FPSO HULL STRUCTURES WITH SANDWICH PLATE SYSTEM IN CARGO TANKS

João Pedro Cunha Machado da Silva

Thesis to obtain the Master of Science Degree in Naval Architecture and Ocean Engineering

Examination Committee:

President: Prof. Ângelo Palos Teixeira
Supervisors: Prof. Paulo Maurício Videiro and Prof. Baiqiao Chen
Members: Prof. Yordan Garbatov

December 2021
FPSO Hull Structures with Sandwich Plates System in Cargo Tanks
João Pedro Cunha Machado da Silva
DECLARATION:

I declare that this document is an original work of my own authorship and that it fulfils all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.

Signature

João Pedro Cunha Machado da Silva
ACKNOWLEDGEMENTS:

I hereby express my gratitude first to Prof. Paulo Videiro and Prof. Baiqiao Chen for helping me through the development of this master thesis with all the guidance, patience and support. It wouldn’t be possible to do it without them.

I would like to thank Oleg Sukovoy, Senior Design Engineer from SPS Technology, for also providing all the material needed regarding the sandwich plates and also the guidance and support as well.

I would like to thank PNV from Escola Politécnica de Universidade de São Paulo and CENTEC for the development of my professional career, which will be undoubtedly helpful in my future as engineer.

I would like to thank both my family from Brazil and Portugal which provided me all the emotional support to move to another country and pursue my dreams of studying abroad. Also, all my friends from all countries that made all this experience something unique and valuable that will mark me forever.
ABSTRACT:

Nowadays, the floating production storage and offload system (FPSO) is one of the most common platform types for offshore oil production. The traditional FPSO hulls are built with steel stiffened panels, similar to tankers structures and the classification societies demand its inspection. However, these surveys are a time consuming and risky activity. The traditional arrangement of the stiffened panels creates obstacles for automated cleaning and inspections by remote devices. In order to overcome this problem, a proposed approach is the use of the sandwich plates system (SPS) in cargo tank structures.

This paper summarizes the results of an initial study for the design and construction of FPSO’s hulls with SPS. The main goal is to have the walls and bottom of the cargo tanks free of stiffeners to allow remote cleaning and thickness inspection of bottom and longitudinal bulkhead plates using autonomous equipment. This research is carried out by first designing the hull with a conventional structural arrangement using steel according to the ABS rules as a benchmark. Following that, the equivalent hull structure with sandwich plates is designed in accordance with the guidelines for SPS construction from DNV rules. Finally, this paper provides the results of a finite element analysis to compare the stresses and ultimate strength of both types of structures. Briefly, the main results were that the SPS design provided a reduction of 2.8% of the total weight and a better overall structural performance by an increase of 26% for the ultimate strength of the hull.

Keywords:

Floating Production Units, Sandwich Plate System, Ultimate Strength, Finite Element Analysis
RESUMO:

Atualmente o *floating production storage and offload system* (FPSO) é um dos tipos de plataforma mais comuns para a produção de petróleo offshore que são construídas com painéis reforçados de aço, semelhantes às estruturas de petroleiros e as sociedades classificadoras exigem sua inspeção. No entanto, estas inspeções podem ser demoradas e arriscadas. O arranjo tradicional cria obstáculos para limpeza automatizada e inspeções por dispositivos remotos. Desta forma, uma abordagem proposta é a utilização do sistema de placas sanduíche (SPS) na estrutura.

Este artigo resume os resultados de um estudo inicial para o projeto e construção de cascos de FPSO com SPS. O principal objetivo é ter as placas do fundo e das anteparas longitudinais nos tanques de carga livres de reforços para permitir a limpeza e a inspeção remota por meio de equipamentos autônomos. Primeiramente, foi projetado o casco com um arranjo estrutural convencional em aço de acordo com as regras do ABS como referência. Em seguida, a estrutura do casco equivalente com SPS foi projetada de acordo com as diretrizes para construção SPS das regras da DNV. Finalmente, este artigo fornece os resultados de uma análise de elementos finitos para comparar as tensões e a resistência final de ambos os tipos de estruturas. Resumidamente, os principais resultados foram que o projeto SPS proporcionou uma redução de 2,8% do peso total e um melhor desempenho estrutural geral por um aumento de 26% para a resistência última do casco.

**Palavras-chave:**

Unidades de Produção Flutuantes, Sistema de Placa Sanduíche, Resistência Última, Análise em Elementos Finitos
TABLE OF CONTENTS:

Declaration: .................................................................................................................................i
Acknowledgements: ...................................................................................................................ii
Abstract: .......................................................................................................................................iii
Resumo: ..........................................................................................................................................iv
Table of Contents: ..........................................................................................................................v
List of Tables ....................................................................................................................................viii
List of Figures .................................................................................................................................x
Acronyms: .......................................................................................................................................xii
Symbology: ......................................................................................................................................xiii

1. Introduction.................................................................................................................................1
   1.1. Background and Motivation .................................................................................................1
   1.2. Objectives .............................................................................................................................3
   1.3. Structure of the Thesis ..........................................................................................................3

2. Literature review ..........................................................................................................................4
   2.1. Beam Theory .........................................................................................................................4
       2.1.1. Shear Force and Bending Moments distributions ...........................................................4
       2.1.2. Shear and Normal Stress ...............................................................................................5
   2.2. Fundamentals of Ultimate Strength ......................................................................................5
       2.2.1. Introduction ....................................................................................................................5
       2.2.2. Analytical Methods .......................................................................................................6
       2.2.3. Numerical Methods .......................................................................................................7
   2.3. Ultimate Strength of Structural Elements ............................................................................8
       2.3.1. Stiffened Panels .............................................................................................................8
       2.3.2. Sandwich Plate System (SPS) ......................................................................................10

3. Global Loads Estimation ............................................................................................................13
   3.1. FPSO for Case Studies ..........................................................................................................13
   3.2. Software Introduction .........................................................................................................15
   3.3. GeniE Modelling .................................................................................................................17
3.3.1. Hydrodynamic Model ................................................................. 17
3.3.2. Structural Model ................................................................. 18
3.4. HydroD Modelling ................................................................. 20
  3.4.1. Input Data ........................................................................ 20
  3.4.2. Results ............................................................................ 22
4. Traditional Steel Structure Scantling ........................................... 24
  4.1. Design According to the FPI Rules ......................................... 24
    4.1.1. Nominal Design Corrosion Values (NDCV) ...................... 25
    4.1.2. Bottom Structure ............................................................ 26
    4.1.3. Side Structure ............................................................... 28
    4.1.4. Deck Structure .............................................................. 31
    4.1.5. Longitudinal Bulkhead .................................................... 32
    4.1.6. Transverse Bulkhead ....................................................... 34
    4.1.7. Web Frame Structure ....................................................... 36
  4.2. Design According to the DNV Rules ....................................... 39
    4.2.1. Bottom Structure ............................................................ 40
    4.2.2. Side Structure ............................................................... 41
    4.2.3. Deck Structure .............................................................. 41
    4.2.4. Longitudinal Bulkhead .................................................... 42
  4.3. Strength Criteria ................................................................. 42
    4.3.1. Buckling Analysis ........................................................... 43
    4.3.2. Yield Stress ................................................................. 44
    4.3.3. Ultimate Strength .......................................................... 44
    4.3.4. Final Design ................................................................. 45
5. SPS Plates Scantling ................................................................. 49
  5.1. Initial Assumptions .............................................................. 49
  5.2. Design Process ................................................................... 50
    5.2.1. Buckling Criteria ........................................................... 50
    5.2.2. Lateral Pressure Criteria .................................................. 51
  5.3. Results .............................................................................. 52
5.4. Hull Weight Estimation .............................................................................................. 54

6. Ultimate Strength Analyses ....................................................................................... 56
   6.1. Finite Element Model ............................................................................................. 56
      6.1.1. General Guidelines ......................................................................................... 56
      6.1.2. Geometry ......................................................................................................... 57
      6.1.3. Element Type and Mesh .................................................................................. 59
      6.1.4. Materials Properties ....................................................................................... 61
      6.1.5. Boundary and Load Conditions ...................................................................... 61
   6.2. Static Loads ........................................................................................................... 63
   6.3. Ultimate Loads ...................................................................................................... 66

7. Conclusions .................................................................................................................. 70

8. References ................................................................................................................... 72

9. Appendix 1 .................................................................................................................. 78
LIST OF TABLES

Table 2-1 - Uncertainties in Ultimate Strength Assessment (ULS). Copied from [27] ......................... 6
Table 3-1 - Main Dimensions of the FPSO .................................................................................. 13
Table 3-2 - Loads to be considered in the structural model ......................................................... 19
Table 3-3 - Estimation of the number of cargo tanks required to reach equilibrium point for a draught of 17.5m ................................................................................................................................................. 21
Table 4-1 - Nominal design corrosion values (NDCV) for the IACS rules. Copied from [63]......... 26
Table 4-2 - Bottom plate net thickness for the FPI design ............................................................ 27
Table 4-3 - Bottom plate gross thickness for the FPI design ........................................................ 27
Table 4-4 - Final design for the bottom stiffener ........................................................................... 27
Table 4-5 - Side plate net thickness for the FPI design ................................................................. 28
Table 4-6 - Gross thickness for the side plates of the FPI design .................................................. 28
Table 4-7 - Final design for the side stiffeners ................................................................................ 29
Table 4-8 - Net thickness estimation for the horizontal plates in the ballast tank ...................... 30
Table 4-9 - Gross thickness estimation for the horizontal plates in the ballast tank .................... 30
Table 4-10 - Final design of the stiffeners of the horizontal plates located in the ballast tanks .... 30
Table 4-11 - Net thickness estimation for the deck plates ............................................................. 31
Table 4-12 - Gross thickness estimation for the deck plates ........................................................ 31
Table 4-13 - Final design for the deck stiffeners ............................................................................ 32
Table 4-14 - Net thickness for the center longitudinal bulkhead plates ........................................ 32
Table 4-15 - Net thickness for the side longitudinal bulkhead plates .......................................... 33
Table 4-16 - Gross thickness of the center longitudinal bulkhead plates ..................................... 33
Table 4-17 - Gross thickness of the side longitudinal bulkhead plates ........................................ 33
Table 4-18 - Final design of the stiffener for the longitudinal bulkhead ....................................... 34
Table 4-19 - Net thickness of the transverse bulkhead plates ....................................................... 34
Table 4-20 - Gross thickness of the transverse bulkhead plates ................................................... 35
Table 4-21 - Final design for the stiffeners of the transverse bulkhead ........................................ 36
Table 4-22 - Net thickness for the plates of the web frame structure ............................................ 37
Table 4-23 - Gross thickness of the plates from the web frame structure .................................... 38
Table 4-24 - Web frame stiffeners final design .............................................................................. 38
Table 4-25 - Keel plate net and gross thickness estimation according to the DNV rules .............. 40
Table 4-26 - Bottom plate's net and gross thickness estimation according to the DNV rules ............. 41
Table 4-27 - Side plating net and gross thickness estimation according to the DNV rules ............... 41
Table 4-28 - Deck net and gross thickness estimation according to the DNV rules ..................... 42
Table 4-29 - Net and gross thickness of the plates from the longitudinal bulkheads ...................... 42
Table 4-30 - Load conditions considered as input data .................................................................. 43
Table 4-31 - Final thickness from plates showing the buckling and yielding criteria .................... 46
Table 4-32 - Final thickness showing the ultimate strength criteria ........................................... 47
Table 4-33 - Geometric properties from midship section ............................................................. 47
Table 5-1 - Mechanical properties for the steel and core to be used in the SPS plate ....................... 49
Table 5-2 - Minimum net and corrosion addition for the steel part of the SPS ............................... 50
Table 5-3 - Final distribution of thickness for the SPS panels ...................................................... 52
Table 5-4 - Geometric Properties of the SPS Midship Section ..................................................... 53
Table 5-5 - Buckling and Yielding Criteria for Static and Dynamic Load case for the SPS arrangement ......................................................................................................................... 53
Table 5-6 - Ultimate Strength Criteria for the SPS Arrangement .................................................. 54
Table 5-7 - Calculations of the weight for each part of the structure for both types of arrangements .. 55
Table 6-1 - Equivalent thickness for the steel structure .............................................................. 58
Table 6-2 - Equivalent thickness for the SPS plates ..................................................................... 59
Table 6-3 - Comparison between the FPI rules and a refined mesh ............................................. 60
Table 6-4 - Loads to be applied to the FEM .............................................................................. 64
Table 6-5 - Vertical static displacement in mm for both types of structures in sagging .................. 64
Table 6-6 - Comparison with the values from the FEM with reference taken from the beam theory and the spring reactions criteria .................................................................................................................. 65
Table 6-7 - Ultimate strength multipliers and ultimate bending moment .................................... 67
LIST OF FIGURES

Figure 1-1 - Total Oil Production of a floating platform along the years .................................................. 2
Figure 1-2 - SPS 16-30-14 panel. Copied from [1] ..................................................................................... 2
Figure 2-1 - Summary on how to find the shear forces and bending moments curves. Copied from [21] .............................................................. 4
Figure 2-2 - (A) Overall collapse after overall buckling. (B) Beam-column type collapse of a stiffener with attached plating. (C) Collapse of the plating between stiffeners without their failure. (D) Flexural-torsional buckling (tripping) of a stiffener. Copied from [34] .................................................................................. 8
Figure 2-3 - SPS panel and simplification of the structure ......................................................................... 10
Figure 3-1 - P66 hull model. Figure copied from [49] ............................................................................. 13
Figure 3-2 - Hull model for the FPSO considered in the thesis ............................................................... 14
Figure 3-3 - Midship section of the FPSO considered in the thesis ....................................................... 14
Figure 3-4 - Plate numeration for the bottom, side, deck and longitudinal bulkhead structures ......... 15
Figure 3-5 - Types of hydrodynamic models .......................................................................................... 17
Figure 3-6 - Compartments of the hull .................................................................................................. 18
Figure 3-7 - Distribution of loads alongside the hull of the FPSO .......................................................... 19
Figure 3-8 - GeniE model .......................................................................................................................... 19
Figure 3-9 - Input data used to create the HydroD model ...................................................................... 21
Figure 3-10 - HydroD flowchart to achieve a solution for a certain draught ......................................... 22
Figure 3-11 - Bending Moment distribution for different draughts ....................................................... 23
Figure 3-12 - Shear Force distribution for different draughts ................................................................. 23
Figure 4-1 - Representation of the horizontal stiffener of the transverse bulkhead (Copied from [5]) . 35
Figure 4-2 - Web frame measures to be used according to the FPI rules (Copied from [5]) ............... 36
Figure 4-3 - Web frames measures for the midship section of the FPSO considered ............................ 37
Figure 4-4 - Example of web frame structure of a FPSO. Source: [4] ....................................................... 39
Figure 4-5 - Iterative process to determine the final thickness of the plates for the buckling analysis . 44
Figure 4-6 - Distribution of the plates thickness and longitudinal stiffeners ......................................... 48
Figure 5-1 - Flowchart to design the SPS panel ...................................................................................... 50
Figure 6-1 - Example of 3-D Global Finite Element Model according to the FPI guidelines (Copy from [5]) ......................................................................................................................... 57
Figure 6-2 - Geometry of the model .......................................................................................................... 57
**ACRONYMS:**

- **ABS** American Bureau of Shipping
- **ALS** Accidental Limit States
- **BV** Bureau Veritas
- **CFM** Close Form Methods
- **DNV** Det Norske Veritas
- **ESFs** Environmental Severity Factors
- **FEA** Finite Element Analysis
- **FEM** Finite Element Model
- **FLS** Fatigue Limit States
- **FPI** Floating Production Installation
- **FPSO** Floating Production Storage and Offloading
- **IACS** International Association of Classification Societies
- **ICM** Increased Corrosion Margin
- **IE** Intelligent Engineering Limited
- **ISSC** International Ship and Offshore Structures Congress
- **LRFD** Load Resistance Factor Design
- **SLS** Serviceability Limit States
- **SPS** Sandwich Plate System
- **SSP** Stiffened Steel Plate
- **TSA** Total Strength Assessment
- **ULS** Ultimate Limit States
- **VCG** Vertical Center of Gravity
- **WSD** Working Stress Design
SYMBOLOGY:

$\tau_i$ - Shear stress in plane $i$

$A_i$ - Area of element from node $i$

$B$ - Breadth of the vessel

$b_e$ - Equivalent width of the panel

$C_b$ - Block coefficient of the vessel

$D$ - Depth of the vessel

$E$ - Young Modulus of the material

$f(x)$ - Resultant vertical/horizontal forces

$f_1$ - Permissible bending stress, in the longitudinal direction

$f_2$ - Permissible bending stress in the vertical direction

$f_a$ - longitudinal stress

$f_b$ - Permissible bending stresses

$f_{ci}$ - Critical buckling stress

$f_{EI}$ - Ideal elastic buckling stress

$f_{LB}$ - Calculated total compressive stress in the longitudinal direction for the plate

$f_{LT}$ - Calculated total in-plane shear stress, $F_{nodal,i}$ - Nodal force applied on node $i$

$f_{TB}$ - Calculated total compressive stress in the transverse/vertical direction

$f_{UL}$ - Ultimate strengths with respect to uniaxial

$f_{UT}$ and $f_{ULT}$ - Ultimate strengths with respect to edge shear,

$f_w$ - The width of the flange or face bar

$f_y$ - yield strength

$F_z$ - Vertical Shear Force

$I$ - The hull girder moment of inertia

$I_{NA}$ - Hull girder moment of inertia along neutral axis

$k_3$ - Axial stiffness of the spring

$K_i$ - Buckling stress factor

$k_t$ - Transversal stiffness of the spring

$k_v$ - Vertical stiffness of the spring

$I$ - Web spacing of longitudinal stiffeners

$L$ or $LOA$ – Overall length of the vessel

$M(x)$ – The resultant bending moment

$M_h$ - The bending moment in harbor conditions, to be considered as reference.

$M_u$ - Ultimate bending moment capacity of the hull transverse section considered.

$M_a$ - Longitudinal twisting moment

$M_v$ - Longitudinal bending moment in the (ship’s) vertical plane

$M_b$ - Longitudinal bending moment in the (ship’s) horizontal plane

$N_i$ – Force in that plate, where $i$ equals to 10,20 or 30

$p$ - Nominal pressure

$P_{plate}$ - Pressure on plate

$Q$ - Material conversion factor

$Q(x)$ - Resultant shear force

$R_{eh}$ – Yield Stress

$s$ - Spacing of longitudinal stiffeners

$SM$ - Hull girder section modulus

$S_m$ - Strength reduction factor

$T$ – Draught of the vessel

$t_{corrosion}$ - Thickness from corrosion margin
$t_{\text{gross}}$ - Gross thickness of plate
$t_{\text{min}}$ - Minimum thickness
$t_{\text{net}}$ - Net thickness from plate
$t_{\text{plate}}$ - Thickness of the plate
$t_{\text{req}}$ - Required thickness
$t_{\text{res}}$ - Residual thickness
$y_a$ - Height of the plate considered
$y_n$ or $y_{na}$ - Height of neutral axis from the baseline
$\varepsilon_{\text{eng}}$ - Engineering deformation
$\varepsilon_{\text{true}}$ - True deformation of the material

$\eta$ - Actual buckling usage
$\Lambda_B$ - Buckling load factor
$\Lambda_F$ - Eigenvalue of the load factor at which the steel face plate reaches the material yield
$\rho$ - Material density
$\sigma_{\text{eng}}$ - Engineering stress of the material
$\sigma_i$ - Normal stress in plane i
$\sigma_{\text{true}}$ - True stress of the material
$\nu$ - Poisson ratio
1. INTRODUCTION

1.1. Background and Motivation

The production of oil and gas reservoirs can be separated by the onshore and offshore production. For the second category, there are several types of floating ocean platforms to be used in deep waters such as semi-submersibles, FPSOs, monocolumns, TLPs and SPARs. The development of this master thesis will be focused on one type of structure: the FPSO.

A floating production storage and offloading (FPSO) unit is a floating vessel used by the offshore oil and gas industry for the production and processing of hydrocarbons, and for the storage of the processed oil. A FPSO vessel is designed to receive hydrocarbons produced by itself or from nearby platforms or subsea template, process them, and store oil until it can be offloaded into a shuttle tanker. FPSOs are preferred in frontier offshore regions as they are easy to install, and do not require a local pipeline infrastructure to export oil. FPSOs can be a conversion of an oil tanker (VLCC) or can be a vessel built specifically for the application. They have become common tools for offshore oil production in areas worldwide over the past 10 to 20 years. Today’s total fleet consists of approximately 150 units, of which 80 are FPSOs and 70 are FSOs. The use of these units as a cost effective means of developing offshore fields continues to accelerate [1].

The FPSO’s structure is based on stiffened panels and the classification societies demand three kinds of inspections for safety reasons: annually, every 2.5 years (intermediate) and every 5 years (Special Periodical Survey). However, these surveys are a time consuming and risky activity, requiring, for instance, the entrance of people inside the tanks for cleaning and thickness gauging. This activity can be dangerous and time-consuming because it involves confined and higher places. Another reason is that this survey is carried out while the FPSO is at sea in full operation. This is due to the fact that, for example, it takes 1 to 1.5 years just to install the risers to the vessel. In order words, there is no possibility to dislocate it to a dry dock and do the inspection there, once it would turn it financially unattractive. Thus, the FPSO crew needs to first reallocate the liquids from the tank, which will be inspected, to the others from the vessel without jeopardizing the oil and gas production. The oil tank to be inspected may be out of operation for up to 10 or 15 days. The storage of the produced oil in this period shall be rearranged in the remaining tanks. This rearrange can be quite tricky in the earlier years after the beginning of the operation, because it is where the production reaches its peak as can be seen in Figure 1-1. Therefore, the faster the crew can clean it and inspect it, the less time the production capacity will be reduced and, therefore, the more revenue the FPSO will generate.
In this context, new technologies are arising to try to overcome or minimize this problem. One of them is the use of sandwich plates in offshore structures. A sandwich plate is a fabricated material that consists of two steel plates joined to either side of a low-density core material or structure [2]. For example, there are concrete sandwich plates as shown in [3] and the Sandwich Plate System (SPS) as shown [1]. It was developed by Intelligent Engineering in the late 1990s at Canada’s Carleton University in response to protecting offshore structures in the Beaufort Sea from impact damage due to ice sheet loads. The solution was a steel-elastomer-steel composite panel, with a high strength-to-weight ratio and durability that would enable the offshore structures to withstand the heavy loads, as shown in Figure 1-2. The elastomer, as a two-part liquid, is injected into closed cavities formed by the steel. Generally, this kind of construction has several advantages that make them a suitable option such as [2]:

- High stiffness to weight ratio, making them suitable for lightweight design.
- Good buckling resistance compared to thin orthotropic plate structures.
- Good crashworthiness properties.
- Large unsupported spans, thereby reducing the requirement for supporting elements and increasing architectural freedom.
- Reduced assembly times via modular approaches to construction.
- Flat and smooth surfaces.

Although this technology has several uses in civil (buildings and bridges), marine, military and offshore applications, the main market is the marine/offshore one and it made the debut in 1999 with Ro-Ro and bulk carriers projects. Moreover, the fastest growing sector since 2005 is the offshore specially for FPSO, in which SPS can be used for newbuild structures or to upgrade or retrofit existing structures (Overlay Construction) for enhanced performance or larger footprints. New panels are factory built to very high dimensional tolerances and are ideally suited to modular construction allowing rapid roll-out of building units for a wide range of demanding requirements. Focusing on the overlay construction,
there are mainly two uses: repair and conversion. The first one is related to extending the life of the
structure by installing SPS panels in corroded/grooved area in order to reinstate the local strength of the
plate while arresting its future corrosion. Several FPSOs already used this alternative such as the FPSO
Independence – ConocoPhilips, FPSO Zafiro Producer – ExxonMobil, FPSO Conkouati – Perenco and
FPSO Sendje Ceiba – Hess. The second use is to protect the side shell of converted hull plates against
collisions from supply vessels. For collision condition, the panels are proven to be a good design option,
once they can withstand a greater load than the traditional steel arrangement before failing, giving
protection similar to double-side hulls to single-hull converted units [4]. This type of structure can be
observed in the FPSOs from Petrobrás (FPSO Cidade De Angra Dos Reis). In this last case, SPS was
installed directly to the existing side shell plating with minimal disruption to concurrent works.

1.2. Objectives

In the light of the problem presented in section 1.1, this master thesis will focus on the research for
design and construction of hulls of FPSOs with sandwich plate system without stiffeners in the bottom
plate and longitudinal bulkheads of cargo tanks. The main goal is to have the walls and bottom of the
cargo tanks free of stiffeners to allow remote cleaning and thickness inspection of bottom and bulkhead
plates using autonomous equipment. The risk is reduced because people won't need to inspect all areas
from the vessel and these devices halve the time required for cleaning and inspection, thus, less harm
to the operation of the FPSO. In order to do that, this study is divided into four steps which are:

- Literature review about the SPS in the offshore industry
- Design of a midship section in traditional naval steel structures to be used as a benchmark
- Design of a midship section with sandwich plates in cargo tanks
- Ultimate strength analyses of the midship section for both arrangements.

1.3. Structure of the Thesis

The thesis is organized into seven chapters and respective appendices. Chapter 1 is the introduction of
the topic to be discussed the related background, main goals and structure of the work. Chapter 2
contains the bibliographic research about ultimate strength and the usage of sandwich panels for this
topic. Chapter 3 is the FPSO main dimensions and characteristics that will be used in this master thesis
and the estimation of the global loads of the FPSO with the auxiliary of the software HydroD from
SESAM. Chapter 4 details the design process for the traditional midship section in steel according to
FPI from ABS [5]–[8] and DNV rules [9]–[17]. Chapter 5 shows the design of a midship section with the
sandwich plates in the cargo tanks according to the classification society rules (DNVGL-CG-0154 and
Lloyds guidelines rules [18], [19]) and compare the weight between both arrangements. Chapter 6
focuses on the FEM analysis for the steel and composite model and the ultimate strength analysis of
both sections. In the end, chapter 9 indicates the main conclusions and future work of this thesis.
2. LITERATURE REVIEW

2.1. Beam Theory

The hull girder analysis assumes that the structure satisfies simple beam theory (Bernoulli-Euler). It is a simplification of the linear theory of elasticity which provides a means of calculating the load-carrying and deflection characteristics of beams [20]. Therefore, the hull girder analysis deals only with those longitudinally integrated forces and moments that are dealt with in beam theory: vertical shear force, $F_z$, longitudinal bending moment in the (ship’s) vertical and horizontal planes, $M_y$ and $M_z$, and longitudinal twisting moment, $M_x$. This theory provides the means to estimate the still water shear force/bending moment distribution and also the normal and shear stress for any member of the structure and this master thesis will briefly describe the process to obtain each variable from the load distribution and equilibrium equations.

2.1.1. Shear Force and Bending Moments distributions

As stated in Hughes et. al. [21], the vertical shear force and bending moments distributions can be caused mainly by the unequal distributions of weight and buoyancy along the length of the ship, accentuated by waves. While the horizontal component occurs when the ship is in an inclined condition, as a result of rolling. Once knowing this distribution of resultant vertical/horizontal forces ($f(x)$) from the balance between weight and buoyancy, a free body diagram can be used to calculate for each infinitesimal length $dx$ the shear force ($Q(x)$) and bending moment ($M(x)$) by the following equation [22]. A summary of the procedure to find this curve is presented in Figure 2-1.

![Figure 2-1](image)

Figure 2-1 - Summary on how to find the shear forces and bending moments curves. Copied from [21]

These curves have some unique characteristics that will be useful to validate the ones obtained in chapter 4 through suite software SESAM [23], [24]. The first one is that both variables must be zero at
both ends of the model, because the hull girder is a “free-free” beam. The second one is the shape of
the function. In most cases the loading is approximately similar forward and aft of amidships. Under
these conditions the shear force is approximately symmetric, passing through zero somewhere near
amidships and having maximum values, positive and negative, near the quarter points. Therefore, since
the bending moment is the derivative from the shear force, its shape will be, in general, will be a
maximum, positive or negative, near amidships. However, if the load is very asymmetrical, this behavior
can change.

2.1.2. Shear and Normal Stress

Besides deflection, the beam equation describes forces and moments and can thus be used to describe
stresses. This is due to the fact that Hooke’s law of deformation is valid for this case. Thus, both the
bending moment and the shear force cause different stresses in the beam. The first one is related to the
normal stress while the second one with the shear stress. Generally, the stress due to shear force is
maximum along the neutral axis of the beam while and the maximum normal stress is at either the top
or bottom surfaces. The main formulas for both are described below [22]. These formulas are extremely
important because they provide a way to analyze how close or far are the stresses compared to the
yield stress, which is the point where plastic deformation begins. They will be extensively used in chapter
5 to design the thickness of the steel plates.

\[ \sigma = M \cdot (z - z_N) / I_N \]
\[ \tau = Q \cdot S / (I_N \cdot t) \]

These formulas are valid for beams with only one homogenic material. However, it is common in
engineering to have beams with two or more kinds of material as it is the case for this thesis. Therefore,
a modification in the formula must be made in order to calculate the stress for each material. The
approach used in this master thesis is described in chapter 6.10 from Introduction to Solids Mechanics
from Popov 2010 [22] and it is based on the equivalent area method. The transformation of a section is
achieved by changing the dimensions of a cross section parallel to the neutral axis in the relation of the
moduli of elasticity. For example, if the equivalent section is desired in material 1, the corresponding
dimensions in material 1 are not changed. The dimensions of material 2 are changed by the relation n,
where \( n = E_2 / E_1 \). In the end, the stresses in material 1 are calculated normally while in material 2 it will
be the multiplication of this by n. This will be very useful in order to design and predict the stresses for
the SPS panels.

2.2. Fundamentals of Ultimate Strength

2.2.1. Introduction

A good practice in any design of ships and offshore structures is to use one or more limits states as
criteria in addition to the yield stress during the total strength assessment. A limit state is a condition
under which a particular structural component or an entire structural system fails to perform its
designated function [25]. In other words, it is any condition in which a structure or a structural member
has become unfit for one of its intended roles because of one or more loads and/or load effects [21].
The main ones are: serviceability limit states (SLS), ultimate limit states (ULS), fatigue limit states (FLS) and accidental limit states (ALS). This master thesis is concerned with ULS.

Ultimate strength is a critical and fundamental part of the strength assessment in the design of a ship or offshore structure [26]. It is defined as a point beyond which the loading exceeds structural capacity and the structure collapses [27]. There are various methods available in the literature to compute the ultimate strength of different structural elements. They can vary from a more simplified to a more sophisticated one. However, determining this property is a challenging task because it depends on three types of uncertainties: geometry, material and numerical. Each of them has factors that can influence on each other and are summarized on Table 2-1

| Source of Uncertainty | Geometric | Material |
|-----------------------|-----------|----------|
| Model imperfections   | Yield strength |          |
| Initial imperfection  | Plasticity model |    |
| Boundary conditions   | Stiffness (Young’s Modulus) |    |
| Plate thickness       |        |          |
| **Numerical/Software**| **Mesh density** | **Element type** |
|                        | **Solver** | **User’s experience** |

Nowadays, there are three ways to determine the ultimate strength of ships and marine structures: experimental, numerical simulations and analytical modelling. Due to the very large size of some ships, and the fact there is no standardization of ship types, the shipping industry is in a difficult position to make frequently experimental tests. Therefore, the development of numerical and analytical approaches proofs to be a good solution to this problem [25]. Although numerical simulations can provide good predictions without the need to build/test a structure as the experimental one, the complexity of the problem can increase drastically when considering different kinds of uncertainties. This can be quite time-consuming and expensive, because requires good computers [27]. Thus, analytical methods also have their use once they provide simplified and quicker checks to use it. In this light is that classification societies enter. Their main responsibilities are to provide both analytical and numerical approaches, based on the literature and studies, with the recommended safety factors in order to achieve a safe design of structures. Each classification society such as ABS, BV, DNG GL, LR and more has develop guidelines for both approaches for the corresponding limit state based on either the working stress design (WSD) and the load resistance factor design (LRFD) method.

2.2.2. Analytical Methods

Analytical methods proofed to still be worth in times where the development of numerical methods steady increase yearly. The main causes of that are they can provide a rapid evaluation at the early design stages and easily implemented using a spreadsheet environment, thus, not requiring specific software. There are two kinds of approaches to solve it: closed form methods and progressive collapse methods.
Close form methods (CFM) are a set mathematical expression expressed using a finite number of standard operations and are usually based on semi-empirical data. They are highly used in the classification societies such as in DNV [16] and ABS [5], since they are easy to be implemented. However, they neglect that ultimate failure is a progressive event, which cannot predict the premature collapse of some structural elements [27]. One of the first attempts to evaluate the ultimate strength was proposed by Caldwell [28] in 1965. He applied “Rigid Plastic Mechanism Analysis” to evaluate the ultimate hull girder strength. The influence of buckling was considered by reducing the yield stress of the material in the buckled part [26]. Since then, several related closed forms were proposed to develop the model such as Paik and Mansour (1995) [29], Paik et. al. (2001) [30], Paik et al. (2013) [31] and more.

The progressive method was firstly proposed by Smith (1977) [32] and it is an iterative method. Curvature is applied to the section, and the strain experienced by each individual unit is then determined by assuming that plane sections remain plane. Based on this strain, the average stress in each unit is estimated taking into account whether it is in tension or compression, the yield strength of the material, and the buckling behavior of the plating and stiffeners in compression. Summing the contributions over the section determines the bending moment. The curvature is incremented and calculations repeated. The end result is a nonlinear moment-curvature relationship, the peak value of which defines the ultimate strength of the hull.

### 2.2.3. Numerical Methods

According to the International Ship and Offshore Structures Congress (ISSC-2015) [26], non-linear finite element models have been growing steadily as a way to assess the ultimate strength of a structure. This is due to the continued development of computer technology and software such as ANSYS, ABAQUS, NASTRAN-PATRAN etc. Typically, the analyzes utilize a progressive method inside the solver together with an equilibrium convergence iterator using either the Riks arc length method or modified Newton-Raphson method [33]. However, as stated by [34] in his doctorate thesis, this is still a challenging task because of model size limitations imposed by software and hardware. Generally, the models are more focused on local parts of the hull in order to optimize the computational time required. Therefore, based on reviewed guidelines from different classification societies [5], [10], [35], [36] and several suggestions from different ISSC [25]–[27], [37]–[39], some good practices can be done to overcome or minimize the problems related to Table 2-1 and are displayed below.

- Nonlinear plate/shell and beam element types should be used; first-order elements are normally the easiest to generate meshes.
- Selective refinement of the model is recommended to keep the model size under control, with the smallest element size used in regions where the results must be more accurate.
- Element formulations must allow for geometric and material nonlinearity; large dis-placement and/or rotation formulations are necessary.
- Equivalent methods to simplify the geometry in order to reduce the computational time. One example is done by [40], which proposes an equivalent thickness method to estimate the
ultimate strength for panels submitted to combined biaxial compression and lateral pressure loads

- Use of commercial software once they have an extensive library and community to help the user
- An appropriate selection of the longitudinal length of the model to the loading and response effects being modelled. For the hull girder strength, there is, for instance, the suggestion from ABS to use the extension of 3 cargo tanks [5]
- For an implicit solver, it is necessary to select an appropriate step size and convergence tolerance. Too large a tolerance will lead to inaccurate solutions; too small a step size may cause convergence difficulties.

2.3. Ultimate Strength of Structural Elements

This section presents the recent research and developments on the ultimate strength for both stiffened steel and SPS panels.

2.3.1. Stiffened Panels

A stiffened panel is an assembly of plating and stiffeners. It is normally designed so that the buckling of a local plate panel between stiffeners initially takes place and is then followed by overall collapse due to excessive yielding and/or stiffener failure [25]. As stated in [41], there are 6 types of primary failures for a stiffened panel and 4 of them are presented in Figure 2-2:

- Mode I: Overall collapse after overall buckling
- Mode II: Collapse of the plating between stiffeners without their failure
- Mode III: Beam-column type collapse of a stiffener with attached plating
- Mode IV: Local buckling of stiffener web (after buckling collapse of attached plating)
- Mode V: Flexural-torsional buckling (tripping) of a stiffener
- Mode VI: Gross yielding

![Figure 2-2](image)

Figure 2-2 - (A) Overall collapse after overall buckling. (B) Beam-column type collapse of a stiffener with attached plating. (C) Collapse of the plating between stiffeners without their failure. (D) Flexural-torsional buckling (tripping) of a stiffener. Copied from [34]

The interaction between the plate elements and support members in terms of their geometrical and material properties and other factors such as loading condition and initial imperfections plays an
important role in the ultimate strength, buckling, and plastic collapse patterns of stiffened panels [21].

Moreover, Collapse mode I represents the overall collapse after overall buckling. In this mode, the stiffeners buckle with the plating as a unit, and overall buckling often occurs under an elastic regime. This collapse mode typically occurs when the stiffeners are relatively weak compared with the plating. Collapse mode II occurs when the panel is pre-dominantly subjected to biaxial compressive loads, causing the panel to collapse because of yielding along the plate–stiffener intersection at panel edges, with no distinct stiffener failure. This mode assumes that the stiffeners do not fail first in contrast to collapse modes III, IV, and V.

Hughes et. al. (2004) [41] presents an improved prediction of simultaneous local and overall buckling of stiffened panels. It studied 55 types of panels with proportions suitable for use in ship design using finite element software and derived modified expressions for elastic local plate buckling and overall panel buckling. In addition to that, it also compared the results with the orthotropic method and it was found that for panels having crossover proportions, orthotropic-based methods are unsatisfactory and the beam-column method is most suitable for ultimate stress prediction.

Paik et. al. (2008) [42] shows in his Part II of a series of three papers useful methods for the ultimate limit state assessment of ships and ship-shaped offshore structures, but specifically for stiffened panels. Although the vessel studied was a hypothetical AFRAMAX-class and not a FPSO, the paper compares three candidate methods that are employed nowadays for the prediction: ANSYS nonlinear finite element method, DNV PULS method, and ALPS/ULSAP method. The main conclusions are that ALPS/ULSAP tends to slightly underestimate the panel ultimate strengths at the pessimistic side, while DNV PULS tends to overestimate them at the somewhat optimistic side, compared with the nonlinear FEA. Based on the comparison results with more refined nonlinear FEA, however, it is considered that the three methods are useful enough for practical design purposes.

Saad-Eldeen et.al. (2011) [43] described an experimental assessment of the ultimate strength of a severely corroded box in order to simulate how different levels of corrosion degradation of ageing ship structures can affect the ultimate bending capacity of the ship. Moreover, it also studied how the defects can influence the failure mode that will occur during an ultimate strength test.

Seo et. al. (2011) [40] presents a validation of the equivalent plate thickness approach for ultimate strength analysis of stiffened panels with non-uniform plate thickness. The main cause is due to the introduction of non-uniform plate thicknesses renders such calculations difficult when analytical methods and design equations are used. Therefore, the authors proposed an equivalent plate thickness method that is based on the weighted average approach to analyze the strength of stiffened panels with non-uniform plate thicknesses. This is checked through nonlinear finite element method computations and the main results are that the method is accurate for panels under combined biaxial compression and lateral pressure loads.

Amante (2017) [34] studied how external events, specifically the collision of vessels in FPSO, can lead to a ULS scenario and generate the progressive collapse of several structural elements. The thesis investigates how the different types of damages can influence this scenario through experimental tests and numerical methods.
Rizzo et. al. (2018) [44] studied how to make a quick estimation of the ultimate strength and the residual strength of a panel under combined compression and shear with initial imperfections and damage. The cause of this research is also related to collision to the FPSO side from striking objects such as supply vessels. The main results are an empirical formula for predicting the ultimate strength of damaged stiffened panels under combined loading of shear and longitudinal compression is empirically derived in this work based on curve fitting of quasi-static non-linear finite element analyses.

2.3.2. Sandwich Plate System (SPS)

As introduced in chapter 1, the FPSO studied will use a sandwich plate developed by Intelligent Engineering Limited (IE) and patented as the Sandwich Plate System (SPS), which integrates a steel-elastomer-steel composite structural laminate in place of conventional stiffened steel plates (Figure 2-3). The resulting structure has greatly enhanced impact absorption capability compared to conventional steel structures [4]. This is due to the so called “sandwich effect”, because the separation of the facings by a lightweight core acts to significantly increase the second moment of area (and hence the bending stiffness) of the material cross-section with only a small increase in weight [2]. Moreover, according to IE, this technology has civil (such as bridges [45]), military, maritime and industrial applications because of key benefits such as

- Lightweight
- Eliminates stiffeners – simplified structure (reduction of construction costs)
- Improved space utilization
- Fatigue and corrosion resistance
- Impact, blast and fire protection

![Figure 2-3 - SPS panel and simplification of the structure](image)

Regarding the marine and offshore structure environment, the SPS panels have been proofed to be a reliable and versatile material in several designs. For example, Bond et. al. (2011) [4] described the structural engineering study conducted to confirm the impact resistance of the SPS Overlay 20-30-20 (20mm thickness of the upper steel plate – 30mm thickness of the core – 20mm thickness of the lower steel plate) in the form of a compact double hull for the prescribed impact between an offshore supply vessel and the FPSO in way of the boat landing area. This is studied as a form to offer equivalent protection to a FPSO monohull as a double hull. The main results of the paper showed that the SPS attached to the side plates provides a package of risk reduction benefits over that of cofferdams and sponsons that include; a significant increase in local impact resistance, a strengthened side shell that
reduces critical fatigue stresses, schedule reduction for fabrication and installation, reduced risks during fabrication, less maintenance and eliminates the risks and costs for through life void space inspections.

Also, Bond et.al (2003) [1] studied an innovative approach to hull repair on in-service FPSOs using sandwich plates system overlay as a way to reinstate the strength and corrosion allowance without removal of the existing plate. An SPS Overlay utilizes the existing stiffened plating of the structure as one of the plates. The second plate is attached to the existing plating with an injected elastomer core to form an SPS plate. The technique allows the existing structure and any services attached to it and its stiffening elements to remain in place while the strength, stiffness and corrosion allowance are restored. The study carried out several structural evaluations comparing both arrangements (AH/DH32 steel and SPS overlay) for the bottom structure of the FPSO with the help of finite elements. The main results showed that the sandwich plate configuration had a better performance reducing the stresses at the static load case and also increased the ultimate strength of the panels.

In addition, other projects were carried out by SPS Technology in this field of repair and conversion of FPSOs. The first example is in FPSO Independence from ConocoPhillips. Excessive pitting corrosion of the bottom shell plating in the Cargo Oil Tank resulted in the FPSO Independence requiring local steel reinstatement, which was solved with an SPS Cold Work repair. The FPSO Independence repair was carried out on-station. The repair area was localized and required only one tank to be closed, enabling FPSO Independence to maintain 100% operational capacity throughout the project, which took less than two weeks to complete. The cold work version of SPS delivered a permanent repair, reinstating the existing hull and creating a new composite section. SPS Technology has a solution that uses structural adhesives to join the steel components and form airtight cavities into which the elastomer core is injected. Another example is the FPSO Capixaba. The same installation method from FPSO Independence was used to deliver this permanent repair that reinstated the existing deck and created a new composite section. A combination of bolts and structural adhesive were used to fit and join the steel components that formed airtight cavities into which the elastomer core was injected. All steel components were prefabricated before shipping on-board for installation. This reduced the cost of the project, eliminated welding requirements, reduced time offshore for the installation team and simplified project logistics.

In the scope to provide a safe design to shipyards and engineers, DNV-GL (DNVGL-CG-0154 [18]) and Lloyd’s Register [19] developed rules for designing this plate. They provide closed form methods in order to obtain the desirable steel and core plate thickness and, also, strength assessments for the buckling and ultimate strength for both new and overlay construction. The first rule also provides a numerical procedure to estimate both properties.

The Transport Industries Under European Commission in 2013 [2] with the help of several classification societies and universities proposed a coordination action on advanced sandwich structures in the transportation industry (SANDCORE). The result was a guide for best practices for sandwich structures, including the SPS, in marine applications with the main objective to provide knowledge of different types of sandwich plates mainly for shipyards in order to help their integration in ship design and fabrication. The one that stands out for this thesis is the chapter 3. It is focused mainly on the design of plates with
the analytical/numerical/experimental analysis of several limit states such as ultimate strength, buckling and fatigue and other types as vibration and crash response.

In the light of the numerical analysis, two studies will be discussed. The first one from Zou. et. al (2019) [46] discuss a global buckling analysis approach for sandwich plates based on a theoretical study and implemented by finite element model (FEM). The research carried out several simulations to determine the different influential factors for the ultimate buckling loads. The main conclusions show that the theoretical model had a good adherence with the FEM and experimental results and, also, that the SPS is more resistant to both local and global buckling than a steel arrangement.

Moreover, Feng et. al. (2010) [47] presents a comparison between two approaches to model the SPS panels for a FEM. The first one is a mixture of shell and solids elements and the other is only shell elements. The object of study was double-bottom structure and the main conclusions were that the method of the shell elements presented in the paper gives satisfactory results compared to the theoretical models. Also, compared with the result of the mixture of shell and solid elements, the only shell method proposed in the paper is more efficient and easier to be accomplished. This is paper is important, because one of the main discussions in chapter 7 is how to model the SPS panels for the cargo tanks to make it efficient, easy and return accurate results.

The last paper is a master thesis written by Boersma from Delft University [48]. The main goal of this research is to find an optimal (cost-effective) solution for protection against dropped impact loads comparing a Stiffened Steel Plate (SSP) versus Sandwich Plate System (SPS) structures. The thesis presents several SPS and SSP designs first obtained through analytical methods in order to obtain a preliminary design. Further, by simulating the impact loads with FEM, it tries to obtain an optimum design that can support the load conditions without yielding and other associate failure modes. It also carried out research to obtain the maximum load to obtain the ultimate strength of some candidates for an optimum design. This thesis is valuable for this project because the design process is similar.
3. GLOBAL LOADS ESTIMATION

3.1. FPSO for Case Studies

The objective of this section is to provide the main characteristics of the FPSO for the case studies of this master thesis. It includes data such as main dimensions, initial drawings (longitudinal and transverse division of the ship), materials selected for the midship section and so on.

The main dimensions of the FPSO are presented in Table 3-1. It is a ship with a length overall (LOA) of 323m, a breadth (B) of 57.8m, a depth (D) of 32.3m with a block coefficient (C_b) of 0.92. The design draught is 26.8m. This load case will be further discussed in section 3.2, 3.3 and 3.4, but it is obtained by filling the maximum amount of cargo tanks (10 of 12) and complying with the equilibrium conditions imposed.

| Variable | Value | Unit | Description                      |
|----------|-------|------|----------------------------------|
| Loa      | 323   | [m]  | Overall length                   |
| B        | 57.8  | [m]  | Breadth                          |
| D        | 32.3  | [m]  | Depth                            |
| T        | 26.8  | [m]  | Design draught (Fully Loaded)    |
| C_b      | 0.92  | [-]  | Block Coefficient                |

Taking into account these initial dimensions, the next step is to define the shape and the longitudinal division of the hull. One reference for it is the hull of the FPSO P-66 of Petrobras [49], which has an overall length of 288m, a beam of 54m and a depth of 31.5m. It can be seen in Figure 3-1. In addition to that, the longitudinal division of the FPSO is segmented by the aft part, where the machinery, accommodation modulus, pump and so on will be located, followed by 6 cargo tanks with 2 ballast tanks for each side and in the fore most part a forepeak tank. Moreover, it was considered as well a spacing (s) of 850 mm for longitudinal stiffeners and a web spacing (l) of 5100 mm for the cargo tanks. This proportioned to generate the form of the hull, its longitudinal division and a proposed midship section which are presented in Figure 3-2 (more detailed in appendix 1) and Figure 3-3.
Some other initial assumptions were made before the design of the midship section according to the classification society rules. This regards the still water bending moment and the material used for the construction. Based on the still water bending moment from similar FPSOs and the formulas proposed from ABS [9] and DNV [9], [13] a still water bending moment of 950,000 tonf*m was assumed as an initial value. This will be recalculated in chapter 4 with the help of the software SESAM. Also, the material used for the traditional steel midship is the high tensile steel grade 36, which has mechanical properties according to [8], [9], [12].

The final assumption regards the plate division and three aspects need to be considered. First, the dimensions (length, width and thickness) of the plate must comply with the market availability, the width varies between 3.0m to 5.0m. Second, the FPI and DNV rules give formulas to calculate the minimum and/or maximum breadth a type of plate can have. Third, according to DNV Rules [17], the welds between plates and the stiffeners with the plates shall not be less than 50 mm, but does not need to be greater than 100 mm apart from each other. Keeping in mind these three factors, the plate division could be made and it is shown in Figure 3-4. The green symbol is for the plates of the bottom, side, deck and longitudinal bulkhead (center and side) structure and in purple is the plates of the web frame and transverse bulkhead.
Also, as a design parameter, it was assumed that for a specific structure (bottom or side or deck etc.) there would be only one pattern of the longitudinal stiffener. Although the structure can be over dimensioned for some regions, this helps simplify the construction of the midship section. First, because it is easier for the shipyard to organize the fewer different types. Second, it is cheaper to buy in bulk the same kind of plates/stiffeners. Third and last, the shipyard does not need to change the calibrations of the machines for welding and cutting for one type of structure (i.e.: bottom) since there is only one type of stiffener.

3.2. Software Introduction

These sections have the main goal to detail the methodology to estimate the global loads (bending moments and shear forces) that will be considered for the following chapters. It is very important, once the stresses and ultimate strength are directly related to the value and distribution of both curves. In order to accomplish this, it was used two modules from the software SESAM (GeniE [24] and HydroD [23]) to model the structure with the loads/weights and after solve the equilibrium problem. The solution is the cargo/ballast distribution for a certain equilibrium and load condition, thus, having the distribution of all weights and buoyancy, the global loads can be achieved.

This first section will introduce the software SESAM with its capabilities/uses, the tutorials used both in GeniE and HydroD, the general methodology to estimate the global loads and some initial assumptions. The following part will detail the construction of the model in GeniE and also the loads considered. The last part is the construction of the model in HydroD and the global loads results from different draughts.

SESAM is a software suite for hydrostatic, hydrodynamic and strength analyses of ships and floating offshore structures developed by DNV. This includes barges, FPSOs, semi-submersibles, TLPs, Spar, buoys and gravity-based structures. Two modules of SESAM have been used in this research work: HydroD and GeniE. HydroD is an interactive application for the computation of hydrostatics and stability, wave loads and motion response for ships and offshore structures [23]. The wave loads and motions are computed by Wadam [50] or Wasim in the SESAM suite of programs. It is based on one common
model, fully integrated with finite element analysis (FEA), which is the GeniE. It is a tool for modelling structures composed of beams, flat plates and stiffened shells, which can be meshed to a variety of element types. The load modelling includes equipment, explicit loads, wind loads and generation of compartments in floating structures [24].

The sequence to solve the hydrostatics problem of the master thesis FPSO with the Sesam software is described in several tutorials provided by the company [51]–[55] and by the user’s manual of GeniE, HydroD and Wadam [23], [24], [50]. The first step is to create the hydrodynamic and mass model in the GeniE. The first one can be a Panel, Morison, Dual or Composite model and the adequate choice depends on the type of the problem. The difference between the configurations is how the hydrodynamic forces are calculated. The first one is through potential theory while the second is from the Morison’s equation. The last two are combination methods. The dual is used when potential theory and the Morison’s equation are applied to different parts of the model. While the composite one is used when both formulations are applied to the same part of the model. An example can be seen in Figure 3-5.

The chosen hydrodynamic model is the panel method, which is based on potential theory. The theory behind is further developed in [56]–[59] and the potential proposal provides the necessary and adequate bases used to define the wave problem, linearized from the premise that the incident wave amplitudes are reasonably smaller than their respective wavelengths wave. As a consequence of linearization, the classical hydrodynamic problem of a floating unit subjected to wave passage can be treated from the sum of three main components: hydrostatic portion, radiation portion and diffraction portion [60].

In this master thesis, the hydrostatic problem will be the focus once the main goal is just to obtain the compartment distribution for a still water condition. Therefore, in order to take into account this contribution in the computation of the hydrostatic forces, it is introduced to the system stiffness coefficients, which make up a hydrostatic restoration matrix. This matrix is applied to all panels, which will be generated for all element sides below the still water level and above the sea bed. With that, the rigid body equations can be applied for each one and, by solving it, an equilibrium condition can be found [50].

The next step is the creation of the mass model. It covers the creation of the structure of the FPSO, the boundary conditions and loads imposed. The mass is used both in the hydrostatic calculations to report imbalances between weight and buoyancy of the structure and in the hydrodynamic motion analyses.

In addition to the models, the environmental data and loading conditions must be applied and, then, a hydrostatic analysis is performed. The module returns as output different parameters such as the distribution of contents (oil and ballast) in the tanks for a static equilibrium condition, the GZ curve, still water sectional loads (shear force and bending moments) and stability checks against international codes such as the IMO MODU code [61] and the NMD [62].
3.3. GeniE Modelling

This section will cover the procedure to model the traditional steel structure of the FPSO that was designed in chapter 4 of this master thesis. The methodology is strongly based on the tutorials [53], [54] and the user’s manual [24] provided by the company DNV.

3.3.1. Hydrodynamic Model

The first step is to create the structural properties, which includes the material and thickness of the plates. For the main steel properties are: yield strength ($f_y$) = 355 MPa (High steel strength grade 36), $\rho$ = 7850 kg/m$^3$, $E$ = 2.06*10$^{11}$ Pa, Poisson ratio $(\nu)$ = 0.3. The initial plate’s thickness along the hull was calculated by doing the first round of design considering the assumptions made in chapter 3 with the FPI rules [5] and the result was a structure with a total weight around 42,000 tons. This is an important step in order to predict accurately the distribution of bending moments and shear forces at the HydroD software, once the structure’s weight plays an essential role in the force equilibrium equations.

The following phase is to create the geometry of the hull. Thus, it is needed to set guide planes alongside the hull to create the external and internal parts of the cargo tank, forepeak and aft part of the FPSO. From these guide planes, create the surfaces are created with the correct structural property (material and thickness) that compose each part of the hull. After that, a hydrodynamic model itself can be created.

By following the user’s manual from HydroD [23] and GeniE [24] guidelines, the appropriate hydrodynamic model for an FPSO hull is the panel one. In order to do this, the next steps should be made as follow and are based on the specific tutorial [53].

a. Select all wet surfaces, which are those subjected to water. In this master thesis, they are all surfaces from the bottom, side and deck of the hull.

b. Add a wet surface property to them providing that all surface normal points outwards. This is an important step, because if any surface points inwards, this will result in a negative contribution for the buoyancy force [53].

c. Mesh all the selected surfaces with the desired element length. As stated in the user’s manuals [23], [24], this part must have a balance between the accuracy of the results with the speed of computational time. This is done automatically by the software to find a good combination of both.
d. The last step is to assign a load case with the dummy hydro pressure option turned on for the set, because the elements within the set selected will be the ones used for the hydrodynamic force’s calculation.

### 3.3.2. Structural Model

With the tanks modelled from the previous section, load cases were assigned for each compartment that is going to be used in the hydrostatic analysis of HydroD. These compartments are the ones that will be filled with either oil or ballast with the desired quantity to reach the stability for a certain draught, heel and trim of the FPSO. Thus, it was created a load case for all the ballast and cargo tanks presented in Figure 3-6.

Besides the hull, cargo and ballast weights, a FPSO has other types of loads that must be considered in the model. For instance, this master thesis assumed values for the process plant weight above the deck, for the risers located in one of the sides of the hull (portside), for the weight of the machinery located in the aft part of the hull and for mooring loads based on similar FPSOs. These are presented in Table 4-1. Although they can be modeled as line loads in GeniE, the hydrodynamic analysis in HydroD required that they are represented as point masses rather than line loads [53]. Therefore, these loads were modeled as point masses. The first weight is the superstructure/process plant which was uniformly distributed along the centerline of the deck with a height of 47.3m above the baseline. The second one is the riser group, which includes the riser loads and the lower and upper balconies. All of them were placed at the portside of the ship (Y=28.9m) with the respective vertical center of gravity (VCG) and shown in table 3-2. The third load is the hull stern load was placed similar to the superstructure/process plant, because it was at the centerline of the deck but with a height of 41.3m from the baseline. The fourth weight, which the hull items (equipment, pipes, painting, mooring system), has a VCG of 26m from the baseline. However, the software can only identify the point mass if it is joint with an element from a plate or beam. Therefore, the weights were distributed between the deck and bottom centerline to reach the desired weight and VCG. The fifth one is the hull bow (flare tower, hull equipment, offloading system) and was located in the centerline of the deck as well but with a VCG of 52.3m from the baseline. The last one is the mooring loads and it was divided into 4-point masses located at the region from the yellow arrow from Figure 3-7 at the deck height (Z=32.3m). In all of the cases except for the mooring loads, it was supposed a spacing between the masses of 5.1m, which is the spacing between web frames. A representation of this step can be seen in Figure 3-7.
The final step before the meshing is to input the boundary conditions, which the most adequate one depends on the type of analysis and type the results that are pursued.

With all these steps done, the structural model could be meshed through GeniE and the final result can be seen in Figure 3-8.

**Table 3-2 - Loads to be considered in the structural model**

| ITEM             | Weight [tons] | VCG [m] | VCG Reference | Description                                                                 |
|------------------|---------------|---------|---------------|-----------------------------------------------------------------------------|
| Process Plant    | 30,000        | 15.0    | Main Deck     | Structure & Equipment                                                       |
| Hull Items       | 7,200         | 26.0    | Baseline      | Equipment, Machinery, Pipes, Painting, Mooring System                       |
| Hull Bow         | 4,500         | 9.0     | Main Deck     | Accommodation, Helideck, Fire Fight, Offloading System                      |
| Lower Riser Balcony | 600        | 4.0     | Baseline      | Structure & Equipment                                                       |
| Upper Riser Balcony  | 1,500      | 5.0     | Main Deck     | Structure & Equipment                                                       |
| Riser Loads      | 10,000        | 4.0     | Baseline (Stability) | Structure & Equipment                                      |
| Mooring Loads    | 5,000         | 15.0    | Baseline (Stability) | Structure & Equipment                                      |
|                  |               | 0.0     | Main Deck (Structure) | Structure & Equipment                                      |

**Figure 3-7 - Distribution of loads alongside the hull of the FPSO**

The final step before the meshing is to input the boundary conditions, which the most adequate one depends on the type of analysis and type the results that are pursued.

With all these steps done, the structural model could be meshed through GeniE and the final result can be seen in Figure 3-8.
3.4. HydroD Modelling

This section will describe the method to solve the hydrostatic and compartment balance of the FPSO of this master thesis through the HydroD module. The procedure is based on tutorials provided by the company [52], [55] and by the User's manual [23], [50] and it is divided into two parts. First it will be shown the input data such as loading conditions and environmental data. Then, the results of the weights distribution and the cross-sectional loads (shear force and bending moments) in still water will be shown.

3.4.1. Input Data

Before the hydrostatic/hydrodynamic analysis can be done, several information must be provided for the software so it can find a distribution of the tanks for static equilibrium. The main ones can be divided into four groups: GeniE model, environmental data, tanks characteristics and equilibrium condition. The first group is both panel and structural files made in GeniE, which were introduced to the program. The most relevant information from the second group are the water depth and density, which is assumed as 2000m (deep water) with a density of 1025 kg/m³ (salt water). The third group described the equilibrium point the software has as an objective when computing the filling for each ballast/cargo tank. The main ones are the desired draught, heel angle and trim angle. The heel angle is considered as zero, while, the trim angle is not. Generally, the FPSOs have an aft trim angle in order to help the drainage in the process plant. Thus, in this project it will be considered equal to 1%. For example, if the draught in the fore part is 10m, in the aft part will be 13.23m (10m+0.01×323m). The third group is to inform the software which are ballast and cargo tanks and their liquids properties. As seen in Figure 3-7 and 3-9, there are a total of 6 cargos tanks, 12 ballast tanks (2 for each cargo tank) and one forepeak tank, which is divided into two tanks. The cargo tank shall receive oil with a density of 900 kg/m³ while the ballast and forepeak ones shall receive salt water as content with a density of 1,025 kg/m³. Also, it will be calculated 5 draughts: the minimum (7.8m), the maximum (26.8m) and 3 intermediate values (12.5m; 17.5m; 22.5m). The minimum and maximum draft could be obtained through an iterative process with the compartments balancing taking as initial draught guess the one from the equilibrium between buoyancy and mass (obtained from GeniE) for a trim equal to 0°. This is explained in the following formula below

\[ B buoyancy = L \times B \times T \times C_b \times \rho_{salt \ water} = Weight_{structure} + Weight_{loads} + Weight_{tanks} \]

In order to calculate the weight of the tanks, it was assumed that a “full” cargo tank would have 95% and an “empty” one 3% of its volume filled. This tank isn’t filled 100%, because of the inert gases presented in the tank that occupies some space. Also, it doesn’t reach the 0% mark, because there is always a small amount of oil that the pumps cannot drain from the tanks.
After all this input data is given, the following model could be generated and it is presented in Figure 3-9. Thus, the next step is to obtain the filling ratio of the compartments of the FPSO for the desired equilibrium point. The software can’t balance tanks with different liquids; thus, a methodology was followed to obtain the final distribution. The first step was to fix a certain amount of ballast for all tanks, for example, 10-20% of the ballast tank capacity and obtain a range of how many “full” cargo tanks would be needed to balance the FPSO using the weights equilibrium forces equation. Then, a certain distribution of these “full” tanks was guessed and the software would compute the filling ratio for each ballast tank to obtain a certain draught. The solver of the software has as objective the maximization of the bending moments. An example is described to illustrate the problem in Table 3-3.

Table 3-3 - Estimation of the number of cargo tanks required to reach equilibrium point for a draught of 17.5m

| Variable                  | Value   | Unit |
|---------------------------|---------|------|
| Bouyancy                  | 321,487 | ton  |
| Weight Structure          | 41,619  | ton  |
| Weight Loads              | 59,400  | ton  |
| Weight Ballast            | 8,856   | ton  |
| Weight Cargo              | 211,612 | ton  |
| Volume of Single Cargo Tank | 34,903 | m³   |
| Number of Cargo Tanks     | 6       |      |

Moreover, after a solution was found, the model also was checked by some stability criteria imposed by the classification society rules such as the IMO, ABS and NMD. If the model passed the stability checks, the solution was accepted as definitive. The flowchart representing the iterative process to find the filling ratio of each tank is described below (Figure 3-10).
3.4.2. Results

Applying the methodology of Figure 3-10, the tanks filling and its distribution could be found for each draught. The first results are the minimum and maximum one is 7.8m and 26.8m respectively. These are the load cases with all cargo tanks empty (only 3% of the capacity) and with 10 of 12 cargo tanks filled. The solver couldn’t find any draught and distribution of tanks that would satisfy the equilibrium conditions imposed of trim and heel when 12 of 12 cargo tanks were filled.

The second set of results is the tanks distribution for the tanks and the cargo stored for each draught. The maximum amount of cargo stored (T = 26.8m) is equal to, approximately, 306,977 tons of oil or 2.1 million bbl. This value is similar to the ones carried by VLCC, which are, generally, the type of hull inspired for FPSO.

The third set of results is the bending moments and shear forces distribution shown in Figures 3-11 and 3-12. As it can be seen, the maximum bending moment is the one for the case of 26.8m at station 10 with a value of -29,453,568 kN*m. This case will be the one used during the second round of the design process of chapter 5 and for the FEM in chapter 7. Moreover, the shape of the bending moment and shear force distribution is in accordance with the result expected by the beam theory from section 2.1.
Figure 3-11 - Bending Moment distribution for different draughts

Figure 3-12 - Shear Force distribution for different draughts
4. TRADITIONAL STEEL STRUCTURE SCANTLING

This chapter has the purpose of detailing the process of dimensioning a midship section of a FPSO according to the FPI from ABS [5]–[8] and DNV rules [9]–[17]. It is divided into three parts. The first section (5.1) will detail how the dimensions of different elements such as plates, longitudinal stiffeners, brackets and so on were obtained by the FPI rules. The second part (4.2) will do the same but following the DNV rules. The last part (4.3) is a strength analysis of the structure. Both rules recommend doing a hull girder strength (global loads and ultimate strength) and a buckling analysis for the different elements. The first criteria will be studied with the help of MARS 2000 software from the Bureau Veritas. The other criteria will be studied through the method presented by DNV Rules. With both criteria satisfied, the final distribution of thickness from the plates, dimensions of longitudinal stiffeners, the thickness of brackets can be obtained.

4.1. Design According to the FPI Rules

As stated in FPI rules [5], “The design criteria contained in Part 5A, Chapter 3 are applied in two phases. The first phase provides the basic hull design to reflect overall hull girder and local structural component strength”. In another word, it consists of the initial requirements for plating, the section modulus of longitudinal/stiffeners, and the scantlings of the main supporting structures in accordance with Section 5A-3-3 for the “net” ship. Then, the relevant nominal design corrosion values are added to them in order to obtain the full scantling requirements. The second phase is referred to as the Total Strength Assessment (TSA) phase. “It requires the performance of finite element structural analyses using either a three-cargo tank-length model or cargo block-length model to validate the selected scantlings from the first phase.” [5]. This part will be done in chapter 7.

Therefore, a methodology must be followed in order to estimate the dimensions for each element of the midship section. The first one is to check the material properties and their units that are required in the given formulas of the rules. Following that, estimate the global loads of the hull and the local loads for its structure. In the first phase, it is considered the nominal, maximum expected loadings that a component is likely to experience in its lifetime for the full ocean service as stated by the classification society rules. This includes loads/accelerations from pitch, roll and yaw and the different kinds of pressure existing in the ship such as external, internal, sloshing etc. Moreover, to adjust the loadings and load effects produced by the site-specific long-term environment at the installation site (compared to the full ocean service), a series of “Environmental Severity Factors” (ESFs). In this thesis, it was supposed that the betas are equals to one. The third step is to estimate the hull girder strength design parameters such as minimum section modulus and inertia of the section. With all this information in mind, the last step is to use all of this as input in the different formulas to estimate the thickness (net and gross), take the bigger one and round it up so it can have a practical thickness to be built. For example, a thickness of 12.4 mm is rounded up to 13mm.

This design will include the dimensioning of:

- Bottom plates and longitudinal stiffeners
• Side plates and longitudinal stiffeners
• Deck plates and longitudinal stiffeners
• Longitudinal bulkhead (Center and Side) plates and longitudinal stiffeners
• Transverse bulkhead plates, vertical and horizontal stiffeners
• Web frame structure: plates, stiffeners and brackets

The main characteristics of the steel used for the dimensioning are:

• $f_y$ minimum specified yield point of the material in N/cm$^2$, taken as 355 MPa for Grade H36 Steel [8]
• $E$ modulus of elasticity of the material, may be taken as $2.06 \times 10^7$ N/cm$^2$ for steel [5]
• $Q$ material conversion factor, taken as 0.72 for Grade H36 Steel [5]
• $S_m$ strength reduction factor taken as 0.908 [5], [8]

The main characteristics of the hull girder strength used for the dimensioning are:

• $SM$ required hull girder section modulus, in cm$^2$-
  
  $SM = C_1 \times C_2 \times L^2 \times B \times (C_b + 0.7) = 1,076,092 \text{ cm}^2 - \text{ m} (107.6 \text{ m}^3)$ [7]
  
  $C_1 = 10.75$ for $300 \text{ m} < \text{ LOA} < 350 \text{ m}$ [7]
  
  $C_2 = 0.01$ [7]

• $I$ the hull girder moment of inertia in cm$^2$-

  $I = L \times SM / 33.3 = 10,437,770 \text{ cm}^2 - \text{m}^2 (1,044 \text{ m}^4)$

• Assuming a neutral axis as the one obtained later in the calculations (section 5.3: $y_{na} = 15.47 \text{ m}$), the minimum section modulus for the bottom and the deck can be estimated

  $SM_{Bottom} = I / y_N = 67.14 \text{ m}^3$
  
  $SM_{Deck} = I / (D - y_N) = 62.33 \text{ m}^3$

4.1.1. **Nominal Design Corrosion Values (NDCV)**

As stated in section 5A-3-1/1.7 of the FPI rules [5], “The “net” thickness or scantlings correspond to the minimum strength in Part 5A, Chapter 3 regardless of the design service life of the installation. In addition to the coating protection specified in the Rules for all ballast tanks, minimum corrosion values for plating and structural members are to be added to the net scantlings. These minimum corrosion values are intended for a design service life of 20/25 years.”. However, instead of using directly the FPI rules, the International Association of Classification Societies (IACS) [63] increased corrosion margin (ICM) was consulted as well. By comparing both, the second one (IACS) suggest minimum values bigger than the first set of rules, in other words, a more conservative approach. Also, one of the main objectives of an oil company is to maximize the profitability of its business and one way to do it is by extracting more oil/gas with the least number of interruptions on its operation. One example of this interruption is sending the FPSO to a dry dock for maintenance and repair. Therefore, with these arguments in mind, it was selected the IACS corrosion margin.

According to Chapter 3 in IACS CSR Rules [63], the corrosion margin can be determined by the following equation.
• \( t_{\text{gross}} = \text{RoundUp}_{\text{int}}(t_{\text{corrosion}} + t_{\text{net}}) \) mm
  o Roundup \( \text{int} \) (t) means that t is rounded to the upper integer millimeter

• \( t_{\text{corrosion}} = \text{Roundup}_{0.5}(t_{c1} + t_{c2}) + t_{\text{res}} \) mm
  o \( t_{\text{res}} \) equals to 0.5 mm
  o Roundup \( 0.5 \) (t) means that t is rounded to the upper half millimeter
  o \( t_{c1} \) is the value specified in Table 4-1 for one side exposure to that compartment and in this project \( t_{c1} = t_{c2} \) and it is called ICM.

Table 4-1 - Nominal design corrosion values (NDCV) for the IACS rules. Copied from [63]

| Compartment type | Structural member | \( t_{c1} \) or \( t_{c2} \) |
|------------------|-------------------|---------------------|
| Ballast water tank, bilge tank, drain storage tank, chain locker | Face plate of PSM | Oil Tankers |
|                  | Within 3m below top of tank | 2.0 |
|                  | Elsewhere | 1.5 |
|                  | Face plate of PSM | Within 3m below top of tank | 1.7 |
|                  | Elsewhere | 1.2 |
|                  | Other members | Within 3m below top of tank | 1.7 |
|                  | Elsewhere | 1.0 |
| Cargo oil tank, slop tank | Face plate of PSM | Inner-bottom plating/bottom of tank | 2.1 |
|                  | Within 3m below top of tank | Elsewhere | 1.4 |
|                  | Other members | Within 3m below top of tank | 1.7 |
|                  | Elsewhere | 1.0 |
| Exposed to atmosphere | Weather deck plating | 1.7 |
| Other members | 1.0 |
| Exposed to seawater | Shell plating between the minimum design ballast draught waterline and the scantling draught waterline | 1.5 |
| Fuel and lube oil tank | 0.7 |
| Fresh water tank | 0.7 |
| Void Spaces | Spaces not normally accessed, e.g. access only via bolted manhole openings, pipe tunnels, inner surface of stool space not common with a dry bulk cargo hold or ballast cargo hold, etc | 0.7 |
| Dry space | Internals of machinery spaces, pump room, store rooms, steering gear space, etc | 0.5 |

4.1.2. Bottom Structure

According to the FPI rules [5], the definition for the term “bottom shell plating” refers to the plating from the keel to the upper turn of the bilge for 0.4L amidships. Therefore, for the case of this project there are three kinds of plates to be specified: keel plate, cargo tank plate and ballast tank plate. The net thickness for these elements is provided by section 5A-3-3/7.3.1 [5] as:

• \( t_{\text{net}} = \max(t_1, t_2, t_3, t_4) \) mm
  o \( t_1 = 0.73s\sqrt{k_1p/f_1} \) mm
  o \( t_2 = 0.73s\sqrt{k_2p/f_2} \) mm
  o \( t_3 = cs\sqrt{S_mf_y/E} \) mm

• An observation is also done for the keel plate according to the FPI rule. The net thickness of the flat plate keel is to be not less than that required for the bottom shell plating at that location by 5A-3-3/7.3.1 increased by 1.5 mm.
Using as input the system of equations above and the observation for the keel plate, the net thickness can be calculated and are presented in the table below (Table 4-2).

| Plate Number | Net Thickness [mm] | t1 [mm] | t2 [mm] | t3 [mm] |
|--------------|--------------------|---------|---------|---------|
| Keel Plate   | 19.0               | 17.34   | 13.99   | 14.93   |
| Cargo Area   | 18.0               | 17.34   | 13.99   | 14.93   |
| Ballast Tank | 18.0               | 17.34   | 13.99   | 14.93   |

By applying the respective corrosion margin in the plates, the gross thickness can be calculated as presented in the table below (Table 4-3).

| Bottom | Net Thickness Rule [mm] | ICM [mm] | t res [mm] | Gross Thickness Rule [mm] | Final Thickness [mm] |
|--------|-------------------------|----------|------------|--------------------------|---------------------|
| Keel Plate | 19                      | 4.5      | 0.5        | 24                       | 24                  |
| Cargo Area   | 18                      | 4.5      | 0.5        | 23                       | 23                  |
| Ballast Tank | 18                      | 3        | 0.5        | 21.5                     | 22                  |

Following the FPI requirements as well, the longitudinal stiffener to be fitted in the bottom structure can be calculated by 5A-3-3/7.5. The main parameter is the net section modulus in association with the effective plating to which it is attached. It can’t be less than obtained from the following equation.

- \( SM = \frac{M}{f_b} \text{ cm}^3 \)
  - \( M = 1000 \text{psi} \text{ft}^2/k \) (Bending moment applied to the stiffener)
  - \( f_b = (1.0 - 0.65a_1 SM_{RB}/SM_B)S_mf_y \leq 0.55 S_mf_y \) for the longitudinal bottom stiffeners

The main results are presented in Table 4-4. Moreover, as stated in the definition, the longitudinal is associated with an effective plating. Its width can be calculated in section 5A-3-3/7 in Figure 6 item a. The following formula can be used and this results in an effective width of 728 mm.

- \( \frac{b_e}{S} = 1.219 - 0.965\left(\frac{c_{10}}{S}\right) \)

Generally, a T profile is used at this location, because of the high section modulus required. Also, the dimensions for the web vary from 400mm to 550mm in length with a net thickness of 10 to 14mm and for the flange, the length varies from 300mm to 450mm with a net thickness between 20 to 35 mm. Thus, by calculating the section modulus with this data in mind and the effective plate width and thickness, the final profile dimensions can be obtained and presented below.

| Bottom Stiffener | SM Stiff min [cm3] | 3,726 |
|------------------|---------------------|-------|
| Type Selected    | T Profile           |       |
| Net Dimensions [mm] | 500x10 + 400x30   |       |
| Gross Dimensions [mm] | 500x14 + 400x34 |       |
| Area [mm2]       | 20,600              |       |
| SM [cm3]         | 7,504               |       |
| Inertia [cm4]    | 147,143             |       |

Table 4-4 - Final design for the bottom stiffener
4.1.3. Side Structure

As stated in section 5A-3-3/9.1 from the FPI rules [5], the net thickness of the side shell plating cannot be less than the maximum of the following thickness as specified below for the midship 0.4L:

- \( t_{net} = \max(t_3, t_2, t_3, t_4) \) mm
  - \( t_1 = 0.73s\sqrt{k_1p/f_1} \) mm
  - \( t_2 = 0.73s\sqrt{k_2p/f_2} \) mm
  - \( t_3 = cs\sqrt{S_mf_y/E} \) mm
  - \( t_4 = 90(s/1000 + 0.7)[BT/(S_m f_y)]^{1/2} + 0.5 \) mm

- Two observations are also done as well for the shear strake plate according to the ABS rule [7]. The first one is in the aspect of its minimum width, which must be above 1800mm for the ship’s thesis. The second one is that the net thickness shall not be less than the thickness of the adjacent side shell plating.

Using as input the system of equations above and the observation for the shear strake plate, the net thickness can be calculated and are presented below (Table 4-5).

| Plate Number | Net Thickness [mm] | t1 [mm] | t2 [mm] | t3 [mm] | t4 [mm] |
|--------------|--------------------|--------|--------|--------|--------|
| 5            | 16.0               | 15.30  | 13.08  | 14.93  | 5.37   |
| 6            | 15.0               | 14.71  | 13.04  | 14.93  | 5.37   |
| 7            | 15.0               | 14.66  | 13.00  | 14.93  | 5.37   |
| 8            | 15.0               | 14.62  | 12.96  | 14.93  | 5.37   |
| 9            | 15.0               | 14.58  | 12.92  | 14.93  | 5.37   |
| 10           | 15.0               | 13.79  | 12.23  | 14.93  | 5.37   |
| 11           | 15.0               | 12.51  | 11.09  | 14.93  | 5.37   |
| 12           | 15.0               | 11.08  | 9.82   | 14.93  | 5.37   |
| 13           | 15.0               | 9.43   | 8.36   | 14.93  | 5.37   |
| 14           | 15.0               | 8.50   | 7.53   | 14.93  | 5.37   |

By applying the respective corrosion margin in the plates, the gross thickness can be calculated as presented in the table below (Table 4-6).

| Plate | Net Thickness Rule [mm] | ICM [mm] | t res [mm] | Gross Thickness Rule [mm] | Final Thickness [mm] |
|-------|-------------------------|----------|------------|---------------------------|---------------------|
| 5     | 16                      | 2.5      | 0.5        | 19                        | 19                  |
| 6     | 15                      | 2.5      | 0.5        | 18                        | 18                  |
| 7     | 15                      | 2.5      | 0.5        | 18                        | 18                  |
| 8     | 15                      | 2.5      | 0.5        | 18                        | 18                  |
| 9     | 15                      | 2.5      | 0.5        | 18                        | 18                  |
| 10    | 15                      | 2.5      | 0.5        | 18                        | 18                  |
| 11    | 15                      | 2.5      | 0.5        | 18                        | 18                  |
| 12    | 15                      | 2.5      | 0.5        | 18                        | 18                  |
| 13    | 15                      | 3.5      | 0.5        | 19                        | 19                  |
| 14    | 15                      | 3.5      | 0.5        | 19                        | 19                  |
By the FPI rules, the longitudinal stiffener to be fitted in the side structure can be calculated by 5A-3-3/9.5. The main parameter is the net section modulus in association with the effective plating to which it is attached. It can’t be less than obtained from the following equation.

- \( SM = \frac{M}{f_b} \text{ cm}^3 \)
  - \( M = 1000 \text{psi} l^2/k \) (Bending moment applied to the stiffener)
  - \( f_b = [0.86 - 0.52a_1 \left( SM_{RB}/SM_b \right)(y/y_N)]S_m f_y \leq 0.75 S_m f_y \) for the longitudinal below the neutral axis
  - \( f_b = 2[0.86 - 0.52a_2 \left( SM_{RD}/SM_D \right)(y/y_N)]S_m f_y \leq 0.75 S_m f_y \) for longitudinal above the neutral axis

The main results are presented in the following Table 4-7. Moreover, an effective width of 728 mm is also used as in the bottom structure section.

According to similar midship sections [64], generally an L profile is used in this location so that the water doesn’t accumulate in the stiffener when the ship has a roll displacement. Also, the dimensions of the web vary from 350 to 650mm in length and a thickness between 11.5 and 13mm. While the flange has a width of 120mm and a thickness between 18 to 35mm in the bigger profiles. Thus, by calculating the section modulus with this data in mind and the effective plate width and thickness, the final profile dimensions can be obtained and presented below.

| Side Stiffener | SM Stiff min [cm³] | Type Selected | Net Dimensions [mm] | Gross Dimensions [mm] | Area [mm²] | SM [cm³] | Inertia [cm⁴] |
|----------------|-------------------|---------------|---------------------|-----------------------|-----------|---------|-------------|
| SM Stiff min [cm³] | 3,086 | L Profile | 650x15 + 120x23 | 650x17 + 120x25 | 13,625 | 3,701 | 389,208 |

As can be seen in Figure 3-3 and 3-4, there are horizontal plates that connect the side shell plating of the ship with the side longitudinal bulkhead. The FPI rules [5] and Marine Vessel Rules [7] states that they can be modelled with the equations from the side shell plating with some modifications. They are presented below.

- \( t_{net} = \text{ma}\times(t_1, t_2, t_3, t_4) \text{ mm} \)
  - \( t_1 = 0.73s\sqrt{k_1 p/f_1} \text{ mm} \)
  - \( t_2 = 0.73s\sqrt{k_2 p/f_2} \text{ mm} \)
  - \( t_3 = cs\sqrt{S_m f_y/E} \text{ mm} \)
  - \( t_4 = \min (11; 0.012 + L + 7.7) \text{ mm} \). This is presented in section 5A-3-3/11.9 from FPI rules [5]

- No internal pressure is considered, once the pressure slightly above and slightly below the plate is quite close. Therefore, only the external pressure is considered. For this project, it was
considered the maximum external pressure (14.88 N/cm²) of the side shell plating for all the horizontal plates.

Using this system of equations and the observation regarding the pressure, the net thickness of the 6 horizontal plates could be estimated and it is presented below. The lower the number of the plate, the close it is from the bottom region (Table 4-8).

Table 4-8 - Net thickness estimation for the horizontal plates in the ballast tank

| Plate Number | Net Thickness [mm] | t1 [mm] | t2 [mm] | t3 [mm] | t4 [mm] |
|--------------|--------------------|---------|---------|---------|---------|
| 5 H          | 15                 | 11.89   | 10.54   | 14.93   | 11.00   |
| 6 H          | 15                 | 11.89   | 10.54   | 14.93   | 11.00   |
| 7 H          | 15                 | 11.89   | 10.54   | 14.93   | 11.00   |
| 8 H          | 15                 | 11.89   | 10.54   | 14.93   | 11.00   |
| 9 H          | 15                 | 11.89   | 10.54   | 14.93   | 11.00   |
| 10 H         | 15                 | 11.89   | 10.54   | 14.93   | 11.00   |

By applying the respective corrosion margin in the plates, the gross thickness can be calculated as presented in the table below (Table 4-9).

Table 4-9 - Gross thickness estimation for the horizontal plates in the ballast tank

| Horizontal Plates Wing Tanks | Plate | Rule Thickness [mm] | ICM [mm] | t res [mm] | Gross Thickness Rule [mm] | Final Thickness [mm] |
|------------------------------|-------|---------------------|----------|------------|---------------------------|---------------------|
| 5 H                          | 15    | 2                   | 0.5      | 17.5       | 18                        |
| 6 H                          | 15    | 2                   | 0.5      | 17.5       | 18                        |
| 7 H                          | 15    | 2                   | 0.5      | 17.5       | 18                        |
| 8 H                          | 15    | 2                   | 0.5      | 17.5       | 18                        |
| 9 H                          | 15    | 2                   | 0.5      | 17.5       | 18                        |
| 10 H                         | 15    | 2                   | 0.5      | 17.5       | 18                        |

The same formulation for calculating the longitudinal stiffeners of the side was used for this kind of plates with the pressure specification. The main results are shown in the table below (Table 4-10).

The profile selected for this element was as well the L, because of the same reason for the side longitudinal stiffener. Thus, by calculating the section modulus with this data in mind and the effective plate width and thickness, the final profile dimensions can be obtained and are presented below.

Table 4-10 - Final design of the stiffeners of the horizontal plates located in the ballast tanks

| Side Stiffener | SM Stiff min [cm³] | Type Selected | Area [mm²] | SM [cm³] | Inertia [cm⁴] |
|----------------|--------------------|---------------|------------|----------|---------------|
| For 5H and 10H Plates | 3,086             | L Profile     | 13,625     | 3,701    | 343,710       |
| For 6H to 9H Plates  |                   |               |           |          |               |

Inertia [cm⁴] 343,710
4.1.4. Deck Structure

According to the Marine Vessel Rules [7], the deck structures can be classified as freeboard, bulkhead and strength deck. This section will be focused on dimensioning the plates of the strength deck, which is the one that forms the top of the effective hull girder at any part of its length [7]. The net thickness can be calculated by 5A-3-3/9.5 from FPI rules and is presented below.

\[ t_{\text{net}} = \max(t_1, t_2, t_3) \text{ mm} \]

- \[ t_1 = 0.73s\sqrt{k_1p/f_1} \text{ mm} \]
- \[ t_2 = 0.73s\sqrt{k_2p/f_2} \text{ mm} \]
- \[ t_3 = cs\sqrt{S_mf_y/E} \text{ mm} \]

Compared to the bottom and side structures, the pressure input is not that great, once there are not any external or and the sloshing effects are minimum according to the FPI rules [5]. Thus, only the internal pressure from the tank is used, which is not that higher for this region. Consequently, it returns low values of \( t_1 \) and \( t_2 \). However, in order to balance this, the minimum thickness (\( t_3 \)) provided by the rules is different from the bottom and side structure, because it gives higher values compared to them (14.93 mm to 18.23 mm). Thus, the thickness of the deck will be driven by the values of \( t_3 \). The final net values results are shown below, where the 15 and 16 plates refer to the ballast and cargo region respectively (Table 4-11).

| Plate Number | Net Thickness [mm] | \( t_1 \) [mm] | \( t_2 \) [mm] | \( t_3 \) [mm] |
|--------------|--------------------|----------------|----------------|----------------|
| 15           | 19.0               | 13.58          | 7.11           | 18.23          |
| 16           | 19.0               | 13.58          | 7.11           | 18.23          |

By applying the respective corrosion margin in the plates, the gross thickness can be calculated as presented in the table below (Table 4-12).

| Deck | Plate | Rule Thickness [mm] | ICM [mm] | \( t_{\text{res}} \) [mm] | Gross Thickness Rule [mm] | Final Thickness [mm] |
|------|-------|---------------------|----------|----------------------|--------------------------|----------------------|
|      | 15    | 19                  | 2.5      | 0.5                  | 22                       | 22                   |
|      | 16    | 19                  | 3.5      | 0.5                  | 23                       | 23                   |

By the FPI rules, the longitudinal stiffener to be fitted in the deck structure can be calculated by 5A-3-3/9.5. The main parameter is the net section modulus in association with the effective plating to which it is attached. It can’t be less than obtained from the following equation.

\[ SM = M/f_b \text{ cm}^3 \]

- \[ M = 1000psl^2/k \text{ (Bending moment applied to the stiffener)} \]
- \[ f_b = [1.0 - 0.60a_2(SM_{RD}/SM_{DB})]S_mf_y \text{ for deck longitudinal} \]

The main results are presented in following Table 4-13. Moreover, an effective width of 728 mm is used as in the bottom structure section. Moreover, according to similar ships [64], the profile generally used in this region is the L or FB profile. This is due to the water retain effect explained in the side structures.
section and the lower section modulus required. However, as will be detailed in section 3.4, using a profile with a section modulus close to the minimum required (864 cm³) does not comply with the global hull girder strength and buckling criteria. This is due to the proximity of the neutral axis to the bottom structures, once it would provide higher stresses for the deck structures according to the beam stress theory. Therefore, after some iterations with L profiles similar to the ones used in the side structures, a selection was made and it is presented in the table below (Table 4-13). Notice that the required section modulus required to pass the strength and buckling criteria is close to 3 times the minimum required.

Table 4-13 - Final design for the deck stiffeners

| Deck Stiffener | SM Stiff min [cm³] | Type Selected | Net Dimensions [mm] | Gross Dimensions [mm] | Area [mm²] | SM [cm³] | Inertia [cm⁴] |
|----------------|-------------------|---------------|----------------------|-----------------------|-----------|---------|-----------|
|                | 866               | L Profile     | 650x13 + 120x31      | 650x17 + 120x35       | 14,655    | 4,317   | 389,481   |

4.1.5. Longitudinal Bulkhead

The net thickness provided in section 5A-3-3/13.1 in FPI rules [5] is valid both for the center and side longitudinal bulkhead plating. It can't be lower than as specified below.

- \( t_{net} = \max(t_1, t_2, t_3) \text{ mm} \)
  - \( t_1 = 0.73s\sqrt{k_1p/f_1} \text{ mm} \)
  - \( t_2 = 0.73s\sqrt{k_2p/f_2} \text{ mm} \)
  - \( t_3 = cs\sqrt{S_mf_y/E} \text{ mm} \)

- For this kind of structure, the sloshing and internal pressure are the relevant ones. Thus, the sloshing pressure is calculated as specified in 5A-3-2/11.5.1 of FPI rules [5].

Using this system of equations and the observation regarding the pressure, the net thickness of the plates for the center and side could be estimated and it is presented below. The lower the number of the plate, the close it is from the bottom region (Table 4-14 and 4-15).

Table 4-14 - Net thickness for the center longitudinal bulkhead plates

| Center Longitudinal Bulkhead | Plate Number | Net Thickness [mm] | t1 [mm] | t2 [mm] | t3 [mm] | t4 [mm] |
|-----------------------------|--------------|-------------------|--------|--------|--------|--------|
|                             | 17           | 17.0              | 16.62  | 15.02  | 13.25  | 9.5    |
|                             | 18           | 15.0              | 14.55  | 13.84  | 11.41  | 9.5    |
|                             | 19           | 14.0              | 13.11  | 12.81  | 11.41  | 9.5    |
|                             | 20           | 13.0              | 11.39  | 12.08  | 11.41  | 9.5    |
|                             | 21           | 13.0              | 10.16  | 12.08  | 11.41  | 9.5    |
|                             | 22           | 13.0              | 10.35  | 12.08  | 11.41  | 9.5    |
|                             | 23           | 13.0              | 10.97  | 12.08  | 11.41  | 9.5    |
|                             | 24           | 13.0              | 11.71  | 12.08  | 11.41  | 9.5    |
|                             | 25           | 13.0              | 12.63  | 12.08  | 11.41  | 9.5    |
By applying the respective corrosion margin in the plates, the gross thickness can be calculated as presented in the table below (Table 4-16 and 4-17).

**Table 4-15 - Net thickness for the side longitudinal bulkhead plates**

| Side Longitudinal Bulkhead | Plate Number | Net Thickness [mm] | t1 [mm] | t2 [mm] | t3 [mm] | t4 [mm] |
|---------------------------|--------------|--------------------|---------|---------|---------|---------|
| 17 S                      | 19.0         | 18.66              | 15.02   | 13.25   | 9.5     |
| 18 S                      | 17.0         | 16.01              | 14.30   | 11.41   | 9.5     |
| 19 S                      | 14.0         | 13.91              | 13.54   | 11.41   | 9.5     |
| 20 S                      | 13.0         | 12.16              | 12.73   | 11.41   | 9.5     |
| 21 S                      | 12.0         | 10.64              | 11.87   | 11.41   | 9.5     |
| 22 S                      | 12.0         | 10.01              | 10.94   | 11.41   | 9.5     |
| 23 S                      | 12.0         | 9.71               | 9.92    | 11.41   | 9.5     |
| 24 S                      | 12.0         | 9.29               | 8.78    | 11.41   | 9.5     |
| 25 S                      | 12.0         | 8.66               | 7.48    | 11.41   | 9.5     |

**Table 4-16 - Gross thickness of the center longitudinal bulkhead plates**

| Center Long. Bkd. | Plate | Rule Thickness [mm] | ICM [mm] | t res [mm] | Gross Thickness Rule [mm] | Final Thickness [mm] |
|-------------------|-------|---------------------|----------|------------|--------------------------|---------------------|
| 17                | 17    | 2                   | 0.5      | 19.5       | 20                       |
| 18                | 15    | 2                   | 0.5      | 17.5       | 18                       |
| 19                | 14    | 2                   | 0.5      | 16.5       | 17                       |
| 20                | 13    | 2                   | 0.5      | 15.5       | 17                       |
| 21                | 13    | 2                   | 0.5      | 15.5       | 17                       |
| 22                | 13    | 2                   | 0.5      | 15.5       | 17                       |
| 23                | 13    | 2                   | 0.5      | 15.5       | 17                       |
| 24                | 13    | 2                   | 0.5      | 15.5       | 17                       |
| 25                | 13    | 2                   | 0.5      | 15.5       | 16                       |

**Table 4-17 - Gross thickness of the side longitudinal bulkhead plates**

| Side Long. Bkd. | Plate | Rule Thickness [mm] | ICM [mm] | t res [mm] | Gross Thickness Rule [mm] | Final Thickness [mm] |
|----------------|-------|---------------------|----------|------------|--------------------------|---------------------|
| 17 S           | 19    | 2.5                 | 0.5      | 22         | 22                       |
| 18 S           | 17    | 2.5                 | 0.5      | 20         | 19                       |
| 19 S           | 14    | 2.5                 | 0.5      | 17         | 17                       |
| 20 S           | 13    | 2.5                 | 0.5      | 16         | 16                       |
| 21 S           | 12    | 2.5                 | 0.5      | 15         | 16                       |
| 22 S           | 12    | 2.5                 | 0.5      | 15         | 16                       |
| 23 S           | 12    | 2.5                 | 0.5      | 15         | 16                       |
| 24 S           | 12    | 2.5                 | 0.5      | 15         | 16                       |
| 25 S           | 12    | 2.5                 | 0.5      | 15         | 16                       |

By the FPI rules, the longitudinal stiffener to be fitted in the side structure can be calculated by 5A-3-3/13.5. The main parameter is the net section modulus in association with the effective plating to which it is attached. It can’t be less than obtained from the following equation.

- \( SM = \frac{M}{f_b} \text{ cm}^3 \)
  - \( M = 1000c_ipsi^2/k \) (Bending moment applied to the stiffener)
  - \( f_b = 1.4[1.0 - 0.28(z/B) - 0.52a_1 \left( \frac{SM_{RB}}{SM_B}(y/y_N) \right)}S_{mf_y} \leq 0.90S_{mf_y} \) for the longitudinal below the neutral axis
  - \( f_b = 2.2[1.0 - 0.28(z/B) - 0.52a_2 \left( \frac{SM_{RB}}{SM_B}(y/y_N) \right)}S_{mf_y} \leq 0.90S_{mf_y} \) for longitudinal above the neutral axis
  - \( z \) equals zero and 23.8 m for the center and side longitudinal bulkhead respectively
The main results are presented in Table 4-18. Moreover, an effective width of 728 mm is used as in the bottom structure section. The characteristic profile for this region is also the L profile for the same reason stated in the side structure section. Moreover, the same range of pattern of longitudinal in the side structure was used to determine the most appropriate for both. After some iterations calculating the section modulus of different patterns, the final profile was selected for both bulkheads and the main characteristics are presented below.

Table 4-18 - Final design of the stiffener for the longitudinal bulkhead

| Center and Side BKD Stiffeners |   |
|--------------------------------|---|
| SM Stiff min [cm³]             | 3,454 |
| Type Selected                  | L Profile |
| Net Dimensions [mm]            | 650x13 + 120x33 |
| Gross Dimensions [mm]          | 650x15 + 120x35 |
| Area [mm²]                     | 13,425 |
| SM [cm³]                       | 4,317 |
| Inertia [cm⁴]                  | 343,710 |

4.1.6. Transverse Bulkhead

The transverse bulkhead formulas apply for the watertight ones located at the ends of the cargo tanks. Its net thickness plating, which is in 5A-3-3/13.3, is to be not less than t, as specified below:

- \( t_{net} = \max(t_1, t_2) \text{ mm} \)
  - \( t_1 = 0.73s\sqrt{k_2p/f_2} \text{ mm} \)
  - \( t_2 = 9.5 \text{ mm} \)

- For this kind of structure, the sloshing and internal pressure are the relevant ones. Thus, the sloshing pressure is calculated as specified in 5A-3-2/11.5.1 of FPI rules [5].

Using this system of equations and the observation regarding the pressure, the net thickness of the plates could be estimated and it is presented below. The height of each plate from the transverse bulkhead coincides with the ones from the center longitudinal bulkhead.

Table 4-19 - Net thickness of the transverse bulkhead plates

| Plate Number | Thickness [mm] | t [mm] | t min [mm] |
|--------------|---------------|-------|-----------|
| 17 T         | 17            | 16.26 | 9.5       |
| 18 T         | 16            | 15.48 | 9.5       |
| 19 T         | 16            | 15.04 | 9.5       |
| 20 T         | 14            | 13.92 | 9.5       |
| 21 T         | 14            | 13.12 | 9.5       |
| 22 T         | 14            | 13.12 | 9.5       |
| 23 T         | 14            | 13.12 | 9.5       |
| 24 T         | 14            | 13.12 | 9.5       |
| 25 T         | 14            | 13.12 | 9.5       |

By applying the respective corrosion margin in the plates, the gross thickness can be calculated as presented in the table below (Table 4-20).
The stiffeners for this plating are relative different compared to the other ones. It has both vertical and horizontal elements. One piece of the vertical extends from the bottom to the deck of the midship section and are spaced from the centerline to the side with a spacing of 850mm. While the horizontal goes from the centerline until the side longitudinal bulkhead as shown in Figure 4-1. Although the formula is the same, the difference is the l in the bending moment. When considering the vertical stiffeners from the transversal bulkhead, the l used is 5.1m, while, for the horizontal stiffeners the l is equal to the breadth of the cargo tank (23.8m). The formula from section 5A-3-3/13.5 and results are presented below for both stiffeners.

- \( SM = \frac{M}{f_b} \text{ cm}^3 \)
  - \( M = 1000c_1pst^2/k \) (Bending moment applied to the stiffener)
  - \( f_b = 0.7S_mf_s \) for transverse bulkhead stiffeners

![Figure 4-1 – Representation of the horizontal stiffener of the transverse bulkhead (Copied from [5])](image)

Analyzing similar midship sections and the one from P66, it was determined that the profile for the vertical and horizontal stiffener would be an L and a T profile respectively. The dimensions possible for both are the ones established in the bottom and side structures section. After some iterations calculating the section modulus of different types, the final profiles for both were selected and the main characteristics are presented below (Table 4-21).
4.1.7. Web Frame Structure

The design of the web frame structure consists of three steps. The first one is the dimensions of the plates by section 5A-3-3/11.11 from the FPI rules. The second step is the calculation of its thickness and stiffeners. The last one is the determination of the dimensions of the brackets.

Section 5A-3-3/11.11 states that “In general, webs, girders and transverses are not to be less in depth than specified below, as a percentage of the span”. The bottom and deck height enters in the category from 5A-3-3/11.11.1 “for deck transverses without deck girders for ship-type installations with centerline longitudinal bulkhead”. This results in a value of 12.5% of \( l_t \), which is the breadth of the cargo tank (23.8m), or 2.975m. Once, this structure will have stiffeners to strengthen it, this value was rounded up to the next multiple of 0.85m. Consequently, the height of the bottom and deck transverse is 3.4m.

Another element is in respect of the longitudinal bulkhead region. In line with 5A-3-3/11.11.3, the depth of the web in this region is equivalent to 14% of \( l_s \), which is the distance in Figure 4-2. The outcome is a value of 3.57m. After rounding it up to the next multiple of 0.85m, the final value is 4.25m or approximately 2.2m for each side of the centerline. A scheme is presented in Figure 4-3.

Moreover, the rules demand some vertical openings or manholes through the ballast transverse bulkhead as stated in section 5A-3-1/5.21. The minimum clear opening is not to be less than 600 mm (24 in.) by 800 mm (32 in.) at a height of not more than 600 mm (24 in.). It will be fitted 8 manholes between two horizontal plates from section 3.2.2 or two manholes every 640mm in the vertical.

![Figure 4-2 - Web frame measures to be used according to the FPI rules (Copied from [5])](image)
The next stage is the dimension of the plate net thickness. As stated in the rules, it cannot be less than the maximum of the following thickness as specified below for the midship 0.4L from 5A-3-3/13.1:

- \( t_{\text{net}} = \max(t_1, t_2, t_3, t_4) \) mm
  - \( t_1 = 0.73s_{\sqrt{k_1p/f_1}} \) mm
  - \( t_2 = 0.73s_{\sqrt{k_2p/f_2}} \) mm
  - \( t_3 = cs\sqrt{S_{\text{m}}/E} \) mm
  - \( t_4 = \min(11; 0.012L + 7.7) \)

- The pressure to be taken is the maximum between the external, internal and sloshing pressure when relevant.

Using as input the system of equations above and the observation for the pressure, the net thickness can be calculated and are presented in the table below (Table 4-22).

| Plate Number | Net Thickness [mm] | t1 [mm] | t2 [mm] | t3 [mm] | t4 [mm] |
|--------------|-------------------|--------|--------|--------|--------|
| Bottom       |                   |        |        |        |        |
| 1            | 20.0              | 19.75  | 14.99  | 13.18  | 11.00  |
| 2            | 17.0              | 16.48  | 14.27  | 11.41  | 11.00  |
| 3            | 15.0              | 14.94  | 14.22  | 11.41  | 11.00  |
| 4            | 14.0              | 12.83  | 13.22  | 11.41  | 11.00  |
| 5            | 13.0              | 11.00  | 12.13  | 11.41  | 11.00  |
| 6            | 13.0              | 10.98  | 12.10  | 11.41  | 11.00  |
| 7            | 13.0              | 11.76  | 12.10  | 11.41  | 11.00  |
| 8            | 13.0              | 12.73  | 12.10  | 11.41  | 11.00  |
| Deck         |                   |        |        |        |        |
| 9            | 14.0              | 13.99  | 12.10  | 11.92  | 11.00  |

By applying the respective corrosion margin in the plates, the gross thickness can be calculated as presented in the table below (Table 4-23).
By the FPI rules, the vertical and horizontal stiffener to be fitted in the different plates can be calculated by $5A-3/13.5$. The main parameter is the net section modulus in association with the effective plating to which it is attached. It can’t be less than obtained from the following equation.

$$SM = M/f_b \text{ cm}^3$$

- $M = 1000C_plsi^2/k$ (Bending moment applied to the stiffener)
- $f_b = 0.7S_{nfy}$ for transverse bulkhead stiffeners

The main results are presented in Table 4-24. Moreover, an effective width of 728 mm is used as in the bottom structure section. Analyzing the section modulus required and the choice of it for the different regions of the midship section, the most appropriate is an L profile with the range defined in the side structure section. After some iterations calculating the section modulus of a different type, the final profile for both was selected and its main characteristics are presented below.

| Plate Number | Gross Thickness [mm] | ICM [mm] | Net Thickness [mm] |
|--------------|----------------------|----------|-------------------|
| Bottom       | 1                    | 23       | 3.0               | 20                |
|              | 2                    | 20       | 3.0               | 17                |
|              | 3                    | 18       | 3.0               | 15                |
|              | 4                    | 17       | 3.0               | 14                |
|              | 5                    | 16       | 3.0               | 13                |
|              | 6                    | 16       | 3.0               | 13                |
|              | 7                    | 16       | 3.0               | 13                |
|              | 8                    | 16       | 3.0               | 13                |
|              | 9                    | 17       | 3.0               | 14                |

| Plate Number | Gross Thickness [mm] | ICM [mm] | Net Thickness [mm] |
|--------------|----------------------|----------|-------------------|
| Deck         | 9                    | 17       | 3.0               | 14                |

Table 4-23 - Gross thickness of the plates from the web frame structure

The last step to finish the dimensioning of the web frame structure regards the four brackets located in Figure 4-4. The dimensions of it were inspired in similar ships such as [4], which have a leg of length between 3 and 4 meters. Thus, considering the spacing of 850mm and its multiple, the final leg has a length of 3.4m. Moreover, the FPI rules section 5A-3-11.13 determines that “Generally, brackets are to have a thickness not less than that of the member supported, are to have flanges or face plates at their edges and are to be suitably stiffened”. Therefore, the thickness of the bracket’s web is 23mm and 17 for the bottom and deck structures respectively. Regarding the flange dimensions, it must comply with section 5A-3-8/1.9.4 and 5A-3-4/1.9.6

- 5A-3-4/1.9.4: “The breadth-thickness ratio of flanges is to satisfy the limits given below”
  - $f_w/t_f = 0.4\sqrt{E/f_y} = 9.63$
- 5A-3-4/1.9.6: “The width of the flange or face bar $f_w$ is not to be less than:”

The main results are presented in Table 4-24. Moreover, an effective width of 728 mm is used as in the bottom structure section. Analyzing the section modulus required and the choice of it for the different regions of the midship section, the most appropriate is an L profile with the range defined in the side structure section. After some iterations calculating the section modulus of a different type, the final profile for both was selected and its main characteristics are presented below.

| Web Frame Stiffener | SM Stiff min [cm3] | Type Selected | Net Dimensions [mm] | Gross Dimensions [mm] | Area [mm2] | SM [cm3] | Inertia [cm4] |
|---------------------|--------------------|---------------|---------------------|-----------------------|------------|----------|--------------|
|                     | 3,128              | L Profile     | 650x13 + 120x33     | 650x15 + 120x35       | 9,750      | 3,845    | 343,710      |

Table 4-24 - Web frame stiffeners final design
Thus, assuming a width of the flange equals 365 cm and using the formulation in 5A-3-4/7.9.4, the flange thickness is approximately 38mm. Notice that this flange extends for the whole web frame structure as seen in Figure 4-4.

![Figure 4-4 - Example of web frame structure of a FPSO. Source: [4]](image)

### 4.2. Design According to the DNV Rules

Although the midship section is already designed by the FPI rules, the DNV is one of the most used in the world for different kinds of ships. Therefore, it is interesting to design the solution proposed by this classification society for two purposes. The first one is to check if the values founded by the first set of rules are realistic, once the results of the plates thickness are similar for all these highly used classification societies. The second purpose is to identify if the DNV Rules design gives a better design or not using as criteria weight of the midship section and the stress in the structure.

However, this section will be focused on the net thickness of the plates. This includes the plates from section 3.2.2. to 3.2.4 (bottom, side, deck and longitudinal bulkhead structures). The other elements such as stiffeners, the transverse bulkhead and the web frame structure and parameters such as stiffeners spacing and increased corrosion margin will remain the same.

The process to obtain the net and gross thickness of the different plates is similar to the one in section 3.2. First, check the material properties and their units that are required in the given formulas of the rules [9], [12]. Second, estimate the loads and accelerations for each section [9], [13]. Moreover, the “Environmental Severity Factors” (ESFs) used in FPI rules were considered the same in the design. The third step, is to estimate the hull girder strength design parameters such as section modulus and inertia of the section [9], [14]. With all this information in mind, the last step is to use all of this as input in the different formulas to estimate the thickness [9], [15], take the bigger one and round it up so it can have a practical thickness to be build.

The main characteristics of the steel used for the dimensioning are:
• $f_y$ minimum specified yield point of the material in N/mm², taken as 355 MPa for Grade H36 Steel [9], [12]
• E modulus of elasticity of the material, may be taken as 206.000 N/mm² for steel [9], [12]
• $f_s$ material conversion factor, taken as 1.39 for Grade H36 Steel [9], [12]

The main characteristics of the hull girder strength used for the dimensioning are:

- $I$ the hull girder moment of inertia in cm⁴, amidships, is to be not less than [9], [14]
  - $I = 3C_wL^3B(C_b + 0.7) = 104,524,583,627 cm^4 (1,045 m^4)$
    - $C_w = 10.75$
- Assuming a neutral axis the same neutral axis height obtained later in the calculations ($y_N = 15.46m$), the minimum section modulus for the bottom and the deck can be estimated
  - $SM_{Bottom} = I/y_N = 67.61 m^3$
  - $SM_{Deck} = I/(D - y_N) = 62.07 m^3$

### 4.2.1. Bottom Structure

The bottom structure dimensioning is based on Section 6 from [9]. It includes the dimensioning of the keel plate (minimum breadth, net and gross thickness), the cargo tank plate (net and gross thickness) and the ballast tank plate (net and gross thickness). The keel plate will be designed by following the equations C201 and C202 from Section 6. These equations give the minimum breadth and minimum thickness of the plate respectively and are shown below.

- S6 – C201: $b_{min} = 800 + 5L [mm]$
- S6 – C202: $t_{gross, min} = 7 + 0.05L/\sqrt{f_1} + t_k [mm]$
  - Where $t_k$ is the ICM given in section 3.2.1 equals to 5mm
- Observation: The thickness is in no case to be less than the adjacent bottom plate

Thus, the principal dimensions on the keel plate are represented in the table below (Table 4-25)

| Plate | Min Breadth [m] | Breadth [m] | Material | Thickness [mm] | ICM [mm] | Gross Thickness [mm] |
|-------|----------------|-------------|----------|----------------|----------|---------------------|
| n°    | $b_{min}$      | $b$         | $f_1$    | $t_{min}$      | $t_k$    | $t$                 |
| K     | 2.415          | 4.25        | 1.39     | 25.70          | 5        | 26                  |

The bottom, which are the plates located in the cargo and ballast tanks, will be designed by following the equations C302 and C304. These equations give the required and minimum thickness of the plate respectively. Also, the pressures to be considered are the maximum external and internal. The results are shown below (Table 4-26).

- S6 – 302: $t_{req} = \frac{15.8k_w s \sqrt{p}}{\sqrt{\sigma}} [mm]$
- S6 – 304: $t_{min} = 5.0 + 0.04L/\sqrt{f_1} + t_k [mm]$
4.2.2. Side Structure

This section will cover the dimensioning of the side structures by following the formulae given in Pt3. Ch1. Section 7 of the DNV Rules [9]. It includes the side plating (plate 5 to 12) and the shear strake plate (plate 13). The first elements will be designed by following the equations C101 and C102. These equations give the required and minimum thickness of the plate respectively and are shown below. While the second type of plate will be designed by following the equations C201 and C202. The results are shown below (Table 4-27).

Table 4-27 - Side plating net and gross thickness estimation according to the DNV rules

| Plate | Gross Thickness [mm] | ICM | t_min | t_req |
|-------|----------------------|-----|-------|-------|
| Cargo (1) | 25 | 5 | 24.4 | 21.0 |
| Ballast (3) | 24 | 3.5 | 23.3 | 19.5 |

4.2.3. Deck Structure

This section will cover the dimensioning of the deck structures by following the formulae given in Pt3. Ch1. Section 8 of the DNV Rules [9]. The strength deck is divided the same way as the bottom structure: region of the cargo and ballast tank. The results are shown below. Notice that the thickness is way below the ones obtained in section 3.2.3. Therefore, the deck region in this design will be more focused to be assured it passes the strength criteria (Table 4-28)
4.2.4. **Longitudinal Bulkhead**

This section will cover the dimensioning of the deck structures by following the formulae given in Pt3. Ch1. Section 9 of the DNV Rules [9]. The plates will be designed by following the equations C100, C102 and C104. These equations give the required, a general minimum and specific minimum for longitudinal bulkhead thickness of the plate respectively and the results are shown below (Table 4-29).

| Plate | Gross Thickness | ICM [mm] | t_min | Net Thickness t_net [mm] | t_min long | t_req |
|-------|----------------|----------|-------|--------------------------|------------|-------|
| Ballast | 14 | 3 | 11.0 | 10.98 | 7.27 |
| Cargo | 15 | 4 | 11.0 | 10.98 | 7.10 |

### Strength Criteria

As specified in the beginning of chapter 5, a total strength assessment (TSA) of the structures must be carried out against the following three failure modes: Buckling, Material Yielding and Ultimate Strength. All of the criteria will be done based on the rules [5], [9].

Moreover, the load conditions (shear forces and bending moments) to be considered in the buckling analysis and the ultimate check are the ones presented in Table 4-30, which are the ones obtained in section 3.4.2 and were obtained by the FPI formulations [5].
4.3.1. Buckling Analysis

In this project the axial compressive stress applied to the plate panels of the midship section will be studied. The method adopted is briefly described below and it is summarized in the flowchart of Figure 4-5.

- Guess a certain net thickness \( t_n \) for the desired plate.
- The ideal elastic buckling stress may be taken as:
  \[
  f_{EI} = K_i \cdot \left[ \frac{\pi^2 E}{12 (1 - \nu^2)} \right] \left( \frac{t_n}{s} \right) \left[ \frac{N}{\text{cm}^2} \right]
  \]
  - Where \( s \) is the spacing of longitudinal stiffener
  - \( \nu \) is the Poisson ratio of steel, equals to 0.3
  - In this project, the buckling stress factor \( K_i \) is 4
- The critical buckling stress, \( f_{ci} \), is given by:
  \[
  f_{ci} = \begin{cases} 
  f_{EI} \left[ \frac{N}{\text{cm}^2} \right], & \text{when } f_{EI} < 0.6 \cdot f_{\text{yield}} \\
  f_{\text{yield}} \cdot (1 - 0.24 \cdot f_{\text{yield}}/f_{EI}) \left[ \frac{N}{\text{cm}^2} \right], & \text{when } f_{EI} > 0.6 \cdot f_{\text{yield}}
  \end{cases}
  \]
  - Where \( f_{\text{yield}} \) is 35,500 N/cm²
- The plate panels subjected to longitudinal stress, \( f_a \), is given by
  \[
  f_a = \frac{M}{I_{NA}} \cdot (y_{NA} - y_a) \cdot 10^5 \left[ \frac{N}{\text{cm}^2} \right]
  \]
  - \( M \) is the bending moment
  - \( y_{NA} \) is the neutral axis height
  - \( I_{NA} \) is the moment of inertia for neutral axis
  - \( y_a \) is the height of the plate considered
- Criteria: if the following inequality is true, the plate won’t suffer from buckling
  \[
  (f_a/f_{ci})^2 \leq 1
  \]
- After the minimum buckling thickness is calculated, the final thickness of the plate is taken as the maximum between this analysis and the one required by the rules.

| Load Conditions | Load Condition | Value   | Unit     |
|-----------------|----------------|---------|----------|
| VMB             | Still Water    | -29,453,568 | kNm      |
|                 | Wave Load      | -11,873,315  | kNm      |
| VSF             | Still Water    | 344,989    | kN       |
|                 | Wave Load      | 97,328     | kN       |
| HBM             | Wave Load      | 5,976,145  | kNm      |

Table 4-30 - Load conditions considered as input data
4.3.2. Yield Stress

The MARS 2000 is a software developed by Bureau Veritas (BV), which allows to input sections, bulkheads and torsion models, and compute the main geometrical properties of the section, the stress in the plates and stiffeners (primary and secondary) and the ultimate bending capacity all according to the rules [65]. By following the user guide [65]–[67], the midship section from the FPI design with its loads (bending moments and shear forces presented in Table 4-30) could be created and the stresses could be obtained. According to the FPI rules [5], the stresses obtained should be compared with the yield stress multiplied by a safety factor, which is 0.6 for the static case and 0.908 for the dynamic case. According to the user guide [67], the permissible one stress for the static case from MARS 2000 is 243 MPa (a safety factor of 0.68) for the Grade H36 steel, according to the BV rules. Therefore, it will be used the safety factor from FPI since they are more conservative for both cases.

4.3.3. Ultimate Strength

The last check is the ultimate strength, which was done with the section 5A-3-4/5.3.3. from the FPI rule [5]. The check for the ultimate strength was done based on as stated previously by section 5A-3-4/5.3.3. from the FPI rule [5]. It focuses more on the ultimate strength of a plate between stiffeners. According to the section, the following formulae must be respected:

\[
\frac{(f_{LB}/fuL)^2}{2} + \frac{(f_{LT}/fuLT)^2}{2} \leq S_m = 0.908 \\
\frac{(f_{TB}/fuT)^2}{2} + \frac{(f_{LT}/fuLT)^2}{2} \leq S_m = 0.908 \\
\frac{(f_{LB}/fuL)^2}{2} + \frac{(f_{TB}/fuT)^2}{2} - \eta(f_{LB}/fuL)(f_{TB}/fuT) + \frac{(f_{LT}/fuLT)^2}{2} \leq S_m = 0.908
\]

Where,

- \( f_{LB} \) - Calculated total compressive stress in the longitudinal direction for the plate
- \( f_{LT} \) - Calculated total in-plane shear stress,
- \( f_{TB} \) - Calculated total compressive stress in the transverse/vertical direction
- \( fuL \) - Ultimate strengths with respect to uniaxial
- \( fuT \) and \( fuLT \) - Ultimate strengths with respect to edge shear,
4.3.4. Final Design

In any project, one of the crucial objectives are is to design a product with the lowest cost as low as possible in order to make profit from it. In the shipbuilding industry, this can be achieved by building a ship or a platform without over dimensioning the whole structure. In this master thesis, the optimal design is the one with the lightest structure that satisfies all the strength criteria (buckling, yield and ultimate strength) imposed for both load conditions (static and dynamic) simultaneous. However, this isn't a simple task. For example, in this master section there are 37 plates whose thickness can vary between the minimum value imposed by the rule and a maximum value, which will be considered in this thesis as 32mm. In this aspect alone, finding an optimal solution is complicated. In addition to that, each individual plate interferes directly with the strength criteria from the other plates, because they can modify the neutral axis height and the moment of inertia and, therefore, the normal and shear stress in the structure. Thus, in order to obtain a feasible solution, it was used a solver. The optimization problem used to do this task is described below.

- **Objective Function**
  - Minimize (Total Weight)

- **Variables**
  - Thickness from longitudinal plates

- **Constrains**
  - Buckling Criteria
  - Yield Criteria
  - Ultimate Strength Criteria
  - Maximum thickness of 32mm
  - Minimum moment of inertia = 1,044 m$^4$
  - Minimum section modulus of bottom = 68.38 m$^3$
  - Minimum section modulus of deck = 61.27 m$^3$

- **Load Cases**
  - Static: Still Water Condition
  - Dynamic: Still Water + Wave Load Conditions

The results from the solver can be seen in Table 4-31 and 4-32. As it can be seen, the solution found complies with most of the strength criteria. The exception is the deck plates for the static load case, which are 3%-5% higher than the allowed (The maximum allowed is 355°0.6 = 213 MPa). Despite this exceed, the solution is feasible for two reasons. First, the condition in which this exceedance of the on-board safety factor takes place is not the worst of all. This helps as a reference for dimensioning, but the important thing is that the plates are able to withstand the loads of the worst condition without exceeding the yield stress, which in fact happens. The second reason is that the vast majority of plates meet the buckling and yield requirements for the calm water condition and all of them are within the stipulated limits for the buckling, yield and ultimate strength criteria for the worst condition, which is that where there are loads of calm waters plus waves.
Moreover, most the of values range from 0.4 to 0.5 and 0.75 to 0.85 from the yield stress for the static and dynamic load case respectively. This is a good sign that the achieved solution is in fact a good one because the structure is not over dimensioned.

Table 4-31 - Final thickness from plates showing the buckling and yielding criteria

| Plate Location | Structure | Buckling Static | Yielding Static | Buckling Dynamic | Yielding Dynamic |
|----------------|-----------|-----------------|-----------------|------------------|------------------|
| Cargo          | Bottom    | 0.46            | 0.59            | 0.90             | 0.81             |
| Ballast        | 0.75      | 0.85            |                 |                  |                  |
| Cargo          | Side      | 0.44            | 0.59            | 0.85             | 0.81             |
| Ballast        | 0.84      | 0.75            |                 |                  |                  |
| Cargo          | Deck      | 0.51            | 0.62            | 0.98             | 0.86             |
| Ballast        | 0.83      | 0.75            |                 |                  |                  |
| Cargo          | Long Bkd  | 0.43            | 0.54            | 0.83             | 0.75             |
| Ballast        | 0.53      | 0.57            |                 |                  |                  |
| Cargo          | Side Long. Bkd | 0.43 | 0.54 | 0.82 | 0.75 |
| Ballast        | 0.52      | 0.57            |                 |                  |                  |
| Cargo          | Horizontal Plates | 0.43 | 0.54 | 0.82 | 0.75 |
| Ballast        | 0.52      | 0.57            |                 |                  |                  |

| Plate Location | Structure | Buckling Static | Yielding Static | Buckling Dynamic | Yielding Dynamic |
|----------------|-----------|-----------------|-----------------|------------------|------------------|
| Cargo          | Bottom    | 0.46            | 0.59            | 0.90             | 0.81             |
| Ballast        | 0.75      | 0.85            |                 |                  |                  |
| Cargo          | Side      | 0.44            | 0.59            | 0.85             | 0.81             |
| Ballast        | 0.84      | 0.75            |                 |                  |                  |
| Cargo          | Deck      | 0.51            | 0.62            | 0.98             | 0.86             |
| Ballast        | 0.83      | 0.75            |                 |                  |                  |
| Cargo          | Long Bkd  | 0.43            | 0.54            | 0.83             | 0.75             |
| Ballast        | 0.53      | 0.57            |                 |                  |                  |
| Cargo          | Side Long. Bkd | 0.43 | 0.54 | 0.82 | 0.75 |
| Ballast        | 0.52      | 0.57            |                 |                  |                  |
| Cargo          | Horizontal Plates | 0.43 | 0.54 | 0.82 | 0.75 |
| Ballast        | 0.52      | 0.57            |                 |                  |                  |
The second result is related to the geometrical properties. As stated in the beginning of section 3.2, the ABS classification society requires that the midship section has at least a moment of inertia of 1,044 m⁴, a section modulus of the bottom and deck of 68.38 m³ and 61.27 m³ respectively. The achieved figures for these parameters are, respectively, 2191 m⁴, 141.7 m³ and 130.2 m³. Another geometrical property is the neutral axis height, which was 15.47 m.

### Table 4-33 - Geometric properties from midship section

| Geometric Properties                  | Value   | Unit  |
|---------------------------------------|---------|-------|
| Effective area of cross-section       | 13.14   | m²    |
| Neutral axis (above base line)        | 15.47   | m     |
| Moment of inertia/GY axis             | 2191    | m⁴    |
| Section modulus at bottom             | 141.7   | m³    |
| Section modulus at deck               | 130.2   | m³    |
Figure 4-6 - Distribution of the plates thickness and longitudinal stiffeners
5. SPS PLATES SCANTLING

This chapter has the purpose of detailing the dimensioning of the SPS plates according to DNVGL-CG-0154 and Lloyds guidelines rules [18], [19]. The basis of the SPS design principles is that SPS structures should have strength at least equivalent to that of a conventional steel structure that performs the same function. So, the approach in this case is to take the minimum conventional steel scantlings for structural items, calculated from the Class Rules, and then calculate “equivalent” SPS scantlings.

This chapter is divided into three parts. First, it will be discussed the initial assumptions such as the mechanical properties of the steel and core, plate dimensions, loads considered and minimum thicknesses for the regions to be analyzed. The second part will report the method used to achieve the final design of each composite plate. The last one will display and discuss the results.

5.1. Initial Assumptions

The SPS plate is a structural composite material composed of steel and a polyurethane elastomer. Thus, it is essential to define the mechanical properties of each material for the design of the panel. According to the DNVGL-CG-0154 [18], the mechanical properties of the steel are the same as from chapter 4 (High steel grade 36 [6]) and it will be considered the same grade of steel, Grade H36. The core characteristics were obtained through the DNVGL-CG-0154 [18], the Lloyd's Guidelines [19], a master thesis from Delft University [48]. They are shown in Table 5-1.

Table 5-1 - Mechanical properties for the steel and core to be used in the SPS plate

| Material Properties | Steel H36 | Core Material |
|---------------------|-----------|--------------|
| E [N/mm²]           | 206       | 748          |
| G [N/mm²]           | 79.3      | 297          |
| ν [-]                | 0.3       | 0.26         |
| Yield Stress [N/mm²]| 355       | 21           |
| Density [ton/m³]    | 7.85      | 1.05         |

Moreover, the bending moments and shear forces to be considered are the ones presented in Table 4-30, which are the static and dynamic load cases, and the final plate should withstand both cases. Also, the plates dimensions will be similar to the ones from the conventional steel structure. It will be a square plate with a length of 3.4m.

As stated in the DNVGL-CG-0154 [18], there is a range of thickness in which the steel plates and core elastomer are submitted. Typically, it is from 3 to 30 mm for the first element and from 15 to 100 mm for the second. In addition to this constrain, there are also a minimum net and gross thickness for the top and bottom steel plate of the composite panel. They are dependent on the region of application (i.e., bottom structure, side, deck and so on) and the corrosion addition. Using the formulae given in the DNVGL-CG-0154 [18], the minimum net and the corrosion margin could be obtained and are given below (Table 5-2).
5.2. Design Process

As stated in section 3/1.1.1 from DNVGL-CG-0154 [18], “Scantlings of steel sandwich panels as a part of a hull structure shall satisfy buckling, stress and deflection criteria considering local pressures and in-plane stresses from all relevant hull responses such as global hull girder bending, primary girder/floor bending, double hull bending etc.”. In addition to this, the steel sandwich panels shall also be designed according to the following principles:

- to avoid major plastic yielding of steel face plating
- to avoid major plastic yielding of core material
- to avoid failure of the bond between the core and the steel face plates.
- to be lighter than the traditional steel configuration.

The Lloyd’s Register guidelines [19] proposes a flowchart (Figure 5-1) as a methodology that will be used in this chapter. Moreover, in the Appendix B of DNVGL-CG-0154 [18] there is a support Excel tool developed by DNV for calculating all these strength criteria properties and comparing it with the rules requirements. This tool was used to make sure the classification society method was followed properly.

Also, in summation of the basic principles, it is interesting to keep the thickness of the core as low as possible in order to make the panel cost-effective.

| Structure         | ICM[mm] | Reserve Thickness [mm] | Net Thickness [mm] |
|-------------------|---------|------------------------|--------------------|
| Bottom            | 2.5     | 0.5                    | 8.00               |
| Longitudinal BKD  | 2.5     | 0.5                    | 7.00               |

Table 5-2 - Minimum net and corrosion addition for the steel part of the SPS

5.2.1. Buckling Criteria

The present buckling criteria used to design the SPS panel is based on the DNVGL-CG-0154 [18], DNV-RU SHIP Pt3. Ch8. [16] and on DNVGL-CG-0128 [36]. It is described in the following items.
• Calculate the stresses in the axial, transverse and in-plane shear for each plate \( i \) of the traditional steel net structure. After that, determine the respective loads subjected in each direction
  o N10 for axial, N20 for transverse and N30 for in-plane shear
  o Example: \( N_{10,i} = \sigma_{10,i} \cdot t_{\text{net},i} \)
• Guess a certain net thickness for the core and steel plates.
• Determine the eigenvalue \( \Lambda_F \) of the load factor at which the steel face plate reaches the material yield excluding all buckling effects (von Mises squash yield)
  o \( \Lambda_F = \frac{R_{\text{eff}}}{\sqrt{\sigma_{10}^2 + \sigma_{20}^2 - \sigma_{10} \sigma_{20} + 3\tau_0^2}} \)
  o \( R_{\text{eff}} \) is the minimum yield stress of steel plates in N/mm\(^2\) (355 N/mm\(^2\))
• Determine the eigenvalue \( \Lambda_E \), which is dependent on the ratio between the design loads. For example, if the panel is subject to bi-axial compression or compression/tension combinations or to a single in-plane shear load or to bi-axial and in-plane shear loading in combination.
• Determine the buckling load factor \( \Lambda_B \)
  o \( \Lambda_B = \frac{\Lambda_F}{\sqrt{1 + \lambda^4}} \)
  o \( \lambda = \sqrt{\frac{\Lambda_F}{\Lambda_E}} \)
• Determine the actual buckling usage and compares it to the allowed one.
  o \( \eta = \frac{1}{\Lambda_B} \)
  o \( \eta \leq \eta_{\text{allow}} = 0.9 \)

5.2.2. Lateral Pressure Criteria

The other strength assessment is related to the maximum lateral pressure that the panel can support. This is related to different acting stress on the panel such as the maximum equivalent stress in the steel face plate, the maximum shear stress in the core and the maximum interface shear stress. The procedure to determine all this parameter will be briefly described below.

• For the same thickness, bending moments and shear stresses of the buckling section, calculate the lateral pressure for each plate \( i \) of the traditional steel net structure.
• Calculate the lateral plate deflection for that design pressure \((w)\)
  o \( w = w_b + w_s \)
  o Where \( w_b \) is the bending component and \( w_s \) is the shear component
• Calculate the bending moments related to that deflection
• Calculate the stress components in the steel plates in order to obtain the factor of the equivalent stress \((\eta)\) and compare it with the allowed one

\[
\sigma_{1,\text{plate}} = M_1 \frac{E_f}{D_{\text{PS}}(1 - \varphi_{\text{SPS}}^2)} \frac{t_{\text{PS}}}{2}
\]
\[
\sigma_{2,\text{plate}} = M_2 \frac{E_f}{D_{\text{PS}}(1 - \varphi_{\text{SPS}}^2)} \frac{t_{\text{PS}}}{2}
\]
\[
\tau_{12,\text{plate}} = 2M_{12} \frac{G_f}{D_{\text{PS}}(1 - \varphi_{\text{SPS}}^2)} \frac{t_{\text{PS}}}{2}
\]
\[ \eta = R_{ei} h / \sqrt{\sigma_{10}^2 + \sigma_{20}^2 - \sigma_{10} \sigma_{20} + 3 \tau_0^2} \leq \eta_{allow} = 0.9 \]

- The core shear stress can be calculated by the lateral deflection of the plate and, after that, calculate the factor related (\( \eta \)) and compare it with the allowed one
  - \( \tau_{1,3 \; core} = \frac{S}{d} w_{s,1} \)
  - \( \tau_{2,3 \; core} = \frac{S}{d} w_{s,2} \)
  - \( \tau_{core} = \max (\tau_{1,3 \; core}; \tau_{2,3 \; core}) \)
  - \( \eta = \frac{\tau_{core}}{\tau_{allow}} \leq \eta_{allow} = 0.9 \)

- The last parameter is the interface shear stress that can be calculated the same way as the core shear stress and it is also compared to the allowable load factor.

### 5.3. Results

Therefore, combining the several information in the previous section such as the hypothesis adopted, the goals established, the methodology to follow and the strength criteria to judge, the results to obtain the thickness for the steel and core of the composite plate could be achieved. This is shown in the next tables (Table 5-3 to 5-6). Notice that for the same load, different combinations of thickness pass the several criteria imposed. Therefore, some weights to make the final decision must be set. For this master thesis, the panel selected was the one that had the best combination of least core material used, a lighter structure, lower stresses for each load case. However, it is important to think about how the new neutral axis and moment of inertia will impact the buckling, yielding and ultimate criteria described in the previous chapter for the other plates. Therefore, the final plate thickness (Table 5-3) is the one that could withstand both load cases (static and dynamic) and also provide all steel plates to pass the buckling, yielding and ultimate criteria from FPI ABS [5]. The new design passed both the buckling and yield criteria (Table 5-5) and the ultimate strength as well (Table 5-6). Thus, the thickness from Table 5-3 were selected as the final ones. Also, this implies new geometric properties for the structure that are shown in Table 5-4.

### Table 5-3 - Final distribution of thickness for the SPS panels

| Structure       | Plate Number | St. Net Thickness [mm] | St. Gross Thickness [mm] | Core Thickness [mm] | Weight SPS [ton] | Steel [ton] | Difference  |
|-----------------|--------------|------------------------|--------------------------|---------------------|-----------------|-------------|-------------|
| Bottom          | Keel         | 15                     | 18                       | 55                  | 0.73            | 0.85        | -13.6%      |
| Cargo           | 15           | 18                     | 55                       | 0.73                | 0.85            | -13.6%      |
| Ballast         | 15           | 18                     | 55                       | 1.76                | 2.20            | -19.9%      |
|                 | 17           | 12.5                   | 16                       | 50                  | 1.25            | 1.29        | -2.9%       |
|                 | 18           | 12.5                   | 16                       | 50                  | 1.25            | 1.29        | -2.9%       |
|                 | 19           | 12                     | 15                       | 45                  | 0.98            | 0.90        | 8.3%        |
|                 | 20           | 10.5                   | 14                       | 45                  | 0.92            | 0.90        | 2.4%        |
|                 | 21           | 10                     | 13                       | 45                  | 0.92            | 0.90        | 2.4%        |
|                 | 22           | 10                     | 13                       | 45                  | 0.87            | 0.93        | -6.3%       |
|                 | 23           | 10                     | 13                       | 45                  | 0.87            | 0.93        | -6.3%       |
|                 | 24           | 11                     | 14                       | 45                  | 0.92            | 1.04        | -10.8%      |
|                 | 25           | 14                     | 17                       | 55                  | 1.12            | 1.25        | -10.1%      |
### Table 5-4 - Geometric Properties of the SPS Midship Section

| Geometric Properties                      | Value | Unit  |
|-------------------------------------------|-------|-------|
| Effective area of cross-section           | 11.8  | m²    |
| Neutral axis (above base line)            | 16.51 | m     |
| Moment of inertia/GY axis                 | 2391  | m⁴    |
| Section modulus at bottom                 | 145   | m³    |
| Section modulus at deck                   | 151   | m³    |

### Table 5-5 - Buckling and Yielding Criteria for Static and Dynamic Load case for the SPS arrangement

| Plate Location | Plate Nº | Cargo Buckling Static | Cargo Yielding Static | Cargo Buckling Dynamic | Cargo Yielding Dynamic | Ballast Buckling Static | Ballast Yielding Static | Ballast Buckling Dynamic | Ballast Yielding Dynamic |
|----------------|----------|-----------------------|-----------------------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|
| Bottom         |          |                       |                       |                        |                        |                        |                        |                        |                        |
|                |          |                       |                       |                        |                        |                        |                        |                        |                        |
| Side           |          | 5                     | 0.34                  | 0.57                   | 0.66                   | 0.80                   |                        |                        |                        |
|                |          | 6                     | 0.42                  | 0.57                   | 0.82                   | 0.80                   |                        |                        |                        |
|                |          | 7                     | 0.27                  | 0.41                   | 0.52                   | 0.57                   |                        |                        |                        |
|                |          | 8                     | 0.14                  | 0.29                   | 0.28                   | 0.41                   |                        |                        |                        |
|                |          | 9                     | 0.05                  | 0.18                   | 0.10                   | 0.25                   |                        |                        |                        |
|                |          | 10                    | 0.01                  | 0.06                   | 0.01                   | 0.08                   |                        |                        |                        |
|                |          | 11                    | 0.01                  | 0.06                   | 0.01                   | 0.08                   |                        |                        |                        |
|                |          | 12                    | 0.05                  | 0.18                   | 0.10                   | 0.25                   |                        |                        |                        |
|                |          | 13                    | 0.14                  | 0.30                   | 0.27                   | 0.41                   |                        |                        |                        |
| Deck           |          | 15                    | 0.35                  | 0.52                   | 0.67                   | 0.72                   |                        |                        |                        |
|                |          | 16                    | 0.37                  | 0.53                   | 0.72                   | 0.74                   |                        |                        |                        |
| Long Bkd       |          | 17                    | 0.35                  | 0.53                   | 0.68                   | 0.74                   |                        |                        |                        |
|                |          | 18                    | 0.21                  | 0.41                   | 0.41                   | 0.57                   |                        |                        |                        |
|                |          | 19                    | 0.11                  | 0.29                   | 0.22                   | 0.41                   |                        |                        |                        |
|                |          | 20                    | 0.04                  | 0.18                   | 0.08                   | 0.25                   |                        |                        |                        |
|                |          | 21                    | 0.00                  | 0.06                   | 0.01                   | 0.08                   |                        |                        |                        |
|                |          | 22                    | 0.00                  | 0.06                   | 0.01                   | 0.08                   |                        |                        |                        |
|                |          | 23                    | 0.04                  | 0.18                   | 0.09                   | 0.25                   |                        |                        |                        |
|                |          | 24                    | 0.12                  | 0.30                   | 0.23                   | 0.41                   |                        |                        |                        |
|                |          | 25                    | 0.21                  | 0.41                   | 0.40                   | 0.58                   |                        |                        |                        |
| Side Long. Bkd|          | 17 S                  | 0.41                  | 0.53                   | 0.80                   | 0.74                   |                        |                        |                        |
|                |          | 18 S                  | 0.27                  | 0.41                   | 0.52                   | 0.57                   |                        |                        |                        |
|                |          | 19 S                  | 0.15                  | 0.29                   | 0.29                   | 0.41                   |                        |                        |                        |
|                |          | 20 S                  | 0.05                  | 0.18                   | 0.11                   | 0.25                   |                        |                        |                        |
|                |          | 21 S                  | 0.01                  | 0.06                   | 0.01                   | 0.08                   |                        |                        |                        |
|                |          | 22 S                  | 0.01                  | 0.06                   | 0.01                   | 0.08                   |                        |                        |                        |
|                |          | 23 S                  | 0.05                  | 0.18                   | 0.10                   | 0.25                   |                        |                        |                        |
|                |          | 24 S                  | 0.12                  | 0.30                   | 0.24                   | 0.41                   |                        |                        |                        |
|                |          | 25 S                  | 0.22                  | 0.41                   | 0.43                   | 0.58                   |                        |                        |                        |
| Horizontal Plates |      | 5 H                  | 0.32                  | 0.45                   | 0.62                   | 0.63                   |                        |                        |                        |
|                |          | 6 H                  | 0.13                  | 0.28                   | 0.25                   | 0.39                   |                        |                        |                        |
|                |          | 7 H                  | 0.01                  | 0.10                   | 0.03                   | 0.14                   |                        |                        |                        |
|                |          | 8 H                  | 0.01                  | 0.08                   | 0.02                   | 0.11                   |                        |                        |                        |
|                |          | 9 H                  | 0.10                  | 0.25                   | 0.20                   | 0.35                   |                        |                        |                        |
|                |          | 10 H                 | 0.27                  | 0.43                   | 0.52                   | 0.60                   |                        |                        |                        |
Hull Weight Estimation

This section has as the main goal to estimate the hull’s weight for both steel and SPS arrangement. This will be based on the thickness and dimensions of the structural elements obtained in chapter 5 and 6. Moreover, since this master thesis didn’t design the structural elements for the aft part where the machines and pump would be located. Generally, this part corresponds between 5% to 15% of the cargo tanks weight (longitudinal and transversal) and for this project it is considered as 10%. The methodology to calculate each part of the structure is presented below and the results are in Table 5-7.

As can be seen, the final hull with the SPS panels is 2.8% lighter than the traditional steel hull with the bottom structure being the main responsible for reducing the total weight. A reduction of, approximately, 1250 tons. This is due to the fact that it is the area with one of the highest thicknesses for the steel panels and with the stiffeners with the highest weights.

1. **Longitudinal Weight**
   
   a. \( W_{total,long} = (45.9 \times 6 + 10.2) \times \sum \rho_i A_i \)

   b. Where \( \rho \) is the material density and \( A \) is the transversal area of the element \( i \)

2. **Transversal Weight**
   
   a. \( W_{total,trans} = 6 \times W_{bulkhead} + 54 \times W_{web\ frame} \)

3. **Aft Weight**
   
   a. \( W_{aft} = (W_{total,long} + W_{total,trans}) \times 0.1 \)

4. **Total Hull Weight**
   
   a. \( W_{total} = W_{aft} + W_{total,long} + W_{total,trans} \)

### Table 5-6 - Ultimate Strength Criteria for the SPS Arrangement

| Structure      | Plate nº | Formula 1 | Formula 2 | Formula 3 |
|----------------|----------|-----------|-----------|-----------|
| Bottom Cargo   | 0.674    | 0.044     | 0.611     |           |
| Ballast       | 0.674    | 0.046     | 0.599     |           |
| 5             | 0.704    | 0.089     | 0.620     |           |
| 6             | 0.695    | 0.122     | 0.625     |           |
| 7             | 0.586    | 0.209     | 0.543     |           |
| 8             | 0.420    | 0.224     | 0.404     |           |
| 9             | 0.271    | 0.224     | 0.276     |           |
| 10            | 0.189    | 0.235     | 0.213     |           |
| 11            | 0.165    | 0.190     | 0.188     |           |
| 12            | 0.178    | 0.132     | 0.180     |           |
| 13            | 0.285    | 0.106     | 0.263     |           |
| 14            | 0.531    | 0.026     | 0.496     |           |
| 15            | 0.588    | 0.066     | 0.499     |           |
| 16            | 0.639    | 0.095     | 0.629     |           |
| 17            | 0.492    | 0.163     | 0.492     |           |
| 18            | 0.374    | 0.206     | 0.374     |           |
| 19            | 0.282    | 0.222     | 0.282     |           |
| 20            | 0.236    | 0.230     | 0.236     |           |
| 21            | 0.213    | 0.226     | 0.233     |           |
| 22            | 0.279    | 0.216     | 0.279     |           |
| 23            | 0.358    | 0.188     | 0.358     |           |
| 24            | 0.605    | 0.273     | 0.605     |           |
| 25            | 0.704    | 0.089     | 0.620     |           |

| Side Long. Bkd | Plate nº | Formula 1 | Formula 2 | Formula 3 |
|----------------|----------|-----------|-----------|-----------|
| 17            | 0.639    | 0.082     | 0.668     |           |
| 18            | 0.517    | 0.140     | 0.474     |           |
| 19            | 0.411    | 0.202     | 0.299     |           |
| 20            | 0.299    | 0.246     | 0.312     |           |
| 21            | 0.214    | 0.246     | 0.246     |           |
| 22            | 0.213    | 0.241     | 0.241     |           |
| 23            | 0.296    | 0.245     | 0.304     |           |
| 24            | 0.241    | 0.093     | 0.213     |           |
| 25            | 0.366    | 0.054     | 0.311     |           |

| Horizontal Plates | Side Long. Bkd | Plate nº | Formula 1 | Formula 2 | Formula 3 |
|-------------------|----------------|----------|-----------|-----------|-----------|
| 5                 | 0.480           | 0.040     | 0.424     |           |
| 6                 | 0.208           | 0.045     | 0.197     |           |
| 7                 | 0.027           | 0.045     | 0.052     |           |
| 8                 | 0.015           | 0.042     | 0.041     |           |
| 9                 | 0.165           | 0.045     | 0.156     |           |
| 10                | 0.387           | 0.036     | 0.332     |           |
| 11                | 0.057           | 0.090     | 0.090     |           |
| 12                | 0.308           | 0.144     | 0.144     |           |
| 13                | 0.163           | 0.200     | 0.200     |           |
| 14                | 0.204           | 0.243     | 0.243     |           |
| 15                | 0.204           | 0.246     | 0.246     |           |
| 16                | 0.202           | 0.244     | 0.244     |           |
| 17                | 0.206           | 0.248     | 0.248     |           |

| Trans. Bkd      | Plate nº | Formula 1 | Formula 2 | Formula 3 |
|-----------------|----------|-----------|-----------|-----------|
| 17 T            | 0.070    | 0.112     | 0.112     |           |
| 18 T            | 0.035    | 0.077     | 0.077     |           |
| 19 T            | 0.027    | 0.045     | 0.052     |           |
| 20 T            | 0.015    | 0.042     | 0.041     |           |
| 21 T            | 0.165    | 0.045     | 0.156     |           |
| 22 T            | 0.387    | 0.036     | 0.332     |           |
| 23 T            | 0.057    | 0.090     | 0.090     |           |
| 24 T            | 0.308    | 0.144     | 0.144     |           |
| 25 T            | 0.163    | 0.200     | 0.200     |           |

| Ultimate Strength Calculation | Bottom | Side Long. Bkd | Horizontal Plates | Trans. Bkd |
|-------------------------------|--------|----------------|-------------------|------------|
| 5.4. Hull Weight Estimation   |        |                |                   |            |
Table 5.7 - Calculations of the weight for each part of the structure for both types of arrangements

| Structure  | Steel Arrangement [ton] | SPS Arrangement [ton] | Difference |
|------------|-------------------------|-----------------------|------------|
| Bottom     | 6,950                   | 5,709                 | -18%       |
| Side       | 8,920                   | 8,920                 | -          |
| Deck       | 6,251                   | 6,251                 | -          |
| Long BKD   | 2,541                   | 2,530                 | -0.4%      |
| Side BKD   | 4,748                   | 4,748                 | -          |
| Trans BKD  | 3,062                   | 3,062                 | -          |
| Web Frame  | 8,487                   | 8,487                 | -          |
| Aft        | 4,096                   | 4,096                 | -          |
| Total Hull | 45,055                  | 43,804                | -2.8%      |
6. ULTIMATE STRENGTH ANALYSES

Many classification societies require the performance of an FEA of ships structures for the Total Strength Assessment (TSA), because it has several advantages [68]. One of them is the adaptability and accuracy of the technique, once a FEM can model complex shapes with several loading and boundary conditions and provide an accurate solution, which would be impractical if done by hand. Consequently, the engineers can easily simulate several conditions without building real life models and spot vulnerabilities in the design before constructing the definitive project.

Therefore, the objective of this chapter is to discuss the finite element analysis done in this master thesis for the traditional steel and the SPS structures. The chapter is divided into two parts. The first one will show the steps to build the FEM (finite element model), which includes the geometry, mesh, boundary condition and loads applied. The second part regards the structural response for each model for the different loading conditions. This chapter is based on the guidelines of the FPI rules from Part 5A-3-A4 [5] and on the chapters from the book The Finite Element Model [68]–[73].

Moreover, for an FEA, many commercial software is available to do so, but, for this master thesis, the ANSYS APDL structural package was used with a student license. Once it is a student version, this has some limitations. For example, as specified on the company’s website, the newest version 2021 R1 have the capacity of 128K nodes/elements for structural analysis. This was be taken in mind during the modelling in order to not surpass the software limit.

6.1. Finite Element Model

6.1.1. General Guidelines

As stated previously, the FPI rules [5] have some requirements for the finite element model that must be followed. First of all, the strength analysis is based on a “net” ship approach. Therefore, the nominal design corrosion margin must be deducted from the scantling for the FEA. Second, the analysis must be a three-dimensional global model of three cargo tank lengths located at about amidships with two frames fore and aft of the two end bulkheads (Figure 6-1, 6-2 and 6-3). Thus, all primary load-carrying members are to be modeled as shown in Figure 6-1, which includes: transverse web frames, longitudinal girders, horizontal girders, side stringers, and centerline ring frames, etc. This is due to the fact that the 3-D global FE analysis’s purpose is to determine the overall structural response of the hull girder structure, including primary and secondary bending, and also to obtain appropriate boundary conditions for use in the local fine-mesh FE analysis of local structures.

Moreover, it is desirable to have consistent modeling throughout the entire length of the three cargo tanks considered. However, the middle tank is to always have the desired mesh, where more accurate results are expected (due to boundary effects) and are therefore used in the strength assessment. If approximations have to be made, do so only in the two end-tanks. The last observation is that manholes on transverse and longitudinal structures, such as double bottom floors and longitudinal girders, are generally ignored in the global model.
6.1.2. Geometry

According to [40], [42], [74], the equivalent thickness model is an accurate model to predict the ultimate strength and the stress distribution of the structure. This model consists in using thicker plates that have an inertia equal to a plate with longitudinal stiffeners. There are two benefits of it. The first one is the simplification of a complex geometry. The second one is that with fewer nodes and elements, less computational power is needed and it is easier to achieve a converged solution. Therefore, the steel plates used both in the traditional and with the SPS plates structures are shown in Table 6-1.
In the context of FE analysis of steel sandwich plates, there are several references on how to model it such as the DNVGL-CG-0154 [18], master thesis [48], guidelines from the company SPS Technology Ltd [75] and others [2], [47], [76]–[78]. Generally, one of the combinations below shall be applied.

- A single layer of layered shell elements through the thickness of the entire sandwich material with isotropic material properties for each layer
- (layered) Shell elements for the faces and solid elements for the core with isotropic material properties for both element types.
- Solid elements for both face and core with isotropic material properties.

The difference between them is related to the size of the model applied. According to private conversations with the engineer from SPS Technology and the DNV-CG-0154 [18], for more complex models, such as the one from this thesis, an accurate solution can be obtained by using the single layer of shell elements for the same reasons from the equivalent thickness model described above. Although the use of solid elements can be modelled the geometry to the degree of detail wanted, this implies a very large number of nodes and elements, and hence the solution time will be very long.

Therefore, the equivalent steel plate would have equal inertia from the plates obtained in chapter 4 of this thesis. Since the geometry should be the same, only the thickness was varied to obtain the equivalent plate. The new plates are shown in the table below (Table 6-2).

| Plate Location | Equivalent Thickness | Structure (Web Frame) | Plate Location | Equivalent Thickness |
|----------------|----------------------|-----------------------|----------------|----------------------|
| Keel           | 47                   | 17 S                  | Bottom         | 1                    |
| Cargo          | 52                   | 18 S                  |                | 2                    |
| Ballast        | 44                   | 19 S                  |                | 3                    |
| Side Long. Bkd | 5                    | 20 S                  | Side Plates    | 4                    |
|               | 6                    | 21 S                  |                | 5                    |
|               | 7                    | 22 S                  |                | 6                    |
|               | 8                    | 23 S                  |                | 7                    |
|               | 9                    | 24 S                  |                | 8                    |
| Side Long. Bkd | 10                   | 25 S                  | Deck           | 9                    |
|               | 11                   | 26 S                  |                | 2                    |
|               | 12                   | 27 S                  |                | 3                    |
|               | 13                   | 28 S                  |                | 4                    |
|               | 15                   | 29 S                  |                | 5                    |
|               | 16                   | 30 S                  |                | 6                    |
| Deck           | 17                   | 31 S                  |                | 7                    |
|               | 18                   | 32 S                  |                | 8                    |
|               | 19                   | 33 S                  |                | 9                    |
|               | 20                   | 34 S                  |                | 10                   |
|               | 21                   | 35 S                  |                | 11                   |
|               | 22                   | 36 S                  |                | 12                   |
|               | 23                   | 37 S                  |                | 13                   |
|               | 24                   | 38 S                  |                | 14                   |
|               | 25                   | 39 S                  |                | 15                   |
| Longitudinal Bulkhead | 17 T          | 31 T                  | FPI Design Equivalent Thickness | 8 |
|               | 18 T                 |                       |                | 9                    |
|               | 19 T                 |                       |                | 30                   |
|               | 20 T                 |                       |                | 30                   |
|               | 21 T                 |                       |                | 28                   |
|               | 22 T                 |                       |                | 28                   |
|               | 23 T                 |                       |                | 28                   |
|               | 24 T                 |                       |                | 28                   |
|               | 25 T                 |                       |                | 28                   |

Table 6-1 · Equivalent thickness for the steel structure

In the context of FE analysis of steel sandwich plates, there are several references on how to model it such as the DNVGL-CG-0154 [18], master thesis [48], guidelines from the company SPS Technology Ltd [75] and others [2], [47], [76]–[78]. Generally, one of the combinations below shall be applied.

- A single layer of layered shell elements through the thickness of the entire sandwich material with isotropic material properties for each layer
- (layered) Shell elements for the faces and solid elements for the core with isotropic material properties for both element types.
- Solid elements for both face and core with isotropic material properties.

The difference between them is related to the size of the model applied. According to private conversations with the engineer from SPS Technology and the DNV-CG-0154 [18], for more complex models, such as the one from this thesis, an accurate solution can be obtained by using the single layer of shell elements for the same reasons from the equivalent thickness model described above. Although the use of solid elements can be modelled the geometry to the degree of detail wanted, this implies a very large number of nodes and elements, and hence the solution time will be very long.

Therefore, the equivalent steel plate would have equal inertia from the plates obtained in chapter 4 of this thesis. Since the geometry should be the same, only the thickness was varied to obtain the equivalent plate. The new plates are shown in the table below (Table 6-2).


### 6.1.3. Element Type and Mesh

For finite element modeling of a steel plate, it is typically represented by shell (or bending plate) elements and, in general, the plate element mesh is to follow the stiffener system as far as practicable, hence representing the actual plate panels between stiffeners. Some examples of the mesh spacing can be seen in Figure 6-4.

![Figure 6-4 - Typical Finite Element Mesh on Web Frame [5]](image)

For each type of element, there are several options to choose and the appropriate one depends on the type of analysis pursuit. According to the ANSYS Manual [79]–[81] and chapter 8 of The Finite Element Method [71] and FPI guidelines [5], for the steel plates, the best type of element is the shell one. Furthermore, the most suitable for the scope of this master thesis is the SHELL181. It is an element based on the Mindlin plate theory and has four nodes with six degrees of freedom at each node: translations in the x, y, and z directions, and rotations about the x, y, and z-axes as seen in Figure 6-5. Moreover, it is well-suited for linear, large rotation, and/or large strain nonlinear applications and may be used for layered applications for modeling composite shells or sandwich construction.

Therefore, for the middle tank, it was used an element size of 0.85m; and for the aft and fore tank, the size was 1.7m. These numbers are in accordance with the FPI guidelines, once it says that for the middle tank the size shall be equal to the distance between the longitudinal stiffeners and a maximum of 2 times these spaces for the other tanks.

In addition to that, it was done a sensitivity analysis in order to check how the results vary with the mesh size (Table 6-3). It was compared proposed by the FPI with a refined one, which has all elements with

| Equivalent Steel Plate for the SPS panel |
|-----------------|-----------------|
| **Structure**   | **Plate**       | **Thickness [mm]** |
| Keel            | Bottom Cargo    | 72                |
| Bottom Ballast  | 72              |
| Longitudinal    | 17              | 33                |
| Bulkhead        | 18              | 33                |
|                 | 19              | 31                |
|                 | 20              | 29                |
|                 | 21              | 27                |
|                 | 22              | 27                |
|                 | 23              | 27                |
|                 | 24              | 29                |
|                 | 25              | 35                |
the size of 0.85m. There are 5 main variables that will be studied: neutral axis height from the baseline, the normal stress from the bottom and deck plates, the spring reaction at the ends of the model (presented in section 6.1.5) and the time required to run the simulation for the static and ultimate load case. The first three parameters of the reference column were obtained through the beam theory using the geometric properties and loads, the spring reference is detailed in section 7.1.5 and the time static/ultimate was considered as reference the mesh proposed by the FPI rules. As it is expected, the refined mesh provided more accurate results compared to the FPI mesh. However, the computational time required to perform it was 72% and 116% more for the static and ultimate load case respectively. Moreover, as it can be seen from the column Difference FPI Mesh, the results obtained aren’t that distance from the reference one. Thus, the best tradeoff between accuracy of results and computational time required is the one from the FPI rules and this is the one that will be used for all models. The model meshed can be seen in Figure 6-6.

Table 6-3 - Comparison between the FPI rules and a refined mesh

| Parameter             | FPI Mesh | Refined Mesh | Reference | Difference FPI Mesh | Difference Refined Mesh |
|-----------------------|----------|--------------|-----------|--------------------|------------------------|
| Neutral Axis [m]      | 15.64    | 15.58        | 15.47     | 1.1%               | 0.7%                   |
| σ St. bottom [MPa]    | 210      | 209          | 208       | 1.0%               | 0.5%                   |
| σ deck [MPa]          | -220     | -230         | -226      | -2.8%              | 1.7%                   |
| Spring Reaction       | 0.20%    | 0.10%        | 0.3%      | OK                 | OK                     |
| Time Static           | 00:20:30 | 00:35:20     | 00:20:30  | 0%                 | 72%                    |
| Time Ultimate         | 00:45:00 | 01:37:00     | 00:45:00  | 0%                 | 116%                   |

As will be explained in section 6.1.4, it will be used uniaxial springs at the ends of the model as the boundary condition. According to the ANSYS Manual [79]–[81], one suitable element is the COMBIN14, which is a uniaxial spring-damper as seen in Figure 6-5. In order to become a spring only, the user must input as zero the damping coefficient.

![FIGURE 6-5 - ELEMENTS USED FOR THE MODEL](image-url)
6.1.4. Materials Properties

The material used in this project is the same as the design process, which is high strength steel with a yield stress of 355 MPa. As seen in ABS material properties [6], the ultimate strength for this steel depends on its grade (AH, DH, EH or FH), which is between 490 MPa to 620 MPa. However, the ANSYS requires the values from the true curve of stress-strain to calculate the stress/displacement of the plates above the yield stress. According to [34], [82]–[84] the grade AH and DH has the highest and lowest ultimate strength respectively as can be seen in Figure 6-7. Therefore, for this master thesis, it was assumed that the structure would be constructed with DH steel. The engineering curve could be obtained by using the relation $\sigma_{\text{true}} = \sigma_{\text{eng}}(1 + \varepsilon_{\text{eng}})$ and $\varepsilon_{\text{true}} = \ln (1 + \varepsilon_{\text{eng}})$. Moreover, according to the Ansys Guidelines [79], [80], one suitable way to model this true curve for steel is the MISO model (Multilinear Isotropic Hardening) which uses the von Mises yield criterion with the associated flow rule and isotropic (work) hardening.

![Finite Element Model](image)

Figure 6-6 – Finite Element Model

![Stress-Strain Curve](image)

Figure 6-7 - Engineering and True Stress-Strain curve for AH36 and DH36 steel

6.1.5. Boundary and Load Conditions

According to the FPI guidelines [5], the boundary conditions to be applied at the ends of the cargo tank FE model are ground spring elements (i.e., spring elements with one end constrained in all 6 degrees of freedom) with stiffness in global z degree of freedom are to be applied to the grid points along the
deck, inner bottom and bottom shell and with stiffness in global y degree of freedom are to be applied to the grid points along the vertical part of the side shells, inner hull longitudinal bulkheads and oil-tight longitudinal bulkheads. This is shown in Figure 6-8. In addition to this, ground springs with stiffness in global x degree of freedom were applied to these points to prevent rigid body motion to the model.

Figure 6-8 - Position to apply the springs for the boundary conditions [5]

The stiffness of one vertical spring can be calculated from the buoyancy equation divided by the total number of vertical springs (n springs), once this can be considered as parallel spring association. The transverse and axial stiffness were considered as 10% of the water plane stiffness coefficient divided by the number of the respective type of spring. This value was taken in order to reduce the stress concentration from the spring in the plates at the ends model. In summary, the stiffness for each spring is:

\[ k_v = \frac{\rho_{\text{salt water}} \cdot g \cdot A_{\text{water plane}}}{n_{\text{vertical springs}}} = 18,377 \text{ kN/m} \]
\[ k_t = 0.1 \cdot k_v = 0.1 \cdot 18,377 = 1,837 \text{ kN/m} \]
\[ k_a = 0.1 \cdot k_v = 0.1 \cdot 4,594 = 4,594 \text{ kN/m} \]

The objective of the application of the loads is to replicate as fairly as possible the vertical shear force and vertical bending moment distributions on the three cargo tanks FE model. Therefore, it is applied at the end of the model the bending moment and vertical force corresponding to that location as Figure 6-9 gives as an example. One observation is done for the shear force, it is only applied to the vertical elements to prevent unrealistic deformation in the horizontal plates as [79] states. Also, according to [79], [80], the moments and forces shall be applied as:

Vertical Bending Moment: \[ F_{\text{nodal,i}} = \sigma_i \cdot (y_i - y_{na}) \cdot A_{\text{nodal,i}} \cdot I_{na} \]
Vertical Shear Force: \[ F_{\text{nodal,i}} = Q \cdot A_{\text{nodal,i}} \]

Where:
- \( \sigma \) is the normal stress at the element i
- \( y_i \) is the height of the element i taking as reference to the bottom plane
- \( y_{na} \) is the neutral axis height
- \( I_{na} \) is the moment of inertia along the neutral axis
- \( Q \) is the shear force applied
• A nodal in the area of the element i

Figure 6-9 - Instructions on how to apply the shear force and bending moments at the ends of the FEM

For the three tanks, it is applied the local forces such as weight of cargo, ballast, static. According to the ANSYS guidelines [79], for 2D Quadratic Isoparametric Element the nodal force at the corner node of an element can be calculated as $F_{\text{nodal}} = P_{\text{plate}} \times \frac{t_{\text{plate}}}{3}$, where $P_{\text{plate}}$ is the net pressure from all the forces acting in the plate.

### 6.2. Static Loads

Before the ultimate strength was calculated, the static load from one load condition was applied (draught equal to 26.8m) for each structure. There are two objectives for this step. The first one is to observe if the model is well calibrated. This is done by comparing the results with the ones expected by the Euler-Bernoulli beam theory and by analyzing how much the reaction force at the spring is related to the resultant forces applied. If the model is well calibrated, the stress at the structures should be similar to the beam theory and the reaction forces at the springs should be lower than 0.3%. The second reason for applying the static load first is because the ultimate strength loads will be obtained using as reference the static load. For example, the input for the ultimate strength analyses can be 2 times the load applied at the static load case.

The loads applied in the tanks for each load case are based on ones obtained in chapter 6. In order to facilitate the understanding of the inputs, it will be divided into two types of loads: fixed and variable. The fixed ones are related to the superstructure, equipment and riser loads and it is equal for all draughts. While the variable ones are related to the volume of liquid inside each tank for that load condition. They are summarized in the table below (Table 6-4). It is important to notice that for the bottom and side plates, the net pressure is obtained by the difference between the interior load (oil or ballast) and the static sea pressure and for the side longitudinal bulkhead plate the net pressure is the difference between the ballast and oil pressures. The ends bending moments and shear forces are derived from the distribution from section 3.4.2.
The first result to compare between structures is the vertical displacement in Table 6-5 and Figure 6-11. As it can be seen, the steel structure has a bigger deflection than the SPS structure, approximately, 19% bigger. This can be explained because the SPS structure has a higher moment of inertia (2391 m^4) rather than the steel structure midship section (2191 m^4), because as higher the moment of inertia, the greater is to bend it.

Table 6-5 - Vertical static displacement in mm for both types of structures in sagging

| Structure | Condition: Sagging |
|-----------|-------------------|
| Steel     | 154               |
| Composite | 130               |

Figure 6-10 - Loads applied to the model

Table 6-4 - Loads to be applied to the FEM

| Type          | Weight [ton] | Ballast Height [m] | Cargo Height [m] | Cargo Height [m] | Ballast Height [m] |
|---------------|--------------|--------------------|------------------|------------------|--------------------|
| Superstructure| 5000         |                    |                  |                  |                    |
| Equipment     | 3600         |                    |                  |                  |                    |
| Risers        | 2017         |                    |                  |                  |                    |

Tank Loads for draught equal to 26.8m

| Tank | SB | PB |
|------|----|----|
| 2    | 31.45 | 30.69 | 30.69 | 31.45 |
| 3    | 31.45 | 30.69 | 30.69 | 31.45 |
| 4    | 31.45 | 30.69 | 30.69 | 31.45 |

Figure 6-11 - Displacement of the FEM for both models
The second result is a comparison between the FEM and beam theory presented in Table 6-6. The points taken to be analyzed are at the midship section of tank 2, where the shear stress is zero according to the shear force distribution from HydroD, in order to minimize the boundary effects on the forces by the extremities. At first, it can be seen that the model’s loads are calibrated because the spring reaction is lower than the reference. Also, the normal stress and neutral axis are similar to the ones expected by the beam theory for both models. The difference between them can be explained by the slight change of the neutral axis and because the beam theory doesn’t consider the plate’s thickness, which can change the stresses. Also, notice that the normal stress for the SPS model is calculated for the steel plate, in order to obtain the stress at the core, the stress should be multiplied by the ratio of the Young Modulus ($\frac{E_{\text{core}}}{E_{\text{steel}}}$ = $\frac{750}{206,000}$). This results in a stress of 0.78 MPa, which is 3.7% from the yield stress of the core.

Table 6-6 - Comparison with the values from the FEM with reference taken from the beam theory and the spring reactions criteria

| Comparison of static load case for both arrangements |
|-----------------------------------------------------|
| Parameter | FEM | Reference | Difference | FEM | Reference | Difference |
| Neutral Axis [m] | 15.64 | 15.47 | 1.11% | 16.86 | 16.51 | 2.12% |
| σ St. bottom [MPa] | 210 | 208 | 0.99% | 205 | 203 | 0.85% |
| σ deck [MPa] | -220 | -226 | -2.75% | -187 | -195 | -3.86% |
| Spring Reaction | 0.20% | 0.3% | OK | 0.27% | 0.3% | OK |

Moreover, during the design process a safety factor for the static load case was considered, which was 0.6 of the yield’s stress (213 MPa). And, according to the beam theory, the deck plates should’ve reached a factor of 0.61-0.62. Since the FEM (Table 6-6) confirmed that these values do not surpass too much the goal of 0.6, the structure fits the design criteria.

Figure 6-12 - Normal stress distribution for both FEM

Figure 6-12 describes how the normal stress is distributed along the structure. As can be noticed from Figure 6-13, there are some differences in the normal stress between parts of the structure for the same height (side, side longitudinal bulkhead and center longitudinal bulkhead). This happens because of two reasons. The first one is because of the difference of thickness between plates and joint of structure (for example: the side and bottom) that can distribute the stresses. The second reason can be explained in
by a phenomenon called warping and it is related to the distortion of the longitudinal stresses in the cross-section due to the transverse shear or torsion.

Figure 6-13 - Normal stress distribution for the side, center and side longitudinal bulkhead for both cases

### 6.3. Ultimate Loads

According to Paik (2018) [64], “A ship’s hull in the intact condition will sustain applied loads smaller than the design loads, and, in normal seagoing and approved cargo loading conditions, it will not suffer any structural damages such as buckling and collapse. However, the loads acting on the ship’s hull are uncertain both due to the nature of rough seas and because of possibly unusual loading/unloading of cargo, the latter due to human error. In rare cases, applied loads may hence exceed design loads and the ship’s hull may collapse globally”. Therefore, when the structural safety of a ship’s hull is considered, the ultimate hull girder strength must then be accurately evaluated. This was first done in chapter 4 and 5 as a first check. However, closed form methods, specially from classification societies, tend to underestimate the real ultimate bending capacity of structures in order to achieve a safety design [85]. Thus, the FEA is a powerful tool to estimate the ultimate bending moment of the hull, because an ability to better assess the true margin of safety should also inevitably lead to improvements in regulations and design requirements.

Moreover, as it was described in chapter 2 and section 6.1.5, the ultimate strength load was obtained by increasing the load from the static load gradually until the structure reaches either a stress value near 665 MPa, which is the maximum stress from the true stress-strain curve of DH36 steel, or there was a collapse of the plates due to buckling. This is due to as applied loads increase beyond the design loads, structural members of the vessel’s hull girder buckle in compression and yield in tension. The vessel’s hull girder can normally carry further loading beyond the onset of limited member buckling or yielding, but the structural effectiveness of any such failed member clearly decreases, and its individual stiffness can even become “negative,” with their internal stress being redistributed to adjacent intact members [64].
The FEA showed that the steel structure and the structure with SPS could withstand 1.94x and 2.45x the static load, which is a 26% increase. This can be explained by the moment of inertia, which is inversely proportional to the normal stress. Therefore, the bigger the inertia, the bigger the bending moment needs to be to reach a specific value. And, since the SPS structure has a bigger one than the steel structure (almost 10% bigger), this structure can reach higher values of bending moments. Table 6-7 summarizes this information.

| Structure | Static Bending Moment [kN*m] | Multiplier | Ultimate Bending Moment [kN*m] |
|-----------|-------------------------------|------------|--------------------------------|
| Steel     | -29,453,568                   | 1.94       | -57,139,922                    |
| Composite | -72,161,242                   | 2.45       | -72,161,242                    |

Moreover, the moment-curvature graphic was also done to compare the ultimate bending capacity between the classification society rules (ABS/DNV) with the finite element results (Figure 6-14). Also, this graph shows the ULS for both types of arrangement and where each plate starts to buckle as well. As it can be observed the ULS for the steel and SPS according to the FEA are 11% and 24% higher respectively than the ones proposed to the classification society rules, because they are more conservative about its estimation. Comparing the values obtained with the same comparison made in Paik (2008) [85], they have a similar behavior and values regarding the comparison between the FEM and the CS.

The points circled in the graph are where the buckling starts to occur in each plate of the side shell. As can be observed, both reach the ULS because of the buckling of plates, however, the bottom plates, which were in tension, could support even more load, once they didn’t reach the value near 665 MPa. The main difference between both structures is where the buckling happens. For the steel design, the buckling happens in the deck plates. This could be previously visualized in chapter 5, in which the deck plates obtained the highest factor for the buckling and ultimate strength criteria. However, for the SPS design the region where the plates fail first is the side shell. Similar to the steel ones, they were the ones
with the highest values as well for the buckling and ultimate strength criteria. Moreover, their thickness is lower than the deck plates, therefore, their resistance for withstanding buckling is lower. This image phenomenon can be seen both in Figure 6-15, 6-16 and 6-17. As it can be seen in Figure 6-15, buckling occurs in the extremities of the side shell for the SPS plates and for the steel one is the deck panels. Figure 6-16 and 6-17 describes the difference between reaching the ULS by occurring buckling or reaching a stress of 665 MPa described previously, once the plates stress is near the 450-500 MPa.

![Steel Arrangement](image1)
![SPS Arrangement](image2)

**Figure 6-15 - Region where the plates fail**

![Steel](image3)
![SPS](image4)

**Figure 6-16 - Distribution of stresses at both designs**
The last result is related to the stresses related to the core of the SPS plates. As seen in chapter 6, the panel has several criteria regarding the core yield and shear. Figure 6-17 presents that the normal stress at the bottom plates was around 450 MPa, therefore, using the ratio of the Young Modulus \( \frac{E_{\text{core}}}{E_{\text{steel}}} = \frac{750}{206,000} \), the yield stress of the core was 1.82 MPa, which is 8% from the yield stress. This resulted also in a shear stress of 3.95 MPa and an interface shear stress, which is related to the bond between core and steel plates, of 4.03 MPa, while the allowable ones are 12 MPa and 7.5 MPa respectively. Therefore, the panel will not collapse because of the core.

To summarize, the SPS design obtained a better structural performance. In the static condition, the stress intensity in the SPS is overall lower than the steel, because of its higher moment of inertia. Consequently, the stress intensity of the bottom and deck plates were reduced by 1.4% and 15% using as reference the steel arrangement. Moreover, in the ultimate bending capacity, the SPS arrangement could withstand 24% more load than the steel one and the main difference between the models is the region where one plate collapses.

However, it is important to mention some limitations regarding the finite element model. For example, it was only analyzed the sagging condition. Also, due to the size/complexity of the model’s geometry and the computational power used, some non-linear properties were simplified in order to achieve a solution. These kinds of limitations can influence the structural behavior of the model and, thus, could be individually analyzed for a deeper understanding of the structure and its ultimate bending strength.
7. CONCLUSIONS

This work focused on the research for an initial design and construction of hulls of FPSOs with sandwich plates without stiffeners in the bottom plate and longitudinal bulkheads of cargo tanks. The main reason is to have the walls and bottom of the cargo tanks free of stiffeners to allow remote cleaning and thickness gauging of bottom and bulkhead plates using autonomous equipment.

The first step was to estimate the global loads for the case study FPSO in chapter 3. This was done with the help of GeniE and HydroD, in which loads and equilibrium conditions were assumed, and 5 cargo/ballast distributions were calculated. One of them is for the empty cargo condition, three intermediate draughts and one for the full cargo condition (10/12 cargo tanks filled). Therefore, with the balance between loads and buoyancy for each equilibrium condition, the bending moments and shear force distribution could be obtained.

In chapter 4 the initial design of the traditional steel arrangement was made by using the results of chapter 3 and guidelines of the ABS FPI rules [5]. This design was also compared to the DNV one to check possible changes and in the last section, the total strength assessment was made. In general, the design obtained passed all the criteria of yielding (static and dynamic load case), buckling and ultimate strength proposed. The only exception was the deck plates at the static load case, which obtained a factor of 0.62 from the yield stress. This design was considered acceptable because it is close to the maximum safety factor (0.6 for the static load case) and, since the static load case won't get near the yield stress, it is very unlikely that these plates permanently deform plastically.

In chapter 5, the design of the hull with SPS panels was made by using the steel panels dimensions and properties with the guidelines of DNVGL [18]. The main results were SPS panels that can withstand both static and dynamic load cases as the steel arrangement, but with a lighter structure. Also, it was calculated FPSO’s hull weight for both types of arrangement and it was observed that the SPS one was overall 2.8% lighter than the steel one primarily due to the bottom structure. This happens because the bottom structure has the plates with the highest thickness and with the more robust stiffener for the traditional hull structural arrangement.

Chapter 6 focused more on the construction of a finite element model for the analysis of the ultimate strength for both arrangements: traditional steel and SPS panels. After the creation of the model, the static load case was used as a load condition in order to validate the model using as reference the results from beam theory. Both steel and SPS models achieved results similar to the ones predicted. Following that the ultimate analysis was done and the main result is that the structure with SPS panels could withstand 26% more load rather than the steel one. This could be explained because the first structure has a higher moment of inertia.

Therefore, to summarize it, the SPS design demonstrated a superior structural performance over the traditional steel one. However, further research in the following areas would be interesting:

- Perform a local ultimate analysis for the SPS plates. This would provide more insights into the buckling and ultimate strength of the panels for the load cases
- Study the building process to investigate how the SPS panels could be efficient build.
• Research about the financial attractiveness of this new panel both during the building and operation step in order to know how the different kind of costs varies.
• Research different fillings materials and methods for the polyurethane in order to have alternatives.
• Research the impact of this new technology during the operational life of the FPSO, converting inspections requirements, maintenance and repair works.
8. REFERENCES

[1] S. J. Kennedy, J. Bond, D. Braun, P. G. Noble, and J. David Forsyth, “An innovative ‘no hot work’ approach to hull repair on in-service FPSOs using sandwich plate system overlay,” *Proc. Annu. Offshore Technol. Conf.*, vol. 2003-May, pp. 2129–2135, 2003.

[2] Transport Industries Under European Commission, “Best Practice Guide for Sandwich Structures in Marine Applications,” Newcastle upon Tyne, 2013.

[3] P. G. Bergan, C. Thienel, and K. Bakken, “Analysis and Design of Sandwich Structures Made of Steel and Lightweight Concrete,” *III Eur. Conf. Comput. Mech.*, no. June, 2006.

[4] J. Bond, A. Ferro, and S. Kennedy, “FPSO side shell impact protection,” *Offshore Technol. Conf. Proc.*, vol. 1, no. May, pp. 622–651, 2011.

[5] American Bureau of Shipping, *Rules for Building and Classing Floating Production Installations*, no. July. Spring: American Bureau of Shipping, 2020.

[6] American Bureau of Shipping, “Rules for Materials and Welding - Part 2,” in *Rules for Building and Classing Marine Vessels*, no. January, American Bureau of Shipping, Ed. Spring: American Bureau of Shipping, 2021, pp. 1–395.

[7] American Bureau of Shipping, “Rules for Building and Classing Marine Vessels - Part 3 Hull Construction and Equipment,” in *Rules for Building and Classing Marine Vessels*, no. 1, American Bureau of Shipping, Ed. Spring: American Bureau of Shipping, 2020, pp. 1–552.

[8] American Bureau of Shipping, “Rules For Materials and Welding,” in *Rules for Building and Classing Floating Production Installations*, no. July, 2020.

[9] Det Norske Veritas, “Classification of Ships Hull Structural Design 100 Metres and Above,” in *Newbuilding Hull and Equipment - Main Class*, no. 1322, 2009, pp. 1–114.

[10] Det Norske Veritas, “Rules For Classification Ships Part 3 Chapter 1 General principles,” in *Rules For Classification Ships*, no. July, 2019, pp. 1–55.

[11] Det Norske Veritas, “Rules For Classification Ships Part 3 Chapter 2 General arrangement design,” in *Rules For Classification Ships*, no. July, 2019, pp. 1–20.

[12] Det Norske Veritas, “Rules For Classification Ships Part 3 Chapter 3 Structural design principles,” in *Rules For Classification Ships*, no. July, 2019, pp. 1–94.

[13] Det Norske Veritas, “Rules for Classification Ships Part 3 Chapter 4 Loads,” in *Rules For Classification Ships*, no. July, 2019, pp. 1–96.

[14] Det Norske Veritas, “Rules For Classification Ships Part 3 Chapter 5 Hull girder strength,” in *Rules For Classification Ships*, no. July, 2019, pp. 1–29.

[15] Det Norske Veritas, “Rules For Classification Ships Part 3 Chapter 6 Hull local scantling,” in *Rules For Classification Ships*, no. July, 2019, pp. 1–55.
[16] Det Norske Veritas, “Rules For Classification Ships Part 3 Chapter 8 Buckling,” in Rules For Classification Ships, no. July, 2019, pp. 1–43.

[17] Det Norske Veritas, “Rules For Classification Ships Part 3 Chapter13 Welding,” in Rules For Classification Ships, no. July, 2019, pp. 1–30.

[18] Det Norske Veritas, DNVGL-CG-0154: Steel sandwich panel construction, April 2016., no. April. Det Norske Veritas, 2016.

[19] Lloyd’s Register, Rules for the application of sandwich panel construction to ship structure, no. July. Lloyd’s Register, 2020.

[20] S. Timoshenko, History of Strength of Materials, 1953 editi. New York: McGraw-Hill Book Company, 1953.

[21] O. F. Hughes and J. K. Paik, Structural Analysis and Design, First Edit. Jersey City, New Jersey, USA: The Society of Naval Architects and Marine Engineers, 2010.

[22] E. P. Popov, Introduction To Mechanics Of Solids, 13ª Editio. Berkeley, USA: Edgard Blücher Ltda., 2016.

[23] Det Norske Veritas, “Sesam User Manual: HydroD - Wave load & stability analysis of fixed and floating structures," in SESAM User Manual, HØVIK: Det Norske Veritas, 2014, pp. 1–137.

[24] Det Norske Veritas, “Sesam User Manual: GeniE," in SESAM User Manual, no. February, HØVIK: Det Norske Veritas, 2012, pp. 1–263.

[25] J. K. Paik et al., "' Committee III . 1 - Ultimate Strength ", Proceedings of the 17th International Ship and Offshore Structures Congress ( ISSC )," Seoul, South Korea, 2009.

[26] T. Yoshikawa et al., "' Committee III . 1 - Ultimate Strength ", Proceedings of the 19th International Ship and Offshore Structures Congress ( ISSC )," CASCAIS, PORTUGAL, 2015.

[27] J. Czujko, S. Eldeen, and G. Notaro, "' Committee III . 1 - Ultimate Strength ", Proceedings of the 20th International Ship and Offshore Structures Congress ( ISSC )," Amsterdam, Netherlands, 2018.

[28] J. B. Caldwell, “Ultimate Longitudinal Strength,” Trans. RINA, vol. 107, pp. 411–430, 1695.

[29] J. K. Paik and A. Mansour, “A simple formulation for predicting the ultimate strength of ships,” J. Mar. Sci. Technol., vol. 1, pp. 56–62, 1995.

[30] J. Paik, O. F. Hughes, and A. Mansour, “Advanced Closed-Form Ultimate Strength Formulation For Ships,” J. Sh. Res., vol. 45, no. 2, pp. 111–132, 2001.

[31] J. K. Paik, D. Park, H. Kim, A. Mansour, and J. B. Caldwell, “Modified Paik-Mansour formula for ultimate strength calculations of ship hulls,” Ships Offshore Struct., vol. 8, no. 3–4, pp. 245–260, 2013.

[32] C. Smith, “Influence of local compressive failure on ultimate longitudinal strength of a Ship’s hull,” Proc. 3th Int. Symp. Pract. Des. Shipbuild., pp. 73–90, 1977.
[33] R. D. Cook, D. S. Malkus, and M. . Plesha, *Finite Elements in Structures*, 3rd Edition. Madison, USA: John Wiley & Sons, 1989.

[34] D. do A. M. Amante, “Resistência Última de Navios e Plataformas Danificados por Colisões,” UFRJ, 2017.

[35] American Bureau of Shipping, *Rules for Conditions of Classification*, no. January. Spring: American Bureau of Shipping, 2020.

[36] Det Norske Veritas, “DNVGL-CG-0128: Buckling,” *Cl. Guidel.*, no. October, pp. 1–124, 2015.

[37] B. C. Simonsen *et al.*, ““ Committee III . 1 - Ultimate Strength ”, Proceedings of the 15th International Ship and Offshore Structures Congress ( ISSC ),” 15 th INTERNATIONAL SHIP AND OFFSHORE STRUCTURES CONGRES, SAN DIEGO, USA, 2003.

[38] T. Yao *et al.*, ““ Committee III . 1 - Ultimate Strength ”, Proceedings of the 16th International Ship and Offshore Structures Congress ( ISSC ),” SOUTHAMPTON, UK, 2006.

[39] M. L. Kaminski *et al.*, ““ Committee III . 1 - Ultimate Strength ”, Proceedings of the 14th International Ship and Offshore Structures Congress ( ISSC ),” Nagasaki, Japan, 2000.

[40] J. K. Seo, B. J. Kim, H. S. Ryu, Y. C. Ha, and J. K. Paik, “Validation of the equivalent plate thickness approach for ultimate strength analysis of stiffened panels with non-uniform plate thickness,” *Thin-Walled Struct.*, vol. 49, no. 6, pp. 753–761, 2011.

[41] O. F. Hughes, B. Ghosh, and Y. Chen, “Improved prediction of simultaneous local and overall buckling of stiffened panels,” *Thin-Walled Struct.*, vol. 42, no. 6, pp. 827–856, 2004.

[42] J. K. Paik, B. J. Kim, and J. K. Seo, “Methods for ultimate limit state assessment of ships and ship-shaped offshore structures: Part II stiffened panels,” *Ocean Eng.*, vol. 35, no. 2, pp. 261–270, 2008.

[43] S. Saad-Elddeen, Y. Garbatov, and C. G. Soares, “Experimental assessment of the ultimate strength of a box girder subjected to severe corrosion,” *Mar. Struct.*, vol. 24, no. 4, pp. 338–357, 2011.

[44] N. A. D. S. Rizzo and M. Caire, “Ultimate strength formulations for fpso stiffened panels under combined compression and shear with initial imperfections and damage,” *Lat. Am. J. Solids Struct.*, vol. 15, no. 11MecSol2017Joinville, pp. 1–13, 2018.

[45] J. D. Martin, “Sandwich Plate System Bridge Deck Tests,” Virginia Polytechnic Institute, 2005.

[46] G. Zou, Y. Wang, Q. Xue, and C. Zhang, “Buckling Analysis of Sandwich Plate Systems with Stiffening Ribs: Theoretical, Numerical, and Experimental Approaches,” *Adv. Civ. Eng.*, vol. 2019, 2019.

[47] G. qing Feng, G. Li, Z. hui Liu, H. lei Niu, and C. feng Li, “Numerically simulating the sandwich plate system structures,” *J. Mar. Sci. Appl.*, vol. 9, no. 3, pp. 286–291, 2010.

[48] P. C. Boersma, “Sandwich Plate Systems: The application of Sandwich Plate Systems as impact
protection in offshore structures," Delft University of Technology, 2017.

[49] Tribunal de Contas da União do Brasil, “Relatório de fiscalização,” Brasília, 2016.

[50] Det Norske Veritas, “Sesam User Manual: Wadam - Wave Analysis by Diffraction and Morison Theory,” in SESAM User Manual, HØVIK: Det Norske Veritas, 2014, pp. 1–216.

[51] Det Norske Veritas, “SESAM User Course – HydroD Workshop 1: Hydrodynamic analysis of a semi-submersible,” in SESAM User Guide: HydroD Tutorial, no. March, HØVIK: Det Norske Veritas, 2014, pp. 1–18.

[52] Det Norske Veritas, “SESAM User Course – HydroD Workshop: Stability and hydrostatic analysis of a barge with a jacket on top,” in SESAM User Guide: HydroD Tutorial, no. March, HØVIK: Det Norske Veritas, 2014, p. .

[53] Det Norske Veritas, “GeniE - Modelling a semisubmersible,” in SESAM User Guide: GeniE Tutorial, HØVIK, 2011, pp. 1–40.

[54] Det Norske Veritas, “GeniE - Semi Pontoon Workshop,” in SESAM User Guide: GeniE Tutorial, HØVIK: Det Norske Veritas, 2015, pp. 1–59.

[55] Det Norske Veritas, “HydroD Tutorial: Stability and Hydrostatic Analysis of SemiSubmersible,” in SESAM User Guide: HydroD Tutorial, no. March, HØVIK: Det Norske Veritas, 2014, pp. 1–66.

[56] J. M. J. Journée and W. W. Massie, Offshore Hydromechanics, First Edit., no. January. Delft University of Technology, 2001.

[57] O. M. Faltinsen, Sea Loads On Ships And Offshore Structures, First Edit. Cambridge, United Kingdom: Cambridge University Press, 1990.

[58] J. N. Newman, The Theory of Ship Motions, vol. 18, no. C. Cambridge, Massachussets: Department of Ocean Engineering Massachusetts Institute of Technology, 1979.

[59] N. Salvesen, E. O. Tuck, and O. M. Faltinsen, Ship motions and sea loads, vol. 78, no. i. 1970.

[60] C. S. Castro, “Análise Dinâmica e Modelagem de Turbinas Eólicas Flutantes,” Escola Politécnica da Universidade de São Paulo, 2020.

[61] Det Norske Veritas, “HydroD Stability Reference: IMO - Code for the Construction and Equipment of Mobile Offshore Drilling Units Consolidated Edition , 2001,” in SESAM User Guide: HydroD Tutorial, HØVIK: Det Norske Veritas, 2014, pp. 1–4.

[62] Det Norske Veritas, “HydroD Stability Reference: Norwegian Maritime Directorate Regulations for Mobile Offshore Units (2003 Edition),” in SESAM User Guide: HydroD Tutorial, HØVIK: Det Norske Veritas, 2014, pp. 1–7.

[63] International Association of Classification Societies, “Common Structural Rules for Bulk Carriers and Oil Tankers,” Common Struct. Rules Bulk Carriers Oil Tankers, pp. 1–816, 2019.

[64] J. K. Paik, “Ultimate Strength of Ship Hull Structures Characteristics of Ship’s Hull Structures - Chapter 8,” in Ultimate Strength of Ship Hull Structures, 2nd Edition, no. 1, Busan, Korea: ohn
[65] Bureau Veritas, “Booklet 1: Introduction Shell/Basic Ship Data,” in Mars 2000 User’s Guide, no. 0, Paris, 2000, pp. 1–21.

[66] Bureau Veritas, “Booklet 2: Definition Of A Section,” in Mars 2000 User’s Guide, no. February, Paris, 2000, pp. 1–51.

[67] Bureau Veritas, “Booklet 3: Calculation Of A Section,” in Mars 2000 User’s Guide, vol. 33, no. 0, Paris, 2000, pp. 1–30.

[68] G. R. Liu and S. S. Quek, “Computational Modeling,” in The Finite Element Method, Second Edi., Elsevier, Ed. Oxford, UK: Elsevier, 2014, pp. 1–11.

[69] G. R. Liu and S. S. Quek, “Fundamentals for Finite Element Method,” in The Finite Element Method, First Edit., Elsevier, Ed. Oxford, UK: Elsevier, 2014, pp. 43–79.

[70] G. R. Liu and S. S. Quek, “FEM for Beams,” in The Finite Element Method, Second Edi., vol. 7, Elsevier, Ed. Oxford, UK: Elsevier, 2014, pp. 111–134.

[71] G. R. Liu and S. S. Quek, “FEM for Plates and Shells,” in The Finite Element Method, Second Edi., vol. 7, Elsevier, Ed. Oxford, UK: Elsevier, 2014, pp. 219–247.

[72] G. R. Liu and S. S. Quek, “FEM for 3D Solid Elements,” in The Finite Element Method, Second Edi., Elsevier, Ed. Oxford, UK: Elsevier, 2014, pp. 249–287.

[73] G. R. Liu and S. S. Quek, “Modeling Techniques,” in The Finite Element Method, Second Edi., Elsevier, Ed. Oxford, UK: Elsevier, 2014, pp. 301–345.

[74] J. Kee Paik, “Ultimate limit state performance of oil tanker structures designed by IACS common structural rules,” Thin-Walled Struct., vol. 45, no. 12, pp. 1022–1034, 2007.

[75] SPS Technoloy Ltd, “Finite Element Analysis of SPS Structures.” SPS Technoloy, England, England, pp. 1–4, 2019.

[76] M. F. Caliri, A. J. M. Ferreira, and V. Tita, “A review on plate and shell theories for laminated and sandwich structures highlighting the Finite Element Method,” Compos. Struct., vol. 156, pp. 63–77, 2016.

[77] K. H. Ha, “Finite element analysis of sandwich plates: An overview,” Comput. Struct., vol. 37, no. 4, pp. 397–403, 1990.

[78] V. Manet, “The use of ANSYS to calculate the behaviour of sandwich structures,” Compos. Sci. Technol., vol. 58, no. 12, pp. 1899–1905, 1998.

[79] ANSYS Inc., “ANSYS Mechanical APDL Theory Reference,” in ANSYS Inc, no. November, ANSYS Inc., Ed. Canonsburg, PA, USA: ANSYS Inc., 2013, pp. 1–952.

[80] ANSYS Inc., “ANSYS Mechanical APDL Element Reference,” in Ansus User Guide, no. November, ANSYS Inc., Ed. Canonsburg, PA, USA: ANSYS Inc., 2011, pp. 1–1416.

[81] ANSYS Inc., “Mechanical APDL Command Reference,” in Ansus User Guide, no. November,
Canonsburg, PA, USA: ANSYS Inc., 2013, pp. 1–1868.

[82] H. Kang and J. Kim, “Progressive Collapse of Steel Moment Frames Subjected to Vehicle Impact,” *J. Perform. Constr. Facil.*, vol. 29, no. 6, p. 04014172, 2015.

[83] M. Jeyakumar and T. Christopher, “Influence of residual stresses on failure pressure of cylindrical pressure vessels,” *Chinese J. Aeronaut.*, vol. 26, no. 6, pp. 1415–1421, 2013.

[84] M. Z. M. Alie, R. Iriani, Juswan, and M. I. Ramadhan, “Ultimate Strength Analysis of FPSO Hull Girder under Longitudinal Bending,” *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 676, no. 1, 2019.

[85] J. K. Paik, B. J. Kim, and J. K. Seo, “Methods for ultimate limit state assessment of ships and ship-shaped offshore structures: Part III hull girders,” *Ocean Eng.*, vol. 35, no. 2, pp. 281–286, 2008.
Figure A-9-1 - Lines plan from the hull