPES_BALLAST           0.32    66.470   0.000    0.000
 33 BALLAST_SYSTEM          4.18    70.700   0.000    0.000         17.220        125.020
 34 TANK_HATCH              7.27    70.080   0.000    0.000         22.850        117.310
 35 LADDERS_CARGO           1.26    70.080   0.000    0.000
 36 SPILL_BARRIER           4.00    71.440   0.000    0.000
 37 RAILING_CARGO           1.54    58.840   0.000    0.000         17.220        125.020
 38 TANK_CLEANING           1.77    70.950   0.000    0.000         21.500        120.400
 39 STAIRS_AFT              0.34    12.030   0.000    0.000          1.250         14.150
 40 ROPE_HATCHES            0.12    65.590   0.000    0.000          0.300        130.880
--------------------------------------------------------------------------------
TOTAL LIGHT SHIP         1346.20    62.340   0.000    0.000
```

In the next table, all the local loads (with a significant weight) applied in the model are summarized:

Reference	Weight [t]	LCG [m]	X1 [m]	X2 [m]
Deckhouse	63,11	10,443	2,567	17,490
Steering Gear	20,62	1,590	0,000	2,500
Engine Room	16,28	11,680	2,500	17,200
Main Engine	26,90	12,810	11,000	16,500
Propeller Nozzles	13,23	4,890	2,500	11,000
Accommodation	34,23	9,730	2,500	17,200
Wheelhouse	33,25	14,300	9,500	17,200
Cargo on Deck	60,72	71,100	17,200	125,000
Bowthruster	52,12	127,220	125,000	130,050
Deck Equipment	14,65	131,220	130,500	135,000
Fore Bulwark	5,47	128,750	125,020	135,000
Tank hatch	9,09	70,080	22,850	117,310
Spill Barrier	5,00	71,440	-	-

The remaining small local loads and three loads (Tank hatch, Spill barrier and the Fore bulwark) which cannot be applied properly in the structure, have a resultant force of 50,25 tons and therefore they cannot be neglected. In order to apply all these loads, they are all summed up and applied on the deck, as a distributed pressure, throughout a selected area (in the model in *Femap*) along the centreline of the vessel. The calculations are shown in the following tables as well as the list of the remaining local loads.

Reference	Weight [t]	Weight [N]	LCG [mm]	M [N mm]
Cargo under Deck	2,50	24525,0	71100	1,744E+09
Fore Bulwark	5,47	53660,7	128750	6,909E+09
Aft Arrangement	0,48	4708,8	9000	42379200
Cargo Manholes	1,34	13145,4	70690	929248326
Midship Bollard	4,72	46303,2	57300	2,653E+09
Cargo Locker	0,54	5297,4	70990	376062426
Manhole Plan	0,86	8436,6	58820	496240812
Cofferdam Entrance	0,33	3237,3	17600	56976480
Fore Cofferdam Entrance	0,67	6572,7	32090	210917943
Deckhouse Pillar	2,02	19816,2	14780	292883436
Watertight Door	0,67	6572,7	32090	210917943

Platform bowthruster	1,60	15696,0	127670	2,004E+09
Draft Marks	0,25	2452,5	67290	165028725
Anchor Chain	0,03	294,3	131510	38703393
Dirty Oil Connection	0,03	294,3	125250	36861075
Fore Pipes	0,53	5199,3	128040	665718372
Aft Pipes	2,26	22170,6	9110	201974166
Aeration Pipes	0,14	1373,4	76060	104460804
Ballast Pipes	0,32	3139,2	66470	208662624
Ballast System	5,23	51306,3	70700	3,627E+09
Tank Hatch	9,09	89172,9	70080	6,249E+09
Cargo Ladders	1,58	15499,8	70080	1,086E+09
Spill Barrier	5,00	49050,0	71440	3,504E+09
Cargo Railing	1,92	18835,2	58840	1,108E+09
Cleaning Tank	2,21	21680,1	70950	1,538E+09
Aft Stairs	0,34	3335,4	12030	40124862
Rope Hatches	0,12	1177,2	65590	77212548
TOTAL SUM	50,25	492952,5		3,458E+10

The mean position of the Longitudinal Centre of Gravity is:

$$\overline{LCG} = \frac{\sum Bending\ Moment}{\sum Weight}$$

The weight's units are set in Newton so as to apply the pressure in MPa.

$$Pressure = \frac{Force}{Area} = \frac{Total\ weight}{Area}$$

Mean LCG	70143,50	mm
Total weight	492952,5	N
Area to apply the P	6644128	mm^2
Pressure	0,074193709	MPa

The significant local loads are applied as a pressure in a surface related to their position. These surfaces are obtained by measuring them directly in the software *Femap*. The values of the weights with their appropriate units and the pressures are shown in the following table.

Reference	x1 [m]	x2 [m]	Weight [t]	Weight [N]	S [mm^2]	P [MPa]
Deckhouse, Engine Room and Accommodation	2,5	17,2	113,62	1114612,2	23645438	0,0471
Wheelhouse	9,5	17,2	33,25	326182,5	12326198	0,0265
Steering Gear	0,0	2,5	20,62	202282,2	30234477	0,0067
Main Engines	11,0	16,5	26,9	263889,0	11640702	0,0227
Propeller Nozzles	2,5	11,0	13,23	129786,3	53737540	0,0024
Cargo on Deck	17,2	125,0	60,72	595663,2	1,62E+09	0,0004
Bowthrusters	125,0	130,1	52,12	511297,2	10635313	0,0481
Deck Equipment	130,5	135,0	14,65	143716,5	26167751	0,0055

Some local loads are shown in the next images. As mentioned before, the weight of each item is applied as a distributed pressure throughout its related surface.

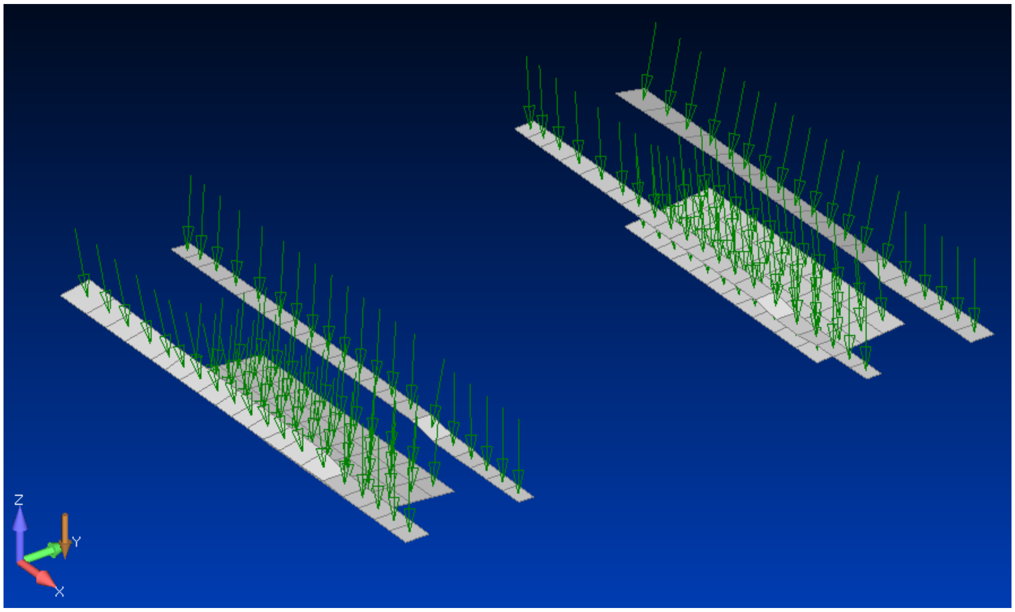


Figure 7.3.4. Local loads: Main engines

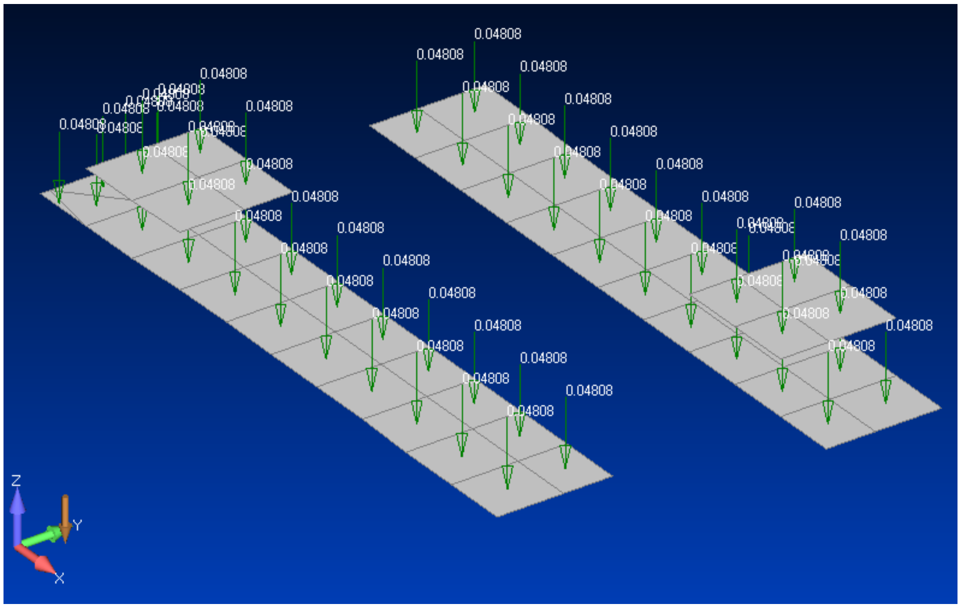


Figure 7.3.5. Local loads: Bow thrusters

7.3.3. Cargo loads

Cargo loads come from the pressure of the cargo that the vessel carries when working. These loads are crucial when looking for the maximum bending moment since the way of loading or unloading the cargo generates this condition. As studied in the software *Argos*, the worst condition is shown in the next image.

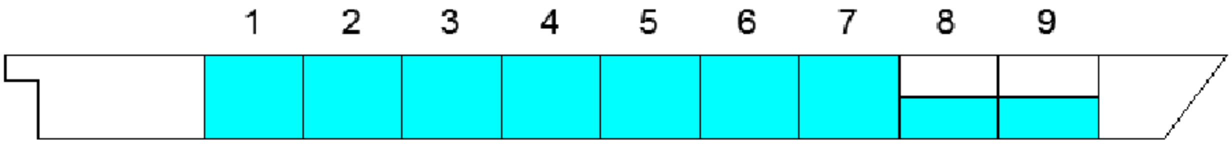


Figure 7.3.6. Loading condition that generates the maximum bending moment. 2 Runs.

At the point in which the four foremost cargo tanks are half empty, the maximum bending moment appears and, consequently, the worst condition. The cargo loads in this condition are the ones which have to be applied into the model.

The weight of the cargo inside each tank is known due to the specifications, the surface of the base of the tanks is calculated in *Femap* and, finally, the pressure is calculated and applied in the model following the next formula:

$$P = \frac{Force}{Area} = \frac{Weight}{Surface}$$

All the cargo loads are summed up in the following table, which also shows the data necessary to calculate the pressures.

Tank number	Weight [t]	Weight [N]	Surface [mm^2]	**P [MPa]**
Cargo tank 1	188,56	1849773,6	75064345	**0,0246425**
Cargo tank 2	184,72	1812103,2	75068091	**0,0241395**
Cargo tanks 3-4	378,90	3717009,0	158300456	**0,0234807**
Cargo tanks 5-6	757,82	7434214,2	158300982	**0,0469625**
Cargo tanks 7-8	757,82	7434214,2	158300982	**0,0469625**
Cargo tanks 9-10	757,82	7434214,2	158300982	**0,0469625**
Cargo tanks 11-12	757,82	7434214,2	158300982	**0,0469625**
Cargo tanks 13-14	757,82	7434214,2	158300982	**0,0469625**
Cargo tanks 15-16	757,62	7432252,2	158300982	**0,0469501**
Cargo tank 17	376,49	3693366,9	81057993	**0,0455645**
Cargo tank 18	380,18	3729565,8	81053100	**0,0460139**
Total cargo load	6055,57			

Figure 7.3.7 shows the cargo load applied as a distributed pressure on the base of the tank number 1, which is situated next to the fore part.

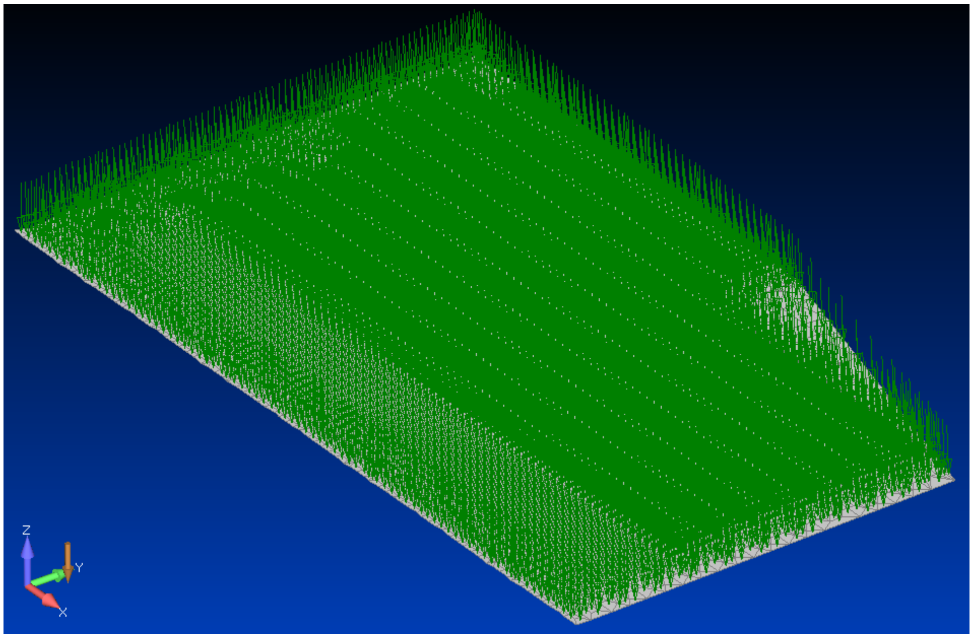


Figure 7.3.7. Cargo load applied in *Femap*. Tank number 1

7.3.4. Hydrostatic pressure

So, all the loads going downwards in the model have been described and, in order to have static equilibrium, those loads must equal all the loads going upwards.

The loads going upwards are the ones which come from the hydrostatic pressure or buoyancy. The hydrostatic pressure is basically the water pressure applied to the hull as per the draft values which correspond to the worst loading condition.

The hydrostatic pressure is not easy to apply into the model because of the hull form and, consequently, an approach to apply this pressure has been made. Taking into account that there is a trim, there is no constant draft and therefore it varies from the aft to the fore part.

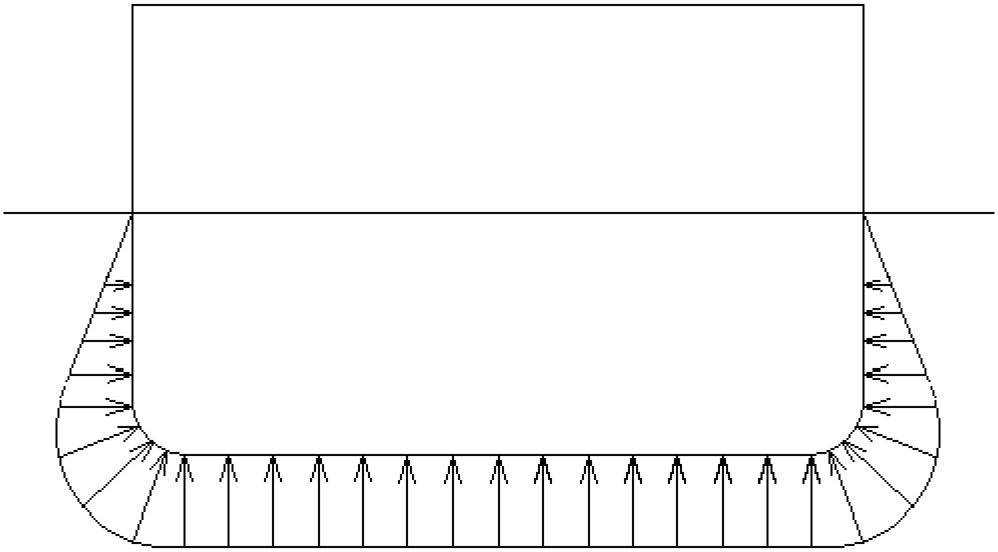


Figure 7.3.8. Hydrostatic pressure on the hull in still water

The approach to apply the hydrostatic pressure consists of, first, selecting the parts of the hull in which the pressure acts and, second, creating groups of these parts. Due to the aim of this project, the pressure is only spread on the parts of the hull which have horizontal projection because the lateral pressure does not affect the longitudinal response of the vessel so, the parts of the hull in which the pressure acts are:

- Bottom: as per the flat part of the bottom
- Bilge: as per the attached bilge of the flat part of the bottom
- Aft part: it is the aft part, including both the bottom and the bilge, until the waterline
- Fore part: it is the fore part, including both the bottom and the bilge, until the waterline

These parts are arranged in *Femap* as groups, which are groups of elements, so that they can be easily selected to apply the pressure or just to visualize them.

When the worst loading condition occurs, there is a specific average draft with a trim. The values of the drafts, measured from the base of the keel, and the trim are:

T_{aft} = 4.677 m
$T_{amidship}$ = 4.149 m
T_{fore} = 3.621 m
t = 1.056 m

Where:

T_{aft} : draft at the aft part of the vessel
$T_{amidship}$: draft at the midship section of the vessel
T_{fore} : draft at the fore part of the vessel
t : trim; is the difference between the maximum and minimum draft

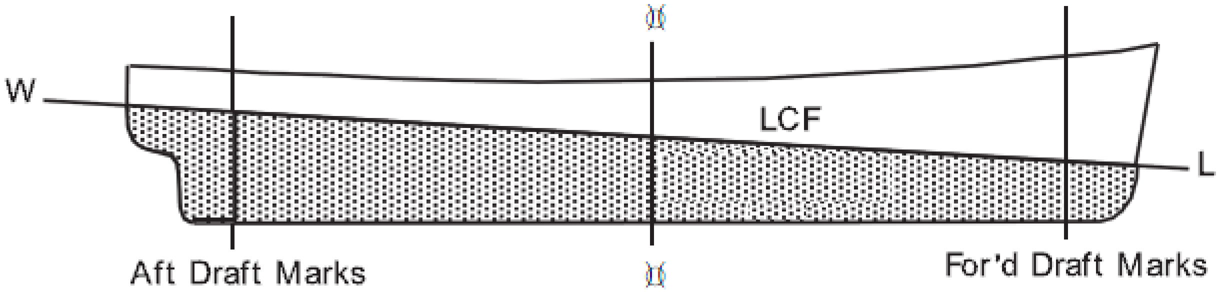


Figure 7.3.9. Draft marks and trim in a vessel

Now that it is known that there are several groups to apply the pressure and with different values of drafts, the hydrostatic pressure at any point along the length of the vessel is obtained by following the next equation:

$$P = \frac{\rho \times g \times h}{10^6} = \frac{\rho \times g \times T}{10^6}$$

Where:

P : hydrostatic pressure (MPa).

ρ : fresh water density (1000 kg/m^3)

g : gravitational acceleration (9.81 m/s^2)

h : height of the fluid column above it, in this case is the draft, T (m)

Using triangles similarity, the draft at any point of the length can be calculated.

Some **simplifications** have been made in order to apply the pressure at each one of the parts:

- In the **aft part**, the hull has been divided into five groups of approximately five meters of length. At each group, the average draft is calculated and that value is the one used to calculate the pressure. As it is difficult to apply the pressure into each one of the five groups, each group has been split into two parts and the pressure is applied by varying its values along the depth. See Figure 7.3.10.

Aft Part						
Position along the length	**ρ [kg/m^3]**	**g [m/s^2]**	**T [m]**	**Average T [m]**	**P [MPa]**	**P/2 [MPa]**
Point 1, x = 5.00 m	1000	9,81	4,6373	4,6572	0,04569	0,02284
Point 2, x = 10.00 m	1000	9,81	4,5976	4,6175	0,04530	0,02265
Point 3, x = 15.25 m	1000	9,81	4,5559	4,5768	0,04490	0,02245
Point 4, x = 15.25 m	1000	9,81	4,5180	4,5369	0,04451	0,02225
Point 5, x = 15.25 m	1000	9,81	4,4805	4,4992	0,04414	0,02207

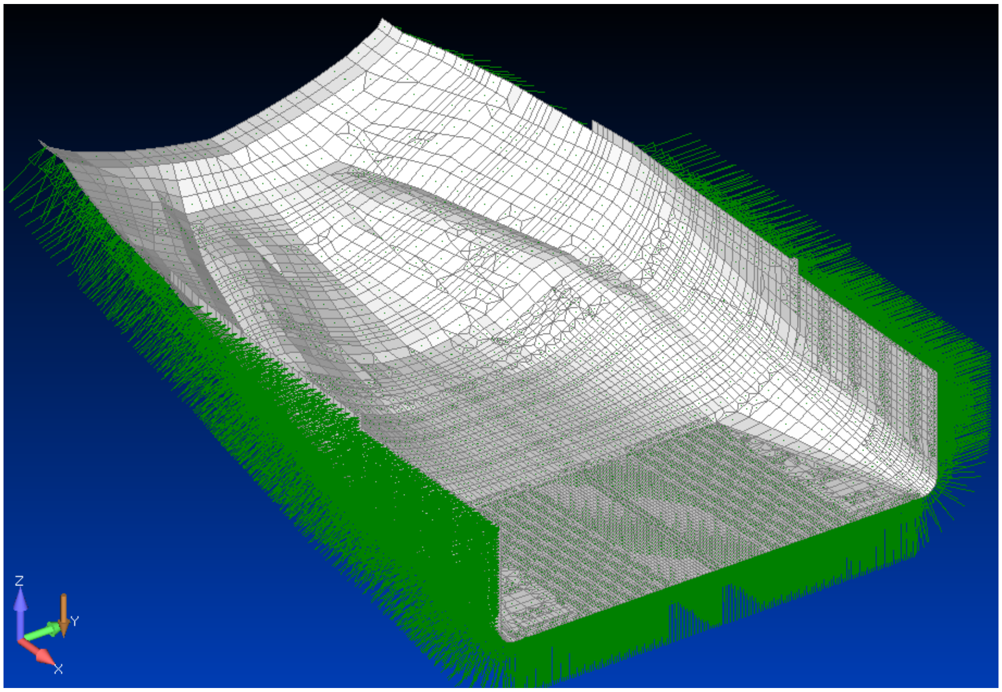


Figure 7.3.10. Aft part group

- In the **bottom**, the pressure is calculated according to three key points: the first point, situated in the aftmost edge of the flat part of the bottom, the second point, situated in the middle of the flat part of the bottom and the third point, situated in the foremost edge. Then, at each one of the three points, the pressures shown in the table are applied.
- In the **bilge**, the technique to apply the pressure is the same than in the aft part. The average draft of the whole bilge which corresponds to the flat part of the bottom has been calculated and then it is applied according to the three values of the table.

Bottom				
Position along the length	**ρ [kg/m^3]**	**g [m/s^2]**	**T [m]**	**P [MPa]**
Point 1, x = 24.754 m	1000	9,81	4,4805	0,04395
Point 2, x = 71.980 m	1000	9,81	4,1054	0,04027
Point 3, x = 119.21 m	1000	9,81	3,7304	0,03660

Bilge				
Position along the depth	**ρ [kg/m^3]**	**g [m/s^2]**	**T [m]**	**P [MPa]**
Point 1, z = 0 m	1000	9,81	4,149	0,04070
Point 2, z = 0.225 m	1000	9,81	3,924	0,03849
Point 3, z = 0.450 m	1000	9,81	3,699	0,03629

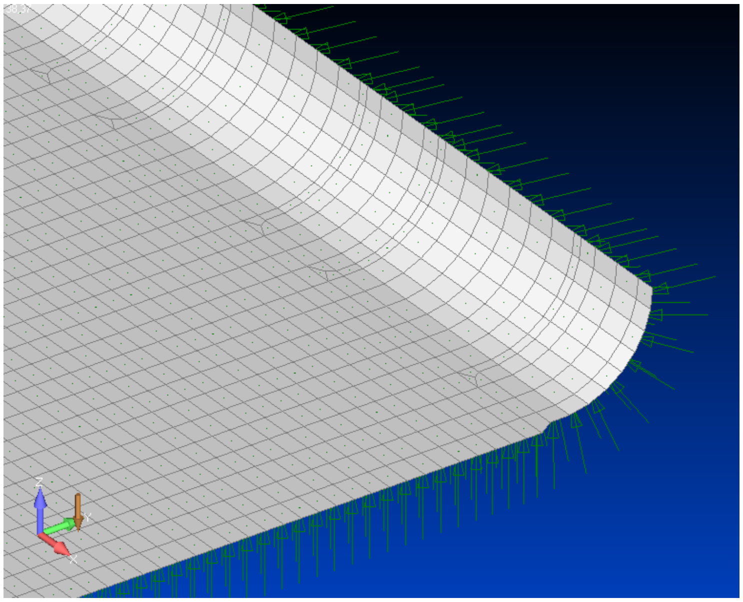


Figure 7.3.11. Bottom and bilge groups

- In the **fore part**, the pressure is applied according to the method used in the aft part as well. The difference is that there are three groups instead of five.

Fore Part						
Position along the length	**ρ [kg/m³]**	**g [m/s²]**	**T [m]**	**Average T [m]**	**P [MPa]**	**P/2 [MPa]**
Point 1, x = 119.21 m	1000	9,81	3,7304	3,7106	0,03640	0,01820
Point 2, x = 124.20 m	1000	9,81	3,6909	3,6758	0,03606	0,01803
Point 3, x = 128.00 m	1000	9,81	3,6607	3,6408	0,03572	0,01786

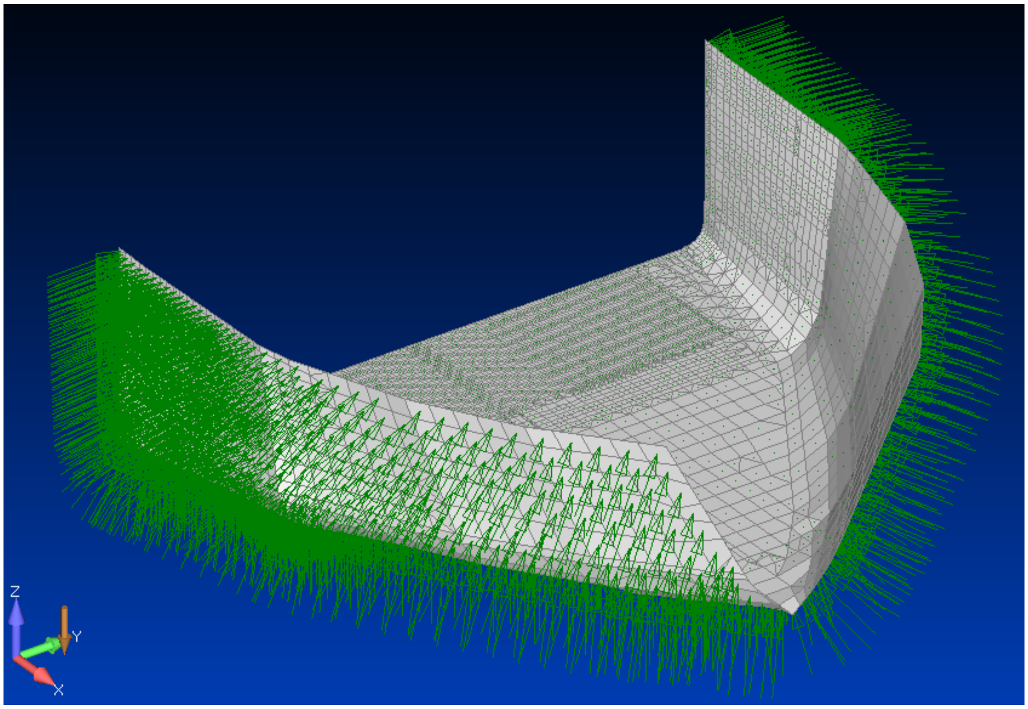


Figure 7.3.12. Pressure applied in the fore part

7.4. Summary of the loads

In the following figures, we can observe a section in which all the loads are shown.

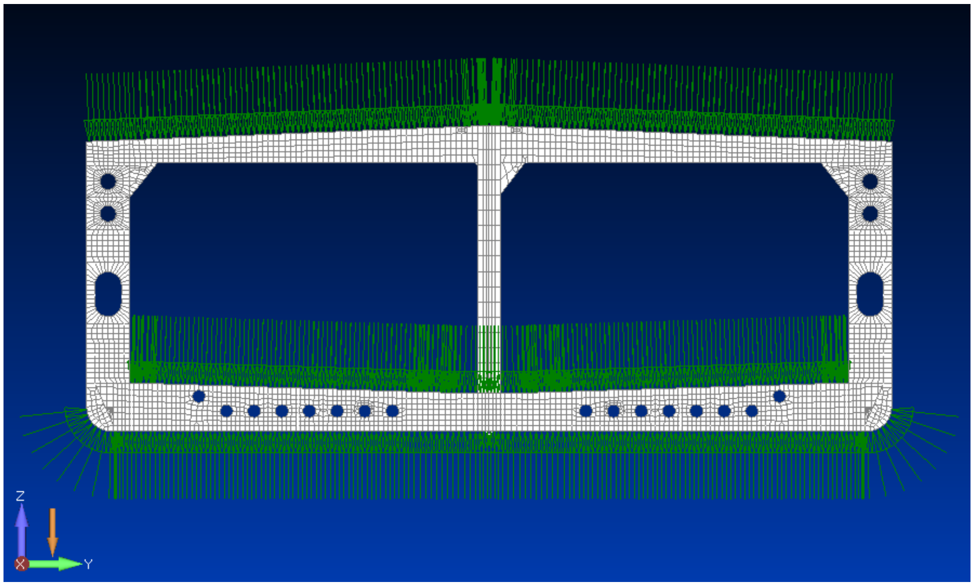


Figure 7.4.1. Sectional view of the loads

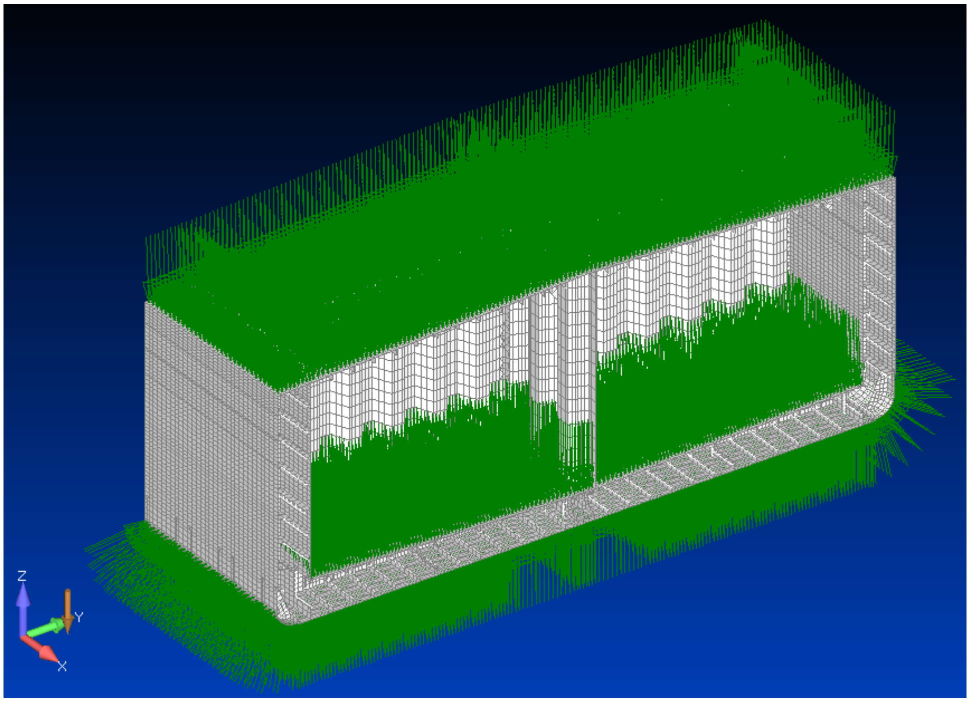
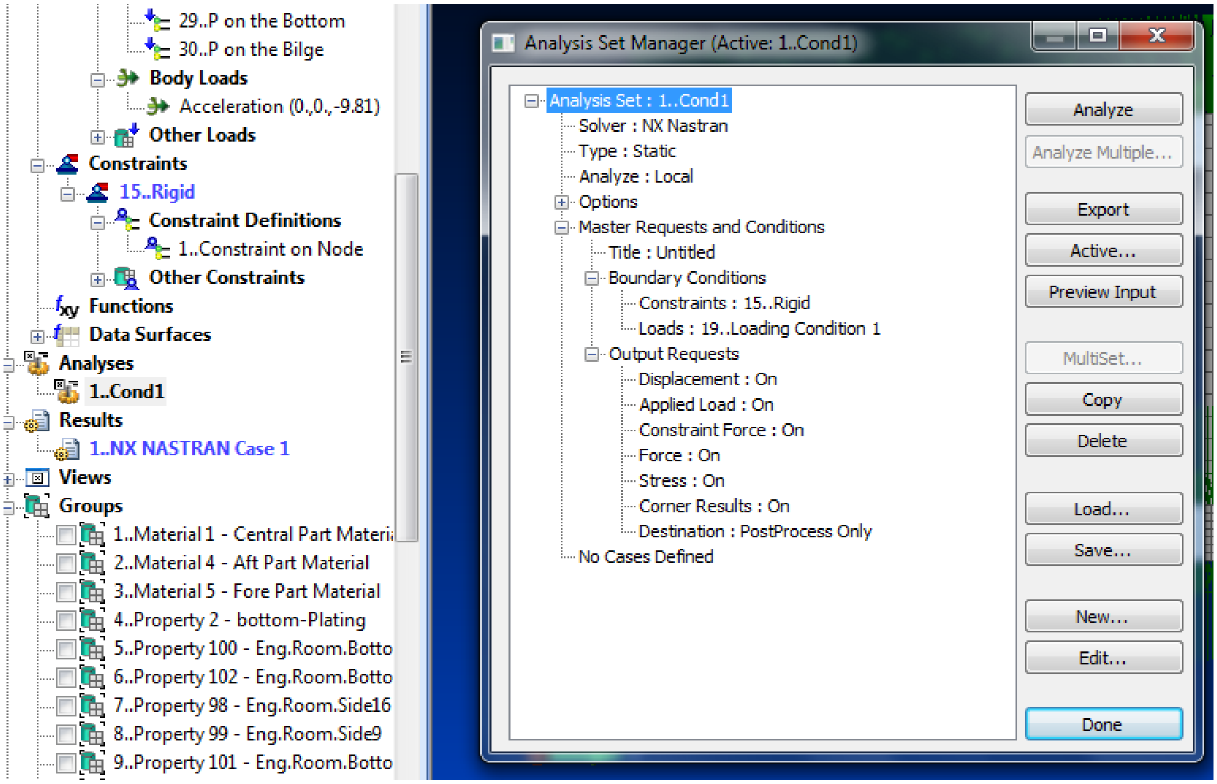


Figure 7.4.2. Perspective view of the loads

7.5. Results: Determination of the deflection

After setting the constraints and applying all the loads, the next step is to analyze the vessel. This can be made in the software *Femap* by creating a new Static Analysis with the solver *NX Nastran*.



- 29..P on the Bottom
- 30..P on the Bilge
- Body Loads
  - Acceleration (0.,0.,-9.81)
- Other Loads
- Constraints
  - 15..Rigid
    - Constraint Definitions
      - 1..Constraint on Node
    - Other Constraints
- Functions
- Data Surfaces
- Analyses
  - 1..Cond1
- Results
  - 1..NX NASTRAN Case 1
- Views
- Groups
  - ☐ 1..Material 1 - Central Part Materi
  - ☐ 2..Material 4 - Aft Part Material
  - ☐ 3..Material 5 - Fore Part Material
  - ☐ 4..Property 2 - bottom-Plating
  - ☐ 5..Property 100 - Eng.Room.Botto
  - ☐ 6..Property 102 - Eng.Room.Botto
  - ☐ 7..Property 98 - Eng.Room.Side16
  - ☐ 8..Property 99 - Eng.Room.Side9
  - ☐ 9..Property 101 - Eng.Room.Botto

Analysis Set Manager (Active: 1..Cond1)

- Analysis Set : 1..Cond1
  - Solver : NX Nastran
  - Type : Static
  - Analyze : Local
  - Options
  - Master Requests and Conditions
    - Title : Untitled
    - Boundary Conditions
      - Constraints : 15..Rigid
      - Loads : 19..Loading Condition 1
    - Output Requests
      - Displacement : On
      - Applied Load : On
      - Constraint Force : On
      - Force : On
      - Stress : On
      - Corner Results : On
      - Destination : PostProcess Only
  - No Cases Defined

Figure 7.5.1. Analysis set manager in Femap

Once the analysis is finished, the model has to be verified by checking the reactions at the constraints, i.e., R_A and R_B at the Figure 7.5.2. Both reactions must be zero in order to confirm that the loads going downwards equal the ones going upwards and because in reality these constraints do not exist.

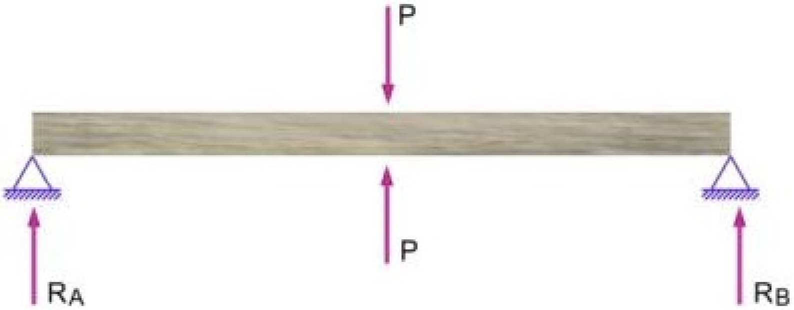


Figure 7.5.2. Simply supported beam

The values of the reactions are the following:

$$R_{aft} = 991937\ N = 101.12\ t$$

$$R_{fore} = 955460\ N = 97.40\ t$$

As the values of the reactions are positive, this means that there is lack of buoyancy (or hydrostatic pressure) of roughly 198.5 tons. For the purpose of ensuring that the hydrostatic pressure is not enough, two more analyses are carried out.

The first checking analysis consists of applying the body loads (weight of the structure) and the local loads. This analysis is also useful so as to check that body loads and local loads are applied correctly. From the specifications it is known that:

Body loads = 1211.27 t

Local loads = 385.36 t

The sum of these “two” loads is the lightship weight, which is 1596.63 tons.

After carrying out the analysis, the sum of the reaction forces at both constraints is:

$$R_{aft} + R_{fore} = 15643380\ N = 1594.63\ t$$

This means that the loads are applied correctly, with a slight difference of 2 tons, due to the amount of tenths when setting the mass densities.

The second checking analysis consists of applying just the buoyancy force or hydrostatic pressure. Once the analysis is finished the reaction forces are:

$$R_{aft} + R_{fore} = -72954212\ N = -7436.72\ t$$

The minus sign means that the direction of the reactions is going downwards to counteract the hydrostatic pressure. As the lightship weight and the cargo load (displacement) sum 7652.2 tons, there is a difference or lack of buoyancy of 215.5 tons.

Therefore, as remarked before when carrying out the main analysis with all the loads, there is a lack of hydrostatic pressure of 198.5 tons because of the hull form in the fore and aft parts, where some elements were simplified for the purpose of simplifying the hull in that areas. Again, because of the hull form, it is difficult to apply precisely the pressure in every group. For instance, in the aft part, the hull form has some “peaks” and therefore the pressure in that areas is not so accurate. Furthermore, there are several groups and the mean draft has been made.

Normally, the remaining pressure must be added for the sake of the accuracy but, in this project, this lack of hydrostatic pressure is neglected since its quantity is a 2.6% of the total displacement of the vessel and this lack of pressure appears mainly near both ends of the vessel, not in the central body. Therefore, the first analysis is acceptable.

So, once the reactions are checked, the model and the analysis are acceptable. In the Figure 7.5.3, the deflection which the vessel undergoes is shown with a certain percentage of deformation view in order to visualize it clearly.

Figure 7.5.3. Numerical deflection of the vessel. Lateral view

The easiest way to measure the deflection is to select a group in *Femap* formed by sections close to the midship section, from 64 m to 68 m approximately. Then, there is a tool in *Femap* to get some physical magnitudes of the nodes of the model like, for example, the forces or displacements.

Using this tool, several nodes in the bottom of the group can be selected, getting their displacement and calculating their average, which is the deflection:

$$\boldsymbol{y_{numerical} = 317\ mm}$$

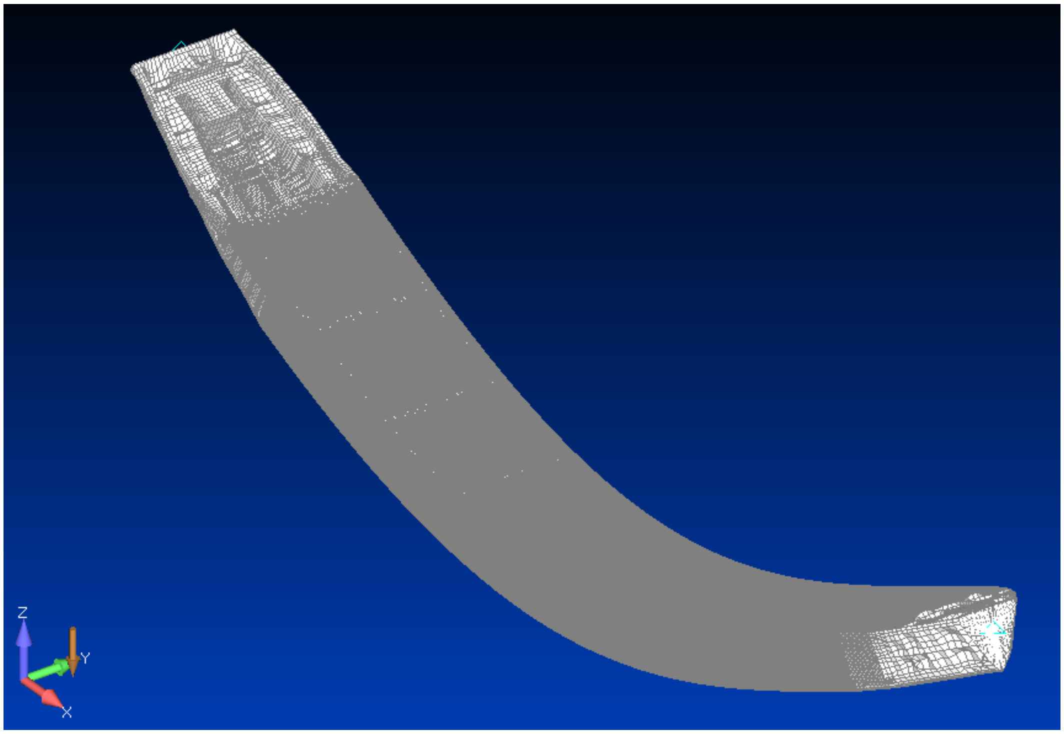


Figure 7.5.4. Perspective view of the deflection

Considering that the numerical determination of the deflection is used to get more accurate results for complex geometries, in this case the numerical result is more conservative since the deflection obtained analytically is 316 mm. The deflection obtained numerically is bigger due to 2 reasons:

1. There is a lack of buoyancy
2. The net scantlings are used (with the weight of the gross scantlings)

Therefore, if the remaining buoyancy is added and the gross scantlings are used, the numerical deflection must decrease.

In any case, taking into account that the deflection obtained analytically is 316 mm, the difference is so slight that **the analytical study is validated** and, therefore, the objective of this project has been reached.

8. STUDIED VESSELS

As per the Introduction of this project, this study's goal consists of the validation of the analytical determination of the hull girder deflection of a standard inland navigation vessel. As this goal has been reached, more standard vessels can be studied analytically in a future project.

In order to set a path for a future development of this project, four standard inland navigation vessels are studied.

8.1. Main features

The **main vessel of this project** is an inland navigation double hull **tanker type C**. It has longitudinal framing system, it is self-propelled and the material is steel grade A.

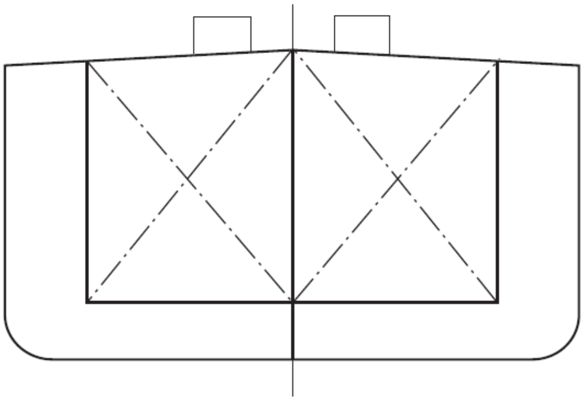


Figure 8.1.1. Double hull tanker section (*Rules*)

A tanker is a vessel specially intended to carry liquid or gaseous cargo in bulk. The list of cargoes the tanker is allowed to carry will be issued by the Society, in the case of transport of dangerous goods. In a double hull tanker, the cargo tanks form part of the vessel's structure.

Type C applies to a tanker built and equipped for the carriage of liquids. The vessel shall be of the flush deck type and double hull type with double hull spaces, double bottoms, but without trunk. The cargo tanks may be formed by the vessel's inner hull or may be installed in the hold spaces as independent tanks.

The loading/unloading sequence of the cargo tanks is 2 runs. This means that the loading and unloading are performed uniformly in two runs of almost equal masses, starting from one end of the cargo space progressing towards the opposite end.

Its range of navigation is IN(0.6). The character IN indicates a vessel on waters covered by *B.V. Rules for the Classification of Inland Navigation Vessels*, i.e.:

- All inland waterways
- All restricted maritime stretches of water up to a significant wave height of 2 meters
- Other waters showing comparable conditions.

The character IN is completed, between brackets, with the significant wave height or maximum wave height for which the vessel has been calculated, in this case, for 0.6 meters.

Other studied vessels in this Section are:

Tanker type G: tanker built and equipped for the carriage in bulk of gases under pressure or under refrigeration, in compliance with the applicable provisions of ADN Regulations.

Tanker type N closed: tanker built and equipped for the carriage of dangerous liquids in bulk, in compliance with the applicable provisions of ADN Regulations.

Container vessel: vessel specially intended for the carriage of containers complying with the rule requirements stated under Pt D, Ch 1, Sec 4.

8.2. Deflection of standard inland navigation vessels

In this Section, the hull girder deflection of four standard inland navigation vessels is obtained, analytically. The deflection is obtained with a constant distribution of the moment of inertia. In a future research, there must be a realistic distribution so as to be precise.

8.2.1. Moment of Inertia and bending moment

The moment of inertia is obtained by modelling the midship section of each one of the four vessels in *Mars Inland*. The moment of inertia is calculated automatically by the software and the bending moment is also got automatically in *Argos* when each loading condition is analyzed in the software.

Vessel no. 1

Vessel number 1 is a tanker type G, with a single hull, and its range of navigation is IN(1.2).

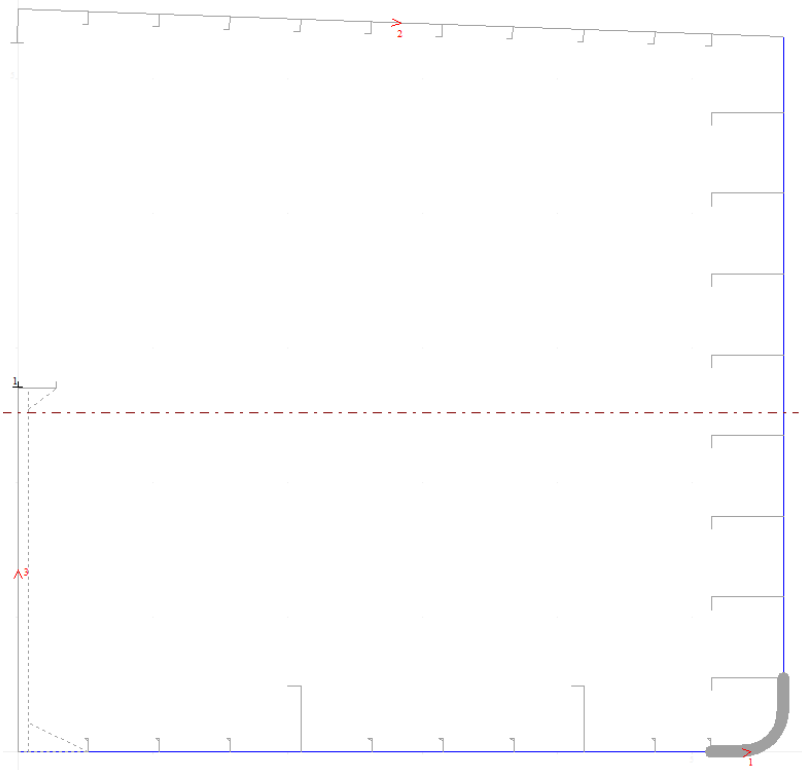
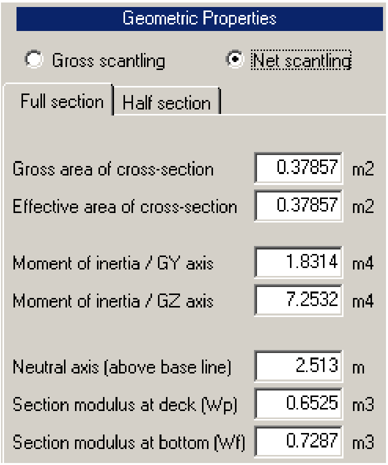


Figure 8.2.1. Midship section in *Mars Inland* of the vessel no. 1



○ Gross scantling ● Net scantling

Gross area of cross-section 0.37857 m2

Effective area of cross-section 0.37857 m2

Moment of inertia / GY axis 1.8314 m4

Moment of inertia / GZ axis 7.2532 m4

Neutral axis (above base line) 2.513 m

Section modulus at deck (Wp) 0.6525 m3

Section modulus at bottom (Wf) 0.7287 m3

Figure 8.2.2. Geometric properties in *Mars Inland* of the vessel no. 1

The maximum bending moment for this vessel is obtained in *Argos*, where several loading conditions have been studied.

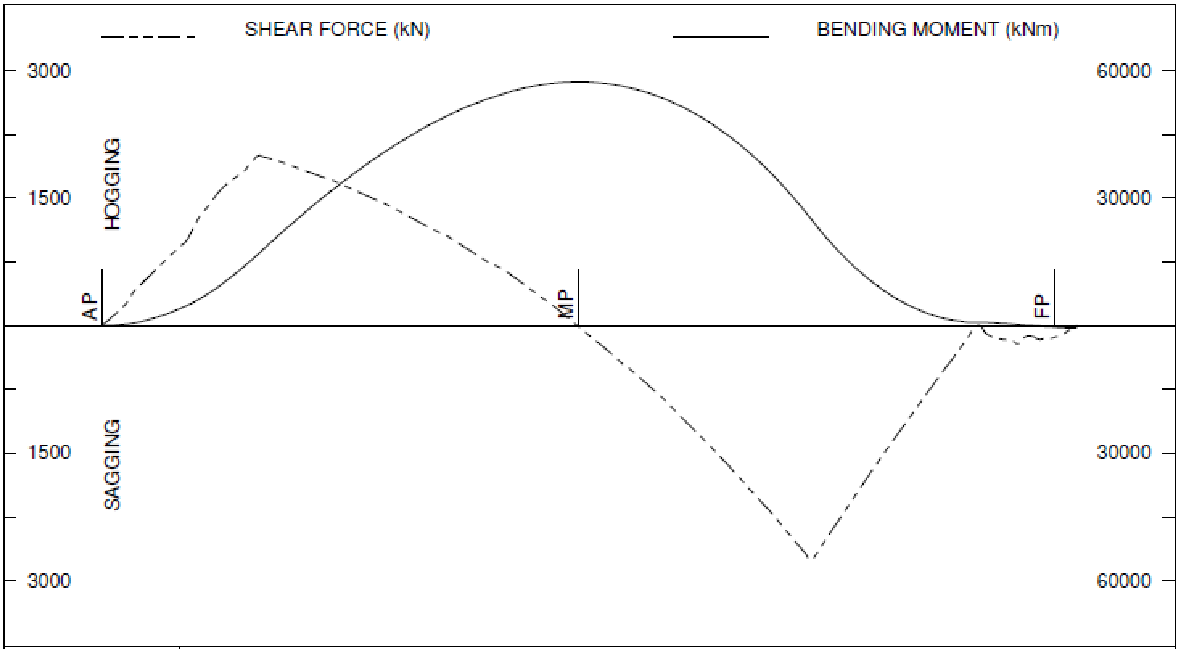


Figure 8.2.3. Maximum bending moment in *Argos* for the vessel no 1.

Vessel no. 2

Vessel no. 2 is a tanker type N closed, with a double hull, and its range of navigation is IN(0.6). The midship section and the maximum bending moment are shown in the images below.

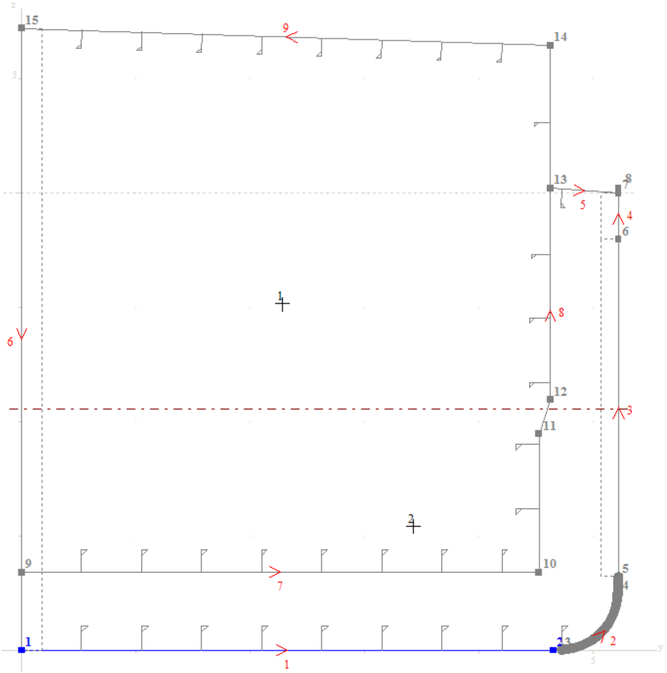


Figure 8.2.4. Midship section in *Mars Inland* of the vessel no. 2

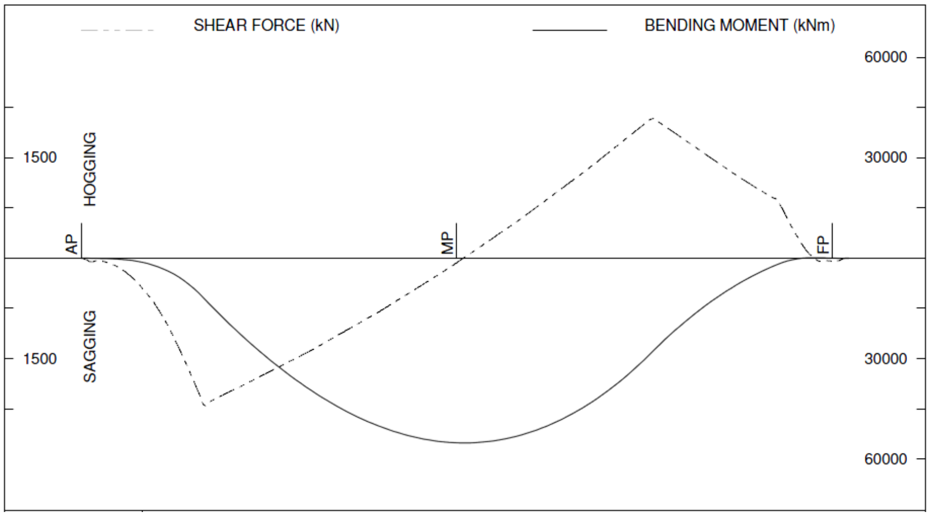


Figure 8.2.5. Maximum bending moment in *Argos* for the vessel no 2.

Vessel no. 3

Vessel no. 3 is a tanker type C, with a double hull, and its range of navigation is IN(1.8). The midship section of this vessel is shown in the next plot.

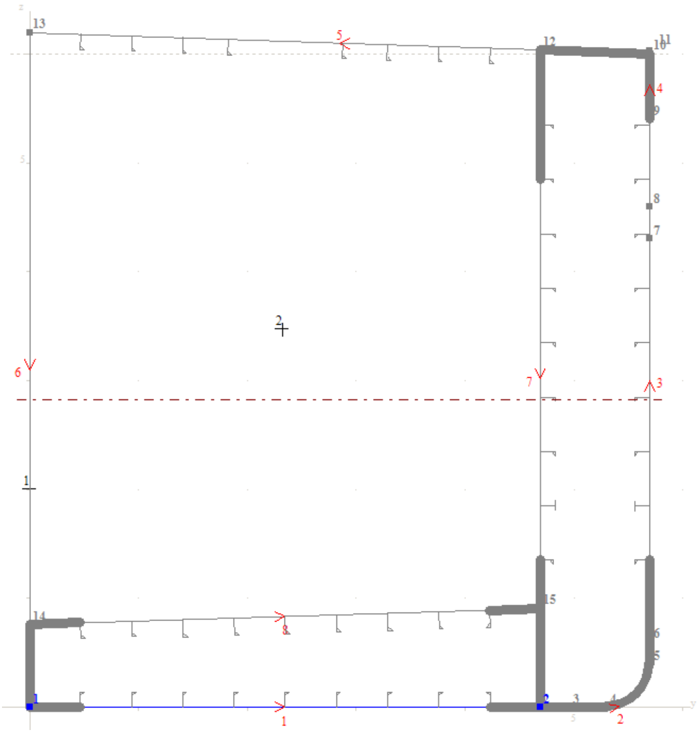


Figure 8.2.6. Midship section in *Mars Inland* of the vessel no. 3

The maximum bending moment is obtained by using *Argos* and its value is shown in the next Section.

Vessel no. 4

Vessel no. 4 is a container vessel, with a double hull, and its range of navigation is IN(1.7). The midship section of this vessel is shown in the Figure 8.2.7.

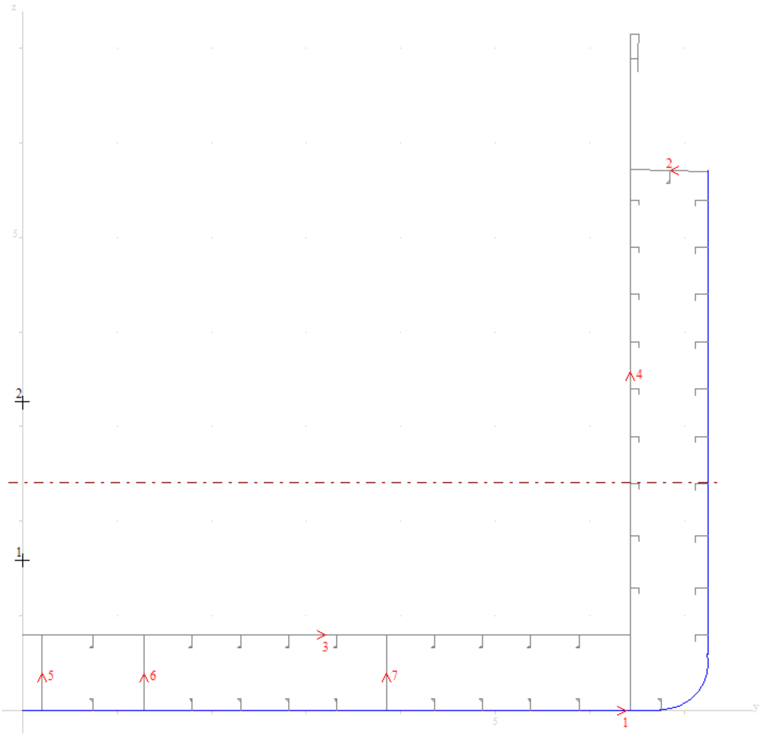


Figure 8.2.7. Midship section in *Mars Inland* of the vessel no. 4

8.2.2. Analytical determination of the deflections

The analytical determination of the deflections of the mentioned four vessels is obtained likewise the deflection in the Section 6.5.3. The difference is that the moment of inertia is not distributed and it is based on the net scantlings. Therefore, for a deeper analysis, the next deflections' values should be higher since it would be a more realistic approach.

In the next table, the analytical determination of the deflection for the vessel no. 1 is shown.

Distance [m]	ARGOS SW BM [kN m]	M Equation	∫∫ M	Deflection [m]
0.000	0.00	782.3	0.0	0.000
3.533	618.09	481.6	2898.4	-0.014
7.067	2724.59	2499.6	14219.3	-0.029
10.600	6221.09	6311.6	58610.0	-0.043
14.133	11569.04	11434.7	183159.8	-0.057
17.667	18185.65	17427.2	451367.7	-0.071
21.200	24995.24	23889.0	937630.7	-0.084
24.733	31349.30	30461.7	1722248.1	-0.097
28.267	37153.77	36828.2	2886946.4	-0.108
31.800	42358.92	42712.9	4510920.6	-0.118
35.333	46883.09	47882.1	6667395.5	-0.127
38.867	50687.95	52143.0	9420704.3	-0.134
42.400	53686.98	55345.0	12823886.1	-0.140
45.933	55876.95	57378.5	16916801.5	-0.143
49.467	57103.82	58175.6	21724766.7	-0.145
51.793	57340.15	58011.0	25286136.7	-0.145
53.000	57275.34	57710.0	27257706.0	-0.145
56.533	56316.32	55996.9	33509822.7	-0.143
60.067	54239.30	53092.8	40459788.1	-0.139
63.600	50900.84	49096.1	48071449.4	-0.133
67.133	46207.12	44146.5	56295055.1	-0.126
70.667	40083.78	38425.1	65068999.9	-0.117
74.200	32455.43	32154.7	74322087.3	-0.107
77.733	23294.86	25599.7	83976310.1	-0.096
81.267	14902.55	19065.8	93950150.6	-0.084
84.800	8528.11	12900.3	104162397.9	-0.071
88.333	4097.38	7492.2	114536484.4	-0.058
91.867	1529.22	3271.7	125005339.9	-0.045
95.400	800.54	710.8	135516765.3	-0.031
98.933	352.62	322.8	146039322.9	-0.018
102.467	-196.82	2662.8	156568747.0	-0.004
103.600	-307.19	4087.8	159951362.9	0.000

The other calculations are included in the Appendix D and summarized in the below tables, which contain other data like the range of navigation or the L/D ratios.

Vessel no.	Type	Hull Type	Rule Length [m]	Depth [m]
1	Tanker Type G	Single	103.60	5.32
2	Tanker Type N closed	Double	107.57	4.00
3	Tanker Type C	Double	118.36	6.00
4	Container	Double	131.55	5.70

Vessel no.	Type	L/D	IN [m]	L/D limit	I net [m^4]	SW BM (kN m)	Condition	y [m]
1	Tanker Type G	19.47	1.2	25	1.8314	57340.15	Hogging	0.145
2	Tanker Type N closed	26.89	0.6	35	2.2410	-55206.06	Sagging	0.128
3	Tanker Type C	19.73	1.8	25	3.4510	89432.94	Hogging	0.133
4	Container	23.08	1.7	25	4.0609	119876.05	Hogging	0.195

Note that, the length-to-depth ratio, according to the Rules, is not to exceed the following values:

- L/D = 25, for inland navigation vessels for a range of navigation of IN(1,2 ≤ x ≤ 2),
- L/D = 35, for inland navigation vessels for IN(0,6).

Vessels having a different ratio are considered by the Classification Society on a case by case basis.

9. CONCLUSION

9.1. Comparison: Analytical and Numerical results

First of all, a strength check has been carried out in this project, analytically and numerically. According to the Section 5.3.3, the strength is validated since the values obtained from both studies are very close. In this case and in both studies, the net scantlings have been considered.

Secondly, the analytical determination of the hull girder deflection is validated according to the numerically obtained deflection, as per the Section 7.5. Although it seems at first sight that both analyses are different, i.e., in the analytical study, gross scantlings have been considered whereas in the numerical study the net scantlings are applied, there is an explanation for this approach.

In the analytical study, all the values come from the gross scantlings for a specific loading condition and, in the numerical study, every condition has been set also according to the gross scantlings and to the same specific loading condition. The only difference is that the net scantlings have been applied for the purpose of getting a more conservative solution.

As the specific loading condition that generates the worst scenario, when performing direct calculations, is applied in both studies, the bending moments are the same since the inertia is independent of the bending moment.

Therefore the results are valid and an analytical study of the deflection of further inland navigation vessels can be carried out.

9.2. Future research

As mentioned in the Section 2.2.3, this thesis is part of a long-term study considering that it requires an extensive research. As stated, the definition of the criteria allowing safeguarding against excessive deflection is a phenomenon that has to be study along with the L/D ratio since they are related to each other.

The determination of the deflection of a wide range of conventional inland navigation vessels, with different structural configurations and with different ranges of navigation, has to be studied so as to check that the condition of 1 mm per meter of vessel’s length is complied with.

So in order to develop this future research, the analytical study of standard inland navigation vessels has to be carried out according to the Section 6 of this current thesis. First of all, there is a lack of database so there should be a previous and careful selection of conventional inland navigation vessels according to their types, ranges of navigation and structural configurations or inertia. Their L/D ratio should be also considered, selecting vessels which ratio is near or exceeding the limit imposed by the *Rules*.

Once the vessels are selected, their distributions of moment of inertia have to be obtained and so that several sections of each vessel must be modelled using *Mars Inland*. This software must be also used to check the strength of each midship section as per the Section 5.2.

The software *Argos* has to be used as well so as to study the worst loading condition, loading each vessel according to the standard loading conditions from the *Rules*. With this study, the maximum bending moment would be obtained and the deflection could be hence determined according to the procedure stated in the Section 6.5.

Note that 2 deflections must be obtained for each vessel. One according to the moment of inertia obtained by using *Mars Inland*, and the second, according to the inertia from the old *Rules*. The old *Rules* from Bureau Veritas are based only in gross scantlings and therefore, net scantlings are disregarded when obtaining the deflection in the future investigation.

Finally, there should be a comparison between the deflections obtained taking into account the old and the new rules as well as all the variables related to each vessel. With this study, a new L/D ratio can be determined for the purpose of updating the *Rules*.

This future research can be developed by either students or by the Classification Society itself.

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11. APPENDIX

In this Section, some important data needed to carry out this project are attached. The appendix is divided into the next parts:

A. **Bending moment distributions for different loading conditions, from *Argos***

B. **Lines Plan of the main tanker, from *Argos***
It includes two views of the vessel and the coordinates of several sections

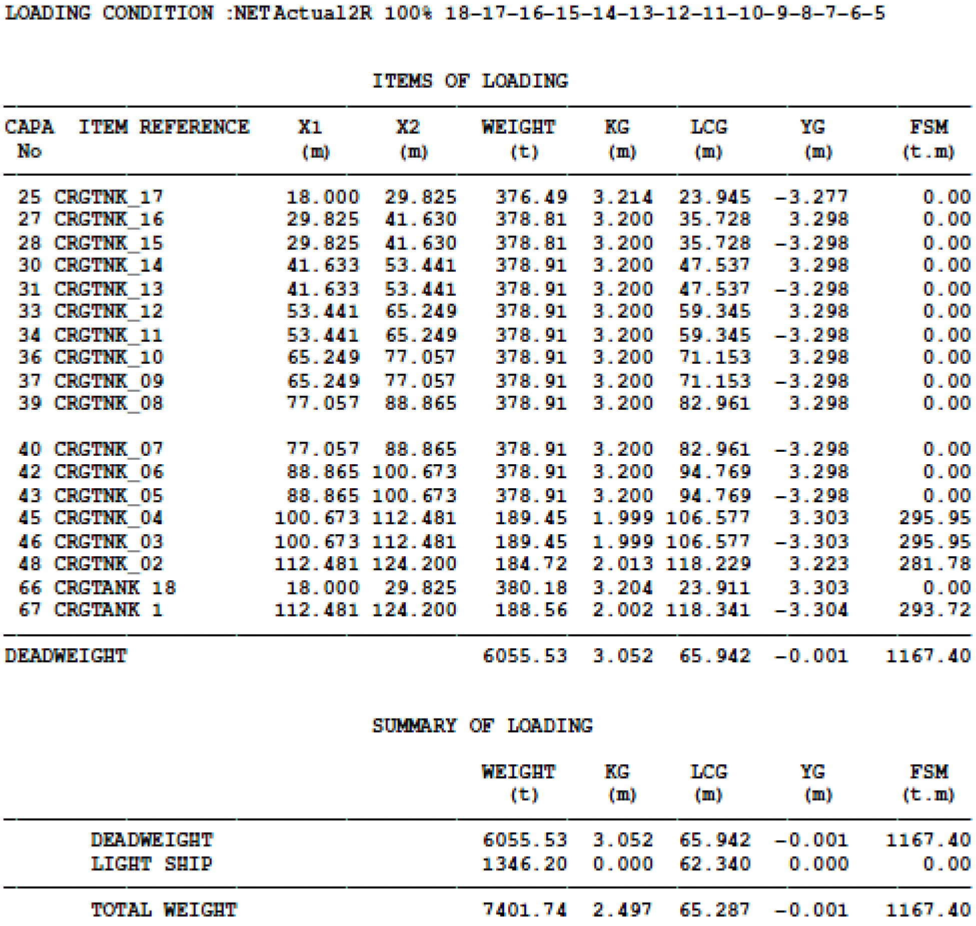
C. **Loading Conditions and Strength Distributions in *Argos***
In this part, it is explained how to create a loading condition and how to get the strength distribution in *Argos*.

D. **Analytical determination of the deflection of the vessels 2, 3 and 4 (from Section 8)**

E. **General Arrangement and Midship Section Plans of the main tanker**
It includes the main 2 drawings used to model the tanker

APPENDIX A

BENDING MOMENTS FOR DIFFERENT LOADING CONDITIONS



```
LOADING CONDITION :NETActual2R 100% 18-17-16-15-14-13-12-11-10-9-8-7-6-5

                                    ITEMS OF LOADING
-------------------------------------------------------------------------------
CAPA  ITEM REFERENCE        X1      X2     WEIGHT    KG     LCG      YG      FSM
 No                         (m)     (m)     (t)      (m)    (m)      (m)    (t.m)
-------------------------------------------------------------------------------
 25 CRGTNK_17            18.000  29.825   376.49  3.214  23.945  -3.277    0.00
 27 CRGTNK_16            29.825  41.630   378.81  3.200  35.728   3.298    0.00
 28 CRGTNK_15            29.825  41.630   378.81  3.200  35.728  -3.298    0.00
 30 CRGTNK_14            41.633  53.441   378.91  3.200  47.537   3.298    0.00
 31 CRGTNK_13            41.633  53.441   378.91  3.200  47.537  -3.298    0.00
 33 CRGTNK_12            53.441  65.249   378.91  3.200  59.345   3.298    0.00
 34 CRGTNK_11            53.441  65.249   378.91  3.200  59.345  -3.298    0.00
 36 CRGTNK_10            65.249  77.057   378.91  3.200  71.153   3.298    0.00
 37 CRGTNK_09            65.249  77.057   378.91  3.200  71.153  -3.298    0.00
 39 CRGTNK_08            77.057  88.865   378.91  3.200  82.961   3.298    0.00

 40 CRGTNK_07            77.057  88.865   378.91  3.200  82.961  -3.298    0.00
 42 CRGTNK_06            88.865 100.673   378.91  3.200  94.769   3.298    0.00
 43 CRGTNK_05            88.865 100.673   378.91  3.200  94.769  -3.298    0.00
 45 CRGTNK_04           100.673 112.481   189.45  1.999 106.577   3.303  295.95
 46 CRGTNK_03           100.673 112.481   189.45  1.999 106.577  -3.303  295.95
 48 CRGTNK_02           112.481 124.200   184.72  2.013 118.229   3.223  281.78
 66 CRGTANK 18           18.000  29.825   380.18  3.204  23.911   3.303    0.00
 67 CRGTANK 1           112.481 124.200   188.56  2.002 118.341  -3.304  293.72
-------------------------------------------------------------------------------
DEADWEIGHT                               6055.53  3.052  65.942  -0.001 1167.40

                                    SUMMARY OF LOADING

                                          WEIGHT    KG     LCG      YG      FSM
                                           (t)      (m)    (m)      (m)    (t.m)
-------------------------------------------------------------------------------
       DEADWEIGHT                        6055.53  3.052  65.942  -0.001 1167.40
       LIGHT SHIP                        1346.20  0.000  62.340   0.000    0.00
-------------------------------------------------------------------------------
       TOTAL WEIGHT                      7401.74  2.497  65.287  -0.001 1167.40
```

```
NET Actual2R 100% 18-17-16-15-14-13-12-11-10-9-8-7-6-5

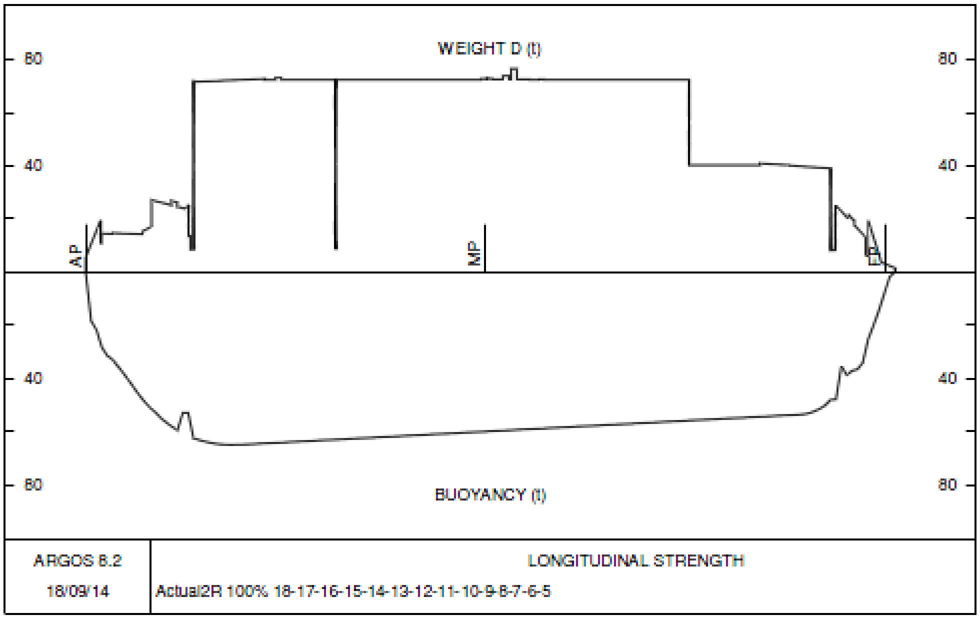
____________________________________________________________________________________
                                  WEIGHT     KG       LCG       YG       FSM    CORR.KG
                                   (t)       (m)      (m)       (m)     (t.m)     (m)
____________________________________________________________________________________
TOTAL WEIGHT                     7401.74   2.497    65.287   -0.001   1167.40   2.655

                              DRAUGHTS AND TRIM AT EQUILIBRIUM
____________________________________________________________________________________
                                                  Aft   Amidship   Fore     Trim
Draught on baseline at perpendicular .......    4.552    4.010    3.468    1.084
Draught under keel at perpendicular ........    4.562    4.020    3.478    1.084
____________________________________________________________________________________

____________________________________________________________________________________
                  DIST./A.P.    SHEAR FORCE          DIST./A.P.  BENDING MOMENT
                     (m)           (kN)                  (m)          (kN.m)
____________________________________________________________________________________
MAX       :       100.859        4731.18              75.852        1004.57
MIN       :        17.682       -4543.55              67.137     -153458.31
RESIDUE                           135.58                            1004.57



                  STILL WATER SHEAR FORCE AND BENDING MOMENT
____________________________________________________________________________________
DISTANCE /A.P.              SHEAR FORCE            BENDING MOMENT
     (m)                       (kN)                    (kN.m)
____________________________________________________________________________________
     0.000                     0.00                     0.00
     4.500                  -475.34                  -803.66
     9.000                 -1592.10                 -5267.84
    13.500                 -2937.89                -15606.20
    18.000                 -4511.60                -32155.17
    22.500                 -4173.88                -51641.95
    27.000                 -3861.39                -69705.55
    31.500                 -3518.72                -86300.48
    36.000                 -3154.34               -101301.13
    40.500                 -2772.58               -114628.94
    45.000                 -2368.42               -126184.54
    49.500                 -1935.35               -135853.06
    54.000                 -1478.31               -143523.55
    58.500                  -997.33               -149086.28
    63.000                  -492.38               -152433.11
    67.500                    41.86               -153450.17
    72.000                   653.84               -151948.06
    76.500                  1235.18               -147688.61
    81.000                  1836.05               -140767.27
    85.500                  2460.78               -131082.89
    90.000                  3109.48               -118528.38
    94.500                  3785.13               -102992.35
    99.000                  4484.77                -84367.23
   103.500                  4318.55                -63820.45
   108.000                  3649.69                -45912.59
   112.500                  3001.65                -30959.90
   117.000                  2394.69                -18811.30
   121.500                  1785.13                 -9411.32
   126.000                  1027.58                 -2881.32
   130.500                   315.76                   164.57
   135.000                   135.58                  1004.57
```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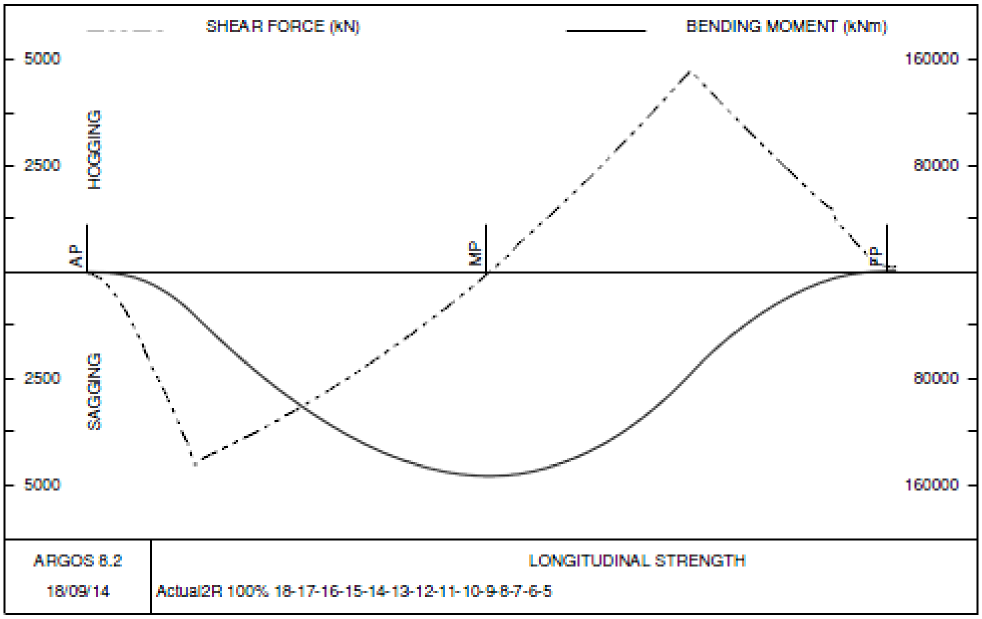
80
40
40
80
BUOYANCY (t)
80
40
40
80
AP
MP
FP
ARGOS 8.2
18/09/14
LONGITUDINAL STRENGTH
Actual2R 100% 18-17-16-15-14-13-12-11-10-9-8-7-6-5


SHEAR FORCE (kN)
BENDING MOMENT (kNm)
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2500
5000
160000
80000
80000
160000
HOGGING
SAGGING
AP
MP
FP
ARGOS 8.2
18/09/14
LONGITUDINAL STRENGTH
Actual2R 100% 18-17-16-15-14-13-12-11-10-9-8-7-6-5

```
LOADING CONDITION :   Actual 2R 1-2-3-4

                                  ITEMS OF LOADING
---------------------------------------------------------------------------------
CAPA  ITEM REFERENCE       X1       X2     WEIGHT    KG     LCG      YG       FSM
 No                        (m)      (m)     (t)      (m)    (m)      (m)     (t.m)
---------------------------------------------------------------------------------
 45 CRGTNK_04           100.673 112.481  189.45  1.999 106.577   3.303    295.95
 46 CRGTNK_03           100.673 112.481  189.45  1.999 106.577  -3.303    295.95
 48 CRGTNK_02           112.481 124.200  184.72  2.013 118.229   3.223    281.78
 67 CRGTANK 1           112.481 124.200  188.56  2.002 118.341  -3.304    293.72
---------------------------------------------------------------------------------
DEADWEIGHT                               752.18  2.003 112.387  -0.037   1167.40

                                  SUMMARY OF LOADING

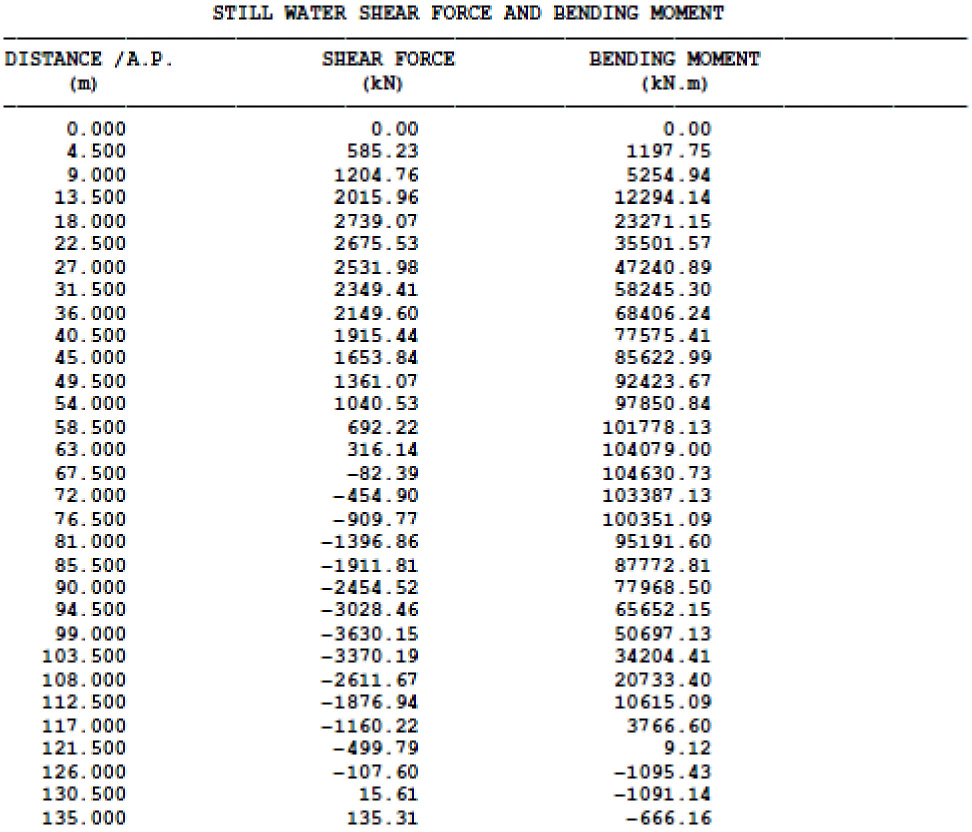
                                          WEIGHT    KG     LCG      YG       FSM
                                           (t)      (m)    (m)      (m)     (t.m)
---------------------------------------------------------------------------------
       DEADWEIGHT                          752.18  2.003 112.387  -0.037   1167.40
       LIGHT SHIP                         1346.20  0.000  62.340   0.000      0.00
---------------------------------------------------------------------------------
       TOTAL WEIGHT                       2098.39  0.718  80.280  -0.013   1167.40
```

```
    Actual 2R 1-2-3-4

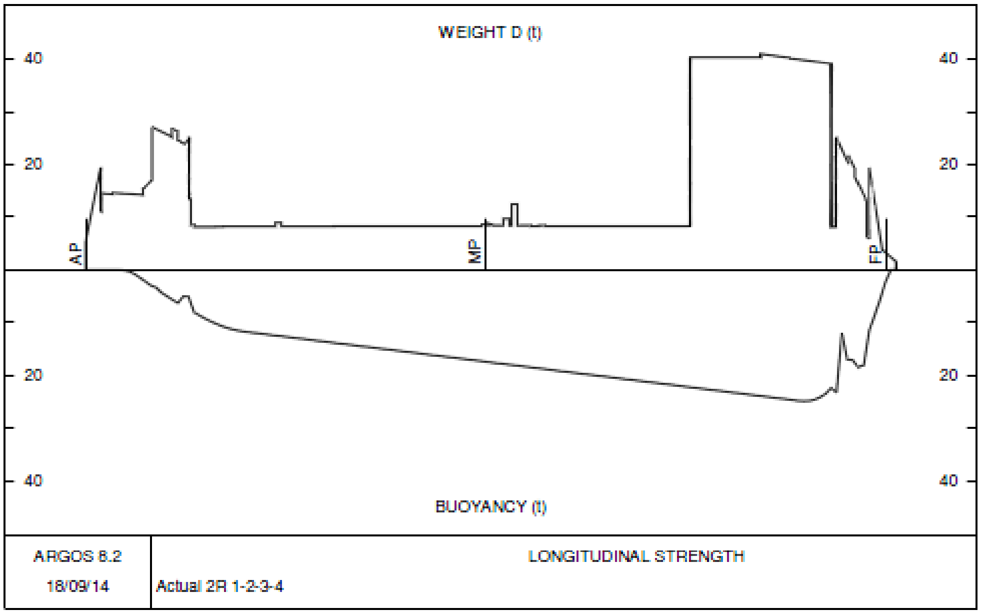
---------------------------------------------------------------------------------
                          WEIGHT      KG       LCG       YG       FSM    CORR.KG
                            (t)      (m)       (m)      (m)      (t.m)     (m)
---------------------------------------------------------------------------------
TOTAL WEIGHT              2098.39   0.718    80.280   -0.013   1167.40    1.274

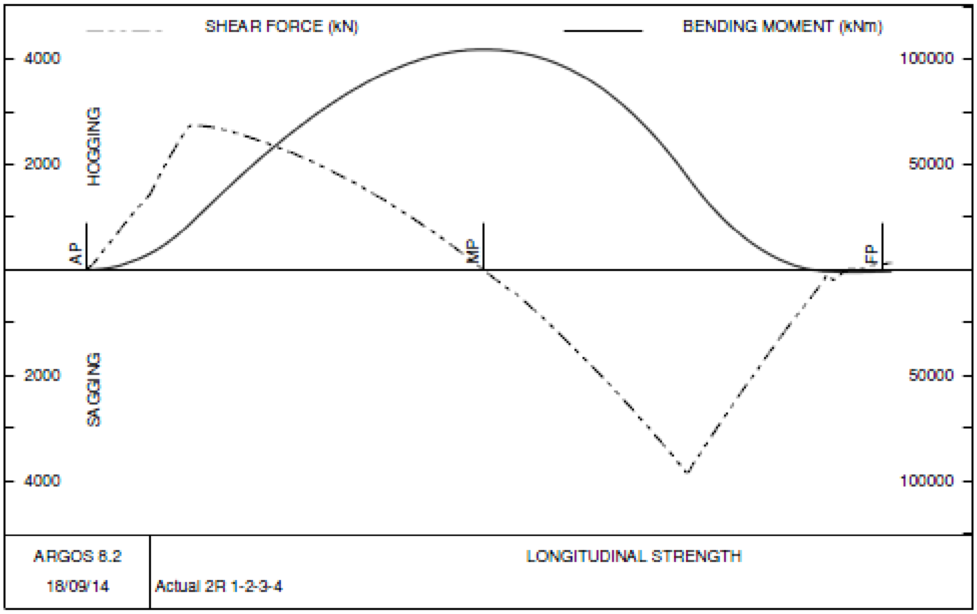
                          DRAUGHTS AND TRIM AT EQUILIBRIUM
---------------------------------------------------------------------------------
                                              Aft    Amidship    Fore      Trim
Draught on baseline at perpendicular .......  0.540    1.168     1.796    -1.256
Draught under keel at perpendicular ........  0.550    1.178     1.806    -1.256
---------------------------------------------------------------------------------

---------------------------------------------------------------------------------
                   DIST./A.P.   SHEAR FORCE       DIST./A.P.  BENDING MOMENT
                      (m)          (kN)               (m)          (kN.m)
---------------------------------------------------------------------------------
MAX       :         18.384       2742.73            66.629       104664.20
MIN       :        100.671      -3840.27           127.743        -1162.83
RESIDUE                           135.31                           -666.16
```



```
                    STILL WATER SHEAR FORCE AND BENDING MOMENT
------------------------------------------------------------------------------
DISTANCE /A.P.            SHEAR FORCE            BENDING MOMENT
     (m)                      (kN)                   (kN.m)
------------------------------------------------------------------------------
     0.000                    0.00                    0.00
     4.500                  585.23                 1197.75
     9.000                 1204.76                 5254.94
    13.500                 2015.96                12294.14
    18.000                 2739.07                23271.15
    22.500                 2675.53                35501.57
    27.000                 2531.98                47240.89
    31.500                 2349.41                58245.30
    36.000                 2149.60                68406.24
    40.500                 1915.44                77575.41
    45.000                 1653.84                85622.99
    49.500                 1361.07                92423.67
    54.000                 1040.53                97850.84
    58.500                  692.22               101778.13
    63.000                  316.14               104079.00
    67.500                  -82.39               104630.73
    72.000                 -454.90               103387.13
    76.500                 -909.77               100351.09
    81.000                -1396.86                95191.60
    85.500                -1911.81                87772.81
    90.000                -2454.52                77968.50
    94.500                -3028.46                65652.15
    99.000                -3630.15                50697.13
   103.500                -3370.19                34204.41
   108.000                -2611.67                20733.40
   112.500                -1876.94                10615.09
   117.000                -1160.22                 3766.60
   121.500                 -499.79                    9.12
   126.000                 -107.60                -1095.43
   130.500                   15.61                -1091.14
   135.000                  135.31                 -666.16
```


WEIGHT D (t)
40
20
AP
MP
FP
20
40
BUOYANCY (t)
40
20
20
40
ARGOS 8.2
18/09/14
LONGITUDINAL STRENGTH
Actual 2R 1-2-3-4


SHEAR FORCE (kN)
BENDING MOMENT (kNm)
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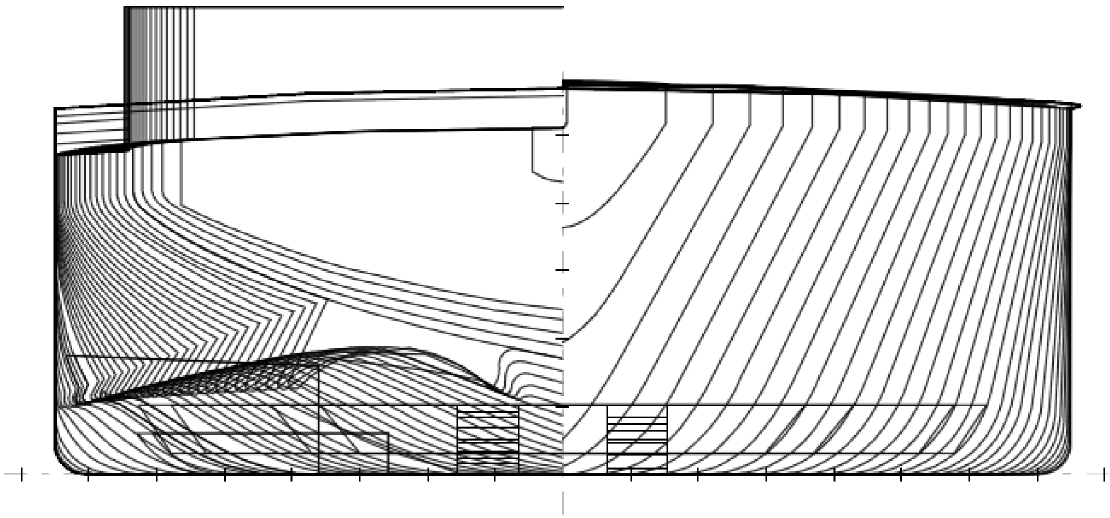
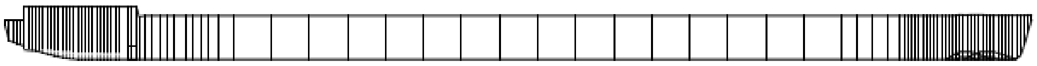
2000
HOGGING
AP
MP
FP
SAGGING
2000
4000
100000
50000
50000
100000
ARGOS 8.2
18/09/14
LONGITUDINAL STRENGTH
Actual 2R 1-2-3-4

APPENDIX B

LINES PLAN OF THE MAIN TANKER



ARGOS 8.2 18/09/14	LINES PLAN Booklet	Scale : 1/100



ARGOS 8.2 18/09/14	LINES PLAN Booklet

```
SECTION No   1

SECTION NAME : sect0          CURVE CODE     = 1      X =    0.000 m
_____________________________________________________________
No      Y           Z
       (m)         (m)
_____________________________________________________________

 1     0.000       4.315
 2     0.129       4.331
 3     0.286       4.375
 4     0.394       4.433
 5     0.446       4.464    Knuckle
 6     0.446       5.120    Knuckle
 7     0.000       5.120
```

```
SECTION No   2

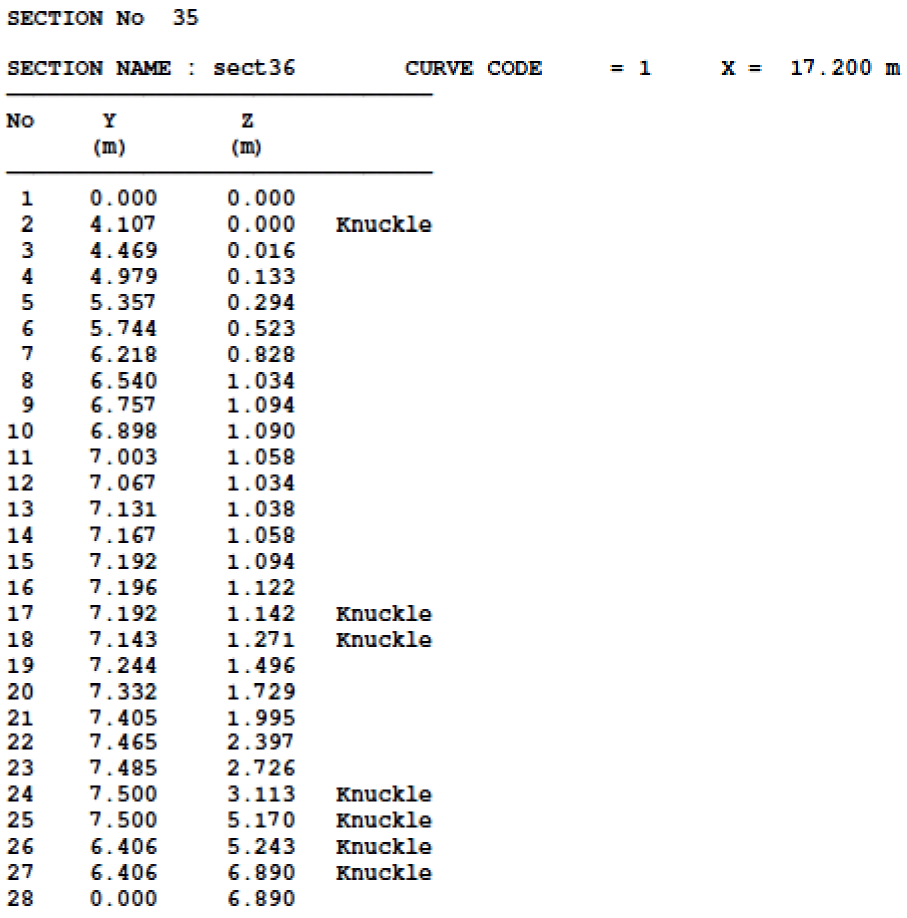
SECTION NAME : sect1          CURVE CODE     = 1      X =    0.500 m
_____________________________________________________________
No      Y           Z
       (m)         (m)
_____________________________________________________________

 1     0.000       2.429
 2     0.446       2.485
 3     1.002       2.566
 4     1.536       2.666
 5     2.003       2.763
 6     2.626       2.908
 7     3.133       3.024
 8     3.672       3.185
 9     4.131       3.342
10     4.754       3.575
11     5.225       3.772
12     5.631       3.969    Knuckle
13     5.631       4.279    Knuckle
14     5.631       4.930    Knuckle
15     2.815       5.057    Knuckle
16     0.000       5.099
```

```
SECTION No   3

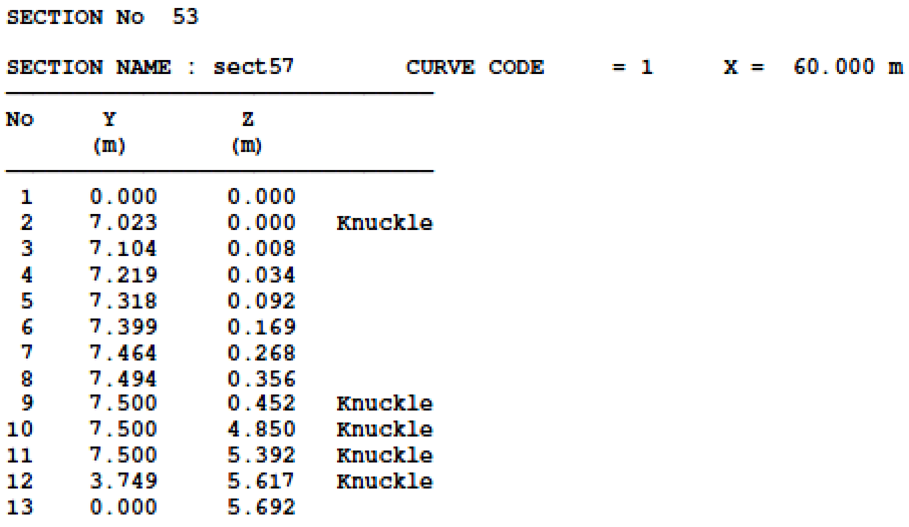
SECTION NAME : sect2          CURVE CODE     = 1      X =    1.000 m
_____________________________________________________________
No      Y           Z
       (m)         (m)
_____________________________________________________________

 1    -0.004       2.280
 2     0.523       2.353
 3     1.006       2.421
 4     1.577       2.538
 5     2.011       2.634
 6     2.546       2.759
 7     3.005       2.867
 8     3.539       3.020
 9     4.002       3.185
10     4.662       3.434
11     5.213       3.680
12     5.748       3.961    Knuckle
13     5.828       4.025
14     5.888       4.090
15     5.913       4.171
16     5.917       4.223    Knuckle
17     5.917       4.920    Knuckle
18     2.958       5.060    Knuckle
19     0.000       5.107
```



```
SECTION No   35

SECTION NAME : sect36        CURVE CODE      = 1      X =   17.200 m
_______________________________________________________
No       Y            Z
        (m)          (m)
_______________________________________________________
 1     0.000        0.000
 2     4.107        0.000    Knuckle
 3     4.469        0.016
 4     4.979        0.133
 5     5.357        0.294
 6     5.744        0.523
 7     6.218        0.828
 8     6.540        1.034
 9     6.757        1.094
10     6.898        1.090
11     7.003        1.058
12     7.067        1.034
13     7.131        1.038
14     7.167        1.058
15     7.192        1.094
16     7.196        1.122
17     7.192        1.142    Knuckle
18     7.143        1.271    Knuckle
19     7.244        1.496
20     7.332        1.729
21     7.405        1.995
22     7.465        2.397
23     7.485        2.726
24     7.500        3.113    Knuckle
25     7.500        5.170    Knuckle
26     6.406        5.243    Knuckle
27     6.406        6.890    Knuckle
28     0.000        6.890
```



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SECTION No   53

SECTION NAME : sect57        CURVE CODE      = 1      X =   60.000 m
_______________________________________________________
No       Y            Z
        (m)          (m)
_______________________________________________________
 1     0.000        0.000
 2     7.023        0.000    Knuckle
 3     7.104        0.008
 4     7.219        0.034
 5     7.318        0.092
 6     7.399        0.169
 7     7.464        0.268
 8     7.494        0.356
 9     7.500        0.452    Knuckle
10     7.500        4.850    Knuckle
11     7.500        5.392    Knuckle
12     3.749        5.617    Knuckle
13     0.000        5.692
```

```
SECTION No   91

SECTION NAME : sect97         CURVE CODE      = 1      X = 129.500 m
______________________________________
No      Y           Z
       (m)         (m)
______________________________________
 1    0.000       0.000
 2    2.470       0.000    Knuckle
 3    2.746       0.031
 4    3.052       0.123
 5    3.424       0.356
 6    3.680       0.617
 7    3.837       0.839
 8    4.002       1.104
 9    4.113       1.334    Knuckle
10    5.691       5.025    Knuckle
11    5.691       5.569    Knuckle
12    2.845       5.699    Knuckle
13    0.000       5.742
```

```
SECTION No   92

SECTION NAME : sect98         CURVE CODE      = 1      X = 130.000 m
______________________________________
No      Y           Z
       (m)         (m)
______________________________________
 1    0.000       0.000
 2    2.060       0.000    Knuckle
 3    2.409       0.031
 4    2.769       0.157
 5    3.052       0.349
 6    3.324       0.632
 7    3.573       1.000
 8    3.757       1.353    Knuckle
 9    5.415       5.037    Knuckle
10    5.415       5.589    Knuckle
11    2.707       5.706    Knuckle
12    0.000       5.745
```

```
SECTION No   98

SECTION NAME : sect104        CURVE CODE      = 1      X = 133.000 m
______________________________________
No      Y           Z
       (m)         (m)
______________________________________
 1    0.000       0.123
 2    0.054       0.138
 3    0.165       0.195
 4    0.322       0.299
 5    0.490       0.425
 6    0.693       0.621
 7    0.869       0.828
 8    1.042       1.058
 9    1.145       1.223
10    1.241       1.391    Knuckle
11    3.251       5.136    Knuckle
12    3.251       5.688    Knuckle
13    1.625       5.730
14    0.000       5.745
```

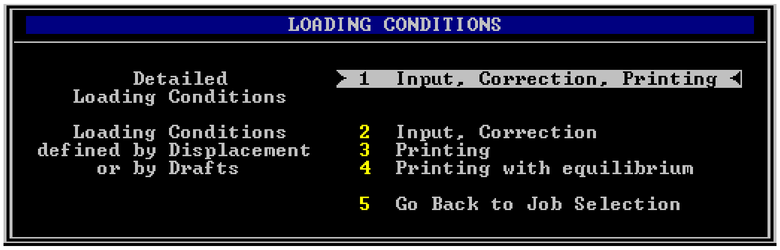
APPENDIX C

LOADING CONDITIONS AND STRENGTH DISTRIBUTIONS IN ARGOS

How to create a Loading Condition in Argos:

Step 1: Selecting *Loading Condition* in *Argos*:

Step 2: Selecting *Input*, so as to create a new Loading Condition

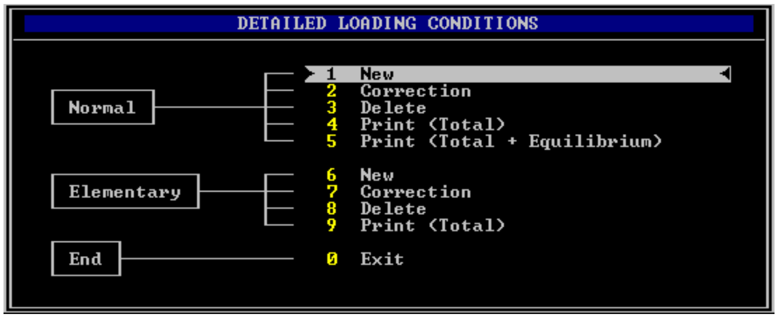


```
                          LOADING CONDITIONS

        Detailed              ► 1  Input, Correction, Printing ◄
   Loading Conditions

   Loading Conditions            2  Input, Correction
 defined by Displacement         3  Printing
     or by Drafts                4  Printing with equilibrium

                                 5  Go Back to Job Selection
```



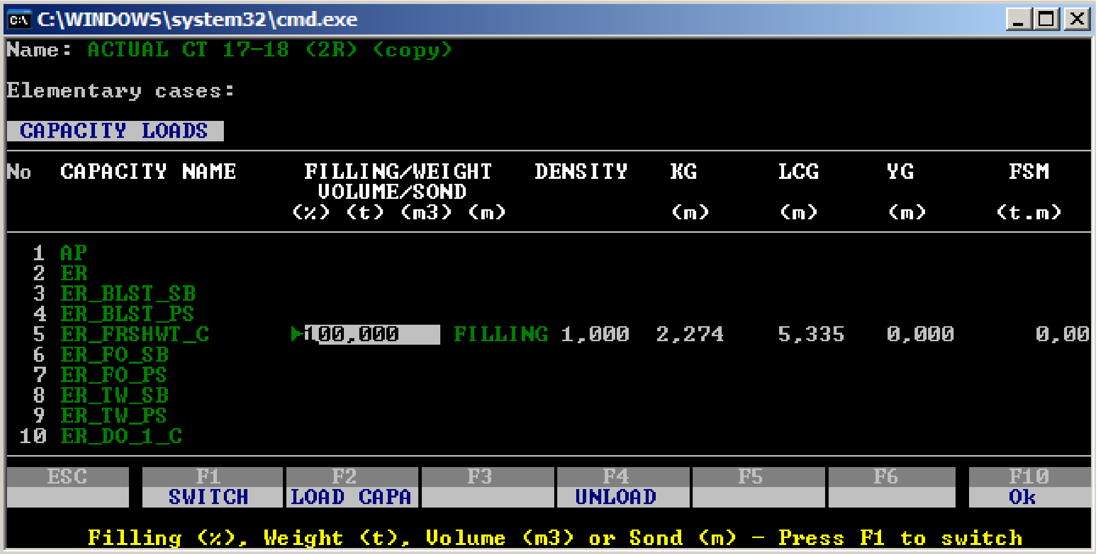
```
                       DETAILED LOADING CONDITIONS

                          ┌─  ► 1  New                                  ◄
                          ├─    2  Correction
 │ Normal │───────────────┼─    3  Delete
                          ├─    4  Print (Total)
                          └─    5  Print (Total + Equilibrium)

                          ┌─    6  New
 │ Elementary │───────────┼─    7  Correction
                          ├─    8  Delete
                          └─    9  Print (Total)

 │ End │──────────────────────  0  Exit
```

Step 3: A cargo hold or a tank is filled in with the percentage of the volume that it is required as well as the fluid density and the centre of gravity of the space. It is assumed that each space has been defined previously. In the next plot, a fresh water tank is filled completely (100%).



```
Name: ACTUAL CT 17-18 (2R) (copy)

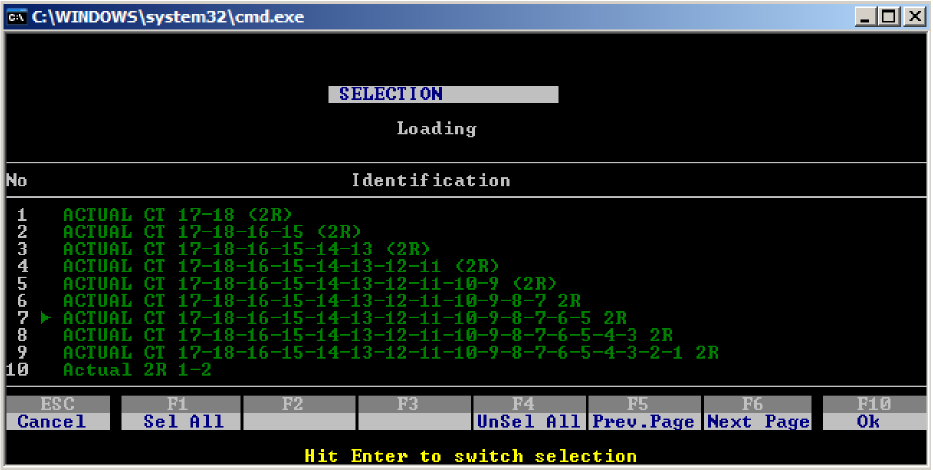
Elementary cases:
 CAPACITY LOADS

No  CAPACITY NAME        FILLING/WEIGHT   DENSITY   KG       LCG      YG        FSM
                          VOLUME/SOND
                         (%) (t) (m3) (m)            (m)      (m)      (m)      (t.m)

  1 AP
  2 ER
  3 ER_BLST_SB
  4 ER_BLST_PS
  5 ER_FRSHWT_C          ▶100,000     FILLING 1,000  2,274    5,335    0,000        0,00
  6 ER_FO_SB
  7 ER_FO_PS
  8 ER_TW_SB
  9 ER_TW_PS
 10 ER_DO_1_C

      Filling (%), Weight (t), Volume (m3) or Sond (m) - Press F1 to switch
```

Step 4: Once the spaces for each loading condition are filled in, the loading condition is created. Then, each loading condition can be selected so as to get the strength distribution.



```
                          SELECTION
                            Loading

No                        Identification

 1    ACTUAL CT 17-18 (2R)
 2    ACTUAL CT 17-18-16-15 (2R)
 3    ACTUAL CT 17-18-16-15-14-13 (2R)
 4    ACTUAL CT 17-18-16-15-14-13-12-11 (2R)
 5    ACTUAL CT 17-18-16-15-14-13-12-11-10-9 (2R)
 6    ACTUAL CT 17-18-16-15-14-13-12-11-10-9-8-7 2R
 7 ▶  ACTUAL CT 17-18-16-15-14-13-12-11-10-9-8-7-6-5 2R
 8    ACTUAL CT 17-18-16-15-14-13-12-11-10-9-8-7-6-5-4-3 2R
 9    ACTUAL CT 17-18-16-15-14-13-12-11-10-9-8-7-6-5-4-3-2-1 2R
10    Actual 2R 1-2

                   Hit Enter to switch selection
```

Finally, a document with all the data is generated (See Appendix A).

APPENDIX D

ANALYTICAL DETERMINATION OF THE DEFLECTION OF THE VESSELS 2, 3 AND 4

Vessel number 2:

Distance [m]	ARGOS SW BM [kN m]	M Equation	∫∫ M	Deflection [m]
0	0.00	190.1	0.00	0.000
3.664	-146.07	845.2	4129.53	0.012
7.328	-721.99	-716.3	17127.57	0.024
10.992	-2564.15	-4021.5	18560.47	0.036
14.656	-6593.40	-8633.6	-35455.43	0.048
18.320	-13573.39	-14151.6	-206388.36	0.060
21.984	-21112.79	-20210.2	-567907.57	0.072
25.648	-27968.80	-26480.4	-1200981.80	0.082
29.312	-34127.50	-32668.9	-2189459.73	0.092
32.976	-39559.04	-38518.1	-3616132.33	0.101
36.640	-44233.31	-43806.7	-5559277.28	0.109
40.304	-48120.83	-48348.9	-8089685.31	0.116
43.968	-51191.52	-51995.2	-11268168.50	0.121
47.632	-53415.66	-54631.7	-15143550.58	0.125
51.296	-54763.53	-56180.6	-19751139.19	0.127
54.876	-55205.32	-56602.9	-24980282.19	0.128
54.960	-55206.06	-56599.7	-25111680.13	0.128
58.624	-54710.61	-55883.1	-31230793.55	0.127
62.288	-53250.30	-54060.5	-38098892.16	0.124
65.952	-50794.20	-51197.6	-45691581.33	0.119
69.616	-47312.72	-47396.1	-53970541.27	0.114
73.280	-42775.92	-42793.5	-62884891.09	0.106
76.944	-37153.72	-37563.1	-72373034.90	0.098
80.608	-30417.01	-31914.4	-82364989.81	0.089
84.272	-23020.19	-26092.4	-92785196.00	0.078
87.936	-16497.85	-20378.4	-103555808.66	0.067
91.600	-10939.01	-15089.2	-114600471.97	0.055
95.264	-6313.87	-10578.0	-125848575.04	0.043
98.928	-2576.54	-7233.4	-137239989.79	0.030
102.592	-209.92	-5480.3	-148730290.84	0.018
106.256	52.56	-5779.1	-160296457.36	0.005
107.570	11.18	-6480.2	-164462742.47	0.000

a = 0.00331182
I net [m^4] = 2.2410 constant

Vessel number 3:

Distance [m]	ARGOS SW BM [kN m]	M Equation	∫∫ M	Deflection [m]
0	0.00	-1707.00	0.00	0.000
4.037	392.19	959.26	-7342.03	-0.013
8.073	2774.60	4689.44	2398.58	-0.026
12.110	7906.12	9546.52	90088.78	-0.040
16.147	15084.08	15500.63	334831.85	-0.053
20.183	23201.16	22440.68	833496.67	-0.065
24.220	31661.69	30185.87	1698922.94	-0.077
28.257	40201.11	38497.32	3056991.11	-0.088
32.293	48626.11	47089.63	5042745.54	-0.099
36.330	56749.39	55642.44	7795759.57	-0.108
40.367	64383.51	63812.01	11454931.13	-0.116
44.403	71341.37	71242.81	16152897.38	-0.123
48.440	77435.82	77579.10	22010257.22	-0.128
52.477	82479.17	82476.46	29129790.08	-0.131
56.513	86284.08	85613.43	37590859.74	-0.133
60.550	88663.23	86703.04	47444191.74	-0.132
64.587	89429.91	85504.39	58707212.99	-0.129
64.821	89432.94	85360.39	59403955.39	-0.129
68.623	88396.41	81834.25	71360142.31	-0.125
72.660	85375.16	75578.62	85343020.33	-0.118
76.697	80178.73	66704.30	100553867.52	-0.110
80.733	72620.16	55270.46	116848158.97	-0.101
84.770	62512.70	41440.25	134039804.42	-0.090
88.807	49668.00	25492.33	151903822.23	-0.078
92.843	33965.10	7832.48	170180896.00	-0.065
96.880	19700.53	-10994.83	188584002.28	-0.053
100.917	9411.51	-30294.89	206807298.12	-0.040
104.953	2923.30	-49211.15	224537457.03	-0.029
108.990	211.46	-66713.64	241467641.99	-0.018
113.027	62.21	-81587.41	257314304.12	-0.009
117.063	-1181.62	-92420.95	271836995.60	-0.002
118.360	-1286.40	-94783.51	276189796.83	0.000

a =	-0.00328239	
I net [m^4] =	3.4510	constant

Vessel number 4:

Distance [m]	**ARGOS SW BM [kN m]**	M Equation	∫∫ M	**Deflection [m]**
0	0.00	-1000.1	0	0.000
4.48	609.28	1143.6	-4871.7421	-0.019
8.95	4048.62	5628.7	17072.7668	-0.039
13.43	11133.66	12263.4	155329.71	-0.058
17.90	20952.25	20774.7	542306.081	-0.077
22.38	32118.09	30821.7	1347876.45	-0.095
26.85	43751.19	42008.3	2772576.58	-0.113
31.33	55475.70	53896.2	5039692.68	-0.130
35.80	67011.81	66017.6	8386504.93	-0.145
40.28	78085.55	77888.7	13054944.2	-0.159
44.75	88422.89	89021.8	19281920.8	-0.171
49.23	97749.85	98938.9	27289583.1	-0.181
53.70	105792.28	107184.5	37275766.8	-0.188
58.18	112276.31	113338.0	49404891.1	-0.193
62.65	116927.88	117027.4	63799562.2	-0.195
67.13	119472.92	117941.7	80533142.8	-0.195
69.95	119876.05	116977.2	92329004.8	-0.193
71.60	119637.48	115843.9	99623545.3	-0.191
76.08	117147.37	110584.0	121028509	-0.185
80.55	111728.80	102112.1	144642616	-0.176
85.03	103107.81	90490.9	170296317	-0.165
89.50	91010.01	75908.8	197757201	-0.152
93.98	75161.73	58693.1	226733798	-0.136
98.45	55288.59	39322.5	256882151	-0.120
102.93	34607.05	18440.4	287815426	-0.102
107.40	18773.68	-3132.6	319116813	-0.084
111.88	7613.64	-24385.4	350355985	-0.066
116.35	854.40	-44103.7	381109366	-0.049
120.83	-1714.48	-60857.0	410984471	-0.033
125.30	-1037.59	-72985.7	439648573	-0.018
129.78	-1972.90	-78587.9	466861962	-0.005
131.55	-2110.24	-78533.9	477224914	0.000

a = -0.00433653

I net [m^4] = 4.0609 constant

APPENDIX E

GENERAL ARRANGEMENT AND MIDSHIP SECTION PLANS OF THE MAIN TANKER