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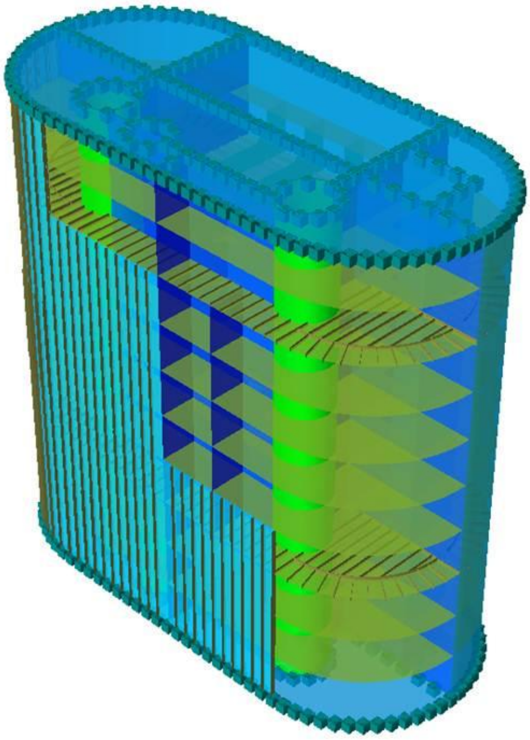

IMPROVED COLUMN DESIGN ON A DP3 SEMI-SUBMERSIBLE UNIT

Master's Thesis in the International Master's Programme Naval Architecture and Ocean Engineering

HALE SAGLAM - OSCAR LINDEKRANTZ

Department of Shipping and Marine Technology
Division of Marine Design, Research Group Marine Structures
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2014
Master's thesis

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Cover:
Column FE-model created using the software Genie showing general and structural arrangement (see Section 4 and 6)

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ABSTRACT

In this thesis a column stabilized semi-submersible drilling platform is analyzed. The purpose is to improve the column design of a generic 4-column semi-submersible with regard to the outer shape, including the general arrangement and layout of the compartments. The aim of this thesis is to decrease the unit's complexity, increase the draught flexibility and reduce the total weight of the column.

The report takes into account the multiple functions and features of a column design including establishing of the governing design factors. Based on these criteria and together with the rules and regulations relating to offshore operations, a design concept is selected for further evaluation. During the work frequent interaction with the affected design disciplines is carried out involving structural analysis, stability, weight management and systems & arrangement. Through this it can be verified whether the concept design was complying with the criteria requirements. Compartment volumes, system capacities and stability calculations are carried out using excel spread sheets. Structural strength assessment is carried out by using DNV PULS and GVA in-house created spreadsheet and input to this assessment is obtained by using a FE-model created in Genie.

The investigation led to the choice of a circular & flat sided column shell with benefits to the structural integrity and hydrodynamic properties. A new larger trunk was established containing staircase, lift, routings, reserve/storage tanks and all equipment. In addition, the new compartment arrangement enables the catering for two horizontal cross bracings, transverse between the columns. The amount of compartments in need of regular personnel access was decreased which resulted in less watertight closures and dedicated supply ducts, thus reducing the inner column complexity.

The new column design indicated an improvement to the unit's draught flexibility, however not all stability requirement were met. In order to verify this it is suggested that a more detailed analysis is carried out involving the use of commercial hydrostatic and stability software. The changes in general arrangement and structural design led to an estimated total weight reduction between 6.2% and 8.3% with regard to the reference design. The results from the structural analysis indicated that further investigation can lead to more weight reduction, with regard to the safety factors against buckling and yield. However some assumptions regarding the input data involving the global stresses may turn out to increase the structural weight, once more accurate data is obtained.

Key words: access trunk, column, drilling unit, DP3, offshore, semi-submersible

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SAMMANFATTNING
I denna avhandlng analyseras en semi-submersible borrplatform. Syftet är att förbättra kolumndesignen av en generisk 4-kolumn semi-submersible med avseende på den yttre skepnaden, inklusive innre arrangemang och rums layout. Målet med denna avhandling är att minska enhetens complexitet, höja flexibiliteten gällande djupgående och minska den totala vikten på kolumnen.

Rapporten tar hänsyn till de många funktioner och egenskaper i en kolumndesign inlkusive upprättandet av de styrande konstruktionsfaktorerna. Utifrån dessa kriterier och tillsammans med de regler och förordningar som involverar offshore verksamhet, väljs det ut ett designkoncept för vidare utvärdering. Under arbetet förekommer det ofta samspel mellan de berörda designdisciplinerna, dessa omfattar strukturanalys, stabilitet, viktkontroll, system och arrangemang. Utifrån detta kan det verifieras huruvida designkonceptet uppfyller kriterierna. Arrangemangs volymer, systemkapaciteter och stabilitetsberäkningar utförs med hjälp av Excel kalkyler. Den strukturella styrke bedömningen utförs med hjälp av DNV PULS och GVA-internt skapade kalkylblad, indata värderna till dessa beräkningar erhålls genom att använda en FE-modell skapat i Genie.

Utredningen ledde till valet av en rund och plansidig yttre kolumn skepnad, med fördelar inom den strukturella integriteten och de hydrodynamiska egenskaperna. Ett nytt och större utrymme etablerades i kolumnen som rymmer trappauppgång, hiss, ledningar, lagringstankar, samt all utrustning. Dessutom möjliggör det nya rumsarrangemanget förmågan att bära två horisontella tvärstag, tvärgående mellan kolumnerna. Andelen utrymmen i behov av regelbunden personaltillgång minskade vilket resulterade i mindre vattentäta stängningar och dedikerade försörjningskanaler, vilket minskar den inre kolumnkomplexiteten.

Den nya kolumndesignen tyder på en förbättring av enhetens flexibilitet gällande djupgående, dock uppfyllde den inte alla stabilitets kraven. För att kontrollera detta föreslås det att det görs en mer ingående analys som omfattar användningen av kommersiella hydrostat och stabilitet programvara. Förändringarna i arrangemanget och den strukturella konstruktionen ledde till en total viktminskning mellan 6,2% och 8,3% med avseende på referenskolumnen. Resultaten från den strukturella analysen visade att en ytterligare utredning kan leda till mer viktminskning, med hänsyn till de säkerhetsfaktorer mot spänning och töjning. Med avseende på de antaganden inom indata värdena för de globala spänningarna, kan det dock visa sig att vikten kommer ökas efter det att noggrannare uppgifter om den global modellen erhållts.

Nyckelord: access trunk, borrplatform, DP3, kolumn, offshore, semi-submersible

Contents

Preface

This report is submitted to fulfill the requirement to the degree of Master of Science in Naval Architecture and Ocean Engineering at Chalmers University of Technology, Gothenburg. The scope of work was developed in collaboration with general arrangement department at GVA Consultants AB. The work with this thesis project was conducted during spring 2014 and is written by Oscar Lindekrantz and Hale Saglam.

First of all we would like to express our gratitude to senior lecturer Per Hogström, examiner and supervisor of this thesis project, for his great effort to always give high quality answers, recommendations and motivation throughout the thesis.

This thesis project requires the involvement of several disciplines such as structural analysis, general arrangement and stability. Several engineers within GVA Consultants have contributed with their theoretical and practical knowledge. We would firstly like to thank our supervisor at the company Magnus Olofsson for his guidance and encouragement, for always providing time for consultation. We appreciate the guidance and assistance of Larry Berggren and Tommy Lager on their expertise and wide knowledge on sizing and stability. We would like to thank them for always providing time.

Special thanks to structural analysis engineers, Henrik Viktorsson and Rasmus Westerdahl Jansson for their continuous contribution and support to understanding of structural analysis.

Göteborg, May 2014

Oscar Lindekrantz & Hale Saglam

Notations and abbreviations

Symbols

A_B	Cross-sectional bracing area, [m^2]
C_W	Smith effect
C_P	Volume weight factor of the pontoon, [ton/m^3]
B	Center of buoyancy, [m]
B'	Shifted center of buoyancy, [m]
BM	Metacentric radius, [m]
D_D	Vertical distance from moulded baseline to the assigned loaded waterline, [m]
F	Force, [N]
F_B	Characteristic breaking strength of one mooring line, [kN]
$F_{d,w1}$	Design load on windlass, [kN]
F_v	Vertical fairlead stress, [kN]
G	Center of gravity, [m]
G'	Shifted center of gravity, [m]
GM	Metacentric height, [m]
GZ	Righting arm, [m]
I	Area moment of inertia, [m^4]
KB	Distance from keel to the center of buoyancy, [m]
KG	Distance from keel to the center of gravity, [m]
KM	Distance from keel to the metacenter, [m]
M	Metacenter, [m]
M_H	Heeling moment, [Nm]
M_R	Restoring moment, [Nm]
P	Pressure, [Pa]
R_k	Characteristic resistance
S_{ki}	Characteristic load effect
T_E	Operational draught, [m]
WB_d	Water ballast desired, [m^3]
Z_s	Section modulus, [mm^2]
∇_a	Added volumetric displacement, [m^3]
∇_n	Needed volumetric displacement, [m^3]
∇_U	Volumetric displacement of the total unit, [m^3]
∇_d	Volumetric displacement of the damaged compartment, [m^3]
∇_T	Volumetric displacement at transit, [m]
∇_P	Volumetric displacement for the Pontoons, [m]
Δ_U	Displacement of the total unit, [ton]
Δ_B	Displacement of the bracings, [ton]
δ_Δ	Difference of the unit's displacement and light weight, [ton]

a	Horizontal distance between the unit's center of gravity and damaged compartment center of gravity, [m]
a_v	Vertical acceleration, [m/s^2]
b	Vertical distance between the unit's center of gravity and damaged compartment center of gravity, [m]
h_{ap}	Air-pipe height, [m]
h_{S-L}	Sea-Loc height, [m]
l	Stiffener span, [mm]
l_B	Bracing length, [m]
g	Gravitational force, [m/s^2]
f_y	Yield stress, [MPa]
f_{yd}	Design yield strength
k_a	Correction factor for aspect ratio of the plate field
k_m	Bending moment factor
k_{pp}	Fixation parameter for plate
n_B	Number of bracings
p_s	Permanent sea pressure, [kN/m^2]
p_e	Environmental sea pressure, [kN/m^2]
p_d	Design pressure, [kN/m^2]
p_{dyn}	Dynamic pressure, [kN/m^2]
r	Shell radius, [m]
s	Stiffener spacing, [mm]
t	Plate thickness, [mm]
t_0	Initial plate thickness, [mm]
z_b	Vertical distance from moulded baseline to the load point, [m]
z_s	Vertical submersion, [m]
α	Angle of heel
β	Azimuth angle
φ	Angle of inclination
ϕ	Resistance factor
γ_F	Load factor
γ_M	Material factor
ρ	Fluid density, [kg/m^3]
ρ_{sw}	Sea water density, [kg/m^3]
ρ_s	Steel density, [kg/m^3]
σ_x	Axial stress in x-direction, [MPa]
σ_y	Axial stress in y-direction, [MPa]
σ_{xd}	Design membrane stress in x-direction, [MPa]
σ_{yd}	Design membrane stress in y-direction, [MPa]
σ_{pd1}	Equivalent design stress for global in-plane membrane stress, [MPa]
σ_{pd2}	Design bending stress, [MPa]

σ_{jd}	Von Misses equivalent design stress, [MPa]
τ_d	Design shear stress in the x-y plane, [MPa]
τ	Shear stress, [MPa]
η_{UC}	Safety factor for ultimate capacity
η_{BS}	Safety factor for buckling strength

Abbreviations

ALS	Accidental Limit State
ASD	Allowable Stress Design
COG	Center of Gravity
DNV	Det Norske Veritas
DP	Dynamic Positioning
FLS	Fatigue Limit State
GVA	Götaverken Arendal
HVAC	Heat Ventilation and Air Conditioning
IACS	International Association of Classification Societies
IMO	International Maritime Organization
LUW	Light Unit Weight
LRFD	Load Resistance Factor Design
MODU	Mobile Offshore Drilling Unit
NCS	Norwegian Continental Shelf
NMA	Norwegian Maritime Authority
PULS	Panel Ultimate Limit State
SLS	Serviceability Limit State
ULS	Ultimate Limit State
VCG	Vertical Center of Gravity
WPA	Water-plane Area
WSD	Working Stress Design

1. Introduction

In the design of a semi-submersible rig, there are several objectives and limitations acting as design drivers. A basic understanding of main design drivers is a key in engineering problems; within the current thesis, those areas are weight optimization, stability, complexity in system and general arrangement and structural feasibility. This thesis focuses on the intersection of aforementioned design drivers, which are not mutually exclusive.

1.1. Background and Motivation

As offshore exploration is progressing towards increased water depths, there is an increasing demand for floating offshore structures. One of the first floating production systems is semi-submersibles, which are widely used for different offshore operations with water depth capabilities ranging from 600 m to 3600 m. A semi-submersible consists of a deck containing equipment and living quarters that are supported by a hull, consisting of vertical columns, horizontal pontoons, bracings and/or wing pontoons (Chakrabarti, 2005). One of the main functions of a column-stabilized semi-submersible drilling unit is to provide excellent stability for drilling operations and withstand harsh environment conditions.

Virtually, all semi-submersibles have at least two floatation states: semi-submerged (afloat on the columns) and afloat on the pontoons (Chakrabarti, 2005). The pontoons are the sole source of floatation of the semi when not semi-submerged. Although they may function structurally, structural strength is not the main function of the columns. The columns are “stability columns” and primarily provide water-plane area and floatation stability to all possible loading conditions. Clauss (1998) showed that the shape of a semi-submersible could be further optimized if the cross-sections of the columns and the pontoons could be adjusted.

Columns contribute to the total rig weight with a great percentage. Achieving some degree of weight reduction in columns – but still serving the same functionality - would affect the total platform weight and economics in a greater extent. This statement solely pioneers this study; as investigating the possible improvements/modifications of traditional design by providing sufficient space for the systems involved, having a feasible structural design and stability as well as achieving weight reduction. Following questions are deemed to be answered within this study: What is the interaction between stability and structural arrangement? How structural arrangement affects the layout? How the structural design can be modified such that the strength is still within the acceptable limits? And with the final design, would it be possible to save weight?

Weight reduction would be achieved by improving any disciplines involved in the column design; however reduction in structural steel weight is always one of the main concerns since it comprises a big part of the total weight. Reducing some steel is always favorable not only because it leads to reduction in fuel consumption but also favorable for the environment. Steel is an essential material for offshore structures and apart from beign convenient for the structural strength, it is also a material that can be totally recycled. Since the quality of steel does not downgrade when it is recycled, it can be used over and over again, making the steel a sustainable material.

The work in this thesis is commissioned by GVA consultants, a world-leading designer for wide variety of semi-submersibles such as drilling, production, accommodation, heavy lift, well intervention units with its patented technologies. The GVA4000 NCS (Norwegian Continental Shelf) Winterized Unit is a tailor-made production drilling semisubmersible designed for Statoil, which is capable to operate all year round in the North Norwegian Sea (see Figure 1.1).

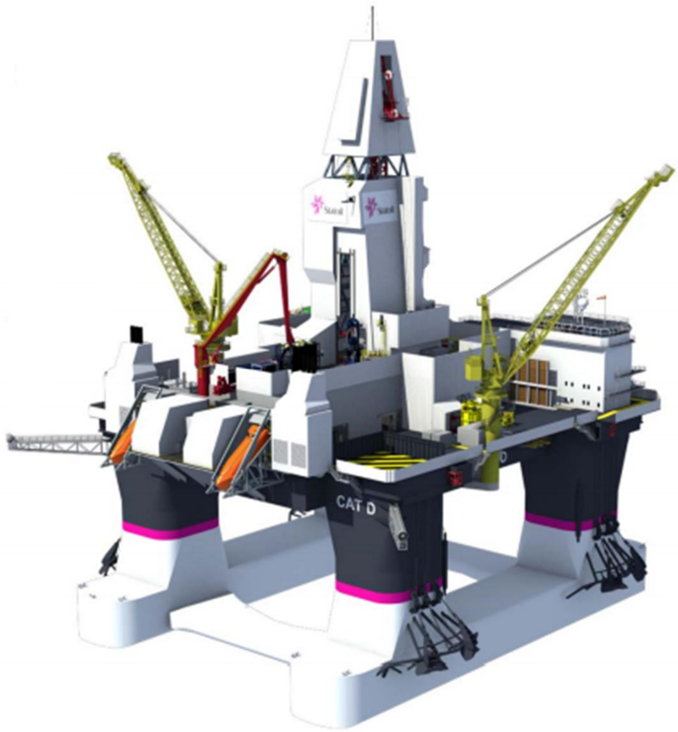


Figure 1.1: The reference drilling unit GVA4000 NCS

Within this study, different GVA designed drilling units are considered and utilized, due to the comparison purposes, the GVA4000 NCS is used as a reference project with the main dimensions shown in Table 1.1.

Table 1.1: Main dimensions of GVA 4000(Cat-D)

Length overall	116 m
Column dimensions	18.2x16.25 m
Pontoon dimensions	114.4x16.25x10.4 m
Height (box bottom)	35.75 m
Height (upper deck)	44.25 m

1.2. Objectives and Tasks

The trend in offshore structures is towards lighter structures in order to handle heavier projects which introduces more flexibility to the units' operations. Steel weight reduction is crucial since it results in increased payload. There is a proportional relation between weight reduction and structural strength and it is essential to provide decent deck load to steel weight ratio. As a starting point of this thesis, the weight reduction is aimed by proposing a new column design that is different from traditional cruciform inner arrangement. This leads to the investigation of possible weight reduction associated with general arrangement, stability and structural strength aspects. The main objectives of this thesis are;

- **Maximize the access trunk volume**
  - The ultimate goal is to fit the staircase, lift and all equipment and bulk tanks in the access trunk and avoid having this compartment as a damage case.
    In addition, consolidate all seawater pipes in a separate pipe trunk by meeting the requirements for dynamic positioning class 3 (DP3).
- **Improve the double shell and horizontal stringers arrangement**
  - The goal is to improve the unit's draught flexibility and investigate usable operational draught ranges.
- **Provide bracing connections instead of wing pontoons**
- **Reduce the number of compartments**
  - The goal is to reduce the number of compartments, in particular compartments requiring regular personnel access and forced ventilation/air conditioning.

All of the above objectives are within the envelope of class rules and regulatory requirements. Within this project, column design is in accordance with DNV rules, IMO MODU code (2009) and NMA rules (1991) (For the full list of reference rules, see Section 12).

1.3. Methodology

The design methodology of this study is iterative, which involves concept design, testing/checking, analyzing/calculation and refining the design by considering the priority levels of the objectives. This methodology allows to focus on issues where many contradictory design factors are involved.

The new column design is investigated in terms of stability – both intact and damage stability – structural strength and general arrangement aspects with the goal to meet the minimum requirements.Hand calculations are used where it is relevant, mostly for stability evaluation, structural strength assessment is carried out by using FE-analysis.

The flow chart in Figure 1.2 represents the procedure used in this study. The procedure starts with the governing design factors where the specifications and criteria for those factors are listed. Prior to the governing design factors, initial familiarization of general semi-submersible design and in particular GVA design philosophy is studied. The next step is evaluating different column shapes with respect to previously defined criteria; those are structural integrity, stability, hydrodynamics and manufacturing cost. In this phase, a literature study is carried out, involving both patents as well as previous studies on different column shapes and design considerations. Ranking of different concepts are carried out in collaboration with engineers at GVA who are specialized on different disciplines. Once the priorities are set, the preliminary dimensioning of the column shape is initiated. This process is deemed to be crucial since some of the criteria are roughly determined at this stage.

The next step is to evaluate different compartment arrangements according to the predefined objectives. Horizontal stringer arrangements are also involved in this process since the damage extents are strongly dependent on stringer arrangements at different draughts. For each compartment arrangement, comparison between existing layouts in terms of damage volumes and damage location is made. Several iterations are carried out between preliminary dimensioning and capacity check until the results are relatively good. This stage is carried out roughly; a more detailed investigation is done at the later stages.

Once the column shape and layout are determined, the design is simultaneously carried out by evaluating the stability and structural strength of the new column. Intact stability calculations are done by using spreadsheets, where the columns of reference project are replaced by the new column design data. Besides the stability evaluation, structural feasibility of the column is carried out by yield and buckling check of each structural component. Yield check is done by using spreadsheet created in GVA and buckling check is done by DNV PULS semi-analytical computer software. Input for yield and buckling calculations are established by the local model created in Genie software (DNV, 2010a)

As a last step, the new column design is evaluated and compared with the reference design within the scope of previously defined design criteria.

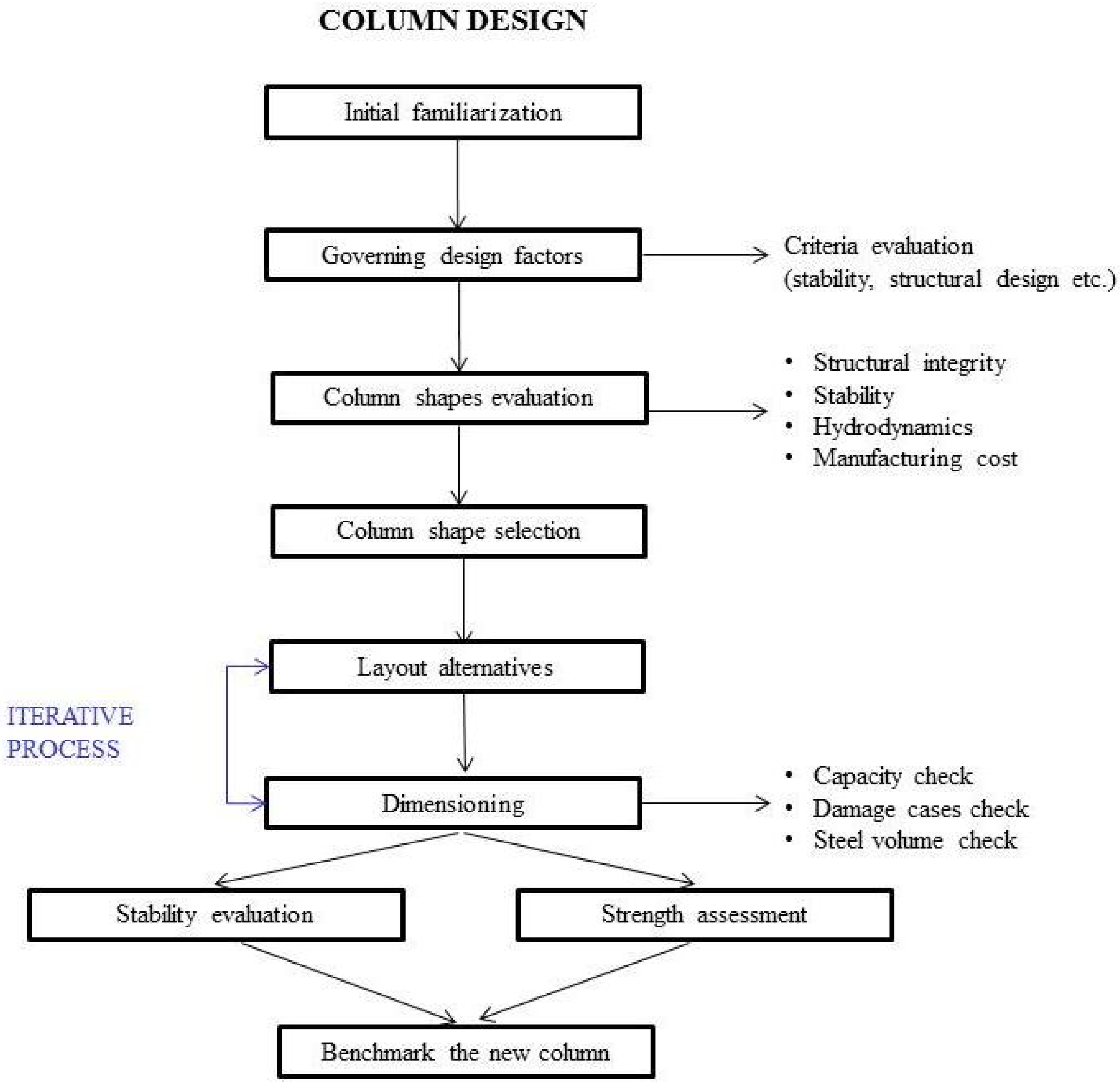


Figure 1.2: General procedure used in the study

1.4. Limitations and Assumptions

Throughout the thesis some simplifications and assumptions are made. The main assumptions are as follows;

There are usually some differences in layout and structural arrangement between the columns. In order to simplify the problem, all columns are assumed to be identical.

The reference design has two wing pontoons that connect two pontoons transversely and provides ballast capacity to the unit. The new column design is to be capable to cater for two horizontal cross bracings per column instead of a wing pontoon arrangement.

One of the purposes of replacing wing pontoons with bracings is to eliminate drag resistance during transit. As it is seen in Figure 1.3, wing pontoons are located at the pontoon level which is under the transit waterline, while the bracings are above the transit draught. This reduces drag resistance and fuel consumption accordingly during transit. Inspection and maintenance of the bracings are performed easily without dry docking the unit, since they are above the transit waterline. Bracings connect columns horizontally and the structural and general arrangement of the columns changes significantly with this arrangement.

As an outcome of replacing wing pontoons with bracings on the existing unit, pontoons require resizing in order to maintain the required displacement during transit. More discussion on resizing the unit parts due to the bracings is mentioned in Section 5. Within this study, bracings are used instead of wing pontoons by considering the effects on column design. Possible arrangements on structure and general arrangement are implemented on design. However, detailed bracing design is not within the scope of this study and any further analysis is done regarding this.

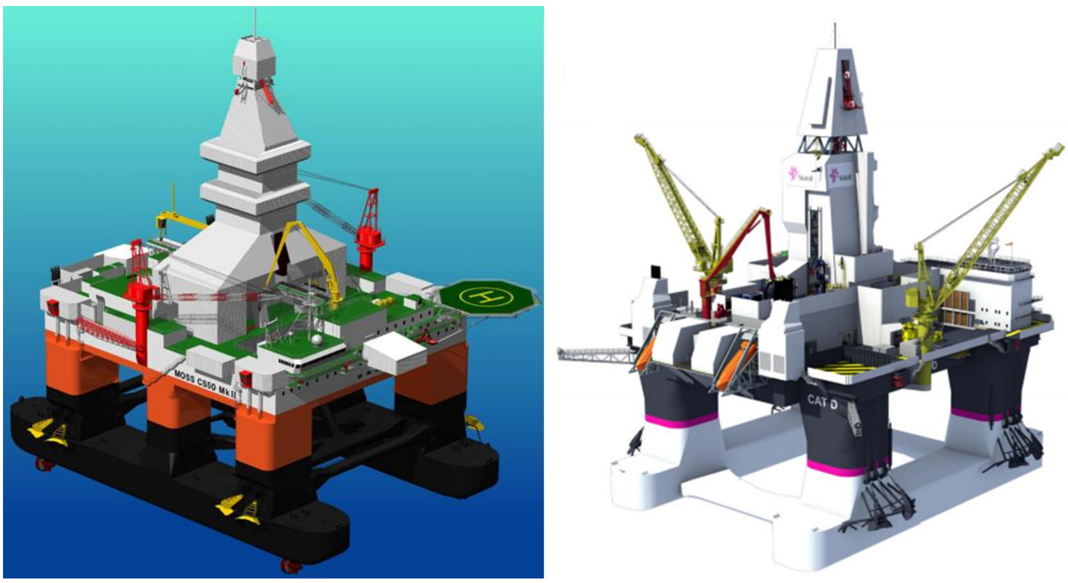


Figure 1.3: Bracing and wing pontoon arrangements

2. Key Functional Requirements

The mobile semi-submersible drilling unit's hull typically consists of four or six columns connected with horizontal pontoons and supports a deck on top. The semi-submersibles have good motion characteristics in severe environment conditions and thus have the advantages of being able to stay in the drilling modes longer than a typical drillship (Chakrabarti, 2005). The modern semi-submersible units can have up to 8 columns. The main functions of columns are defined as,

- Carry lightship and deadweight of/from the decks above
- Transfer global loads from bulkheads/decks above to the pontoons
- Provide air-gap for the decks above by elevating the deck box structure
- Provide DP3 segregation for certain systems by compartmentization
- Carry deadweight in form of bulk tanks, water ballast, and equipment skids etc.
- Provide means of access between pontoon and deck box
- Provide routing volumes for cables, ducts, piping and mooring chain
- Provide waterplane area for operational, survival and damage conditions

2.1. General Arrangement

The general arrangement of the column compartments and tanks is established based on considerations such as simplicity, functionality and safety. Simplicity in layout is crucial both for construction reasons and the crew working on board. Compartments in the columns containing equipment require access through watertight doors or hatches; every compartment requires ventilation and supply/extract ducts.

The unit should be classified into hazardous areas in accordance with the DNV rules (2013a) or alternatively with an acceptable code of practice. Hazardous areas are all those areas where, due to the possible presence of a flammable atmosphere arising from the drilling operations, the use without proper consideration of machinery or electrical equipment may lead to fire hazard or explosion (IACS, 2012). Providing good segregation between hazardous and non-hazardous areas is crucial for drilling units.

2.2. Dynamic Positioning

Dynamic positioning is a key factor in the design of the unit since rules and regulations regarding DP require a high level of redundancy in order to stay safe in case of a system failure or collision. For vessels that shall comply with DYNPOS-AUTRO (2011a) or DPS 3 requirements, the definition of single failure has no exceptions and shall include incidents of fire and flooding, and all technical breakdowns of systems and components, including all electrical and mechanical parts. Loss of stability (e.g. as a result of flooding) is not a relevant failure mode (DNV, 2011a).

GVA Cat-D drilling unit design complies with DP3 (DYNPOS-AUTRO) requirements. All components that require redundancy are physically separated including the piping and cabling regarding fire and flooding that pass through the columns. Redundancy requirements for fire and flooding are easily met by placing at least one pipe trunk on each column. More considerations regarding the dynamic positioning coupling and requirements are discussed under the Section 3.

2.3. Stability

Stability of the unit is analyzed with respect to rules (DNV, 2013b) by considering the intact and damage stability. Requirements for intact stability states that the unit should remain undamaged and watertight under all predefined environmental conditions. The unit is to be designed such that it does not capsize and is able to return to upright position after getting a damage of flooding.

GM, the metacentric height gives a good indication of the unit's stability at small angles of heel and minimum required GM is defined by the rules which is always expected to be positive (Health & Safety Executive, 2006). For small angle of heel, the relation between GZ (righting arm) and GM is given as $GZ = GM * \sin\alpha$. When the unit experiences large angles of heel, it is no longer possible to relate GZ and GM with such equation. Since the buoyancy vector does not pass through the metacenter (see Figure 2.1).

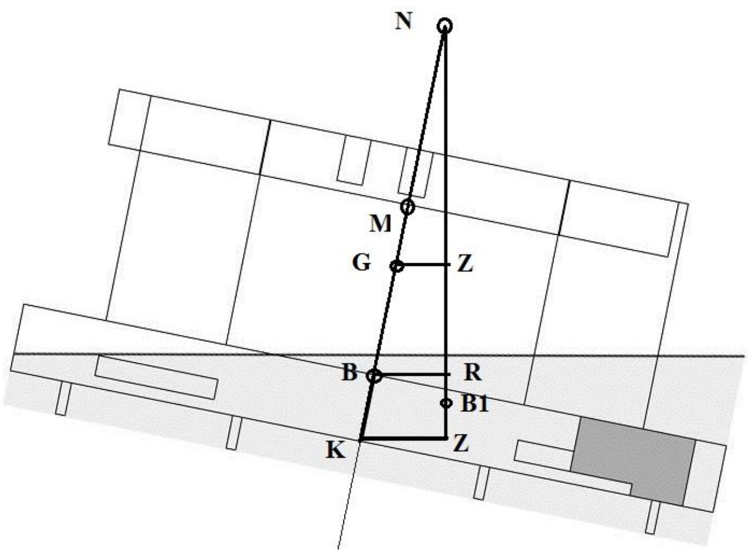


Figure 2.1: Stability at large angles of heel

The GM value is given by the Equation (2.1);

$$GM = KM - KG \tag{2.1}$$

$$KM = KB + BM \tag{2.2}$$

GM Distance from center of gravity to metacenter
KB Distance from keel to center of buoyancy

BM Distance from center of buoyancy to metacenter
KG Distance from keel to center of gravity

The KM value of the unit is mostly dependent on the geometry and location of the columns, pontoons and the draft. At the earlier stages of design, simple check of KM gives a good indication of stability; meaning that high KM leads to high GM which is desirable for stability. KG is another factor influencing the righting arm that is determined by loading conditions of the unit. If KG is lowered, GZ gets larger (see Figure 2.1) and turning the unit back to the upright position is easier or vice versa.

For the overall performance of the rig, the possible reasons why GM is wished to be kept as low as practical are (Health & Safety Executive, 2006),

- to reduce the cost of the unit
- to improve its motion characteristics (by increasing its natural roll and pitch periods)
- to increase the unit's carrying capacity

Conventionally, semi-submersibles lose initial stability when de-ballasting since the ballast tanks are located low in the pontoons, the vertical center of gravity of the vessel is raised when the ballast water is pumped out and GM is reduced accordingly. Dramatic change of hydrostatic properties between loading conditions would not be acceptable. Thus, column design should provide smooth transition between pontoon to column while the pontoons emerge and there is a significant change in waterplane area.

As being one of the objectives of this study, introducing draft flexibility to design is important when a compartment is damaged, change in weight should not result in large impact on stability. Column compartment arrangement has a big role on damage stability, each damage case should be considered.

3. Governing Design Factors

In order to proceed with the establishing of an alternative design for the column, it is important to identify all the relevant factors involved, i.e. what governs the designed shape and inner layout. Examples of these factors are mentioned in Section 2, but will be discussed more in detail in this section. Due to a semi-submersible columns multifunctional purpose there are several design factors included, in particular for a DP3 drilling rig where additional systems are present compared to a production unit. These factors are divided into three categories according to their key area of aspect; general arrangement, stability and structural design. Furthermore, rules and regulations are described under Section 3.4 which determine the requirements regarding these aspects.

3.1. General Arrangement/Layout

Considering that a semi-submersible unit is classified as a DP-3 unit, there are typically two different system couplings present; corner and diagonal (GVA, 2013a). Corner coupling is when DP related cables and piping running through a column is coming from one engine room and is demonstrated in Figure 3.1. In the case of diagonal coupling the cabling and piping from two different engine rooms are running through one and the same column. These engine rooms are located diagonal of each other as shown in Figure 3.2, hence the coupling name.

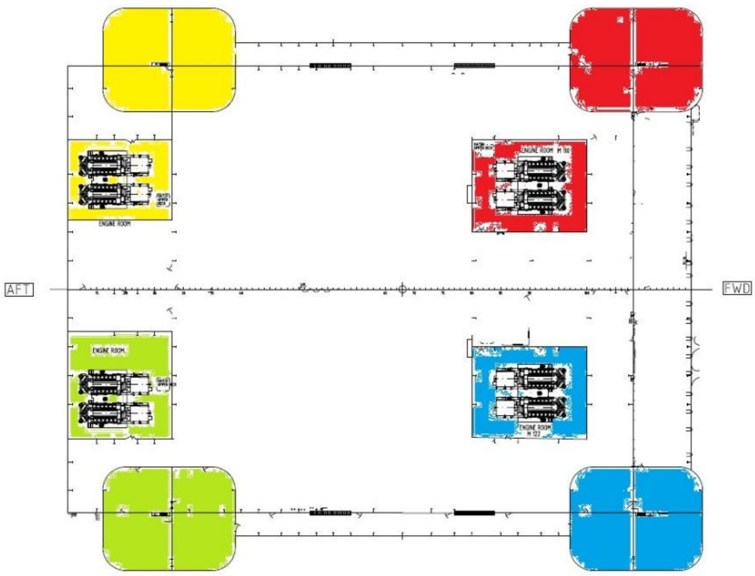


Figure 3.1: Corner coupling

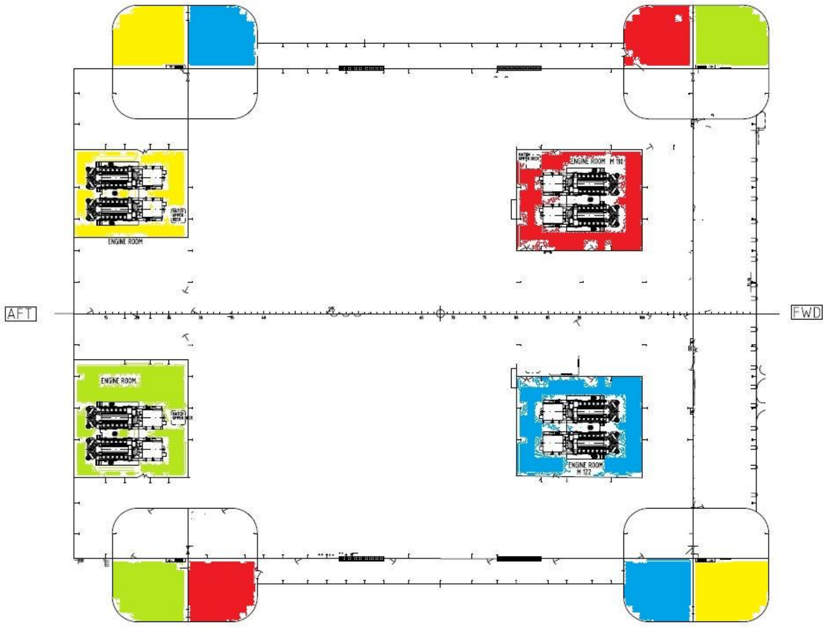


Figure 3.2: Diagonal coupling

The diagonal coupling requires more cabling but provides a higher amount of redundancy in comparison to the corner coupling. In order to achieve this redundancy however, the cables and piping from different engine rooms cannot run through the same trunks, thus requiring a separation from each other (DNV, 2013c). Furthermore, critical pumps may be located in aft or forward section of the pontoons which means that DP related piping and cables must run in separate trunks in a column, even for a corner coupled design (DNV, 2013c). This typically concerns thruster cables, engine coolants (fresh or sea water), auxiliary supplies and in some cases HVAC (heat ventilation and air conditioning). Since the corner coupling has a less complex arrangement and still provides sufficient operability it is usually the preferred alternative, unless specific requirements from the client or classification societies suggest otherwise. Thus it is regarded as the chosen system in this thesis.

Some of the system rooms inside the column are in need of regular access and therefore require ventilation and air conditioning (IACS, 2012). This increases the demand of outfitting steel in terms of piping, cabling and equipment. These factors are adding additional weight to the light unit and simultaneously adding complexity to the routing system, which are both unwanted features as mentioned in Section 2.1. Thus, reducing the number of these compartments is beneficial. The overall number of compartments also determines the amount of doors and hatches needed. Regarding a regular accessed room a watertight passage is generally present, which due to its complexity adds weight and is more space dependent.

A drilling unit contains bulk tank systems for the drilling operations, as mentioned in Section 2. Compartments that are accommodating reserve/storage tanks containing dry bulk (cement or barite/bentonite) or liquid mud are commonly located inside the columns. The amount of dry bulk and liquid mud in a column differs from units and is acquired to meet with the drilling operations. Therefore it needs to be taken into account when doing comparison with existing units and that the space provided for these systems will be able to cater for the same amount of mud and bulk.

In addition, consideration should be made regarding the rules surrounding the access trunk and the fact that it is not considered as a damage case according to NMA (Norwegian Maritime Authority) stability regulations (NMA, 2011§24). That means it has to be placed outside of the damage zone, which is explained more thoroughly in Section 3.4. The access trunk in the column refers to the compartment containing the stairway and elevator, going continuous from the lower deck in the superstructure to the pontoon level. Furthermore, any piping systems connected to sea water (such as ballast-, cooling- and fire water) is not to be placed inside the access trunk as to avoid internal flooding (NMA, 2011§23).

Certain zones on a rig or vessel involved in drilling operations are categorized as hazardous areas where additional considerations have to be made due to classification societies and their safety issues. For convenience sake any hazardous related systems are not placed inside the columns and therefore any hazardous area related rules are not accounted for in this thesis.

3.2. Stability

When accounting for the overall column area that during the operational conditions will make up the waterplane area, it is very important to take this into consideration when comparing against existing units. This has to do with the relation to the area moment of inertia and the displacement of the total unit leading to the stability calculations. Changing the waterplane area will change the area moment of inertia as well as the displacement, considering a condition where the pontoons are fully submerged. These values are inputs in the calculation of the metacentric radius as described in Section 2.3 and therefore part in the equation for the metacentric height, which is commonly referred to a vessel's stability value (Larsson, 2003). It can be mentioned here that the distance from the centerline of the unit to the center cross-section of the column also contributes to the stability. Increasing this length will also increase the area moment of inertia due to the effects of Steiner's theorem (Burton, 1979).

Referring to the objectives with this thesis in Section 1.2, the maximum allowable vertical center of gravity is to be increased. This has a direct relation to the damage cases regarding the location and volume of the damaged compartment. Because of this, it is essential to avoid any large compartments in damage zones and therefore this has an impact on the placements of the bulkheads. Except for damage stability it is also important to consider the damage verification when designing the arrangement layout. This is referred to as the damage extent and the considerations regarding the thoughts on possible double skin and where to place the watertight bulkheads. In addition, the watertight stringer placement relates to the draught flexibility due their impact on the vertical damage extension. Regarding the design aspects surrounding the damage cases there is a more detailed description relating to the rules in Section 3.4.

3.3. Structural Design

One of the largest changes to the design that can be applied is the outer shape of the column. A different column shape can give rise to relocation of stress distribution, waterplane areas, hydrodynamic properties, etc. Also it can have an impact on the inner compartment arrangement and the placement of the bulkheads. Since an optimal and preferable way would be to place the bulkheads connecting to a flat surface which in turn will contribute partially to the inner division. Furthermore, the cost plays an important role in the manufacturing stages, thus a more complex and unconventional design adds to the client expenses.

In addition, when accounting for the possibilities of catering bracings, this has a large interaction with the inner column arrangement, both structural and in general. In order to distribute stresses from bracings in an effective way and minimize stress concentrations, it is beneficial to place the bracing connection attached to a transverse bulkhead. This leads to restrictions in the general arrangement and the placement of the inner compartments, such as the access trunk.

Another bulkhead related issue structural wise is to keep the transverse and longitudinal bulkheads as continuous as possible throughout the column. For similar reasons as above the stresses are able to be transported a longer distance, thereby distributing the load onto a larger area, before ending at an irregularity in the structure, i.e. stress concentration.

The structural arrangement and general arrangement are two components that affect each other very closely. Structural layout design should accommodate the required equipment and utilities while maintaining the structural strength. The transverse and longitudinal bulkhead arrangement determines the subdivision of the column compartments. Figure 3.3 shows schematic representation of the effect of different bulkhead arrangement on compartment arrangements.

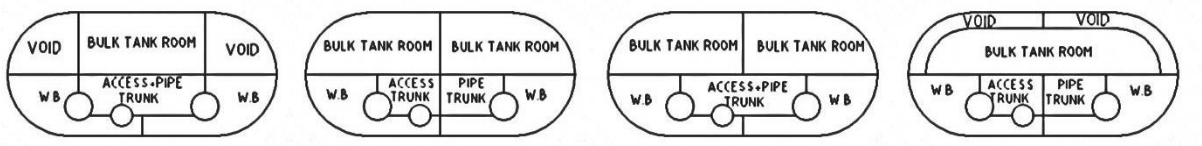


Figure 3.3: Effect of different structural arrangement on layout

3.4. Rules and Regulations

The stability analysis for this project is performed in accordance with the NMA and the drilling unit is classified by the DNV. The intact stability requirement concerning semi-submersible units that is analyzed states that the GM shall be at least 1.0 m for all stationary conditions (NMA, 2011§20), i.e. operating and survival conditions (NMA, 2011§17). For the damage stability criteria, the final angle of inclination after flooding including wind is not to be greater than 17^{o} (NMA, 2011§21). With regard to the damage stability the following assumptions are made. Flooding occurs at any one compartment adjacent to sea or compartment containing piping systems connected to the sea. In the case of piping, shafts and ventilation ducts which may cause flooding, these shall be placed outside the damage area (NMA, 2011§23). This area, i.e. extent of the collision damage for semi-submersible units is shown in Figure 3.4 and specified according to the following (NMA, 2011§27):

- Damage is assumed to occur at exposed parts, which are the sections of the columns located outside a line drawn through the centers of the peripheral columns, see Figure 3.5.
- Vertical limit is set to be from 3.0 m below the minimum transit draught, to 5.0 m above the maximum operational draught.
- The vertical extent is 3.0 m within 5.0 above and 3.0 m below the waterline in question and the horizontal extent is 3.0 m measured along the periphery of the column shell.
- Horizontal penetration is 1.5 m measured at a right angle to the shell.

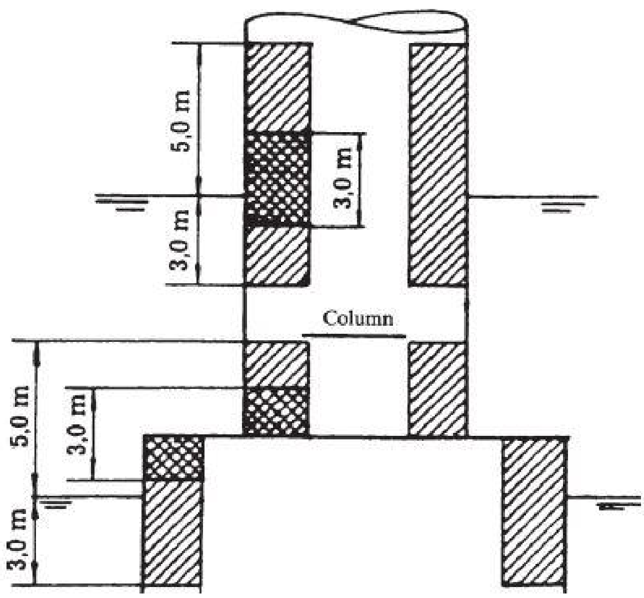


Figure 3.4: Collision damage extent, (NMA, 2011)

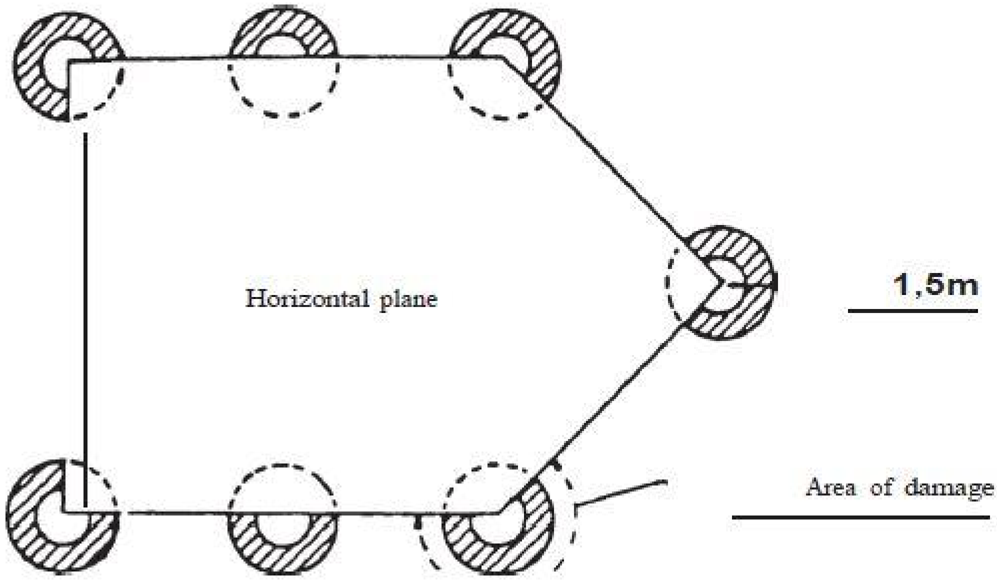


Figure 3.5: Collision exposed column parts, (NMA, 2011)

4. Concept Evaluation

When starting to evaluate the different design alternatives it is important to consider and make reference to all the major criteria that are involved in the decision making. Below the criteria are listed together with their corresponding aspects. It can be noted that some of the thoughts behind these criteria have been previously mentioned throughout Section 3.

Structural integrity

The structural integrity is included for both the column shape and general arrangement. Regarding the outer shape it takes into account the resistance against accidental damage and environmental forces. This relates to the distribution of stresses and the ability to avoid large stress concentrations. Another aspect to consider is the capability of catering bracings and how suited such a connection is for the column. Non flat surfaces can prove to be less suited and difficult to handle bracing supports. Furthermore, with regard to the structural strength it is optimal to put the inner bracing connection attached to a bulkhead which helps to distribute stresses to throughout the structural arrangement. In return this determines and affects parts of the inner compartment layout.

Stability

The columns have a critical role concerning the stability of a semi-submersible. The calculation of the metacentric height involves the metacentric radius which relates to the area moment of inertia of the waterplane area with respect to the center of floatation (Larsson, 2003). The area moment of inertia depends on the shape of the column and may differ around a certain axes of rotations, i.e. transverse or longitudinal. Because the centroid of the column does not align with any axis through the units' center of floatation the Steiner's theorem is applied (Burton, 1979). Therefore different varieties and small changes to the column area have a large impact to the metacentric radius and ultimately to the initial stability of the whole unit.

Damage stability

The damage criterion takes into account the collision damage and the resulting damage stability, i.e. the units' final inclination after compartment flooding. There are rules and requirements on the placements of bulkheads with reference to the column shell and watertight stringers regarding the waterline and unit draught. A more detailed description of these rules and the damage verifications is stated in Section 3.4. Before any damage case calculations are carried out it is sufficient to analyze the damaged compartment volume and distant to the units center of gravity. Due to momentum calculation a lesser compartment volume damage evidently causes a less severe damage case. Therefore it is suitable to arrange for the smaller compartments to be placed in the risk zones for collision damages. Having less severe damage cases will be beneficial for the damage stability curve, which in some cases can be the governing limit on the maximum allowable VCG (vertical center of gravity). This relates to the max VCG curve, which is discussed more in detail in Section 5.2.

Hydrodynamics and seakeeping

The hydrodynamic part takes into account the overall seakeeping capability and interaction with the environmental forces from the wind and waves. Certain column shapes are designed to have a more slender and streamlined body in order to reduce the drag resistance from the wind. Thus the resistance force becomes less, resulting in a decreased wind heeling moment. In a similar way the incoming wave forces, which contribute to the assessment of the structural strength, will be different depending on the design. This follows the dimensioning of bulkheads, stringers, stiffeners, etc. which together add up to the total amount of structural steel used. Another aspect is the ability to counteract the event of wave run-up, when the waves hit critical areas on the lower deck surrounding the columns. Lowering this effect would decrease the minimum required deck to sea surface, if not only reducing loads towards the structure.

Finally because these properties relate to the vessel's seakeeping ability, it is of interest to take into account the probability of having to go into off-hire. This is a strongly unwanted scenario due to the high daily costs of a semi-submersible, adding to the importance of the hydrodynamic aspects in the design evaluation.

Manufacturing

Manufacturing cost is similar to the structural integrity part due to its effect on both column shape and compartment arrangement. Regarding the outer shape as well as inner bulkhead layout it is evident that a simple geometry requires less manufacturing time thus resulting in lower costs. Also considering the overall structural steel in the column can be related to the manufacturing costs. However because this is highly dependent on the structural analysis of plate thicknesses, stiffener profiles, etc. it is hard to fully estimate the steel amount in early design stages.

Arrangement

The system complexity involves all the equipment, bulk and outfitting's present inside the column and how these interact with the compartment arrangement. Some of the major components related to this are the HVAC, pipes, cable routings, watertight doors and hatches. In general and what has been mentioned in the previous Section 3.1 is that the total number of compartments will directly contribute to having a more complex layout, requiring a larger amount of the above mentioned components. This refers to the rooms which are regular accessed by personnel, compared to a void which has considerably less requirements, (IACS, 2012).

Considering the safety aspects, this includes the consequences of flooding due to leakage in the piping system. The rules (NMA, 2011§24) state that any seawater piping, such as pipes connected to the ballast, cooling water and fire systems, are not to be placed in the access trunk as mentioned in Section 3.1. Thus requiring either a separate pipe trunk or to be placed inside other compartments. Comparing these options, a separate pipe trunk is smaller than a void resulting in a less severe accidental damage case, due to the flooded volume. Having the pipes run through voids is convenient because it does not require additional structural steel. However in case this compartment is involved in a collision damage case it would restrict any inspections of the piping, due to the now filled compartment.

Steel weight

Finally the weight accounts for the total structural steel and outfitting steel together with the amount of equipment needed for the different systems such as drilling, HVAC, etc. Regarding the structural steel volume it is difficult to determine whether a design results in more or less. It is highly dependent on plate thicknesses together with girder and stiffener profiles, which are determined both by global and local analysis. Initial comparison should be made with regard to the column shape and bulkhead arrangement and the ability of stress distribution, i.e. an interaction with the structural integrity. The second part involving the outfitting steel and equipment weights relates to the system complexity and the amount of pipe and cable routings.

4.1. Column Shape Alternatives

Together with the reference column shape, see Figure 4.1, a few other design shapes have been analyzed with regard to the criteria stated in the previous section. The different shapes are chosen because they are common shapes seen on early designed rigs (GVA, 2013a), existing units (GVA, 2013a) and patent related designs (Rijken, 2012). They are listed as the following:

- Circular column
- Square column
- Five-sided column
- Circular & flat sided column

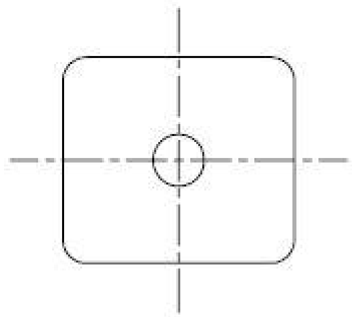


Figure 4.1: Reference column shape

Circular column

A circular column shape, see Figure 4.2, has an efficient way to distribute stresses along its surface, where there are no sharp corners or edges acting as stress concentrations. Due to this aspect the circular shape is regarded as more resistant against environmental forces as well as cases of collision damage. Flat surfaces have a higher drag coefficient and are less optimal for the separation of incoming waves. Because of this the wave loads and wave elevation around a circular column are relatively low in comparison (Borthwick, Eatock Taylor, Grice, Taylor & Walker, 2010). Also the circular shape accounts for a convenient way of handling this attribute independently of the heading angle. Furthermore, a unit that is less sensible to wave run-ups also allows for a more flexible choice of air gap distance.

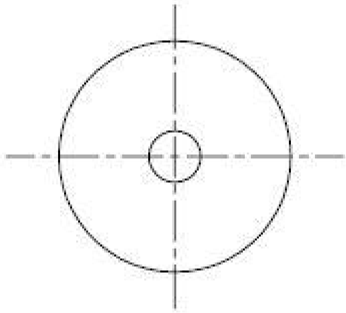


Figure 4.2: Circular column

A drawback with this column design is that the curved shape tends to be more difficult during the manufacturing process, thus contributes to higher manufacturing costs. Accounting for the catering of bracings and regarding the connection to the column shell, non-flat surfaces are considered less suitable as mentioned in Section 4.1. Additionally this effects and restricts the inner bulkhead arrangement in a similar way. One other issue is related to the stability and the area moment of inertia, which is included in calculation of the metacentric height. In order to maintain the same waterplane area compared to a square shaped column, the radius has to be relatively large which can lead to restrictions concerning the pontoon width.

Square column

The next design is the square shaped column, see Figure 4.3, with sharp corner edges compared to the reference column and because of this small difference there are only a few aspects to consider. The manufacturing costs are slightly lower due the simple geometry of only flat sides and no rounded parts. However sharp connections in the structure cause stress concentrations. In order to comply with the structural feasibility, the plate thickness needs to be increased in comparison, which is not desired regarding the added structural steel weight. Also a sharp corner is less slender thus resulting in an increase in the drag force.

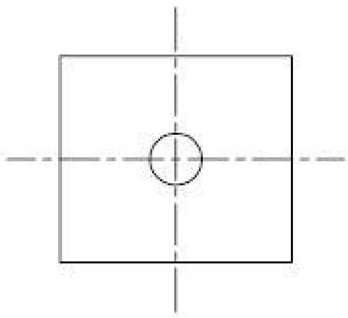


Figure 4.3: Square column

Five sided column

The five sided column shape is an existing patent designed to minimize the loads from wind and sea (Rijken, 2012). The column has five faces, where four are perpendicular to at least one adjacent face. The outermost face is the fifth face at an angle of 45 degrees with regard to the longitudinal axis of the pontoon, as seen in Figure 4.4. It can be noted that this illustrates the column located at starboard forward. The reduction in the loads is achieved by the angled side against incoming environmental forces in both transvers and longitudinal headings. Related to the reference design the five sided shape only includes one additional rounded corner and therefore not adding considerably more to the manufacturing costs. A drawback to this design is the patent related cost which adds to the total costs when introducing this type of column shape. Another positive affect are the benefits to the mooring arrangements. The mooring lines can be connected to the fifth face allowing for an easier load distribution not including shear stresses (Rijken, 2012). Also during the transition between fairlead and windlass or chain jack, the mooring chain does not have to twist resulting in fewer complications for the installations (Rijken, 2012). This is however only the case for a production unit, where there the fifth face of the column is continuous down to the keel. The column on a drilling unit ends at the geometry of the pontoon and thus the outer column shape is not continuous all the way down to the keel. Thus the mooring benefits of the five sided column is not applicable on a drilling unit.

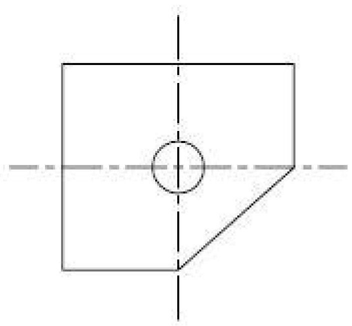


Figure 4.4: Five sided column

Circular & flat sided column

The final alternative for the column shape is a design including circular sections and flat sides, see Figure 4.5. This takes into account the different properties from the circular and square shaped column, in order to obtain the positive effects from both of these designs. For the section with the circular shape the drag forces from the wind are less and the waves are separated in a way that causes lower loads. Additionally no sharp edges for the governing of stress concentrations are present. This will not be the same case for the flat sided section, however in return this side provides a more suitable location for bracing connections. Again because of the geometry containing large round shapes, the manufacturing costs are expected to be higher.

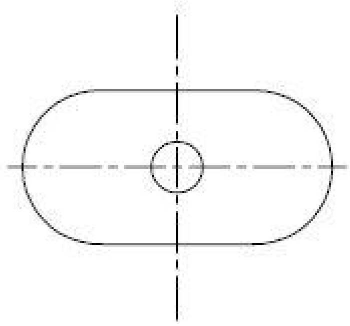


Figure 4.5: Circle & flat sided column

4.2. Concept Selection

The different column shape alternatives are listed in an evaluation matrix, Table 4.1, and rated against the criteria presented under Section 4, in order to select one concept for further analysis. Concept 1 to 4 in Table 4.1 corresponds to the four shapes listed in the beginning of Section 4.1. The criteria are weighted in a scale of one to five based on the importance it contributes to the overall design. In addition, the design concepts are rated from a scale of one to five with regard to the reference design, in terms of whether the alternative is proven to be better or worse considering the given criterion. For both evaluation scales the values are set according to engineering judgment based on the key functional requirements and governing design factors. This analysis is carried out in cooperation with experienced engineers working at GVA who possess many years of knowledge in the field of semi-submersible offshore operations. The weight factors for each criterion are multiplied by the rating of the corresponding concept design and thereafter summed up. This resulted in the total score for each of the design alternatives.

Table 4.1: Column shape evaluation matrix

			Design Concepts			
Criteria	**Weighting**	**Reference Concept**	**Concept 1**	**Concept 2**	**Concept 3**	**Concept 4**
Structural integrity		0				
Stability		0				
Hydrodynamics		0				
Manufacturing cost		0				
SUM		0				

After selecting the column shape design, the general arrangement or compartment arrangement is studied for possible solutions. The reason this is not done simultaneously with the shape evaluation is due to the fact that a different column shape implies various possibilities of layout options and following diverse restrictions. To determine the compartment arrangement a different procedure is used instead of an evaluation matrix. The layout of the arrangement is established by stepwise analyzing the governing design factors individually, starting by accounting for the critical demands with larger restrictions to the design.

These starting points are the access trunk, bracing and ballast tank placements. All of these contribute to the initial transverse and longitudinal bulkhead placement depending on their suitable placements and area space needed as stated in Section 3. It is important to start with the bracing requirements on the first floor because of the desired continuous bulkhead extension vertically throughout the column. This means that the first floor will restrict and govern the layout of the upper compartments. On the second level the critical task is to create the space for a larger access trunk, in order to fit all the all the equipment and bulk tanks in this compartment, according to the desired objectives as stated in Section 1.2. Finally a separate pipe trunk and void tanks are placed in the remaining areas, in order to end up with the chosen column shape. Once the locations of all the trunks and tanks are set, the next step involved the dimensioning of the compartments.

This is carried out with constant interaction with the requirements of the access trunk and pipe trunk spaces. Also considering the overall ballast capacities needed, compartment volumes and the total column cross sectional area which affects the stability as explained in Section 3.2. For this an excel sheet is created (see Appendix A) in order to analyze the different effects of changing the dimensions of the outer shell, inner bulkheads and watertight stringer levels. Through these inputs, all changes to the compartment areas and volumes can be observed. The results give an overview of how well certain dimensions fulfill the criteria and requirements stated Section 3.

To summarize it, the design of the general arrangement is carried out with the overall objectives of this thesis - weight reduction and decreasing the system complexity - as the major focus. Thereafter the above mentioned excel tool is used as an overall comparison of the design alternative and reference project. At early design stages some design factors had to be estimated, such as the total weight which is dependent on the structural steel, equipment, out-fittings, etc. Once the column model is completed, see Section 6, with all the thicknesses of bulkheads, stringers, girders and stiffeners, the actual column weight can be approximated. More on the weight calculation and estimation is presented in Section 7.

4.3. Concept Design

The new column design is presented in Figure 4.6, showing the outer shape together with the inner compartment arrangement. The heights of the column levels are determined by the watertight stinger placements. It should be noted here that this arrangement represents the starboard forward column. The circular & flat shaped column is chosen with regard to its benefits as discussed in Section 4.2, i.e. the distribution of stresses and good hydrodynamic properties such as drag force and wave run-ups. Whereas it showed minor disadvantages regarding stability and manufacturing costs. The corresponding results from the matrix evaluations are located in Appendix A, where the criteria weighting are set accordingly to literature study as well as three different engineers at GVA.

The general arrangement follows the procedure stated in Section 4.2 and the final compartment layout is shown in Figure 4.6. The dimensions of the compartment layout can be found in Appendix A. The aim with the new general arrangement is to cater for the same amount of systems as for the reference unit. With the consideration to maintain the same amount of bulk and ballast capacity, in addition to provide the same amount of space for the access trunk (stair case and lift), cable & piping routing and any remaining systems (generators, machinery control centers, etc.). In comparison with the reference design the new column layout achieves these requirements within a certain percentage, see Table 4.2.

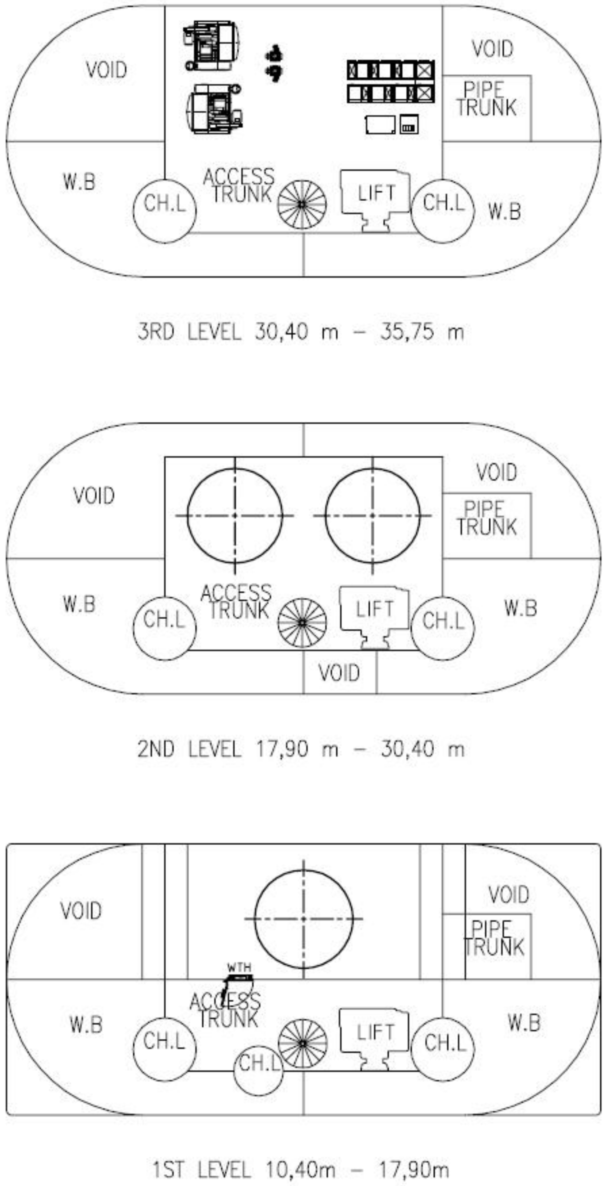


Figure 4.6: General arrangement drawing, starboard forward column.

Table 4.2: Comparison of column requirements

	Difference [%]
Cross-sectional area [m^2]	-5.6
Access + Pipe Trunk area [m^2]	+3.2
Ballast water capacity [m^3]	-3.8
Dry bulk capacity [m^3]	+1.5
Liquid mud capacity [m^3]	-0.7

The calculation sheet used to obtain these results is found in Appendix A. As is noted in the beginning of this Section 4.3, this represents the general arrangement of one column. The structural and compartment arrangement will be the same for the others, however the tank arrangements differ. The reason for this is to obtain close to the same amount of dry bulk and liquid mud regarding the whole unit. Four tanks on the first levels and two tanks on the second levels will be used for liquid mud, whereas the remaining six tanks on the second levels contain dry bulk. A reason for placing the dry bulk tanks in the upper column levels is because this material is harder to pump in comparison with liquid mud.

The pipe trunk is decreased in size and used exclusive to consolidate all piping connected to sea water. This means that the remaining piping though the access trunk will not cause any filling of this compartment, thus the access trunk is not regarded as a single compartment damage case. Furthermore, the access trunk is placed outside the collision damage zone with reference to Section 3.4 and therefore not included in any collision damage case.

The smaller void compartment on the second level, see Figure 4.6, is placed in order to avoid having large compartments next to each other. This relates to the damage stability and the definition of damage extent as is described in Section 3.4, i.e. the water ballast tanks on this level cannot be involved in the same collision damage case. Furthermore, the stringer placement is chosen with regard to the operational draughts and the relation to the vertical collision damage extent, see Section 3.4. In comparison with the reference unit there is a margin increase to the upper watertight stringer at maximum operational draught as well as to the lower watertight stringer at operational draught. With regard to these margins the new stringer arrangement provides a higher draught flexibility in comparison with the reference unit (GVA, 2013a), resulting in a wider range of usable draughts. The equations leading to these statements contain confidential information and are therefore not shown in this report.

In Figure 4.6 CH.L refers to the chain lockers related to the mooring arrangement and in Appendix E a side view of the column is presented, including the bracing locations and radius.

5. Verification of Stability Requirements

One of the most important factors for any type of vessel is the stability, which is referred to as a key functional requirement as mentioned in Section 2. Without a good stability a unit's operability is largely reduced and may be faced with various issues, such as long periods in off-hire or restricted areas of operation. However in a worst case scenario a vessel or unit could capsize due to its incapability, which can lead to lost lives and in some cases severe disasters. In order to avoid these catastrophes there are certain rules and regulations that have to be followed with regard to type of vessel and operational area, as described in Section 3.4. This section takes into account the verification of these stability requirements relating to intact and damage stability. In addition the procedure of how to obtain some of these values is presented.

5.1. Intact Stability

Introducing a new column design on an existing unit causes changes to the hull and will have an impact on the hydrostatic properties. Furthermore, the investigation of catering for bracings leads to the removal of the wing pontoons, causing additional changes to the hull. These changes will contribute to the unit's intact stability, thus as a further investigation the resulting effects are computed and observed. The calculation procedure to obtain the new initial static stability, i.e. the GM (metacentric height), is shown in this chapter and can be found in Appendix B.

First, the new LUW (light unit weight) is calculated, considering that the new column and bracing weights have been sufficiently estimated. This is described more in Section 7. At the same time the new volumetric displacement values are computed. Once these two properties are obtained, they are introduced in the loading condition of the reference unit. The volumetric displacement (∇_U) multiplied with the sea water density minus the LUW (Δ_U) shows the difference in displacement.

$$\nabla_{\mathrm{U}}\rho_{\mathrm{s}} - \Delta_{\mathrm{U}} = \delta_{\Delta} \tag{5.1}$$

Because of large losses in the volumetric displacement of the wing pontoons compared to the decrease in weight, the unit now lacks the needed volumetric displacement (∇_n) for transit condition. To maintain the same loading condition and achieve sufficient volumetric displacement the pontoons have to be made bigger.

To make comparison easier it is desired to keep the same draught according to the reference unit. The waterline during transit is located below the top part of the pontoon; hence increasing the pontoon height and keeping the same draught will not contribute to the needed displacement. Enlarging either the breadth or the length can be beneficial in different ways. Widening the pontoons result in a better transverse stability due to the increasing righting arm, since now the new center of gravity in the pontoons is placed further out with regard to the centerline. The same principal applies to the longitudinal stability when the pontoons are lengthened. However for the latter case, current forces from the side will become larger. In some cases semi-submersibles can have a center of gravity that is slightly off compared to the geometrical origin, with regard to the transverse and longitudinal axis. This can be taken into account when changing the dimensions of the pontoons, by adding weight in a way that places the center of gravity closer to the origin of the geometry. In the reference case the LUW has a transverse center of gravity which is close to zero compared to the longitudinal center of gravity. Therefore it is convenient to change the pontoon length in order to obtain a less displaced center of gravity. This procedure can be seen during design loops of newer rigs where these changes are required. However because this is not regarded as a necessity within this thesis it is not accounted for here, and therefore the pontoons will be re-dimensioned such that the center of gravity of the LUW is kept the same.

Another important factor to consider is the amount of water ballast that is desired (WB_d) to have present during the transit condition. One reason why it is required to have water ballast is because the total LUW (pontoon, bracing, column and deck) together with the payloads has a displaced center of gravity as mentioned above. This results in an inclined intact stability, unless ballast weight is added to stabilize the unit at zero trim and heel. Furthermore, vessels that have a transit draught without any ballast water will not be able to achieve a lesser draught without having to remove deck load. One of the major impacts for not having ballast water present in the pontoons is in the cases of compartment damage. A flooded compartment requires added water ballast weight in or to stabilize, thus disabling the unit from maintaining the same draught while still situated at zero trim and heel. The amount of water ballast that is needed differs from units and depends as mentioned on the center of gravity. The sufficient amount of water ballast in the transit condition (∇_T) has already been obtained for the reference unit. The new hull changes will not contribute to a larger change in the longitudinal and transverse center of gravity and thus the amount of water ballast at transit condition will be kept the same.

A third and final consideration to be made is that an increase in the pontoon size also adds to the pontoon light weight, thus requiring additional displacement volume. Equation 5.2 shows the whole equation with regard to the considerations stated above. From this equation the final volumetric displacement that is added (∇_a) is obtained by using Equation 5.3.

$$\nabla_a \left(\frac{\nabla_T}{\nabla_P}\right) = \nabla_n + WB_d + \frac{\nabla_a C_v}{\rho_{sw}} \quad (5.2)$$

$$\nabla_a = \frac{\rho_{sw}(\nabla_n + WB_d)}{\rho_s \frac{T_T}{T_P} - C_v} \quad (5.3)$$

Once the new pontoon dimensions are obtained, the new displacement and LUW can be established, see Appendix B. These values can then be checked against the loading conditions in order to obtain the amount of required ballast necessary for the different operational draughts.

The GM is calculated using Equation (2.1) in Section 2.3, containing the hydrostatic properties. The new VCG for the LUW is obtained with static moment equation, taken into account the hull changes to the pontoons, columns and bracings; see Appendix B. The VCG for the new column design is obtained from the structural model created in the Genie software (DNV, 2010a), more on the structural model is presented in Section 6. By inserting the LUW VCG into the loading conditions with the included payloads and water ballast, the unit's total VCG is obtained. The same moment equation procedure is used for the calculation of the KB. Finally the BM is acquired from the area moment of inertia (I) together with the new volumetric displacement, see Equation (5.4).

$$BM = \frac{I}{\nabla_U} \tag{5.4}$$

The area moment of inertia is dependent on Steiner's theorem as mentioned in Section 3.2, thus depending on the location with regard to the centerline of the total unit, (Burton, 1979). The new column breadth is less compared to the reference design, thus enabling the column to be placed further out. This means that the transverse distance from the longitudinal centerline to the centroid of the column cross-sectional area is increased, resulting in a higher value of inertia. The change to this distance is indicated in Appendix B. Both the KB and BM are draught dependent and have to be calculated separately for each draught that is to be analyzed. Together these two properties result in the value of KM (see Appendix B) which is an additional input to the loading conditions where the GM is calculated.

Below the intact stability results are presented in Table 5.1 as the difference in percentage with regard to the reference design. It should be noted that the corrected difference of GM is shown (GM'), i.e. taking into account the free surface effects, (Larsson, 2003).

Table 5.1: Comparison of intact stability results

	Difference [%]	
	GMT'	GML'
Transit draught	+19.7	+59.5
Survival draught	-19.5	-22.8
Operational draught	-16.3	-19.4
Max operational draught	-12.1	-14.9

The large changes regarding the transit draught depends on the increased pontoon sizes, where a larger waterplane area increases the BM substantially. Overall the changes to the hull resulted in a decreased GM, which is explained by looking at the results in Appendix B and considering Equation (2.1). The KB is slightly increased due to removed wing pontoons, where the corresponding KB is lower than for the pontoons. The BM is decreased mainly because of the reduced waterplane area, i.e. cross-sectional area of the column (see Table 4.2). Finally the KG is increased because of the removed wing pontoons having a relatively low KG in comparison to the added bracings and pontoon sizing.

5.2. Damage Stability

The general purpose of damage stability analysis is stated in Section 3.4, relating to the final equilibrium state of the unit after damage. In addition, some of the damage cases can have restrictions on the maximum allowable VCG and are therefore very important to take into account. Each vessel has a VCG limit curve, see Figure 5.1, showing the maximum allowable VCG as a function of draught for the stability requirements to be complied with, (NMA, 2011).

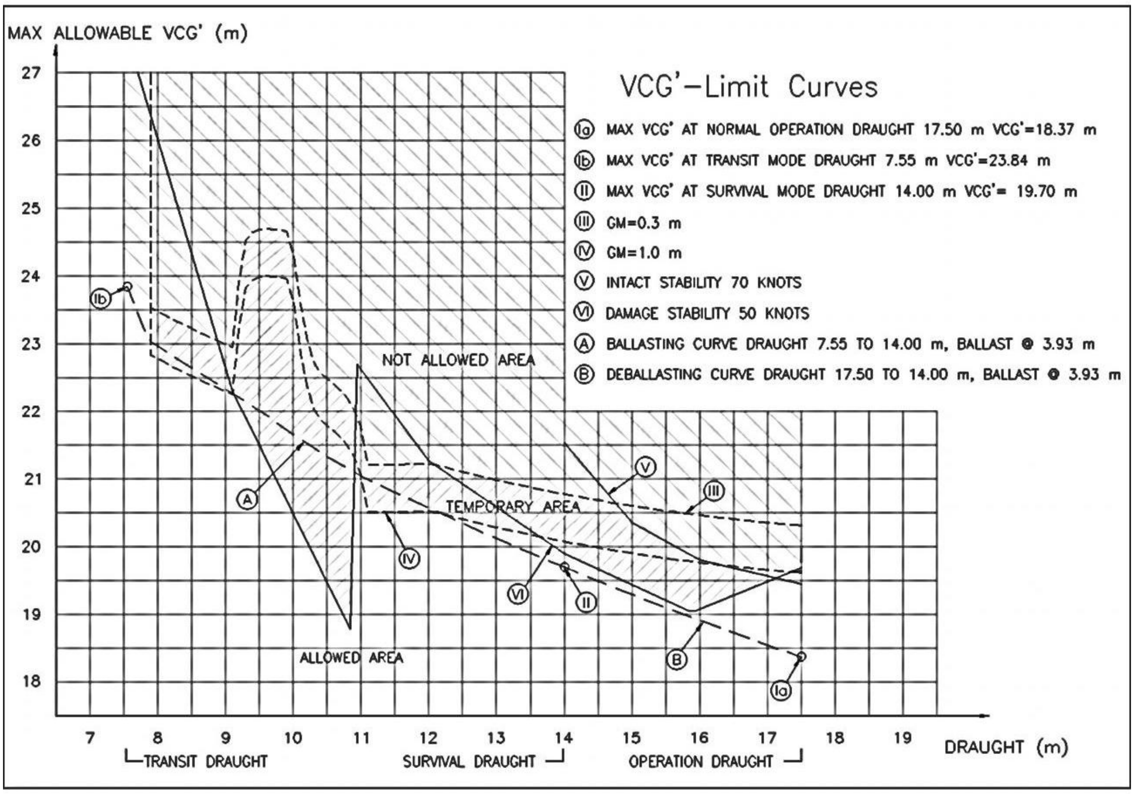


Figure 5.1: VCG limit curve

It is crucial to know the total units maximum allowable VCG at every draught, in order to make sure that the desired loading condition is acceptable. This involves changes to the payloads, rearrangement of ballast water, installation of deck equipment, etc. To see whether a damage case is the limiting criteria on the VCG limit curve, all possible damage cases accordingly to the rules need to be checked. This is usually performed using commercial hydrostatic and stability software such as Autohydro (2014). The stability calculation procedure relates to Figure 5.2, where the damaged compartment acts as an overturning moment (Equation 5.6) and the units center of buoyancy with righting arm (GZ) acts as a stabilizing moment (Equation 5.5), (Larsson, 2003). Similarly the impacts of wind loads are usually referred to as wind heeling moment. Equilibrium occurs when the heeling moment and righting moment are equal to each other. Moment equation is based on lever length and weight, thus the severity of a damage case relates largely to the damage volume and location from the units COG (center of gravity).

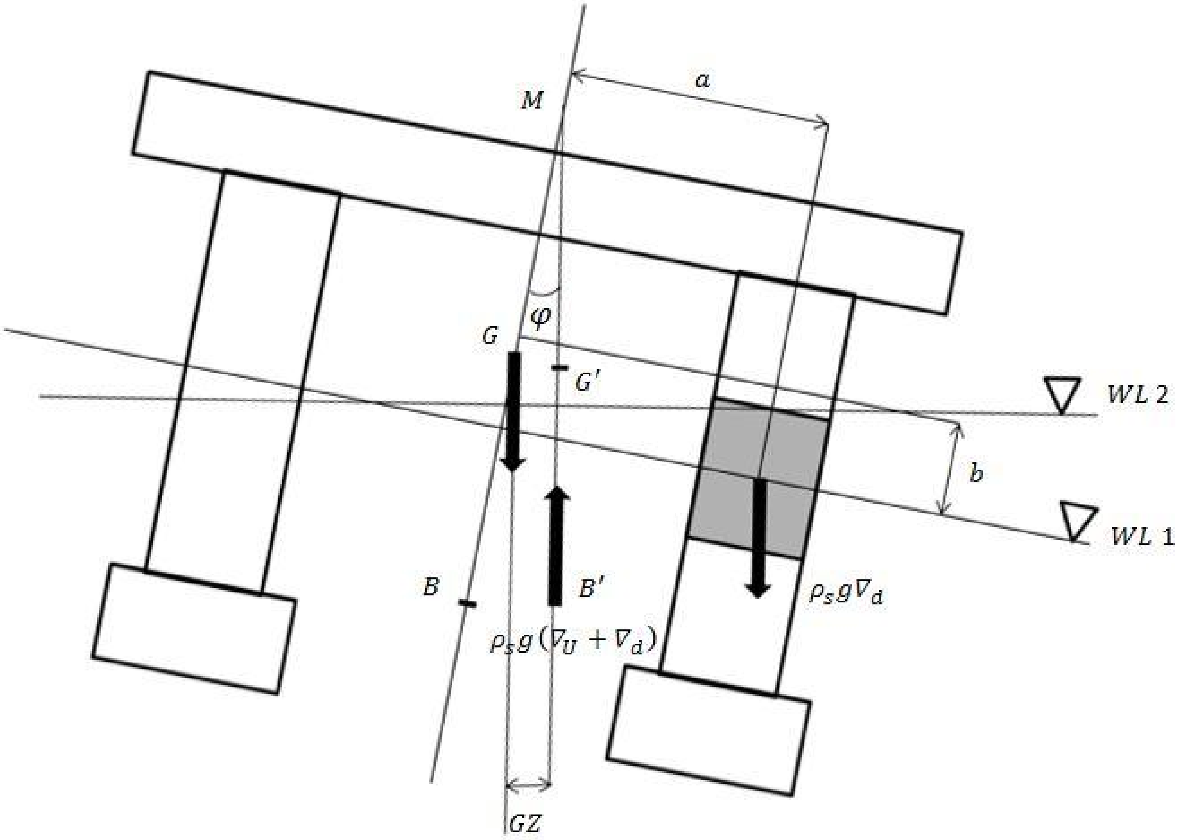


Figure 5.2: Moment equations

Below the equations for the heeling and righting moment are shown with regard to Figure 5.2.

$$M_H = \rho_s g \nabla_d \,(a \cos\varphi - b \sin\varphi) \tag{5.5}$$

$$M_R = \rho_s g (\nabla_U + \nabla_d) GZ(\varphi) \tag{5.6}$$

For certain draughts the damage stability for the reference unit proved to be the limiting criteria regarding the VCG limit curve. Therefore it is relevant to compare all the different damage cases against the new compartment arrangement in terms of damage volume and distance to the units COG, see Table 5.2.

Table 5.2: Damage compartment comparison

Damage case	Distance diff [%]	Volume diff [%]	Moment diff [%]	Result
SC 60	-1.7	-27.7	-28.9	Improved
SC 61	+3.1	-36.3	-34.3	Improved
SC 63	-2.2	-4.8	-6.9	Improved
SC 93	+18.1	-58.2	-50.6	Improved
MC 1	+11.3	-53.9	-48.7	Improved
MC 3	+4.5	+10.2	+15.2	Worse
MC 5	+5.0	-19.6	-15.6	Improved
MC 7	-0.8	+62.8	+61.5	Worse
MC 17	+3.6	-33.1	-30.7	Improved
MC 19	+3.7	-26.7	-24.0	Improved
MC 26	-0.8	+40.9	+39.8	Worse
MC 60	+15.1	-61.0	-55.1	Improved
MC 61	-2.2	-23.7	-25.2	Improved
MC 70	+4.2	-31.3	-28.4	Improved
MC 71	+9.3	-33.9	-27.8	Improved
MC 72	-7.2	-16.8	-22.8	Improved
MC 73	-2.1	+33.8	+31.0	Worse

The calculations behind these values are located in Appendix A, together with the details about which compartments are involved for the different damage cases (SC and MC relates to single- and multiple compartment). The results show that for the new compartment arrangement most of the damage cases are improved. However it is important that the damage cases showing tendencies of being worse are further investigated, more on this is discussed in Section 9.

There is another way of analyzing the damage stability without the use of commercial software and a brief summary of this procedure is explained here. After choosing a damage case to be analyzed, the total volumetric displacement of the unit after damage is calculated. This is obtained by using the added mass method (Larsson, 2003), i.e. the additional volumetric displacement is the same as the added weight from the filled compartment. Thereafter an initial guess is carried out on the final azimuth and inclination angle, for which the unit has reached a state of equilibrium. The azimuth is the angle (β) measured from the longitudinal axis to the inclination axis, as is shown in Figure 5.3.

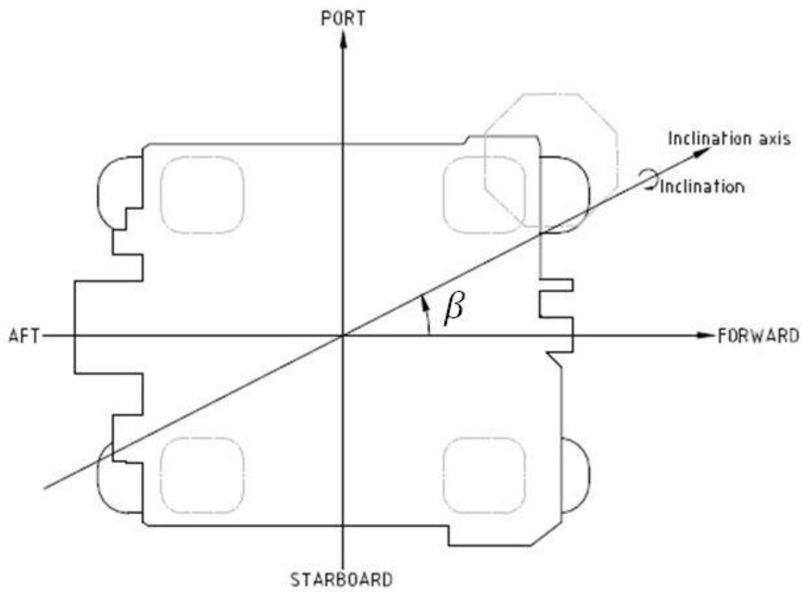


Figure 5.3: Azimuth angle

The initial guess on the azimuth is based on experience and the ability to predict how the unit most likely will behave after damage. If data from similar damage cases are available, these can be used as to predict the angle involving the damage case in question. Once this angle is selected, an initial value of the inclination angle is chosen, conveniently by using the same considerations as for the estimation of the azimuth angle. Having estimated the new state of equilibrium after damage, the changes in displacements are analyzed, regarding the columns, pontoons and deck box. Together these changes in decreased and increased displacement add up to a new total displacement value of the unit. This is then compared with the previous calculated value from the added mass method and should preferably be as close to each other as possible. With regard to this, the inclination angle is then changed until an accurate enough value is obtained, i.e. an iterative process.

This calculation procedure is highly dependent on the initial choices of azimuth and inclination angle in order to avoid numerous iterations. Hence it is important to obtain data of similar damage cases to get a good estimation on these angles, which for a new column design is difficult. Furthermore, calculating the displacement differences in an accurate way is more time consuming in comparison to the moment equations. Hence the moment equations provide a faster way of indicating the damage cases that are in need of further investigation.

6. Strength Assessment

The purpose of the strength assessment is to verify strength and structural stability of stringer frames and watertight stringer decks in the column by checking yield and buckling of girders, stiffeners and plates. Input to these checks is obtained by following steps,

- Minimum required scantling calculations according to DNV (2011b)
- Structural modelling
- Application of load cases
- Local stress analysis of column shell, bulkheads and stringers
- Post-processing/scanning the stress results
- Yield check of girders, stiffeners and plates according to DNV (2011b)
- Buckling check of girders, stiffeners and plates according to DNV (2010b)

6.1. Design Philosophy

Design philosophy is to design the structure against failure modes by using linear theory. The relevant limit states for structures are defined as follows (DNV, 2012a);

- SLS Serviceability limit state
- ULS Ultimate limit state
- ALS Accidental limit state
- FLS Fatigue limit state

SLS covers the evaluation of vibration and deflection. Deflection evaluation is only applied on some beams and slender components and loads in ULS can be used to analyze serviceability limit state. It is assumed that SLS is not governing case for structural design, therefore only ULS and ALS are covered in this study. As already mentioned in Section 1.2, structural design is in compliance with DNV rules. There are two structural design approaches according to DNV; WSD (Working Stress Design) (DNV, 2012b) and LRFD (Load Resistance Factor Design) (DNV, 2012a).

Both methods are based on the linear theory and they both give acceptable results for steel structure design. WSD is an old method, which is also known as Allowable Stress Design (ASD), compares the actual and allowable stresses by multiplication of the characteristic strength or capacity of the structural models with permissible usage factors (Idrus, Potty & Nizamani, 2011). This method accounts for usage factors for different loading conditions, however it is lacking of ability to handle for different load effects (live load, dead load) and resistances (bending, shear etc.). Thus, the usage factors in WSD are fixed or in other words they are combined into a single factor of usage, which results in a conservative design more than it has to be.

As being a reliability based design method, LRFD compares the required strength to actual strength by taking into account of various loading and resistance effects. In this method, significance of individual load effects is accounted by applying different safety factors on independent load and resistance factors. Due to the more consistent handling of safety factors, reliability of structural design can be preserved irrespective of the loading (The Center for Marine and Petroleum Technology, [CMPT], 1998, Sec. 6.5).

The evaluation of structural strength of a fixed structure by using WSD method would give accurate results; however for offshore structures under varying circumstances would create significant responses on the structure, in that case LRFD method gives more consistent results. In addition, handling of different loads and resistance by separate safety factors would result in lighter and cost effective structures. Considering the advantages, LRFD method is chosen to be the design method in this study.

LRFD is a design method by which the target safety level is obtained as closely as possible by applying load and resistance factors to characteristic reference values of the basic variables (DNV, 2011a). The basic variables are the loads acting on the structure and resistance of the structure or resistance of materials in the structure. The level of safety of a structural element is considered to be satisfactory if the design load effects (S_d) does not exceed the design resistance(R_d),

$$S_d \leq R_d \qquad (6.1)$$

$$R_d = \phi R_k \qquad (6.2)$$

$$S_d = \sum_{i=1}^{n}(\gamma_{fi} S_{ki}) \qquad (6.3)$$

R_k	characteristic resistance
ϕ	resistance factor
S_{ki}	characteristic load effect

The main consideration for structural design is to keep actual loads below yielding limit so as to prevent permanent deformations in the structure. In order to ensure that yielding does not occur, load factors greater than 1.0 should be applied to the applied loads. By doing that, the loads are within the safe zone compared to the ultimate strength levels. DNV rules account for the probability of simultaneous occurrence of different types of loads and recommended load factors (γ_f) for ULS is shown in Table 6.1. For ALS, recommended load factor is 1.0 (DNV, 2011a).

Table 6.1: Load factors for ULS (DNV, 2011a):

ϒf	**Load categories**			
Combination of design loads	G	Q	E	D
a)	1.3	1.3	0.7	1.0
b)	1.0	1.0	1.3	1.0
Load categories are: G = permanent load Q = variable functional load E = environmental load D = deformation load				

There are two sets of design load combinations with respect to ULS, a) and b) shall be checked by combining in the most unfavorable way, provided that the combination is physically feasible (DNV, 2012a).

The resistance factor (ϕ) gives an indication of the material factor (γ_M) which is constant for the type of resistance under consideration. Material factors vary with material type and they account for deviations from characteristic values of resistance of the material. Material factors show differences with respect to the limit state under consideration, as well. The resistance factor relates to the material factor as follows (DNV, 2011a):

$$\phi = \frac{1}{\gamma_M} \tag{6.4}$$

6.2. Design Loads

The analysis of a column-stabilized semi-submersible unit typically requires the determination of the various forms of loads on the structure, load and resistance effects, utilization factors etc. The way of handling of load and resistance effects and utilization factors are explained in a general manner in Section 6.1. A comprehensive discussion of loads on the column including the hydrodynamic pressure, operational conditions and accidental forces is discussed in this section.

According to DNV (2012a), a column-stabilized unit may be designed to function in a number of modes, e.g. transit, operational and survival. Limiting design criteria modes of operation shall be clearly established and documented. Such limiting criteria shall include relevant consideration of the following items,

- Intact condition structural strength
- Damaged condition structural strength
- Air-gap
- Watertight integrity and hydrostatic stability

The analysis of air-gap is not the scope of this study. Intact and damaged condition structural strength is analyzed by considering the limit states requirements. Hydrostatic stability including both intact and damage stability is described under the Section 5.

It is normally not practical to analyze all loads – both global and local loads – in one model, due to the complication of analyzing all relevant load combinations. Therefore, total utilization of the column structural strength is assessed by superimposing the responses from global and local model. Stress results are used to check yield and buckling characteristic of the structural components.

6.2.1. Global Loads

Global simulation of the entire unit is usually analyzed by determining the hydrodynamic loads; gravity loads, still water loads and global wave loads. The effects from local water pressures are not included in global simulation. The global model includes the structures that contribute to the global stiffness which are pontoons, columns and deck box.

Global FE analysis is not carried out within this study. Existing global model from reference project is used by assuming that the environmental effects and hydrodynamic loads are kept the same. Global FE-model has been analyzed against ULS at operational and survival draught for both World Wide and Haltenbanken weather condition by including some requirements for the Norwegian Continental Shelf. ALS of the unit has also been analyzed for two conditions, as ballast redistribution and heeled condition.

GVA 4000 NCS is equipped with 12 point mooring system, 3 per each column as it is shown in Figure 6.1. Additional stresses due to mooring forces are calculated according to DNV-RP-C103 Sec. 6.1 for buckling analysis (DNV, 2012c). The design of all structural components that are influenced by the mooring loads shall be taken into account for loads with respect to the limit state. Shell of column and some parts of the transverse bulkheads are assumed to be affected by these forces. Calculation of mooring loads can be found in Sec. 6.5.1.

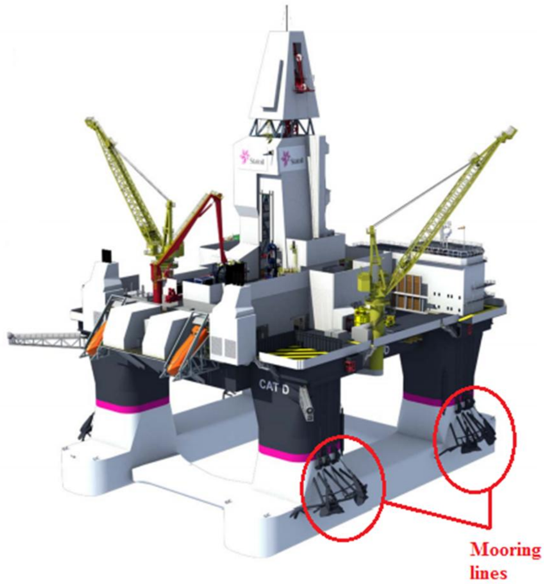


Figure 6.1: Mooring system of GVA 4000 NCS

6.2.2. Column Loads

The purpose of this section is to analyze the form of loading from possible sources acting on the column. Lateral pressures are considered as local loads and these loads are used to verify the structural strength of tanks (ballast, mud tanks etc.), column shells, tank boundaries and all structures that are subjected to accidental flooding. The determination of minimum required scantlings is done by considering the external sea and internal tank pressures.

The means by which external forces are transferred to the column is by the variation of the pressure acting on its wetted surfaces. Internal pressures are acting on the tanks that are filled or emptied during normal condition. The pressure heads (heights) corresponding to the limit state under consideration is listed below,

- Normal (intact) condition (ULS-a, ULS-b) DNV
    - External sea pressure, platform at maximum operation draught
    - Internal pressure, Sea-Loc height above baseline
- Damage condition (ALS) DNV and NMD §22
    - Maximum pressure head

External sea pressure ULS:

External sea pressure is applied on all external wet surfaces and the pressure heads are calculated at still water level and wave crest. Wave trough is not considered since the maximum pressure height is at the half of pontoon height, meaning that the column outer shell is not affected by the wave trough. The parameters for the design pressure calculation are seen in Figure 6.2 (DNV, 2012c).

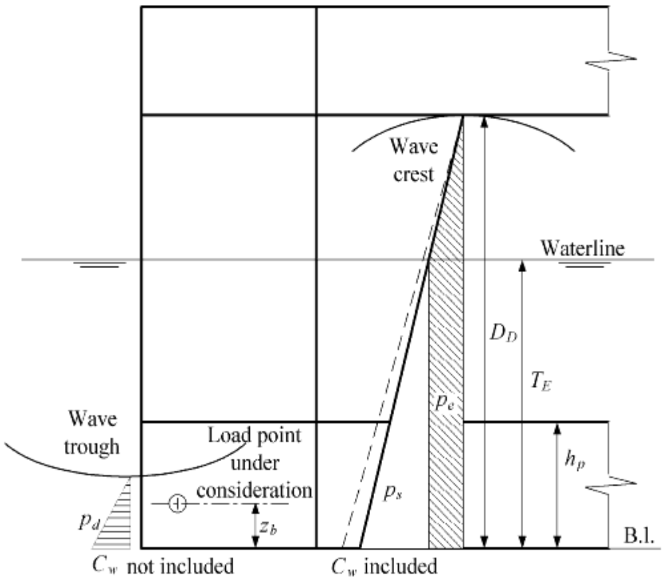


Figure 6.2: Parameters for sea pressures (DNV, 2012c)

The design pressure acting on column at maximum operation draught is calculated as,

$$p_{d,ULS} = p_s \gamma_{f,G,Q} + p_e \gamma_{f,E} \quad (kN/m^2) \tag{6.5}$$

$$p_s = \rho g_0 C_W (T_E - z_b) \quad (kN/m^2) \geq 0 \tag{6.6}$$

$$p_e = \rho g_0 C_W (D_D - z_b) \quad (kN/m^2) \text{ for } z_b \geq T_E \tag{6.7}$$

$$p_e = \rho g_0 C_W (D_D - T_E) \quad (kN/m^2) \text{ for } z_b < T_E \tag{6.8}$$

The load factors are given in Table 6.1. The Smith effect (C_W) is taken as 0.9 for ULS-a and ULS-b. The equations for static sea pressure (p_s) and dynamic sea pressure (p_e) are also calculated at maximum operation draught (T_E), thus the design pressure in Equation (6.5) corresponds to the wave crest elevation, as well.

Internal pressure ULS:

Tanks are designed for the maximum filling height. The categorization of the tanks is done by the system that they are connected to. The ballast tanks are connected to the Sea-Loc system which is a GVA patented ballast tank filling technology. Ballast tanks are filled from deck level that is connected to an overboard discharge system which means there are no penetrations to the hull below the operational draught. All ballast tanks are filled by gravity which eliminates the possibility of over-pressurizing (Liberg, 2010). The parameters for the design pressure calculation are seen in Figure 6.3.

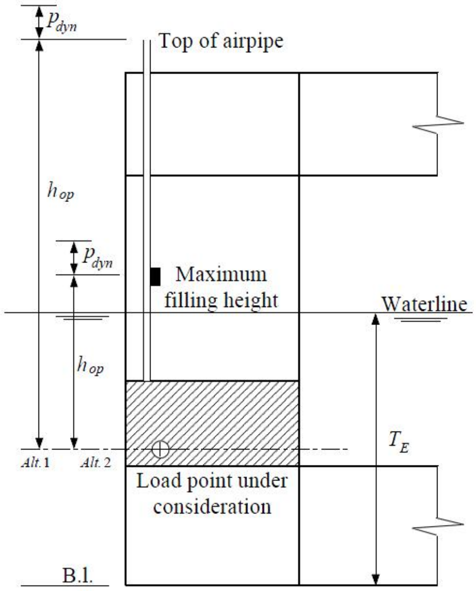


Figure 6.3: Parameters for tank pressures (DNV, 2012c)

The internal design pressure acting on the ballast tanks at Sea-Loc height $(h_{S-L})$is calculated as,

$$p_d = \rho g_0 (h_{S-L} - z_b)(\gamma_{f,G,Q} + \frac{a_v}{g_0} * \gamma_{f,E}) \quad (kN/m^2) \tag{6.9}$$

The vertical acceleration (a_v) used in this study is $0.31g$, this value is taken from the acceleration analysis of reference project (GVA, 2014). Sea-Loc height is assumed to be 1 m below the box bottom. The liquid mud tanks in the column are stand-alone tanks that are not connected to the hull, are ventilated by the air-pipe. Air-pipe is located at the main deck and the design pressure at this height is calculated as,

$$p_d = (\rho g_0 (h_{ap} - z_b) + p_{dyn}) * \gamma_{f,G,Q} + p_e \gamma_E \quad (kN/m^2) \tag{6.10}$$

$$p_e = \rho a_v (h_T - z_b) \quad (kN/m^2) \tag{6.11}$$

Dynamic pressure (p_{dyn}) is due to the flow through pipes and it is taken as the minimum required that is $25\ kN/m^2$. According to the DNV rules (2012a), environmental load (p_e) due to the dynamic tank pressure from rig motion is not considered simultaneously with dynamic pressure, since it is very unlikely that the tank filling operation occur together with extreme waves (DNV, 2012a). Therefore, only the first part of the Equation (6.10) is considered.

External sea pressure ALS – DNV and NMD §22 Heeled Condition:

Design pressure at accidental limit state is calculated by considering both DNV and NMD §22 requirements. DNV requires that the pressure height (h_{17}) is the distance between the load point to the damaged heeled condition still water line after accidental flooding. Inclination of 17 degrees with 2 m of vertical submersion (z_s) is used for the calculations. For simplification environmental loads are disregarded, material factor (γ_M) in ALS is taken as 1.33 instead.

Requirements according to NMD §22, pressure is calculated when the unit is inclined 27 degrees with 0.84 m of vertical submersion. The damaged condition is considered for the extreme operational draught (T_E). The parameters for the design pressure calculation at heeled condition are seen in Figure 6.4.

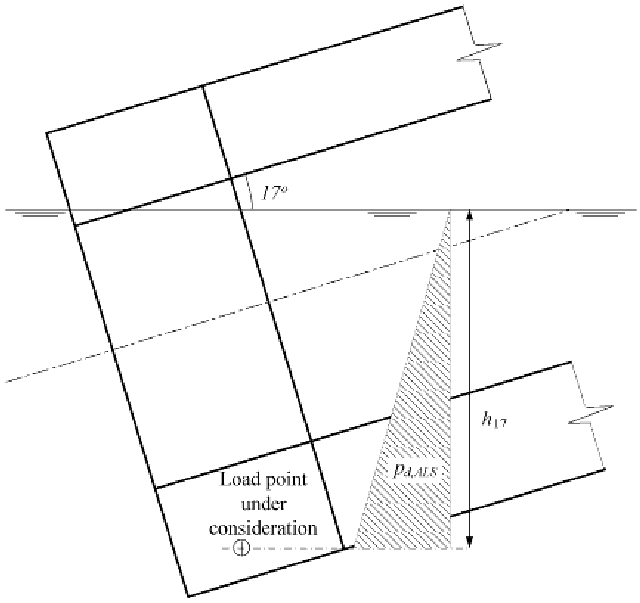


Figure 6.4: Parameters for sea pressure at heeled condition (DNV, 2012c)

The design sea pressure during DNV 17 degrees heeled condition and NMD §22 27 degrees heeled condition is calculated as (DNV, 2012c),

$$p_{d,ALS} = \rho g_0 h_{17/27} \gamma_{f,A} \qquad (kN/m^2) \qquad (6.12)$$

The distance between damaged water line and load point ($h_{17/27}$) is expressed as,

$$h_{17/27} = (T_E + z_S - z_b)\cos(\alpha) + \left(\sqrt{x^2 + y^2}\right)\sin\alpha \qquad (m) \qquad (6.13)$$

Design pressure at heeled conditions is calculated at 6 different points on the unit 3 of which are located on the column. The load point locations are shown in Figure 6.5. The corresponding coordinates (x, y) and all the pressure head values can be found in Appendix C.

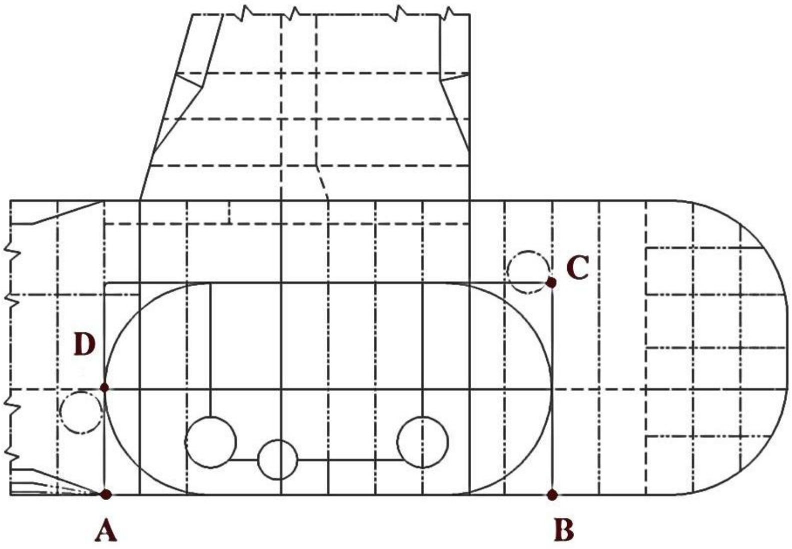


Figure 6.5: Pressure points in ALS heeled condition

6.2.2.1. Basic Load Cases

There are many load cases to consider depending on the limit state under consideration. As previously explained internal pressure is to be applied all tanks and voids in the column; whereas the external pressure is applied to column outer shell. These basic load cases are defined in the FE-model of the column. The response of these loads is to be used to check the yield and buckling characteristics of the column structure.

The external sea pressures are shown in Table 6.2:

Table 6.2: External pressure basic load cases

Limit state	Wet surface	Pressure [kPa]		z-coordinate [m]	
		Top	Bottom	Top	Bottom
ULS-a	Outer shell	0	227.3	35.75	10.4
ULS-b	Outer shell	0	248.6	35.75	10.4
ALS-DNV	Outer shell	87.9	331.7	35.75	10.4
ALS-NMD	Outer shell	177.5	404.6	35.75	10.4

The pressure values are given at the top and bottom of the column, where it is assumed to vary linearly in z-direction. Internal pressures are shown in Table D.1 by using the same assumption. All of the tanks and voids are named as shown in Figure 6.6.

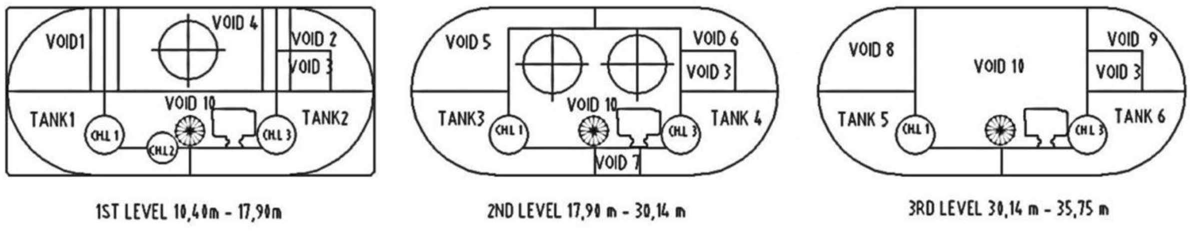


Figure 6.6: Naming of the tanks and voids (starboard forward column is shown)

6.2.2.2. Load Combinations

The load combinations are created in order to evaluate responses of the structure by considering both intact and damaged load conditions. Relevant combinations of all possible tank filling conditions and maximum and minimum sea pressures are used to simulate all stress levels.

Main principle of load combining procedure is in compliance with DNV rules, Sec. 3 (2012c). Combinations with maximum tank pressure from each of the tanks and zero tank pressure from the neighboring tank is considered. For external structural components (stiffened plates adjacent to the sea), the maximum external pressure and the maximum internal pressure do normally not act simultaneously. In general, minimum external pressure and empty tank conditions are also not considered, since this condition is not deemed to be conservative.

The tanks are combined in groups in a way that overlapping of stresses is eliminated. For ULS all water ballast tanks are assumed to be filled. There are in total 31 load combinations when the internal and external pressures are coupled at ULS. For ALS, there are 18 tanks to be filled by accidental damage and the number of load combinations is 256. It should be noted that access trunk (Void 10 in Figure 6.6) shall not be damaged in any cases. Grouping of the tanks is shown in Table 6.3 and Table 6.4 for ULS and ALS respectively.

Table 6.3: Group of tanks for ULS combination

Set	**ULS**			
	Group 1	**Group 2**	**Group 3**	**Group 4**
1	Tank 1	Tank 2	Tank 3	Tank 4
2	Tank 6	Tank 5		

Table 6.4: Group of tanks for ALS combination

Set	ALS	
	Group 1	Group 2
1	Tank 1, Void 6	Tank 5, Void 6
2	Tank 2, Void 5	Tank 6, Void 5
3	Tank 3, Void 2	Tank 3, Void 9
4	Tank 4, Void 1	Tank 4, Void 8
5	Void 3, Void 7	Void 3, Void 7
6	Void 4	Void 10
7	CH-L 1, 2, 3	CH-L 1, 2, 3

Grouping of the tanks are done such that, first group covers the tanks and voids that are in connection with stringer 3, second group covers the tanks and voids that are in connection with stringer 8.

6.3. Structural FE-Model

There are four modelling types that are recommended by DNV-RP-C103 Sec. 5 (DNV, 2012c). These are global structural model, girder model, stiffener between girder model and stress concentration models. Within this study one girder model of column is created to analyze the structural details. The purpose of the local girder model is to simulate the local structural response for the most unfavorable combination of local loads which are not considered in the global analysis (DNV, 2012c). FE model is created by using Genie 5.1-11 (DNV, 2011); stress results are presented by using Xtract (Ceetron ASA, 2008). Structural arrangement that is used for model is shown in Appendix E.

The FE-model represents the forward starboard column of the unit and the model includes the column outer shell, stiffeners, horizontal stringers, longitudinal and transverse bulkheads and chain lockers (see Figure 6.7). Small brackets, tripping brackets, stiffeners on non-watertight structures are not included in this model; the stress results are sufficiently to be accurate without these structures in the model. The column is modelled with second order elements. The linear elastic structural steel is used with the specifications given in Table 6.5.

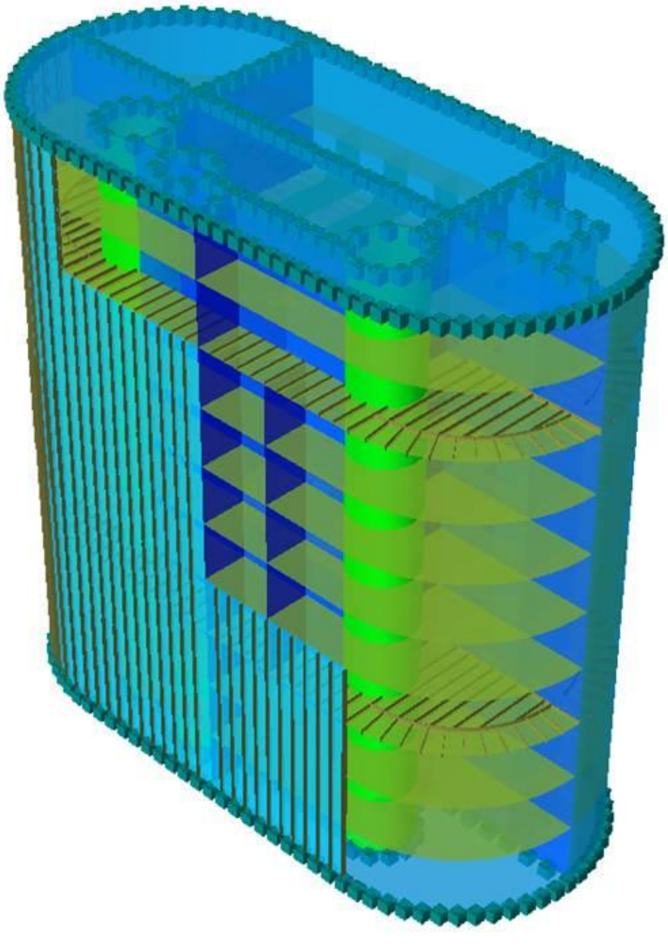


Figure 6.7: Column FE-model

Table 6.5: Structural steel specifications

Yield limit	355	MPa
Density	7850	kg/m^3
Young modulus	210	MPa
Poisson ratio	0.3	
Thermal	$1.2e-5$	$delC^{-1}$
Damping	0.03	Ns/m

Mesh size is taken equal to the frame spacing (650 mm). However, for locations where many stiffener connections occur, mesh size reduced to the half of the frame spacing. In order to have more control of the mesh along the curved details, the mesh option is automatically set to increase of the mesh density. Genie is a powerful tool for automatic mesh generation, however it lacks of ability to have control on specific locations. For that reason, detailed-FE analysis of the column-pontoon and column-upper hull transitions shall be carried out by using a software that has a better control on mesh generation. Nevertheless, regarding the aim of this analysis, created mesh would give adequate results.

Column is modelled with global coordinates; positive forward in X-direction, positive port in Y-direction and positive upwards in Z-direction. Boundary conditions are set in the global coordinate system; column is fixed at all degrees of freedom at the connection to the pontoon and deck box, with the exception of the translation along the Z-direction is set to free. Basic load cases are explained in Section 6.2.2.1 which is defined in the software.

Minimum required scantlings are applied on the model, which are determined by using DNV rules (2011b). The design of the column has a large trunk for access and pipe routing in the middle, which results in a big opening on the stringer plates. In order to maintain the structural strength of the stringer plates, initial buckling check of some of the web plates are carried out at three levels of the column. DNV software called STIPLA is used to check the buckling strength of these plates, an example from the software is shown in Figure 6.8. (DNV, 2012d). Performing this check prior to strength evaluation saves time and enables the modelling of these girder dimensions to be as accurate as possible. After all stress results are obtained, buckling check of all girders is carried out again with the new stresses by using STIPLA. Results from STIPLA check can be found in Appendix K.

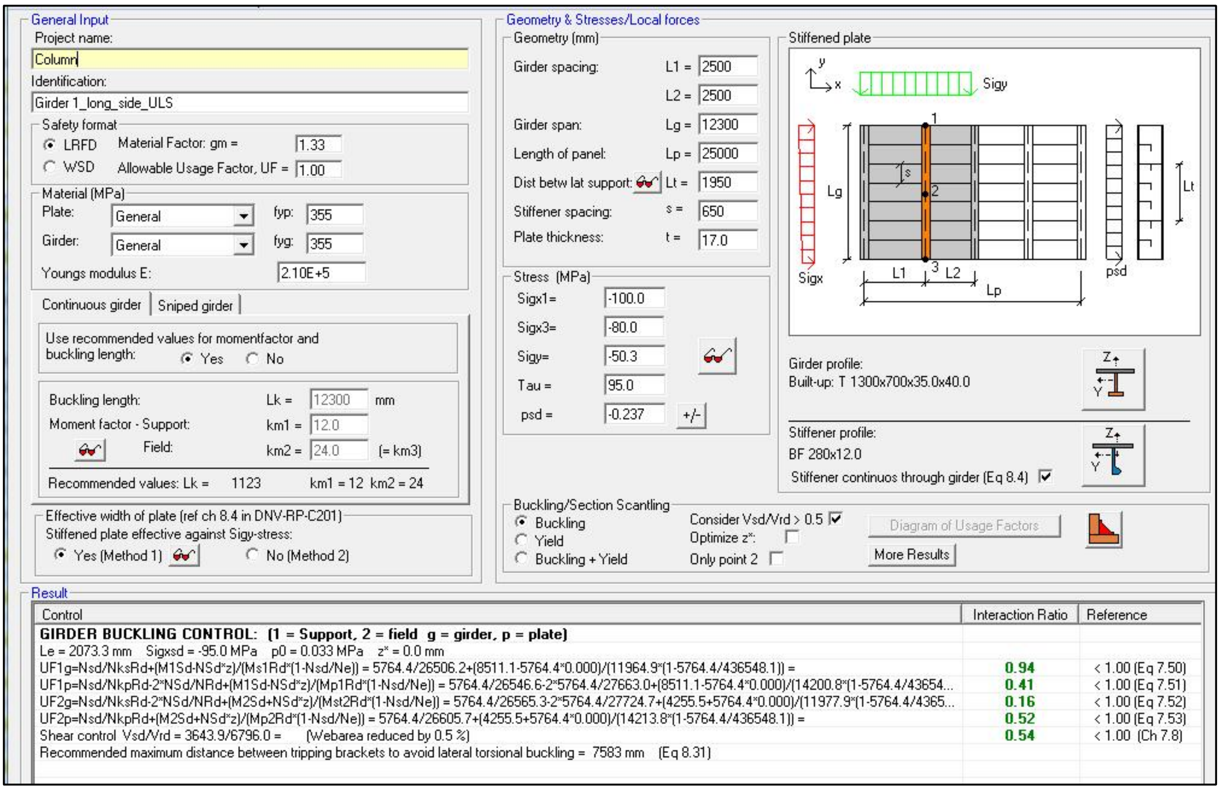


Figure 6.8: Software used to check the buckling strength of the plates (DNV, 2012d)

Input to this program is material properties, geometry definition, stress and design pressure values and stiffener profile. Axial stresses in x-direction (σ_{x1}, σ_{x3}) and shear stress (τ) values are taken from the reference project stress results. However, σ_y stress is not the same, due to the fact that it is dependent to the cross-section of the column and outer shape. Considering this, σ_y is calculated by using simple force-pressure relation ($F = P/A$). An example of the girder under consideration is represented in Figure 6.9.

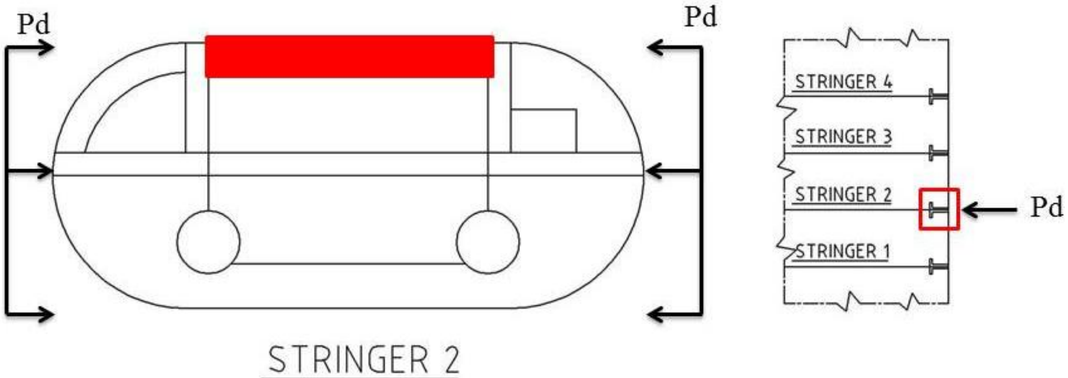


Figure 6.9: Girder under consideration for initial buckling check

The girder marked with red in Figure 6.9 is checked in STIPLA. The pressure is assumed to change linearly along the height of the column. It should be noted that, axial and shear stresses are taken from the global model and σ_y is taken from local and global model where it is relevant. For instance, the locations (i.e. stringer 9) where the column is connected to the upper hull and pontoon, global σ_y stress are relevant for web frame analysis. As an assumption, σ_y is the stress on the neutral axis of the web frame.

6.4. Yield Assessment

Excessive yielding of structural members is checked by using DNV rules (DNV, 2011b). This check is performed in two phases; check of von Mises stresses do not exceed the design resistance and check of minimum required scantlings that are above the minimum limit defined by the rules according to DNV-OS-C101, Sec. 5, F201, F301, F401 and F405.

The von Misses Criterion:

For plated structures the von Mises equivalent design stress is defined as follows (DNV, 2011x):

$$\sigma_{jd} = \sqrt{\sigma_{xd}^2 + \sigma_{yd}^2 - \sigma_{xd}\sigma_{yd} + 3\tau_d^2} \qquad (6.14)$$

σ_{xd}, σ_{yd} Design membrane stresses in x- and y-direction
τ_d Design shear stress in the x-y plane

The von Mises equivalent design stress is calculated for plate and stiffeners for all possible load combinations. Maximum and minimum stresses from local model and global model are scanned for this evaluation.

Minimum Required Scantlings:

Check of minimum required scantlings is done depending on the location of the structural member under consideration. If the area under consideration is not exposed to any lateral pressure, such as the upper part of the column, then the thickness of plates should not be less than (DNV, 2011b):

$$t = \frac{14.4 t_0}{\sqrt{f_{yd}}} \quad \text{(mm)} \qquad (6.15)$$

f_{yd} design yield strength f_y/γ_M
f_y is the minimum yield stress
t_0 =7 mm for primary structural elements
=5 mm for secondary structural elements
γ_M material factor for steel
=1.15 for ULS
=1.33 for ALS

For the parts, where lateral pressure is applied, then Eq. xx is used since the lateral pressure is already taken into account with this equation. The thickness of the plating subject to lateral pressure should not be less than (DNV, 2011b):

$$t = \frac{15.8 k_a s \sqrt{p_d}}{\sqrt{\sigma_{pdl}} k_{pp}} \tag{6.16}$$

k_a	correction factor for aspect ratio of the plate field	
	$(1.1 - 0.25s/l)^2$	
s	stiffener spacing (m)	
p_d	design pressure (kN/m^2)	
σ_{pdl}	equivalent design stress for global in-plane membrane stress	
	$=1.3(f_{yd} - \sigma_{jd})$	
	$f_{yd} = f_y/\gamma_M$	
k_{pp}	fixation parameter for plate	
	=1.0	for clamped edges
	=0.5	for simply supported edges

Minimum Stiffener Section Modulus:

The section modulus Z_s for longitudinal stiffeners, beams, frames and other stiffeners subjected to lateral pressure should not be less than (DNV, 2011b):

$$Z_s = \frac{l^2 s p_d}{k_m \sigma_{pd2} k_{ps}} 10^6 \quad (mm^3) \tag{6.17}$$

l	stiffener span	
k_m	bending moment factor	
σ_{pd2}	design bending stress	
	$=f_{yd} - \sigma_{jd}$	
k_{ps}	fixation parameter for stiffeners	
	=1.0	if at least one end is clamped
	=0.9	if both ends are simply supported

6.4.1. Yield Assessment Results

Each structural member is divided into panels that include plating, primary and secondary stiffeners and for each panel maximum von Mises with and without bending; maximum bending stress, maximum x- and y-stresses and maximum shear stress are calculated. By using these stresses, the von Mises stress criterion and minimum required scantlings are verified by using the design criteria given in Table 6.6.

Table 6.6: Design criteria for strength assessment

Design criteria	Material coefficient γ_M	Allowable usage factor $\eta = 1/\gamma_M$	Yield strength [MPa] f_k	Design yield strength [MPa] f_d
ULS	1.15	0.87	355	309
ALS	1.33	0.75	355	267

The limit state functions are used to control the stresses on material yielding. Each plate, stiffener and girder is checked against the requirements given in Section 6.4. The results are shown as ratios between the actual and allowed values representing the margin to the yield limit for each panel. It is always ensured that maximum membrane stresses to stay below the von Misses yield stress condition (see Equation 6.14) and at the same time having minimum required values giving in Equation (6.15), (6.16) and (6.17). If the calculated values are below the requirements, then an additional row is created in the spreadsheet by marking the new row with star (*). By doing so, either/both plate thickness and stiffener dimension can be updated and the local and global stresses are scaled according to the following;

- $t_{new} > t_{old}$: Linear stress scaling
- $t_{new} < t_{old}$: Square root stress scaling

An example of results can be seen in Figure 6.10. This assessment is carried out for all structural parts in the column and the detailed results can be found in Appendix K.

Project ID: | Drawing ID: | Report ID: COLUMN SHELL OUTER PART
Project Name: MASTER THESIS | Drawing Name: COLUMN STRENGTH VERIFIC | Report Name: MAIN STRUCTURE COLUMNS COLUMN SHELL OUTER PART
2014-05-04

Identification			Geometry									
Panel Name	Load Condition	Material Factor γ_m	t - plate thickness [mm]	Thickness updated?	L - length of Panel [mm]	s - stiffener spacing [mm]	Primary stiffener type	Primary stiffener dimension	Stiffeners updated?	Number of primary stiffeners	Primary stiffener boundary	Yield strength f_y [MPa]
A1	ULSa	1.15	14.0		2500	650	HP	280x12		7	C	355
A1*1	ULSa	1.15	16.0	X	2500	650	HP	280x12		7	C	355
B1	ULSa	1.15	14.0		2500	650	HP	280x12		6	C	355
B1*1	ULSa	1.15	15.0	X	2500	650	HP	280x12		6	C	355
A2	ULSa	1.15	14.0		2500	650	HP	280x12		7	C	355
A2*1	ULSa	1.15	15.0	X	2500	650	HP	280x12		7	C	355
B2	ULSa	1.15	14.0		2500	650	HP	280x12		6	C	355
A3	ULSa	1.15	14.0		2500	650	HP	280x12		7	C	355
B3	ULSa	1.15	14.0		2500	650	HP	280x12		6	C	355
A4	ULSa	1.15	14.0		2500	650	HP	320x12		7	C	355
B4	ULSa	1.15	14.0		2500	650	HP	320x12		6	C	355
A5	ULSa	1.15	14.0		2500	650	HP	240x12		7	C	355
B5	ULSa	1.15	14.0		2500	650	HP	240x12		6	C	355
A6	ULSa	1.15	14.0		2675	650	HP	260x12		7	C	355
B6	ULSa	1.15	14.0		2675	650	HP	260x12		6	C	355

	Stress and Pressure Input															RESULTS					
	Local Stress [MPa]					Global Stress [MPa]					Lateral pressure [MPa]		Bending Stress [MPa]		Von Mises [MPa]		Pt 1. Sec 5.	F201 / (F403)	F301	F401 stiffener	F401 plate
Panel Name	Sig X min	Sig X max	Sig Y min	Sig Y max	Tau XY	Sig X min	Sig X max	Sig Y min	Sig Y max	Tau XY	plate side	stiff side	plate side	stiff side	in-plane	in-plane + bending	$p_{actual}/p_{allowed}$	$t_{allowed}/t_{actual}$	$t_{allowed}/t_{actual}$	$W_{allowed}/W_{actual}$	$W_{allowed}/W_{actual}$
A1	0	0	-75	98	0	-100	0	-20	15	30	0.227	-0.347	64	201	192	301	79%	41%	111%	55%	96%
A1*1	0	0	-70	92	0	-94	0	-19	14	28	0.227	-0.347	58	198	179	291	58%	36%	92%	45%	92%
B1	0	0	-70	98	0	-80	20	-20	10	30	0.227	-0.347	64	201	171	281	73%	41%	102%	47%	88%
B1*1	0	0	-68	95	0	-77	19	-19	10	29	0.227	-0.347	61	199	166	276	62%	38%	94%	42%	86%
A2	0	0	-65	80	0	-85	5	0	0	35	0.200	-0.311	58	180	155	265	62%	41%	92%	37%	81%
A2*1	0	0	-63	77	0	-82	5	0	0	34	0.200	-0.311	54	179	150	261	53%	38%	84%	34%	79%
B2	0	0	-60	90	0	-75	20	0	0	30	0.200	-0.311	58	180	152	255	62%	41%	91%	37%	77%
A3	0	0	-55	75	0	-85	0	0	0	40	0.173	-0.276	51	160	155	245	55%	41%	86%	33%	71%
B3	0	0	-50	75	0	-70	10	0	0	35	0.173	-0.276	51	160	139	230	52%	41%	82%	30%	67%
A4	0	0	-35	50	0	-95	5	0	0	35	0.119	-0.205	32	85	141	180	39%	41%	71%	19%	40%
B4	0	0	-30	50	0	-95	5	0	0	35	0.119	-0.205	32	85	141	180	39%	41%	71%	19%	40%
A5	0	0	-30	40	0	-80	0	-55	0	40	0.066	-0.133	30	112	126	192	24%	41%	55%	16%	49%
B5	0	0	-30	30	0	-80	0	-55	0	40	0.066	-0.133	30	112	120	192	24%	41%	54%	16%	49%
A6	0	0	-20	20	0	-80	0	-40	0	25	0.034	-0.062	14	49	101	129	11%	41%	35%	6.93E-02	21%
B6	0	0	-20	20	0	-80	0	-40	0	25	0.034	-0.062	14	49	101	129	11%	41%	35%	6.93E-02	21%

Figure 6.10: Yield assessment example of column shell outer part

6.5. Buckling Assessment

Buckling strength of all structural members is checked with possible failure modes. The buckling can generally be referred to 'Euler buckling' and can take the form of either plate induced failure mode, where the panel deflects away from the plate or stiffener induced failure mode, where the panel deflects towards the plate due to compressive yielding (Amdahl, 2009). Another buckling failure mode that is related to stiffeners is the lateral torsional buckling of the stiffeners, so called tripping.

The local buckling of stiffened or unstiffened steel plate may happen under in-plane loading (compression load) only, lateral pressure, shear load or sometimes combination of in-plane and lateral pressure can cause buckling.

Buckling strength assessment of plated structures is carried out by using PULS (Panel Ultimate Limit State) spreadsheet (Nauticus, 2013), which is a semi-analytical computerized buckling code for thin-walled plate structures based on the DNV rules (2010d). It computes the elastic buckling stresses and ultimate load bearing capacities under combined loads of stiffened and unstiffened plates. This software allows evaluating many stiffened and unstiffened plates at the same time by defining the geometrical specifications, boundary conditions and load effects. Definition of panels is the same as the ones in the yield assessment, where the plate field should represent the structure adequately, simply having constant plate thickness and stiffener proportions across the panel.

The yield stress (see Table 6.6) is used in PULS as a characteristic value specified for the material type. The usage factors (η) are calculated with respect to the Ultimate Capacity (UC) and Buckling Strength (BS) as a measure of safety margin relative to the required strength by considering the worst buckling mode. The usage factors (η) represent the ratio between the applied combined loads and the corresponding ultimate strength values.

$$\eta_{UC}: \frac{\text{Applied load}}{\text{Ultimate capacity}} < 1$$

$$\eta_{BS}: \frac{\text{Applied load}}{\text{Buckling strength}} < 1$$

Buckling analysis is carried out by combining the lateral pressures with the extracted stress results from global and local FE-analysis in order to have a realistic case. These stress results (see Appendix H and I) are the scanned values from the local FE-model and lateral design pressures are the combination of maximum external and internal pressures.

For strength assessment, the lateral pressure is kept constant while the in-plane loads are scaled until elastic buckling and ultimate capacity strength is within the requirements. If one plate field does not pass the minimum required ultimate capacity and buckling strength limits, then an additional row is created in the spreadsheet by marking the new row with star (*). By doing so, either/both plate thickness and stiffener dimension is updated and the local and global stresses are change according to the following;

- $t_{new} > t_{old}$: Linear stress scaling
- $t_{new} < t_{old}$: Square root stress scaling

In a general manner, axial and shear stress components are taken from global model and y-stress is taken from the local model. The global y-stresses are considered where the effect of y-stress is relevant to use.

Column shell: Both internal and external design pressures are used. At the transition zones where the column shell is connected to the pontoon and upper hull, additional y-stresses from global model are included due the compression of the whole column gives relevant y-stresses.

Additional check is required for the curved plates of column shell if they can either be assumed as flat plate or unstiffened shell. According to DNV rules, lightly stiffened shells where Equation (6.18) applies will behave as an unstiffened shell (DNV, 2010b);

$$\frac{s}{t} > 3\sqrt{\frac{r}{t}} \tag{6.18}$$

s distance between longitudinal stiffeners
t shell thickness
r shell radius

If shell has descent amount of stiffener where the Equation (6.19) applies will behave as a flat plate (DNV, 2010x). In this case, buckling strength of these curved plates is analyzed by using the transverse stresses, otherwise plate fields are assumed to be unstiffened plates.

$$\frac{s}{t} \leq 3\sqrt{\frac{r}{t}} \tag{6.19}$$

In Table F.3 and Table F.4, criteria that are given in Equation (6.18) and (6.19) are checked for column shell curved plates. The results show that, these plates can be assumed as flat plate for buckling analysis. Column inner and outer shell drawings with plate field representation and calculations are in Appendix F.

Bulkheads: Transverse and longitudinal bulkheads are checked for buckling by considering both internal and external pressures. The transition zones where longitudinal and transverse bulkheads in the column are connected to the ones in the pontoon and upper hull are expected to carry the global y-stresses. Same principle applies to the pipe trunk bulkheads.

Brackets that are according to GVA standard do not require any check. These are designed to yield before buckling.

6.5.1. Additional Mooring Stresses

Column shell and transverse bulkheads are assumed to be affected by mooring stresses. As already mentioned in Section 6.2.1, there are 3 mooring system equipment located on each column, totally 12 mooring lines on the unit. The vertical forces due to fairleads are expected to act on the column outer shell and transverse bulkheads located outer part of the column as it is shown in Appendix G.

Design loads are calculated by using the recommendations from DNV-RP-C103 Sec. 6.1.2. These are defined as (DNV, 2012c);

a. Breaking load of one single mooring line

$$F_{d,w1} = F_B \gamma_f \quad (6.20)$$

$F_{d,w1}$	design load on windlass (corresponding one mooring line)
F_B	characteristic breaking strength of one mooring line
γ_f	load factor
	=1.25 (DNV, 2010c)

The breaking load ($F_{d,w1}$) is calculated for a single mooring line by considering the material factor (γ_M) as 1.0. The minimum breaking load per chain is taken from "Preliminary Mooring Analysis" that is done on a sister rig of the reference project which is 8418 kN (GVA, 2012).

b. Operational loads from all mooring lines

According to DNV (2012c), the design of all structural elements influenced by the mooring loads shall take into account relevant loads (ULS and ALS) found from mooring analysis. Acting all mooring lines simultaneously on the structure is assumed to be the maximum possible condition. With the help of GVA engineers, the design load is decided to be estimated by using the 75% of the breaking load.

Total vertical mooring load is calculated as it is shown in Equation (6.21) and the vertical distribution is represented in Figure 6.11. The vertical mooring load is applied constantly between stringer decks and the total mooring load is assumed to be distributed constantly over a cross section area under consideration (column shell, transverse bulkhead etc.). In Table 6.7, vertical stresses with respect to the stringer deck heights are shown.

$$F_v = 3 * 0.75 * F_B \quad (6.21)$$

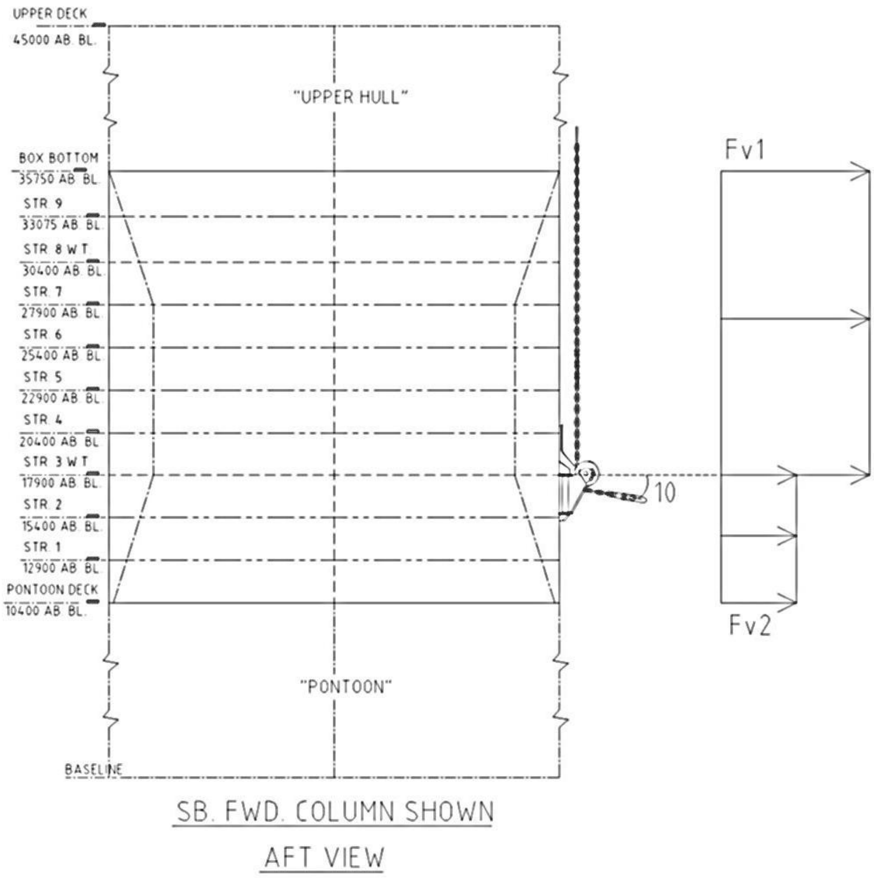


Figure 6.11: Vertical distribution of mooring forces

Table 6.7: Vertical fairlead stresses at each stringer height

F_B	8418	kN		
F_{dw1}	10522.5	kN		
F_{v1}	18940.5	kN		
F_{v2}	15651.5	kN		
Vertical mooring force	**Stringer height [m]**	**Mooring force [kN]**	**Total area [mm2]**[1]	**Vertical stress [MPa]**
Box Bottom	35.75	18940.5	329923	57
Stringer 9	32.9	18940.5	329923	57
Stringer 8 (WT)	30.4	18940.5	331873	57
Stringer 7	27.9	18940.5	331873	57
Stringer 6	25.4	18940.5	306653	62
Stringer 5	22.9	18940.5	309917	61
Stringer 4	20.4	18940.5	308603	61
Stringer 3 (WT)	17.9	18940.5	310553	61

6.5.2. Buckling Assessment Results

The results are evaluated by taking reference the usage factors with ultimate loading and buckling loading. The usage factors gives indication on the difference between the defined loads and the corresponding ultimate capacity (UC) and buckling strength (BS). The stresses are controlled at each panel that maximum membrane stresses[2] always stay below the von Misses yield stress, ensured that permanent yielding and buckling is prevented. An example of results regarding the buckling analysis is shown in Figure 6.12 and all of the detailed buckling assessment results can be found in Appendix K.

11	Identification	Plate geometry			Primary stiffeners									
12		Length of panel	Stiffener spacing	Plate thick.	Number of stiffeners	Stiffener type	Stiffener boundary	Stiff. Height	Web thick.	Flange width	Flange thick.	Flange ecc.	Tilt angle	
13		L	s	t_p	N_s			h	t_w	b_f	t_f	e	β	
14		mm	mm	mm				mm	mm	mm	mm	mm	degrees	
15	A1a	2000	800	17	10	Angle	Cont	250	10	90	15	40	0	
16	A2a	2000	640	16	10	Angle	Cont	200	9	90	14	40.5	0	
17	A3a	2000	800	15	10	Angle	Cont	250	10	90	15	40	0	
18	A4a	2000	640	15	10	Angle	Cont	200	9	90	14	40.5	0	
19	A1b	2000	800	16	10	Angle	Cont	250	10	90	15	40	0	
20	A2b	2000	640	16	10	Angle	Cont	200	9	90	14	40.5	0	
21	A3b	2000	800	15	10	Angle	Cont	250	10	90	15	40	0	
22	A4b	2000	640	15	10	Angle	Cont	200	9	90	14	40.5	0	

11	Identification	Material				Applied loads					Ultimate capacity			Buckling strength		
12		Modulus of elasticity	Poisson's ratio	Yield stress plate	Yield stress stiffener	Axial stress	Trans. stress	Trans. stress	Shear stress	Pressure (fixed)	**Actual usage Factor**	Allowable usage factor	Status	**Actual usage Factor**	Allowable usage factor	Status
13		E	υ	σ_{Fp}	σ_{Fs}	σ_1	$\sigma_{2,1}$	$\sigma_{2,2}$	τ_{12}	p	η_{UC}	$\eta_{allow, UC}$		η_{BS}	$\eta_{allow, BS}$	
14		MPa		MPa	MPa	MPa	MPa	MPa	MPa	MPa						
15	A1a	210000	0.3	355	355	140	52	52	40	0.076	0.51	0.87	Ok	0.58	0.87	Ok
16	A2a	210000	0.3	355	355	120	60	60	70	0.076	0.5	0.87	Ok	0.5	0.87	Ok
17	A3a	210000	0.3	355	355	68	20	20	20	0.076	0.26	0.87	Ok	0.3	0.87	Ok
18	A4a	210000	0.3	355	355	25	50	50	50	0.076	0.35	0.87	Ok	0.37	0.87	Ok
19	A1b	210000	0.3	355	355	140	25	25	50	0.076	0.53	0.87	Ok	0.53	0.87	Ok
20	A2b	210000	0.3	355	355	120	20	20	60	0.076	0.46	0.87	Ok	0.46	0.87	Ok
21	A3b	210000	0.3	355	355	68	15	15	20	0.076	0.26	0.87	Ok	0.28	0.87	Ok
22	A4b	210000	0.3	355	355	30	25	25	40	0.076	0.23	0.87	Ok	0.23	0.87	Ok

Figure 6.12: Example of the input to the PULS

Column outer shell is taken as an example to show a set of buckling results together with 3D buckling representation. In Figure 6.13, fields inside the black marking area are assumed to be exposed to the vertical fairlead stresses in yield and buckling analysis. These stresses create compression above stringer 4, compression and tension between stringer 2 and 4 and tension below stringer 2 as shown for column outer shell in Figure 6.13 (see Figure 6.11 for

[1] For the total cross-sectional area calculation, see Appendix G.

[2] Membrane stresses represent the stresses at the mid-plane of the plate cross-section

connection of mooring lines to the column). Panels marked in blue area taken as an example to represent how the buckling assessment is carried out.

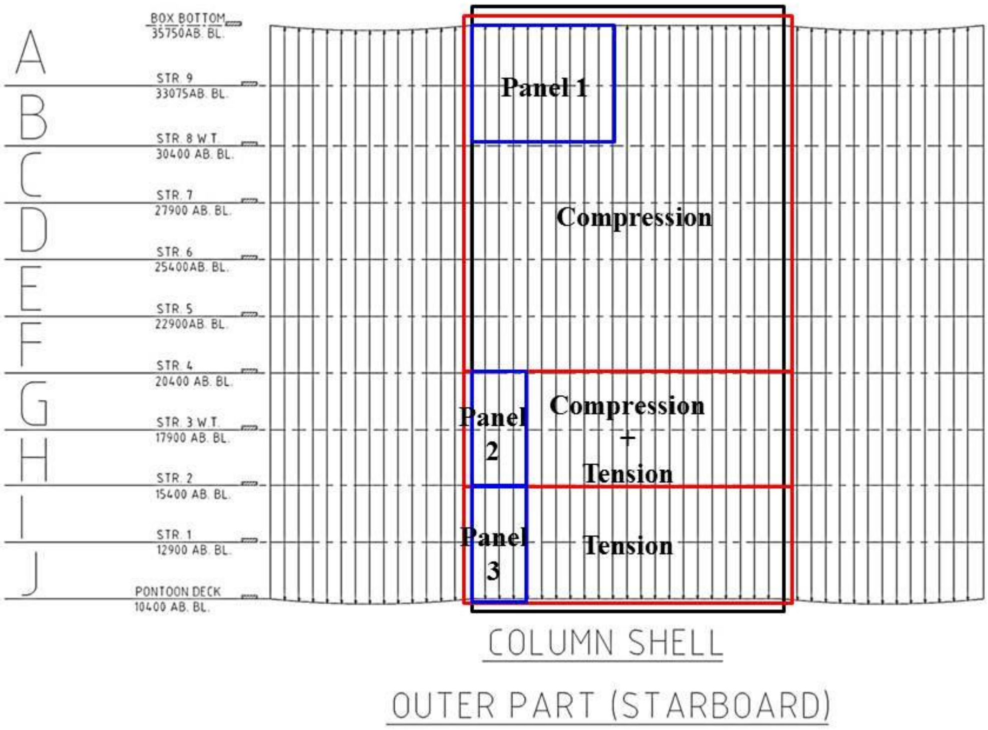


Figure 6.13: Expanded column shell panel identification for buckling assessment

In Figure 6.14, the graphical results in the form of three dimensional deflections plots showing local and global ultimate capacity buckling modes are represented by using PULS Advance Viewer (Nauticus Hull, 2011). The local buckling modes represent the buckling of the plate between stiffeners, buckling of the stiffener web plate as well as the rotation between plate and stiffeners (Nauticus Hull, 2007). Elastic local buckling of any of the component in a panel is accepted. Global buckling or referred as out-of-plane buckling of stiffeners is not accepted within the panel. Most critical positions in the panel are shown in global ultimate capacity modes (see Figure 6.14).

Detailed buckling results are summarized for Panel 1, 2 and 3 in Figure 15 to 17. The results show a prediction for ultimate loads accepting the elastic local buckling deflections of plates and stiffeners. Buckling loads are presented as the minimum of ultimate loads for panel capacity so as to prevent excessive damages. Applied loads show a sufficient margin to buckling and ultimate loads. The component of whose capacity is dominating is deemed to be the ‘weak link’ on the panel. The results in Figure 15 to 17 give a good indication about the weak link with respect to stiffeners and plates. Local buckling modes are more critical than the global buckling modes. When it comes to the component that will buckle first will be the plate in this case.

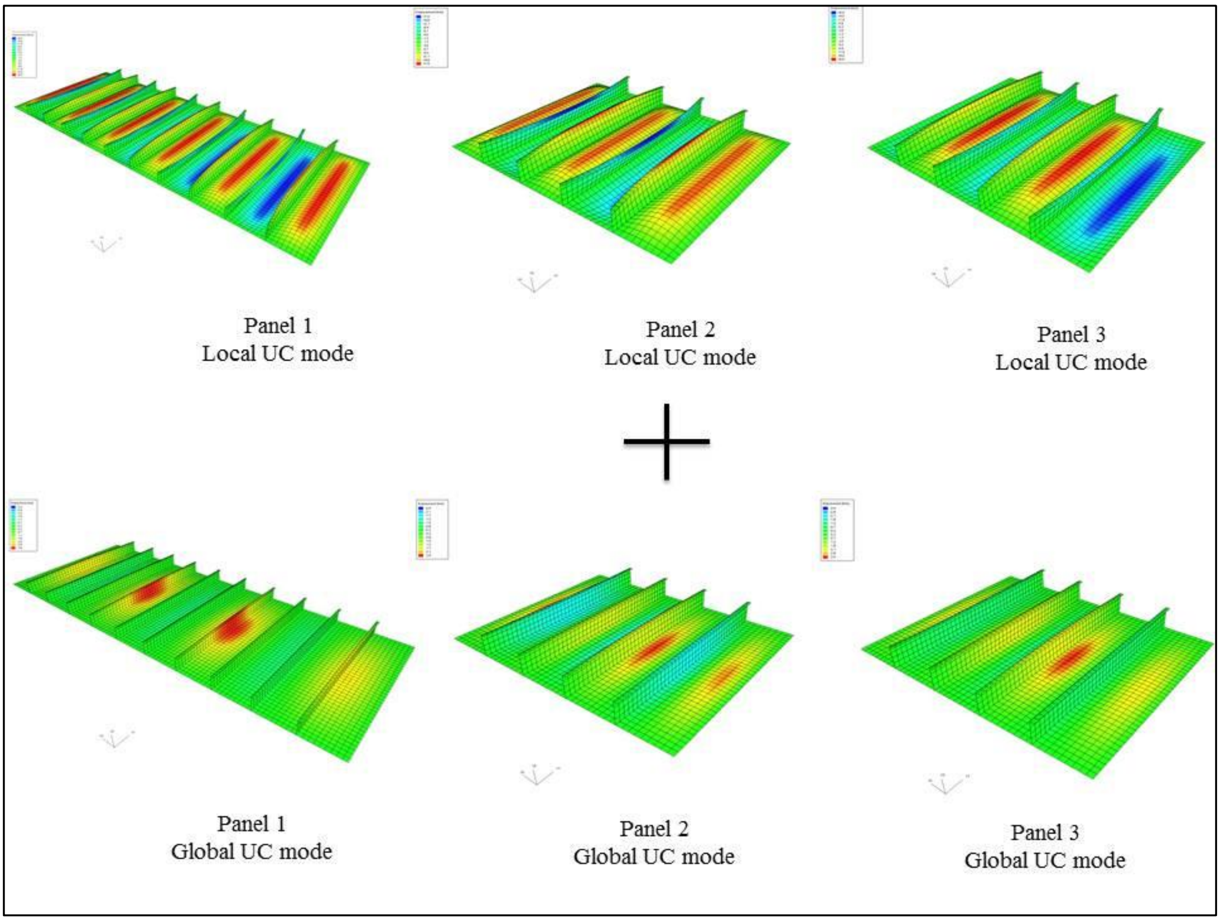


Figure 6.14: Local and global ultimate capacity modes of the Panel 1, Panel 2 and Panel 3[3]

Detailed results summary

		Applied loads	Ultimate loads*	Buckling loads	Local eigenvalue	Global eigenvalue	Ultimate loads**
σ_1	[MPa]	72.00	**95**	73	73	182	95
$\sigma_{2,1}$	[MPa]	86.00	**114**	87	87	217	114
$\sigma_{2,2}$	[MPa]	86.00	**114**	87	87	217	114
τ_{12}	[MPa]	17.00	**22**	17	17	43	22
p	[MPa]	0.136	**0.136**	0.136	N/A	N/A	0.136

Ultimate capacity

Allowable usage	**1.00**
Actual usage	**0.76**
Status	OK

Buckling strength

Allowable usage	**1.00**
Actual usage	**0.99**
Status	OK

Ultimate loads** - panel capacity (accepting local and global buckling).
Buckling loads - minimum of local eigenvalue, global eigenvalue and ultimate loads** (no buckling accepted).
Ultimate loads* - minimum of global eigenvalue and ultimate loads** (global buckling not accepted).

Weakest link displacements at ultimate capacity

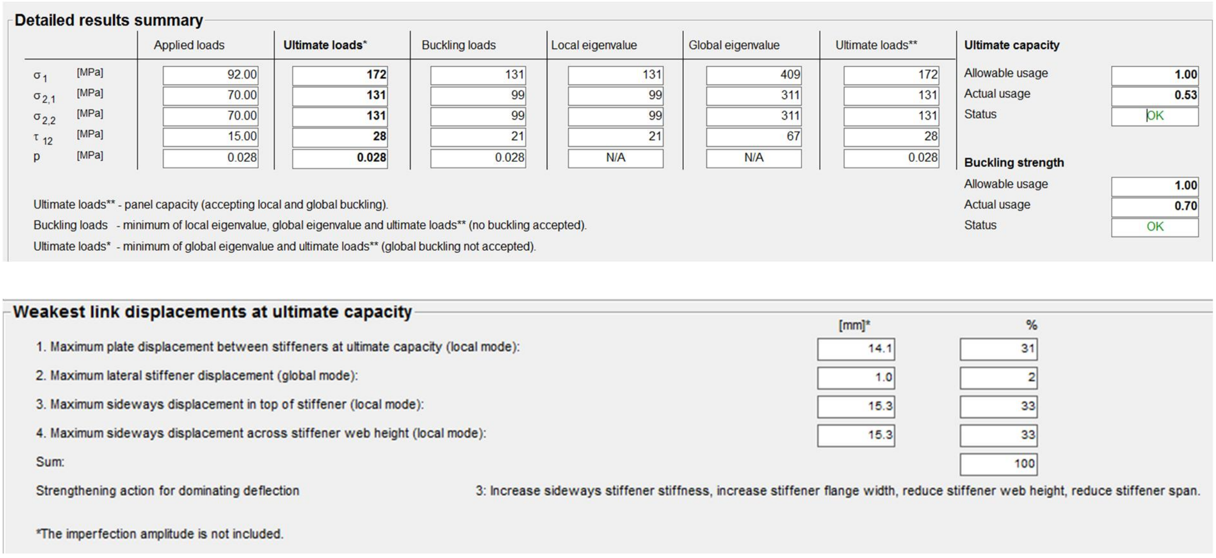
	[mm]*	%
1. Maximum plate displacement between stiffeners at ultimate capacity (local mode):	13.7	34
2. Maximum lateral stiffener displacement (global mode):	1.4	3
3. Maximum sideways displacement in top of stiffener (local mode):	12.4	31
4. Maximum sideways displacement across stiffener web height (local mode):	12.4	31
Sum:		100

Strengthening action for dominating deflection: 1: Increase plate thickness, reduce stiffener spacing, increase web thickness.

*The imperfection amplitude is not included.

Figure 6.15: Detailed buckling results for Panel1

[3] Ultimate capacity modes are magnified 7 times for a better visualization



Detailed results summary

		Applied loads	Ultimate loads*	Buckling loads	Local eigenvalue	Global eigenvalue	Ultimate loads**
σ_1	[MPa]	92.00	**172**	131	131	409	172
$\sigma_{2,1}$	[MPa]	70.00	**131**	99	99	311	131
$\sigma_{2,2}$	[MPa]	70.00	**131**	99	99	311	131
τ_{12}	[MPa]	15.00	**28**	21	21	67	28
p	[MPa]	0.028	**0.028**	0.028	N/A	N/A	0.028

Ultimate capacity

Allowable usage	1.00
Actual usage	0.53
Status	OK

Buckling strength

Allowable usage	1.00
Actual usage	0.70
Status	OK

Ultimate loads** - panel capacity (accepting local and global buckling).
Buckling loads - minimum of local eigenvalue, global eigenvalue and ultimate loads** (no buckling accepted).
Ultimate loads* - minimum of global eigenvalue and ultimate loads** (global buckling not accepted).

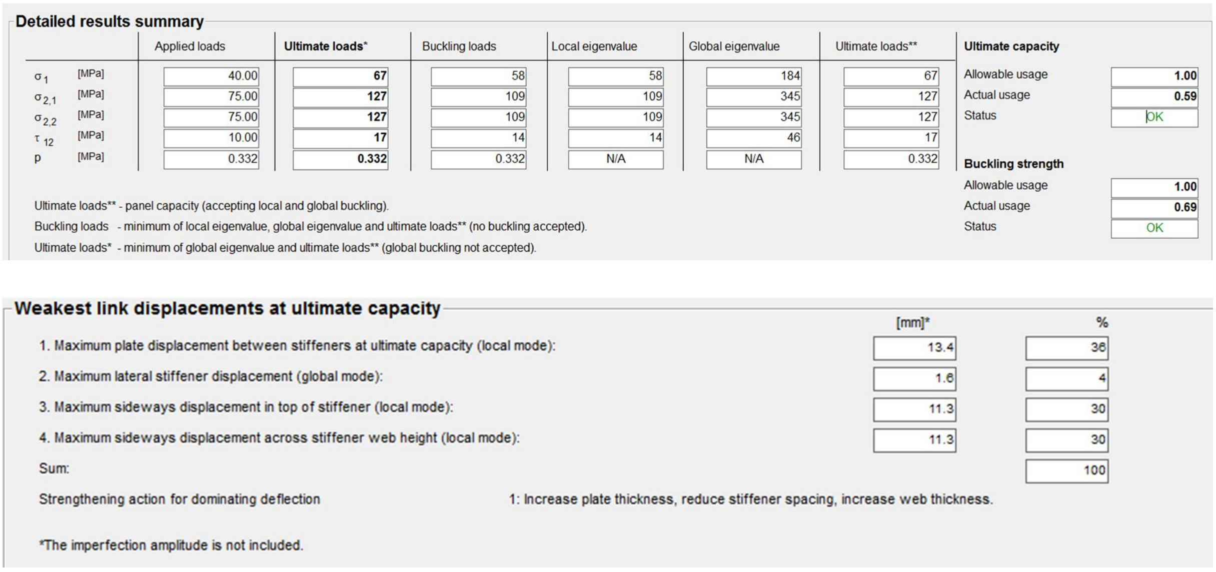
Weakest link displacements at ultimate capacity

	[mm]*	%
1. Maximum plate displacement between stiffeners at ultimate capacity (local mode):	14.1	31
2. Maximum lateral stiffener displacement (global mode):	1.0	2
3. Maximum sideways displacement in top of stiffener (local mode):	15.3	33
4. Maximum sideways displacement across stiffener web height (local mode):	15.3	33
Sum:		100

Strengthening action for dominating deflection: 3: Increase sideways stiffener stiffness, increase stiffener flange width, reduce stiffener web height, reduce stiffener span.

*The imperfection amplitude is not included.

Figure 6.16: Detailed buckling results for Panel2



Detailed results summary

		Applied loads	Ultimate loads*	Buckling loads	Local eigenvalue	Global eigenvalue	Ultimate loads**
σ_1	[MPa]	40.00	**67**	58	58	184	67
$\sigma_{2,1}$	[MPa]	75.00	**127**	109	109	345	127
$\sigma_{2,2}$	[MPa]	75.00	**127**	109	109	345	127
τ_{12}	[MPa]	10.00	**17**	14	14	46	17
p	[MPa]	0.332	**0.332**	0.332	N/A	N/A	0.332

Ultimate capacity

Allowable usage	1.00
Actual usage	0.59
Status	OK

Buckling strength

Allowable usage	1.00
Actual usage	0.69
Status	OK

Ultimate loads** - panel capacity (accepting local and global buckling).
Buckling loads - minimum of local eigenvalue, global eigenvalue and ultimate loads** (no buckling accepted).
Ultimate loads* - minimum of global eigenvalue and ultimate loads** (global buckling not accepted).

Weakest link displacements at ultimate capacity

	[mm]*	%
1. Maximum plate displacement between stiffeners at ultimate capacity (local mode):	13.4	36
2. Maximum lateral stiffener displacement (global mode):	1.6	4
3. Maximum sideways displacement in top of stiffener (local mode):	11.3	30
4. Maximum sideways displacement across stiffener web height (local mode):	11.3	30
Sum:		100

Strengthening action for dominating deflection: 1: Increase plate thickness, reduce stiffener spacing, increase web thickness.

*The imperfection amplitude is not included.

Figure 6.17: Detailed buckling results for Panel3

7. Weight Breakdown

In early design stages for newer units, the weight estimation is usually acquired from weight-volume factors. These values are based on multiple designs which are previously built and provide the weight with regard to the volume. However the use of such factors requires that the new design has a similar structure and arrangement in order to be deemed appropriate. The development of the new column layout in this thesis differentiates itself from previous designs, thus a scale factors will not be used. Instead the new column weights will be obtained by comparing against the reference unit, considering all the major disciplines. As stated in Section 3 the aim is to provide for the same inner systems and space with regard to the governing design factors. This implies that for some weight disciplines the weight-volume factors are applicable, i.e. roughly no weight changes regarding these cases. The equipment located inside the columns can differ from one another, as well as the structural steel volume is different due to varieties in deck loads. Due to these aspects the final weight comparison takes into account all columns, i.e. four.

When estimating the total LUW of the column it is optimal to break down the weights, dividing them in different categories and subdivisions. The two main categories are equipment and bulk. Considering the same system capacity is provided as mentioned above, the weight changes relating to the equipment are negligible for most disciplines. The more visible and larger weight differences fall into the category of the bulk steel. Below the various disciplines are listed with their respective considerations together with the outcome of the weight decrease or increase.

It should be noted that the weight breakdown for the reference unit (GVA, 2013b) is confidential material and that the numbers for estimating the weight changes are based on the values presented in the in-house calculation sheet, (GVA, 2013c).

Architectural

This discipline takes into account the additional wall & ceiling material needed for heat isolation of specific systems. This is not a requirement from the rules; instead it is a choice of convenience made by the designer or client. Examples of these systems are generators, machinery control centers and low voltage rooms. The new compartment layout is arranged to cater for the same systems as present in the reference column. The weight for this insolation material is a small part of the total column weight, thus any differences to this value for the new design is regarded as negligible.

Corrosion protection

The corrosion protection involves painting of the structural steel and placement of possible anode plates (Peabody, 2001) in the water ballast tanks. For the reference unit however no anodes are present. In addition, the size of these plates relate to the water ballast tank volumes, which for the new design are nearly the same, see Table 4.2. The amount of paint needed relates to steel surface area, i.e. the outer shell periphery together with the inner bulkhead lengths multiplied with the column height. The difference in the cross-sectional shell and bulkhead length is approximately less than 5% in comparison (see Appendix A) and the column height is the same. Therefore any weight changed due to paint is also disregarded.

Drilling

This discipline considers the weights depending on the dry bulk tanks. This involves mostly the tank steel, foundation and equipment support. In total all four columns should be able to provide the same amount of bulk material regarding the reference unit, as is shown in Table 4.2. With regard to this an initial statement is that the tank weights are considered unchanged. However small changes in terms of radius and heights, due to the new bulkhead and stringer arrangement, are expected to cause some weight differences. Weather these changes increase or decrease the drilling equipment requires further investigation. It is suggested that a detailed weight breakdown is carried out regarding this, as stated in Section 11.

Electrical & Instruments

The above mentioned systems in need of insolation are regarded as the equipment in this discipline. As mentioned in the architectural part, the same systems are located in the new column design. The same concerns the bulk weight such as the cabling, which is necessary to run the various systems in the column but also in the pontoon (ex. thrusters). Basically, no changes to systems in need of electrical support will result in any weight differences.

HVAC

The HVAC equipment weights are relatively small and dependent on the system capacity which is kept the same for the new column design. The bulk weight involving the ducts will however change. The main HVAC duct that goes through the column is not considered to change, but there is no need for any duct branches for the new compartment arrangement. These duct branches are connected to the main duct and leading to the different regular personnel access rooms. In the new design layout the main duct is going through the only compartment in need of HVAC, thus this design does not require any additional drawn ducts and supports. By looking at the duct and support weights (GVA, 2013c) together with GVA engineers, the expected weight loss is roughly estimated to be 19.4% per column.

Marine

This takes into account the equipment for sewage treatment unit, sewage sludge tank, fresh water generator, etc. which are in general the systems not included in the drilling or electrical discipline. No changes surrounding these systems will be made resulting in no weight difference.

Outfitting & Safety

Considering the bulk weights the major contributors are staircases, vertical ladders, platforms, grating, handrails, etc. Most of these relate to compartment inspections, thus depending on the total number and sizes of the compartments. The general arrangement of the reference unit

(GVA, 2013a) has the same amount of total compartments (Figure 4.6), and Table 4.2 indicates a small difference in the compartment sizing. Therefore, the bulk steel is kept the same. The equipment part takes into account the fairleads, lift, doors and hatches. No changes are done to the fairleads and the lift arrangement is kept the same. The number of watertight doors and hatches on the other hand differs. Comparing with the general arrangement of the reference design the new column layout requires less watertight closures. A watertight door or hatch is needed for compartments involving regular personnel access. The new column layout, as is shown in Figure 4.6, includes one watertight hatch per column. With the weight data for doors and hatches (GVA, 2013c) the change in weight is estimated to be 9.0% less per column.

Piping

Most of the piping running through the column is unchanged, regarding the major pipe routings supporting the column and pontoon systems. Some of these involve the ballast water, cooling water, fresh water, bulk pipes, etc. The only noticeable difference is the piping for ventilation and sound concerning the void tanks (IACS, 2012). The new column design contains five additional void tanks in each column. The added pipe length is measured from the top of the tank to the column height. The weight increase is calculated by using the weight per length of pipe (GVA, 2013c) multiplied by the added pipe length. This resulted in an increase of approximately 1.4% per column.

Structural Steel

Structural steel weight is estimated by using the FE-model created for local analysis purposes. The model includes the column outer shell, horizontal stringers (two watertight and seven non-watertight), longitudinal and transverse bulkheads, three chain lockers, girders on or under the watertight stringers to support long web frames. All of the plates are stiffened by using HP bulb stiffeners and flat bars with various dimensions. Brackets are used at the stringer levels where the stringer plates are connected to the bulkheads. However, for the brackets that are not considered in the model, extra 3 tons for each stringer level are added to the structural steel weight, see Appendix L.

The weight breakdown (GVA, 2013c) for the reference project presents the structural steel weight for four columns with center of gravities (LCG, TCG and VCG). Center of gravities show that all columns weigh differently and steel weights for each column can be calculated within a range by using the LCG and TCG values. Once the column weights are estimated (static moment calculation) for reference design, the scale between starboard forward columns (the column under consideration) can be used to calculate the steel weight for the remaining three columns. The results show (see Appendix L) that structural steel weight is reduced between 6.9-9.7% in total.

In Table 7.1 the summary of the weight changes regarding the total column LUW is presented, considering the combined difference in four columns.

Table 7.1: Weight breakdown comparison

Discipline	**Weight differences [%]**
Architectural	±0
Corrosion protection	±0
Drilling	±0
Electrical & Instruments	±0
HVAC	-19.4
Marine	±0
Outfitting & Safety	-9.0
Piping	+1.4
Structural Steel	- [6.9, 9.7]
Total	**- [6.2, 8.3]**

The result from the weight breakdown shows the weight decrease for the LUW, with a total reduction between 6.2 – 8.3%, see Appendix B. The weight changes due to the equipment and corresponding bulk steel is small in comparison to the reference unit, which relates to having the same amount of system present in the column. The more noticeable changes are made with regard to the lesser amount of watertight doors and hatches, in addition to the decreased ventilation ducting. The largest weight reduction however takes into account to the structural steel. Small changes to this, results in a large part of the total weight reduction. This relates to the weight report and that the structural steel is approximately 70-80% (GVA, 2013b) of the total column's LUW.

In addition to the column LUW, it is necessary to obtain the steel weight of the bracings regarding the intact stability calculations, see Section 5.1. An estimation of the bracing weight is carried out based on the cross-sectional area, which is provided in an in-house calculation sheet, (GVA, 1013c). The bracing displacement is then calculated by multiplying the cross-sectional area with the bracing length, number of bracings & the steel density, as shown in Equation (7.1). The calculation for this weight is located in Appendix B.

$$\Delta_B = A_B l_B n_B \rho_S \tag{7.1}$$

8. Cost Analysis

The present cost analysis work is given an emphasis to a comparative investigation of manufacturing cost and quantifies the effect of weight difference in each discipline. Weight savings that can be observed are watertight doors and hatches related to outfitting equipment, HVAC related bulk weight and structural steel weight. The weight for the rest of the disciplines is regarded the same as the reference design; for that reason, these disciplines are not involved in the cost comparison.

As Shelton (2002) stated, contract costs generally include all direct costs, such as materials, direct labor, subcontracts (if relevant) and indirect costs identifiable with or allocable to contracts. Direct construction costs are expenses for the material, equipment and the labor. Indirect costs are often referred to as operating expenses or in other words ‘overhead’ meaning that costs incurred in the operation of a business that cannot be directly related to individual products or services (Filicetti, 2007). Within this study, indirect costs are considered as a percentage of the direct construction cost.

Another manufacturing cost item is the yard contract management, such as procurement or purchases rates the shipyard charge. The yard contract management is taken as a percentage of the direct construction cost. For the cases when the shipyard needs barges or vehicles for transportation, a production special cost is included as a percentage of direct construction cost. The last cost consideration is the insurance cost which is taken as a percentage over each cost item stated until now.

Direct construction costs are broken into different disciplines as structural steel, outfitting steel, HVAC and piping. Since each task is usually performed by a labor crew including equipment, the man-hour for that specific work is defined and a production rate is established for the task. Direct labor/working costs are calculated by considering man-hour rates at a shipyard in South Korea. For instance, the direct construction cost (C_D) for steel is calculated as shown in Equation 8.1 and the same principle is used for the other disciplines;

$$C_D = W_S PRC_L + C_S W_s \tag{8.1}$$

W_S	Steel weight (ton)
C_S	Material cost (USD/ton)
PR	Man-hours per tons
C_L	Labor cost (USD/man-hour)

Steel is the main cost driver for rigs and steel weight is directly linked to the manufacturing costs; meaning that as the steel weight is increased, material and manufacturing cost increase. Although there are many independent factors affecting the cost, it is still possible to make a judgment regarding the difference in cost. In Table 8.1, a cost comparison with respect to savings associated with the new design is shown regarding the aforementioned disciplines and also the steel weight individually.

The scope of this study covers the design of only one column by assuming that all columns are identical. In reality, there is a slight difference in weight for each column due to the type of the equipment installed and the different loads acting on each column. The cost comparison is done by considering all 4 columns and the other columns weight are estimated by using the reference design (see Section 7). The total steel weight reduction is estimated within a range of 6.9-9.5% of steel weight. Total weight reduction and corresponding cost savings are represented in Table 8.1.

Table 8.1: Cost comparison

Steel weight savings	9.5%	6.9%
Steel cost savings [kUSD]	**1,693**	**1,198**
Weight savings in total	8.3%	6.2%
Cost Saving in Total [kUSD]	**3,435**	**2,890**

9. Discussions

The new general arrangement of the column reduced the amount of compartments in need of regular personnel access from three to one. This reduced the amount of watertight closures (doors and hatches) and extra ventilation ducts. The number of void tanks is however increased, from two to seven, requiring one additional pipe routing per void tank and unwantedly adding more components. Seen to the total number of compartments throughout the whole column, the new design contains the same amount as the reference unit. Considering all aspects, the new column layout shows that the overall complexity is decreased.

The static stability results in Section 5.1 showed a decreased GM value in comparison with the reference unit. However these results are not exclusively based on the new column design and are still complying with the minimum GM value from the rules as stated in Section 3.4. Nevertheless, it is important to consider what changes are to be done in order to improve this value. It is mentioned in Section 5.1 that by increasing the cross-sectional area of the column the BM is increased, resulting in a higher GM. For the new column design this is easily done without any large changes to the layout. Because of the large corner radiuses, see Figure 4.6, they can be increased without affecting the breadth or length of the column and still a larger cross-sectional area is obtained.

Due to the stringer arrangement in the new column design the draught flexibility is increased with regard to the damage collision extent, as stated in Section 4.3, thus indicating a larger span of usable draughts. However the damage stability results (Table 5.2) shows that some cases are proven worse than the reference design. Hence, without further investigation it cannot be concluded whether the new column design improves the draught flexibility or increases usable draughts.

The damage stability results presented in Table 5.2 shows that the outcome in heeling moment is highly dependent on the damaged compartment's volume compared to the distance (lever arm). Hence, to obtain better results for the worse cases it is more convenient to investigate the compartment sizing rather than the locations. Possibilities of improving the damage stability are to change the current void arrangement or adding additional void compartments. This refers to what is stated regarding the void 70S, see Section 4.3, and the utilization of void compartments to prevent large damage volumes. However, it is important to check any new arrangements against the criteria requirements shown in Table 4.2 and the potential outcome in complexity and weight changes.

The final LUW is between 6.2% and 8.3% less in comparison with the reference design, which is a considerable change in weight reduction. However, it should be noted that not all results concerning the new column design are proven to be improved or equally good. As mentioned previously in this section the damage results suggested that changes are to be done regarding the compartment arrangement, i.e. the structural layout. In addition, the intact stability results indicated further changes, one solution being the increasing of the waterplane are, i.e. the cross-sectional column area. Future design changes due to these aspects are expected to increase the LUW, thus lowering the percentage in weight reduction.

The structural strength assessment is carried out to investigate the feasibility of the new design in terms of weight and structural strength. Yield and buckling assessment are carried out and PULS is used to check the ultimate capacity and buckling strength of plates and stiffeners. The results show that this software provides a good approach of optimal steel use with a targeted safety level. The usage factors are calculated and compared against allowable usage factor ($\eta = 1$) and all of the calculated usage factors show a significant margin against failure.

In LRFD method, many uncertainties in loads and resistances are taken into consideration by load and material factors. For a plate that has a usage factor of 0.99 against ultimate capacity and buckling strength would still provide sufficient strength. Therefore, for an improved weight reduction, the panels that have the actual usage factors are around 0.2~0.3 can be re-dimensioned such that the usage factor of 0.9~0.99 is achieved (see buckling results in Appendix K).

On the other hand, usage factors against buckling are not the only criteria that determine the scantlings but also the yield limit. In some cases, even though the ultimate capacity and buckling strength of the panels are obtained far below the limit ($\eta = 1$), panel's yielding (including plates, stiffeners and girders) can be very close to the yielding. Therefore, every time a dimension of a plate is updated, both yield and buckling calculations should be checked in order to avoid any failure.

The non-watertight stringers are modelled as continuous plates without any openings. In reality, there are manholes on the stringer decks to provide accessibility to the tanks. The openings on the plates cause area reduction which leads to increase in stress. Due to the stress concentration, plate and/or stiffener dimensions around these areas can require an increase in dimensions. Within this thesis, manholes are not considered in the model and stresses are not scaled due to the area reduction. For the steel weight reduction perspective, these openings decrease the weight of the plate at some degree. Nevertheless, both aspects are assumed to compensate each other for the steel weight estimation.

Since the semi-submersible unit experiences large wave and wind forces in its offshore location, it needs to be properly designed so that it is able to withstand the forces exerted on it (Reddy and Swamidas, 2014). This is provided by the stiff and rigid box structure of the continuous bulkhead arrangement. With the new column design, it is aimed to align the bulkheads continuous from pontoon to column and column to deck and the distance between frames are regarded as same as the reference design. For some bulkheads, i.e. longitudinal bulkhead, alignment cannot be achieved; however this is deemed to be a reasonable outcome of trying a different design on an existing unit.

Local and global models are usually included in the structural design of the unit in order to account for both local and global stresses. In this study, a local structural model is created to take into account the local effects. These local stresses are then combined with global stresses which are taken from the global FE analysis of the reference design with the assumption that the global stiffness of the original design would not vary with the implemented design changes.

Global loads acting on the structure is differentiated by static and dynamic loads. Static loads on structure come from deck loads and hydrostatic loads, which are regarded as the same in the new design. Dynamic loads originate from waves and wind where the greatest loads are caused by waves on submerged hull; columns and pontoons. The implemented inner structural arrangement changes have no effect on global responses, but the changes in waterplane area and displacement volume affect the heave responses and the other motions accordingly. Considering the implemented changes in pontoon length, breadth and total displacement (see Appendix B) global stiffness of the structure is expected to remain same. Using the stress levels in the original global model is deemed sufficient for the purpose of this study.

10. Conclusions

This thesis addresses the overall design of a semi-submersible column by considering the different governing design aspects; such as general arrangement stability and structural strength. The aim with the new design is to achieve for a less complex system layout, improved draught flexibility and weight reduction. These are investigated by analyzing the feasibility of column’s system arrangement and structural strength.

The following conclusions are made with regard to the outcome of this thesis.

- A larger access trunk is established, providing the required space for all equipment and bulk tanks.
- The column design has the capability to cater for two horizontal bracings, transverse between the columns.
- A separate smaller pipe trunk is created to consolidate all seawater piping.
- The new column layout contains a fewer amount of compartments requiring regular personnel access.
- The new compartment arrangement proved to reduce the column's complexity.
- The new larger access trunk is disregarded from any single compartment or collision damage case.
- The general arrangement and watertight stringer placement indicated an improvement to the unit’s draught flexibility and usable draughts with regard to the damage stability.
- The new column design resulted in a weight decrease between 6.2% and 8.3% with regard to the reference design.
- The structural strength is checked with respect to limit states and ALS according to DNV is deemed the governing limit state for the design.
- One conclusion with regard to the design of the column at the circular sides is that stress distributions on the curved plates are achieved so that the scantlings on and around these areas are decreased significantly.
- The large access trunk in the middle of the column is achieved by cutting out a big part of the transverse and longitudinal bulkheads. However this does not result in a big difference in terms of scantlings.

11. Future Work

- Analyze the practical aspect of the bulk tanks placement inside the access trunk.
- The cross-sectional area of the column is to be investigated further, in order to obtain a better stability in terms of waterplane area.
- It is desired to further analyze different compartment layouts in order to obtain a better arrangement in terms of damage stability.
- In order to verify the possible improvements regarding the draught flexibility, further design changes need to be carried out together with detailed stability calculations involving commercial software.
- Establish a complete and detailed weight breakdown, including routing drawings/concepts for all relevant components (all DP3 components, ducts, piping connected to sea water and other larger lines).
- A detailed design and FE-analysis of bracings should be carried out to investigate the strength of bracing connections.
- A global analysis should be created to analyze the global effects on the new column design. The combinations of local and global results should be further investigated for the strength assessment of the structure.
- Columns are connected to the pontoons and box bottom by using cone plates and castings. A more detailed FE-analysis should be carried out at these connections.
- In the cost analysis, manufacturing parameters, such as man-hour and material cost per ton of steel are regarded as the same as the reference design. In reality, material cost and production time of curved steel plates can differ. All manufacturing aspects of curved steel plates should be further investigated.

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Appendix A: Design Evaluation and General Arrangement

The information under this section is subject to confidentiality agreement with GVA Consultants, therefore required to be hidden.

Appendix B: Stability Results

The information under this section is subject to confidentiality agreement with GVA Consultants, therefore required to be hidden.

Appendix C: Local Pressure Calculation

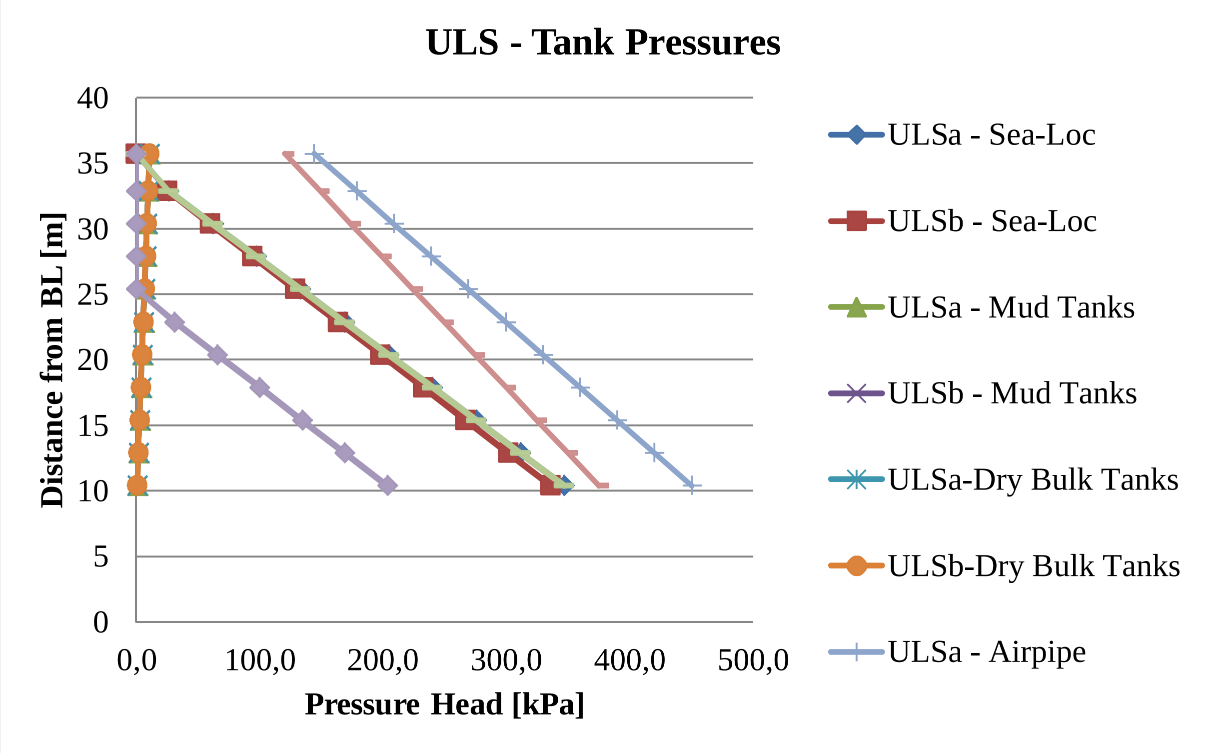


Figure C.1: Tank pressure heads - ULS

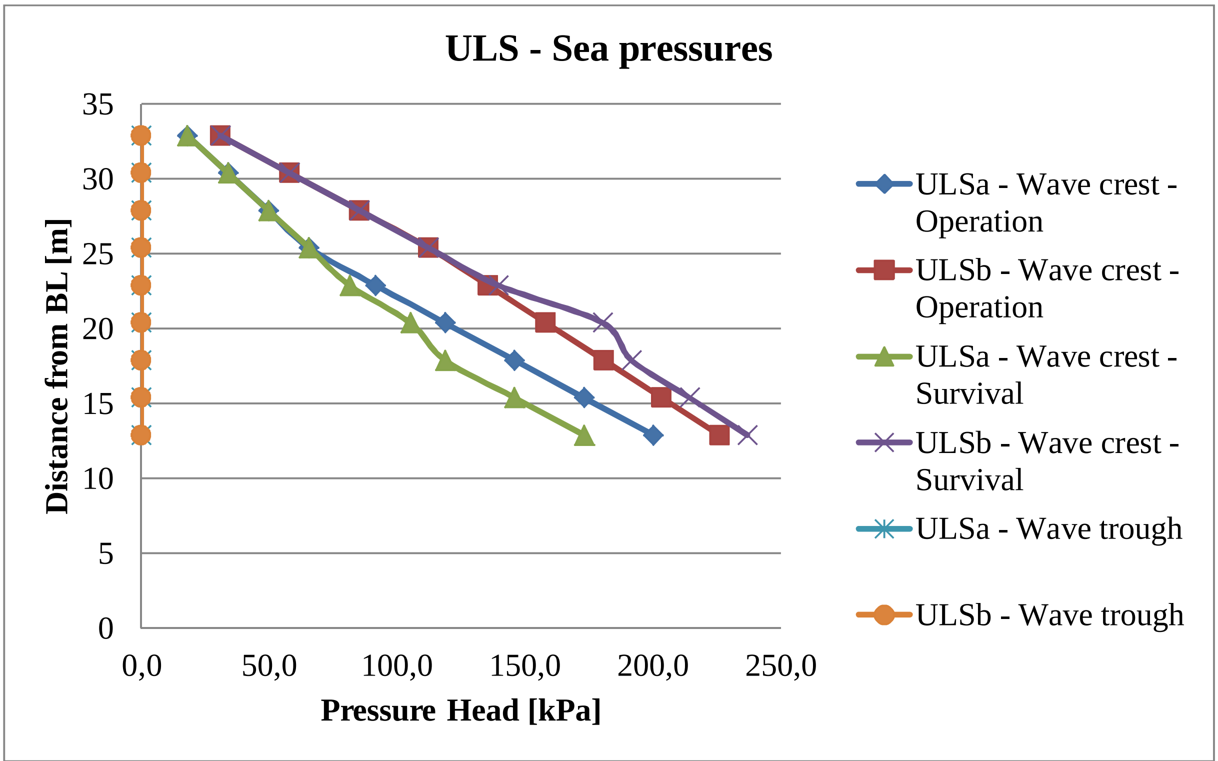


Figure C.2: Sea pressure heads - ULS

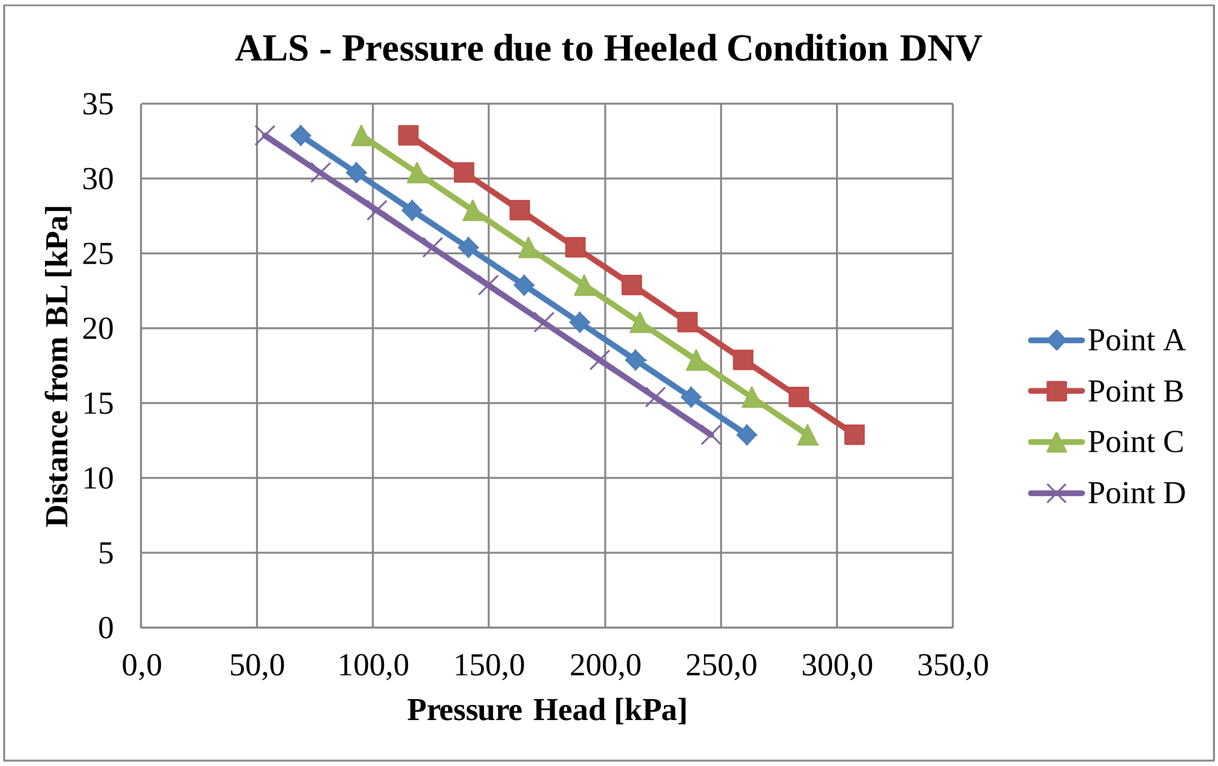


Figure C.3: Damage pressure heads according to DNV - ALS

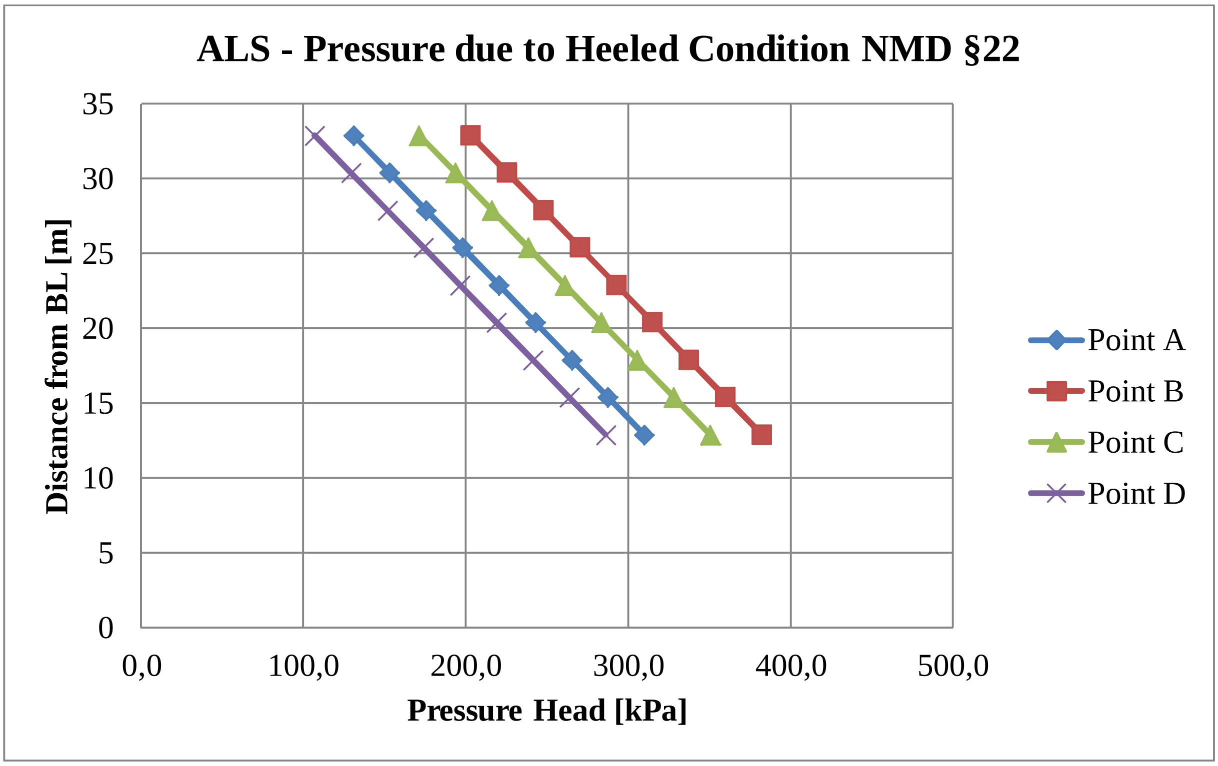


Figure C.4: Damage pressure heads according to NMD §22 - ALS

Appendix D: Basic Load Cases

Table D.1: Internal pressure basic load cases

Limit state/Load condition	Wet surface	Pressure [kPa]		z-coordinate [m]	
		Top	Bottom	Top	Bottom
ULS-a	Tank 1	0	346.9	35.75	10.4
ULS-b	Tank 1	0	335.9	35.75	10.4
ALS-DNV	Tank 1	87.9	331.7	35.75	10.4
ALS-NMD	Tank 1	177.5	404.6	35.75	10.4
ULS-a	Tank 2	0	346.9	35.75	10.4
ULS-b	Tank 2	0	335.9	35.75	10.4
ALS-DNV	Tank 2	87.9	331.7	35.75	10.4
ALS-NMD	Tank 2	177.5	404.6	35.75	10.4
ULS-a	Tank 3	0	346.9	35.75	10.4
ULS-b	Tank 3	0	335.9	35.75	10.4
ALS-DNV	Tank 3	87.9	331.7	35.75	10.4
ALS-NMD	Tank 3	177.5	404.6	35.75	10.4
ULS-a	Tank 4	0	346.9	35.75	10.4
ULS-b	Tank 4	0	335.9	35.75	10.4
ALS-DNV	Tank 4	87.9	331.7	35.75	10.4
ALS-NMD	Tank 4	177.5	404.6	35.75	10.4
ULS-a	Tank 5	0	346.9	35.75	10.4
ULS-b	Tank 5	0	335.9	35.75	10.4
ALS-DNV	Tank 5	87.9	331.7	35.75	10.4
ALS-NMD	Tank 5	177.5	404.6	35.75	10.4
ULS-a	Tank 6	0	346.9	35.75	10.4
ULS-b	Tank 6	0	335.9	35.75	10.4
ALS-DNV	Tank 6	87.9	331.7	35.75	10.4

ALS-NMD	Tank 6	177.5	404.6	35.75	10.4
ALS-DNV	Void 1	87.9	331.7	35.75	10.4
ALS-NMD	Void 1	177.5	404.6	35.75	10.4
ALS-DNV	Void 2	87.9	331.7	35.75	10.4
ALS-NMD	Void 2	177.5	404.6	35.75	10.4
ULS-a	Void 3	0	346.9	35.75	10.4
ULS-b	Void 3	0	335.9	35.75	10.4
ALS-DNV	Void 3	87.9	331.7	35.75	10.4
ALS-NMD	Void 3	177.5	404.6	35.75	10.4
ALS-DNV	Void 4	87.9	331.7	35.75	10.4
ALS-NMD	Void 4	177.5	404.6	35.75	10.4
ALS-DNV	Void 5	87.9	331.7	35.75	10.4
ALS-NMD	Void 5	177.5	404.6	35.75	10.4
ALS-DNV	Void 6	87.9	331.7	35.75	10.4
ALS-NMD	Void 6	177.5	404.6	35.75	10.4
ALS-DNV	Void 7	87.9	331.7	35.75	10.4
ALS-NMD	Void 7	177.5	404.6	35.75	10.4
ALS-DNV	Void 8	87.9	331.7	35.75	10.4
ALS-NMD	Void 8	177.5	404.6	35.75	10.4
ALS-DNV	Void 9	87.9	331.7	35.75	10.4
ALS-NMD	Void 9	177.5	404.6	35.75	10.4
ALS-DNV	CH-L 1	87.9	331.7	35.75	10.4
ALS-NMD	CH-L 1	177.5	404.6	35.75	10.4
ALS-DNV	CH-L 2	87.9	331.7	35.75	10.4
ALS-NMD	CH-L 2	177.5	404.6	35.75	10.4
ALS-DNV	CH-L 3	87.9	331.7	35.75	10.4
ALS-NMD	CH-L 3	177.5	404.6	35.75	10.4

Appendix E: Column Stringers Structural Arrangement

The information under this section is subject to confidentiality agreement with GVA Consultants, therefore required to be hidden.

Appendix F: Shell Curvature Area Representation

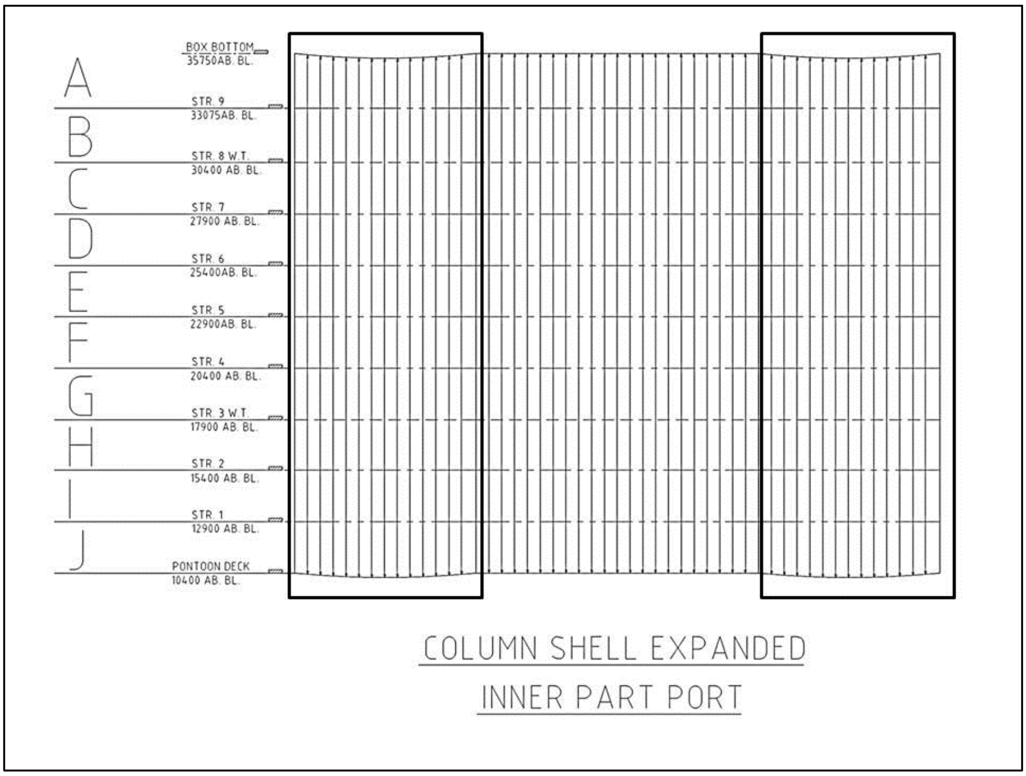


Table F.1: Column inner shell area representation

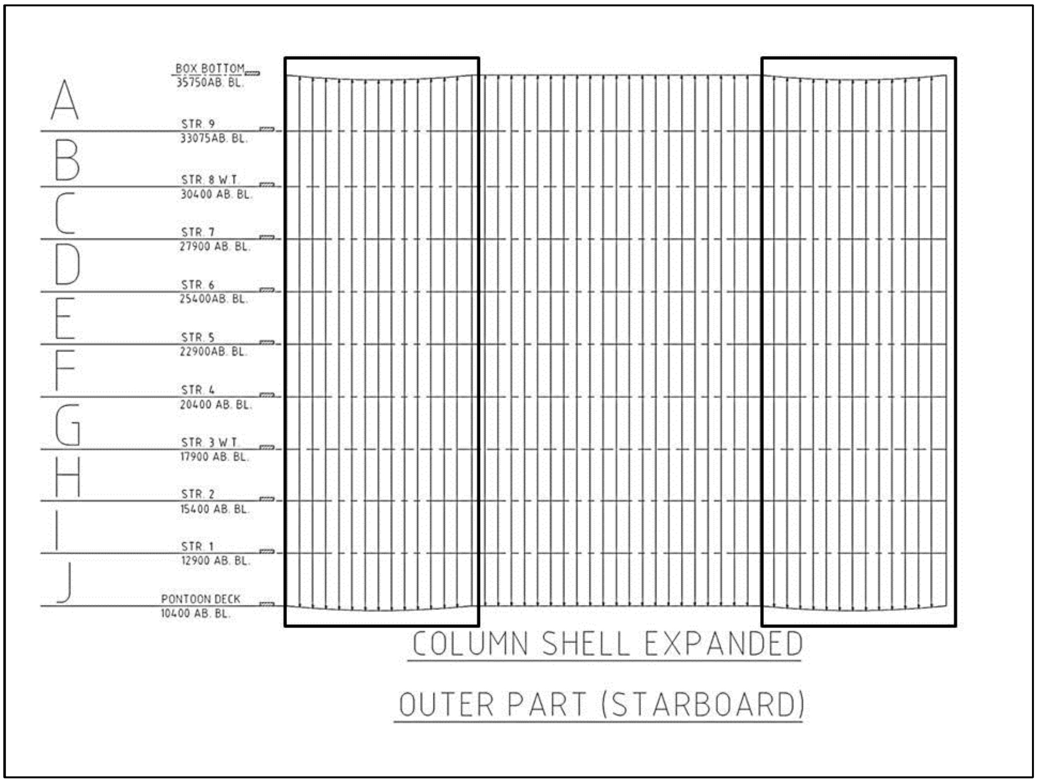


Table F.2: Column outer shell area representation

Table F.3: Column shell outer part plate field calculation

Plate field representation	Radius [m]	Plate thickness [m]	Stiffener spacing [m]	s/t	$3\sqrt{\frac{r}{t}}$	
A1	5.85	0.016	0.65	40.63	57.36	**OK**
B1	5.85	0.015	0.65	43.33	59.25	**OK**
A2	5.85	0.015	0.65	43.33	59.25	**OK**
B2	5.85	0.014	0.65	46.43	61.32	**OK**
A3	5.85	0.014	0.65	46.43	61.32	**OK**
B3	5.85	0.014	0.65	46.43	61.32	**OK**
A4	5.85	0.014	0.65	46.43	61.32	**OK**
B4	5.85	0.014	0.65	46.43	61.32	**OK**
A5	5.85	0.014	0.65	46.43	61.32	**OK**
B5	5.85	0.014	0.65	46.43	61.32	**OK**
A6	5.85	0.014	0.65	46.43	61.32	**OK**
B6	5.85	0.014	0.65	46.43	61.32	**OK**
Plate field representation	**Radius [m]**	**Plate thickness [m]**	**Stiffener spacing [m]**	s/t	$3\sqrt{\frac{r}{t}}$	
E1	5.85	0.014	0.65	46.43	61.32	**OK**
F1	5.85	0.015	0.65	43.33	59.25	**OK**
E2	5.85	0.013	0.65	50.00	63.64	**OK**
F2	5.85	0.012	0.65	54.17	66.24	**OK**
E3	5.85	0.014	0.65	46.43	61.32	**OK**
F3	5.85	0.014	0.65	46.43	61.32	**OK**
E4	5.85	0.01	0.65	65.00	72.56	**OK**
F4	5.85	0.012	0.65	54.17	66.24	**OK**
E5	5.85	0.009	0.65	72.22	76.49	**OK**
F5	5.85	0.012	0.65	54.17	66.24	**OK**
E6	5.85	0.011	0.65	59.09	69.18	**OK**
F6	5.85	0.011	0.65	59.09	69.18	**OK**

Table F.4: Column shell inner part plate field calculation

Plate field representation	Radius [m]	Plate thickness [m]	Stiffener spacing [m]	s/t	$3\sqrt{\frac{r}{t}}$	
A1	5.85	0.015	0.65	43.33	59.25	**OK**
B1	5.85	0.015	0.65	43.33	59.25	**OK**
A2	5.85	0.015	0.65	43.33	59.25	**OK**
B2	5.85	0.015	0.65	43.33	59.25	**OK**
A3	5.85	0.014	0.65	46.43	61.32	**OK**
B3	5.85	0.013	0.65	50.00	63.64	**OK**
A4	5.85	0.012	0.65	54.17	66.24	**OK**
B4	5.85	0.013	0.65	50.00	63.64	**OK**
A5	5.85	0.01	0.65	65.00	72.56	**OK**
B5	5.85	0.014	0.65	46.43	61.32	**OK**
A6	5.85	0.01	0.65	65.00	72.56	**OK**
B6	5.85	0.014	0.65	46.43	61.32	**OK**
Plate field representation	**Radius [m]**	**Plate thickness [m]**	**Stiffener spacing [m]**	s/t	$3\sqrt{\frac{r}{t}}$	
E1	5.85	0.017	0.65	38.24	55.65	**OK**
F1	5.85	0.017	0.65	38.24	55.65	**OK**
E2	5.85	0.017	0.65	38.24	55.65	**OK**
F2	5.85	0.017	0.65	38.24	55.65	**OK**
E3	5.85	0.018	0.65	36.11	54.08	**OK**
F3	5.85	0.018	0.65	36.11	54.08	**OK**
E4	5.85	0.017	0.65	38.24	55.65	**OK**
F4	5.85	0.017	0.65	38.24	55.65	**OK**
E5	5.85	0.022	0.65	29.55	48.92	**OK**
F5	5.85	0.022	0.65	29.55	48.92	**OK**
E6	5.85	0.018	0.65	36.11	54.08	**OK**
F6	5.85	0.016	0.65	40.63	57.36	**OK**

Appendix G: Vertical Fairlead Stress Calculation

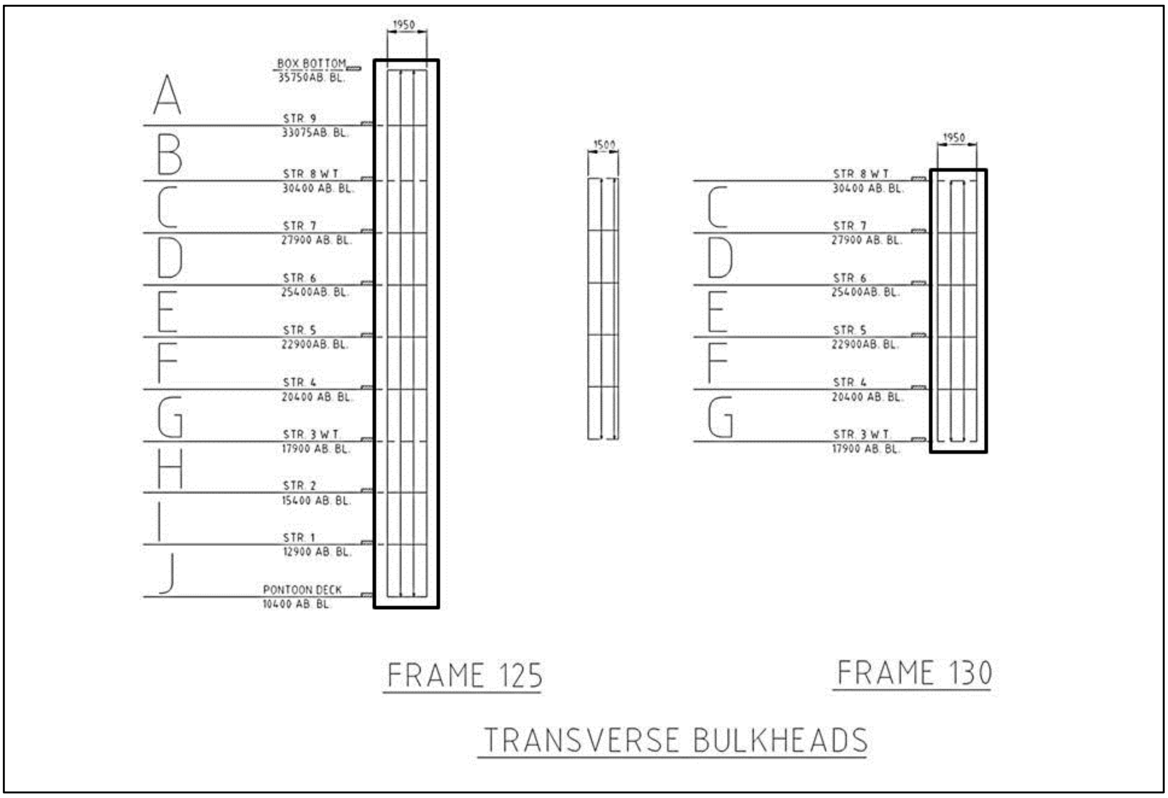


Figure G.1: Transverse bulkheads area identification for vertical fairlead stress calculation

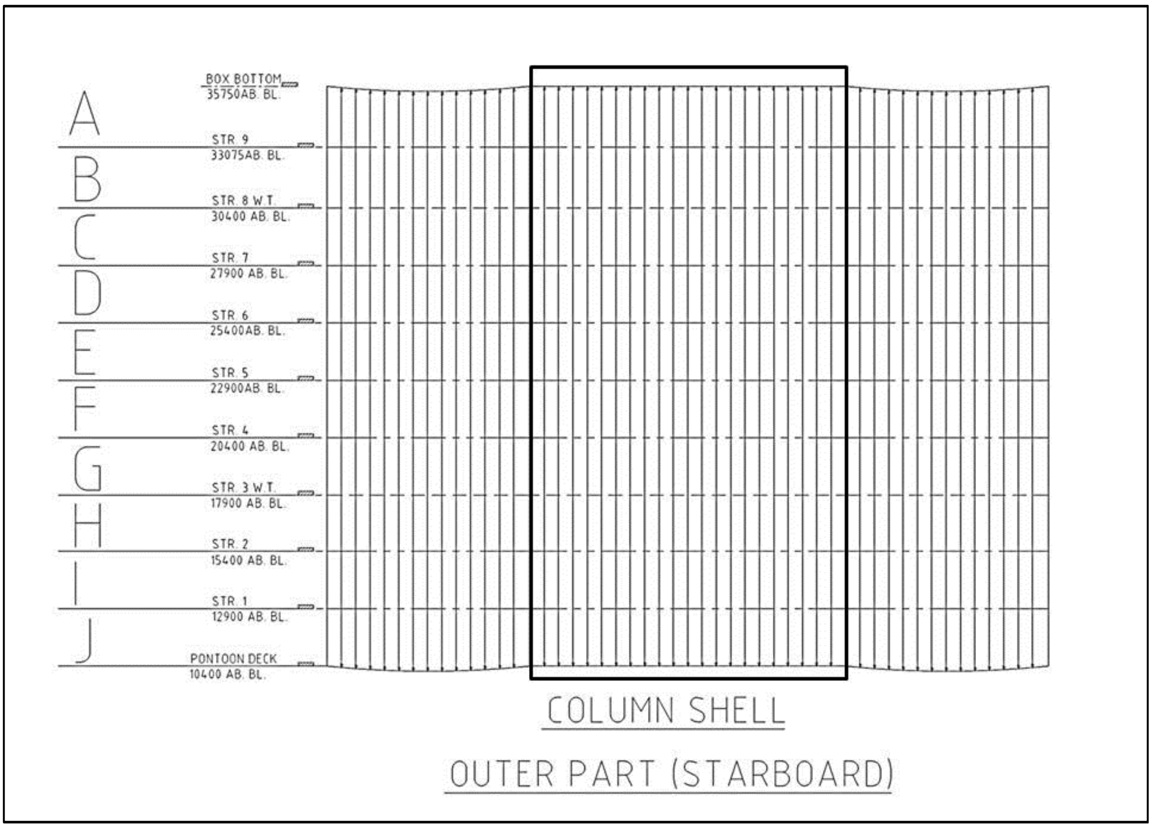


Figure G.2: Column shell area identification for vertical fairlead stress calculation

Table G.1: Column outer shell cross-sectional area calculation

Area ID	Plate thickness	Length of shell [m]	Column shell area [mm2]	Stiffener dimension	Area of stiffener [mm2]	# of stiffener	Stiffener area [mm2]	Total column shell area
A	15	14.3	214500	260x12	4131	21	86751	301251
B	15	14.3	214500	260x12	4131	21	86751	301251
C	15	14.3	214500	240x12	4131	21	86751	301251
D	15	14.3	214500	240x12	4131	21	86751	301251
E	14	14.3	200200	260x10	3611	21	75831	276031
F	14	14.3	200200	260x10	3611	21	75831	276031
G	14	14.3	200200	260x10	3611	21	75831	276031
H	14	14.3	200200	260x10	3611	21	75831	276031
I	14	14.3	200200	260x10	3611	21	75831	276031

Table G.2: Transverse bulkhead cross-sectional area calculation

Area ID	Plate thickness	Length of bulkhead [mm]	Bulkhead area [mm2]	Stiffener dimension	Area of stiffener [mm2]	# of stiffener	Bulkhead stiffener area [mm2]	Total bulkhead area [mm2]
A	11	1950	21450	260x10	3611	2	7222	28672
B	11	1950	21450	260x10	3611	2	7222	28672
C	12	1950	23400	260x10	3611	2	7222	30622
D	12	1950	23400	260x10	3611	2	7222	30622
E	12	1950	23400	260x10	3611	2	7222	30622
F	13	1950	25350	280x11	4268	2	8536	33886
G	13	1950	25350	260x10	3611	2	7222	32572
H	14	1950	27300	260x10	3611	2	7222	34522
I	15	1950	29250	260x10	3611	2	7222	36472

Appendix H: Stress Plots – ULS-a

The stress plots with respect to ULS-a can be found on CD attached to this report.

Appendix I: Stress Plots – ALS-DNV

The stress plots with respect to ALS-DNV can be found on CD attached to this report.

Appendix J: Minimum Required Scantlings

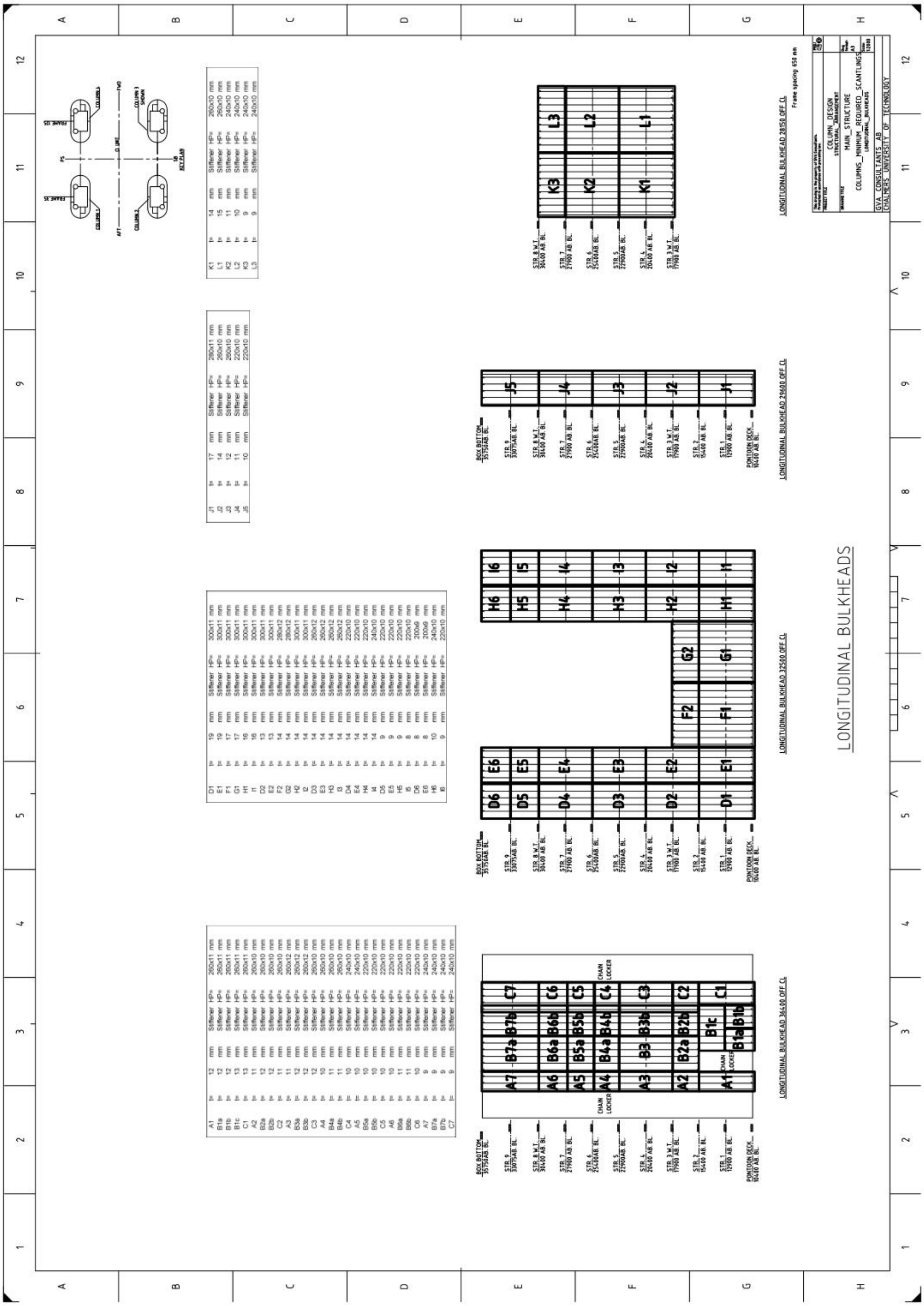


Figure J.1: Longitudinal bulkheads minimum required scantlings

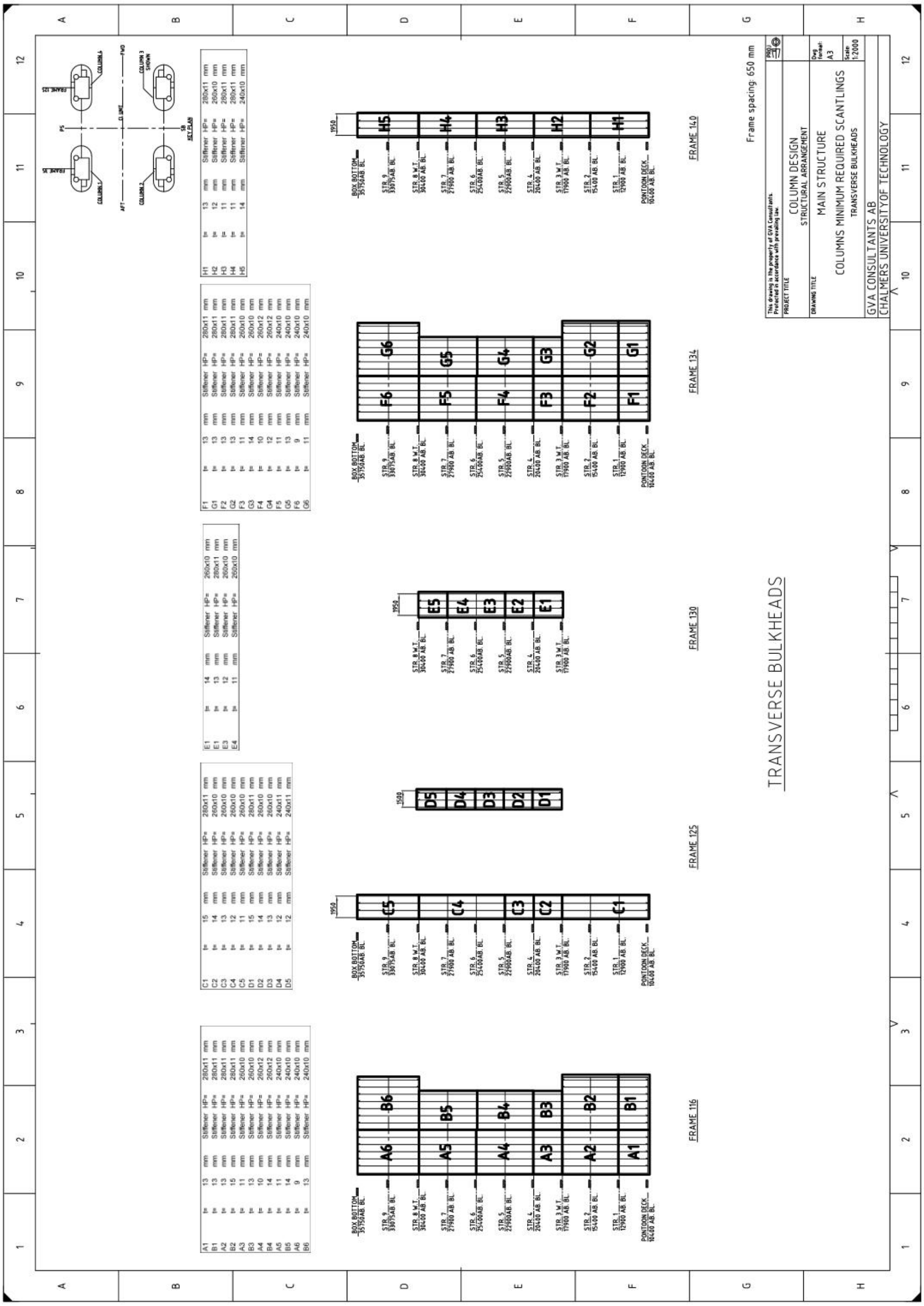


Figure J.2: Transverse bulkheads minimum required scantlings

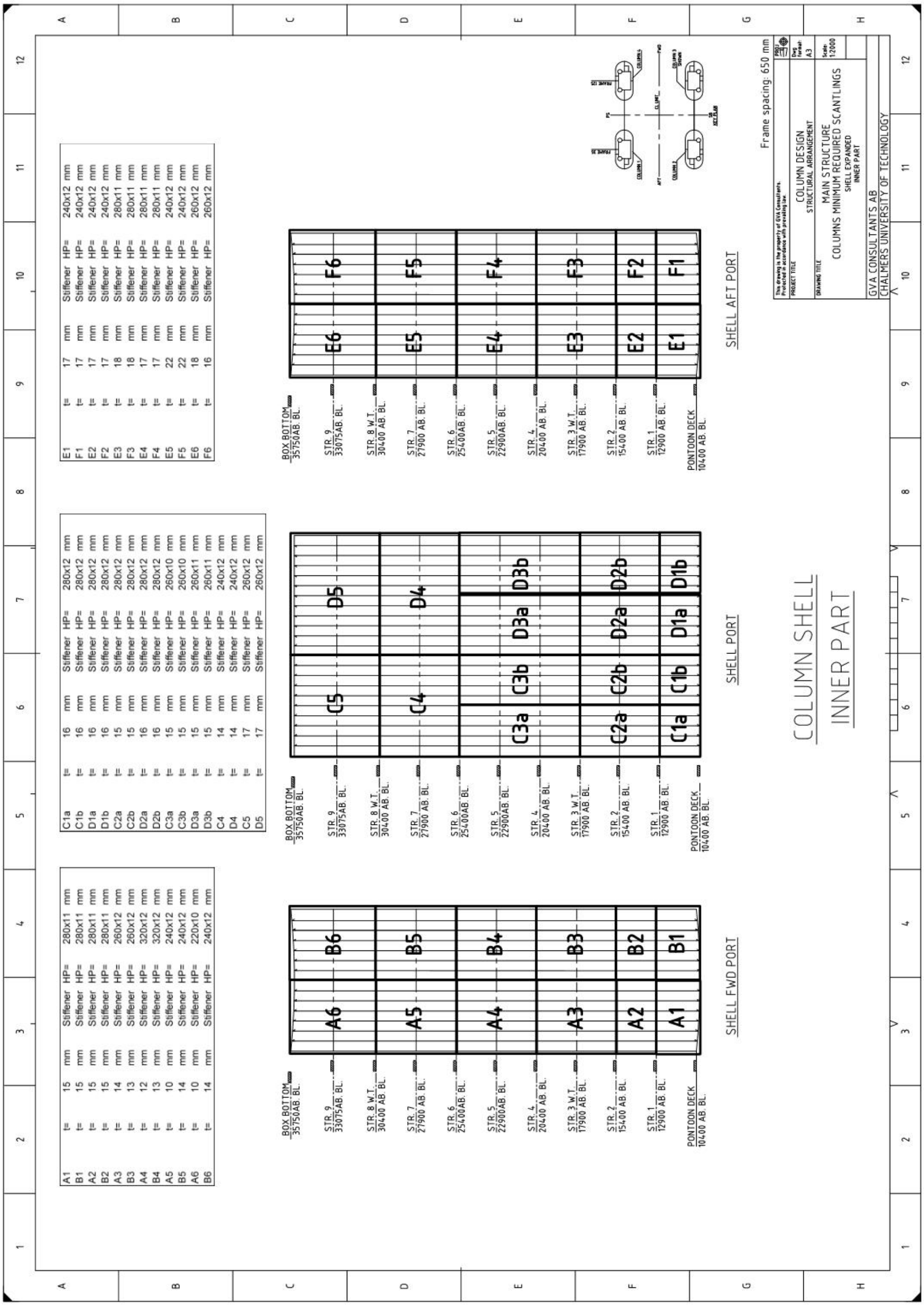


Figure J.3: Column shell inner part minimum required scantlings

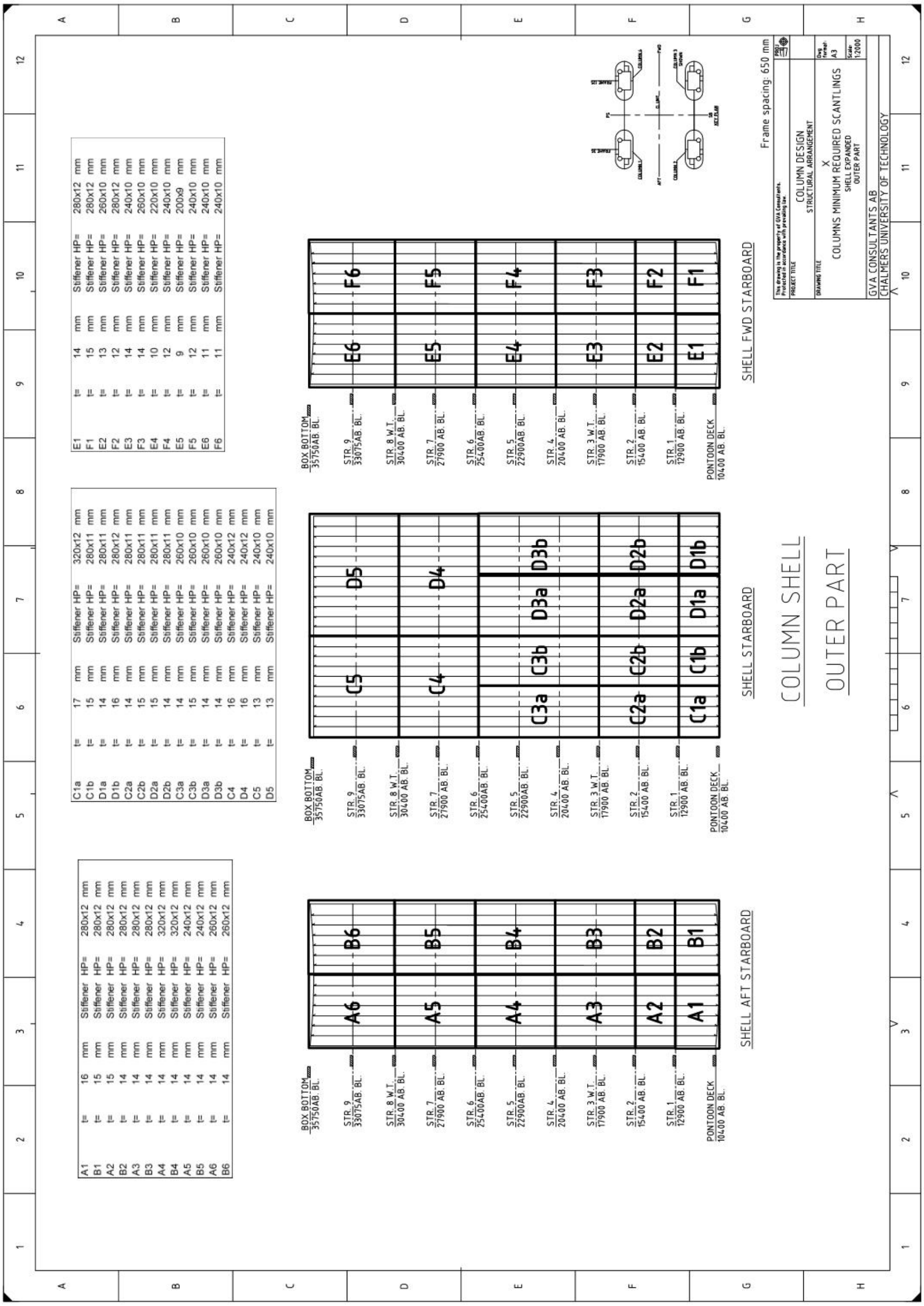
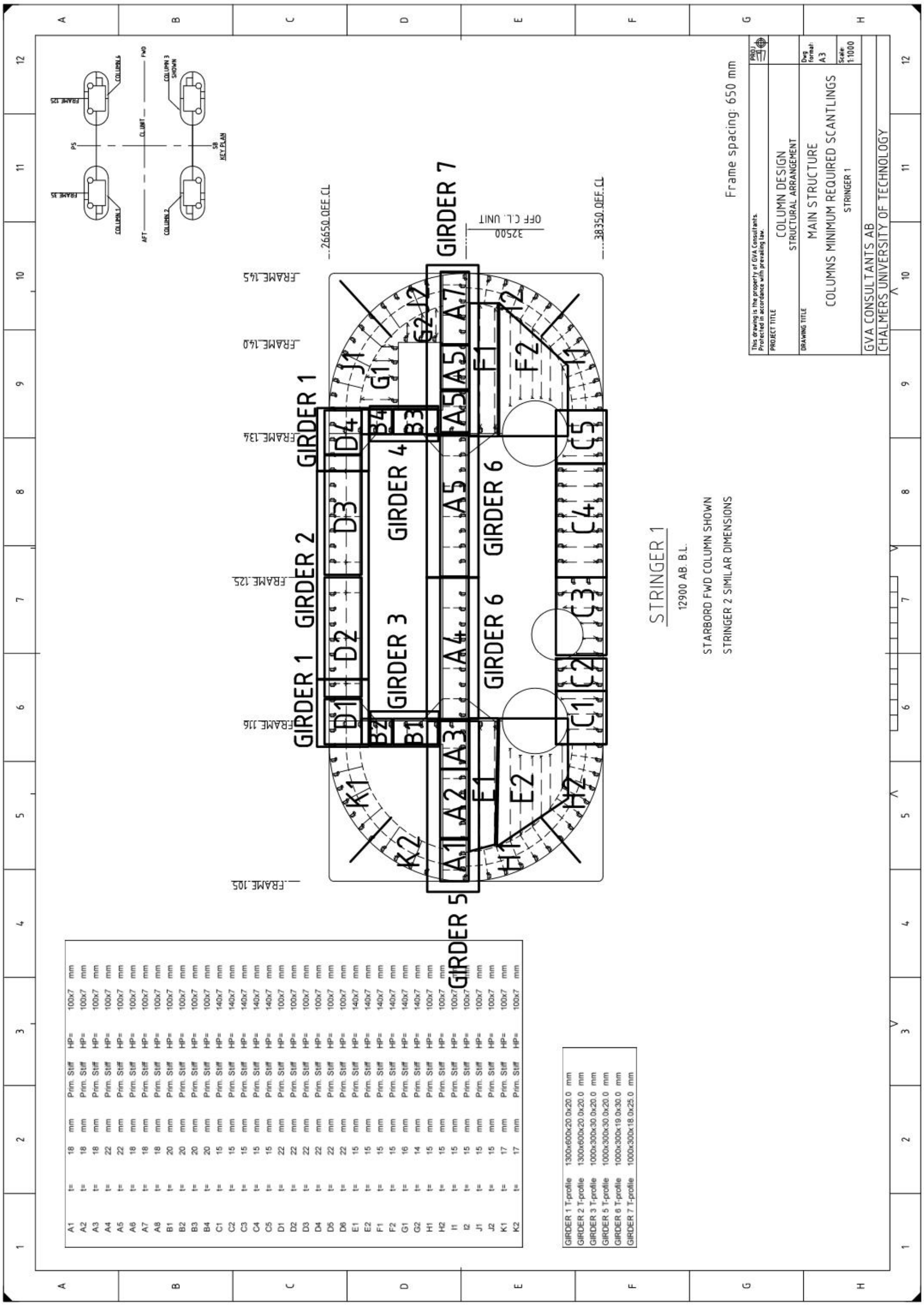


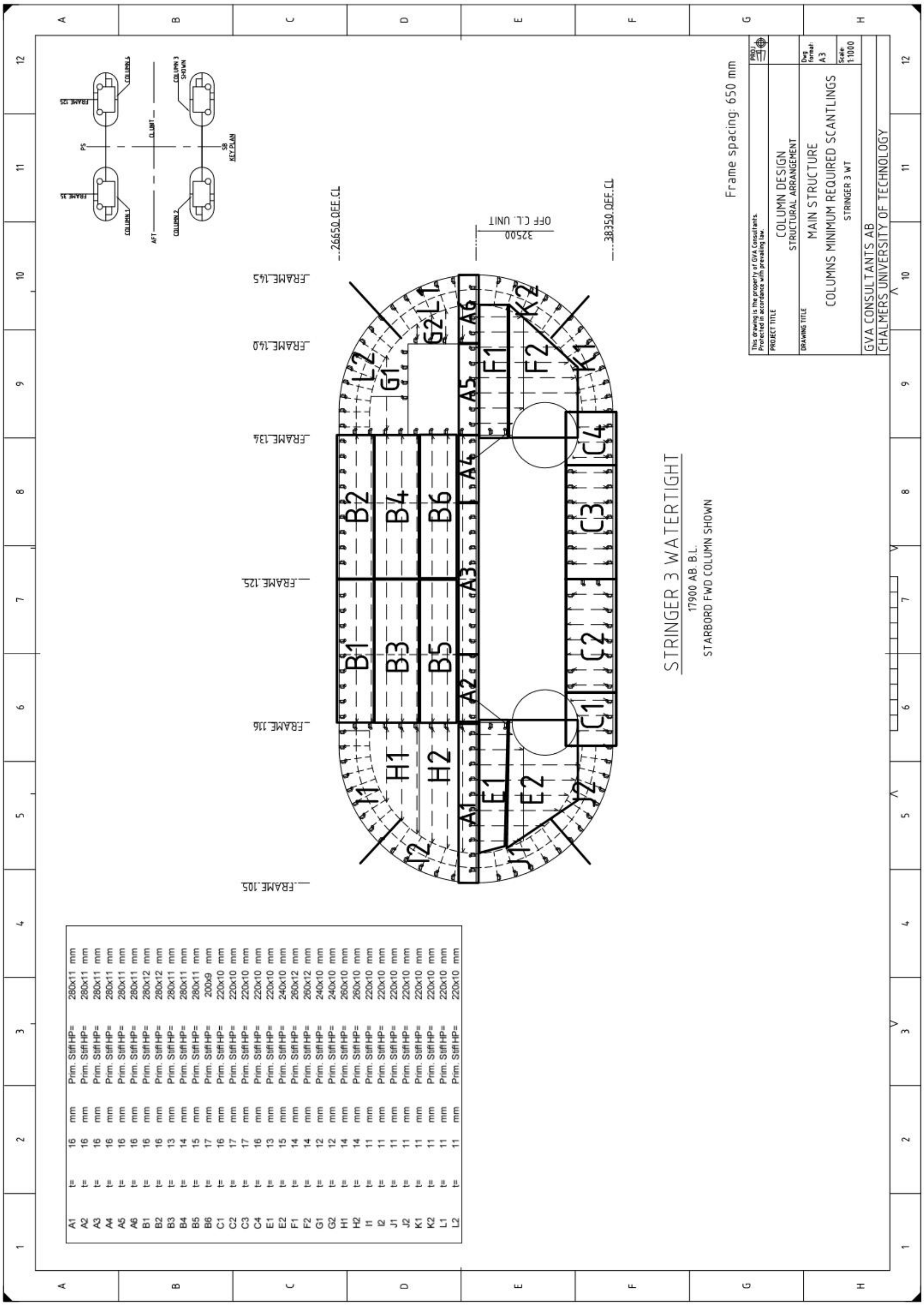
Figure J.4: Column shell outer part minimum required scantlings



A1	t=	18	mm	Prim. Stiff	HP=	100x7	mm
A2	t=	18	mm	Prim. Stiff	HP=	100x7	mm
A3	t=	18	mm	Prim. Stiff	HP=	100x7	mm
A4	t=	22	mm	Prim. Stiff	HP=	100x7	mm
A5	t=	22	mm	Prim. Stiff	HP=	100x7	mm
A6	t=	18	mm	Prim. Stiff	HP=	100x7	mm
A7	t=	18	mm	Prim. Stiff	HP=	100x7	mm
A8	t=	18	mm	Prim. Stiff	HP=	100x7	mm
B1	t=	20	mm	Prim. Stiff	HP=	100x7	mm
B2	t=	20	mm	Prim. Stiff	HP=	100x7	mm
B3	t=	20	mm	Prim. Stiff	HP=	100x7	mm
B4	t=	20	mm	Prim. Stiff	HP=	100x7	mm
C1	t=	15	mm	Prim. Stiff	HP=	140x7	mm
C2	t=	15	mm	Prim. Stiff	HP=	140x7	mm
C3	t=	15	mm	Prim. Stiff	HP=	140x7	mm
C4	t=	15	mm	Prim. Stiff	HP=	140x7	mm
C5	t=	15	mm	Prim. Stiff	HP=	140x7	mm
D1	t=	22	mm	Prim. Stiff	HP=	100x7	mm
D2	t=	22	mm	Prim. Stiff	HP=	100x7	mm
D3	t=	22	mm	Prim. Stiff	HP=	100x7	mm
D4	t=	22	mm	Prim. Stiff	HP=	100x7	mm
D5	t=	22	mm	Prim. Stiff	HP=	100x7	mm
D6	t=	22	mm	Prim. Stiff	HP=	100x7	mm
E1	t=	15	mm	Prim. Stiff	HP=	140x7	mm
E2	t=	15	mm	Prim. Stiff	HP=	140x7	mm
F1	t=	15	mm	Prim. Stiff	HP=	140x7	mm
F2	t=	15	mm	Prim. Stiff	HP=	140x7	mm
G1	t=	16	mm	Prim. Stiff	HP=	140x7	mm
G2	t=	14	mm	Prim. Stiff	HP=	140x7	mm
H1	t=	15	mm	Prim. Stiff	HP=	100x7	mm
H2	t=	15	mm	Prim. Stiff	HP=	100x7	mm
I1	t=	15	mm	Prim. Stiff	HP=	100x7	mm
I2	t=	15	mm	Prim. Stiff	HP=	100x7	mm
J1	t=	15	mm	Prim. Stiff	HP=	100x7	mm
J2	t=	15	mm	Prim. Stiff	HP=	100x7	mm
K1	t=	17	mm	Prim. Stiff	HP=	100x7	mm
K2	t=	17	mm	Prim. Stiff	HP=	100x7	mm

GIRDER 1 T-profile	1300x600x20.0x20.0	mm
GIRDER 2 T-profile	1300x600x20.0x20.0	mm
GIRDER 3 T-profile	1000x300x30.0x20.0	mm
GIRDER 5 T-profile	1000x300x30.0x20.0	mm
GIRDER 6 T-profile	1000x300x19.0x30.0	mm
GIRDER 7 T-profile	1000x300x18.0x25.0	mm

Figure J.5: Stringer 1 minimum required scantlings



A1	t=	16	mm	Prim. Stiff HP=	280x11	mm
A2	t=	16	mm	Prim. Stiff HP=	280x11	mm
A3	t=	16	mm	Prim. Stiff HP=	280x11	mm
A4	t=	16	mm	Prim. Stiff HP=	280x11	mm
A5	t=	16	mm	Prim. Stiff HP=	280x11	mm
A6	t=	16	mm	Prim. Stiff HP=	280x11	mm
B1	t=	16	mm	Prim. Stiff HP=	280x12	mm
B2	t=	16	mm	Prim. Stiff HP=	280x12	mm
B3	t=	13	mm	Prim. Stiff HP=	280x11	mm
B4	t=	14	mm	Prim. Stiff HP=	280x11	mm
B5	t=	15	mm	Prim. Stiff HP=	280x11	mm
B6	t=	17	mm	Prim. Stiff HP=	200x9	mm
C1	t=	16	mm	Prim. Stiff HP=	220x10	mm
C2	t=	17	mm	Prim. Stiff HP=	220x10	mm
C3	t=	17	mm	Prim. Stiff HP=	220x10	mm
C4	t=	16	mm	Prim. Stiff HP=	220x10	mm
E1	t=	13	mm	Prim. Stiff HP=	220x10	mm
E2	t=	15	mm	Prim. Stiff HP=	240x10	mm
F1	t=	14	mm	Prim. Stiff HP=	260x12	mm
F2	t=	14	mm	Prim. Stiff HP=	260x12	mm
G1	t=	12	mm	Prim. Stiff HP=	240x10	mm
G2	t=	12	mm	Prim. Stiff HP=	240x10	mm
H1	t=	14	mm	Prim. Stiff HP=	260x10	mm
H2	t=	14	mm	Prim. Stiff HP=	260x10	mm
I1	t=	11	mm	Prim. Stiff HP=	220x10	mm
I2	t=	11	mm	Prim. Stiff HP=	220x10	mm
J1	t=	11	mm	Prim. Stiff HP=	220x10	mm
J2	t=	11	mm	Prim. Stiff HP=	220x10	mm
K1	t=	11	mm	Prim. Stiff HP=	220x10	mm
K2	t=	11	mm	Prim. Stiff HP=	220x10	mm
L1	t=	11	mm	Prim. Stiff HP=	220x10	mm
L2	t=	11	mm	Prim. Stiff HP=	220x10	mm

Figure J.6: Stringer 3 minimum required scantlings

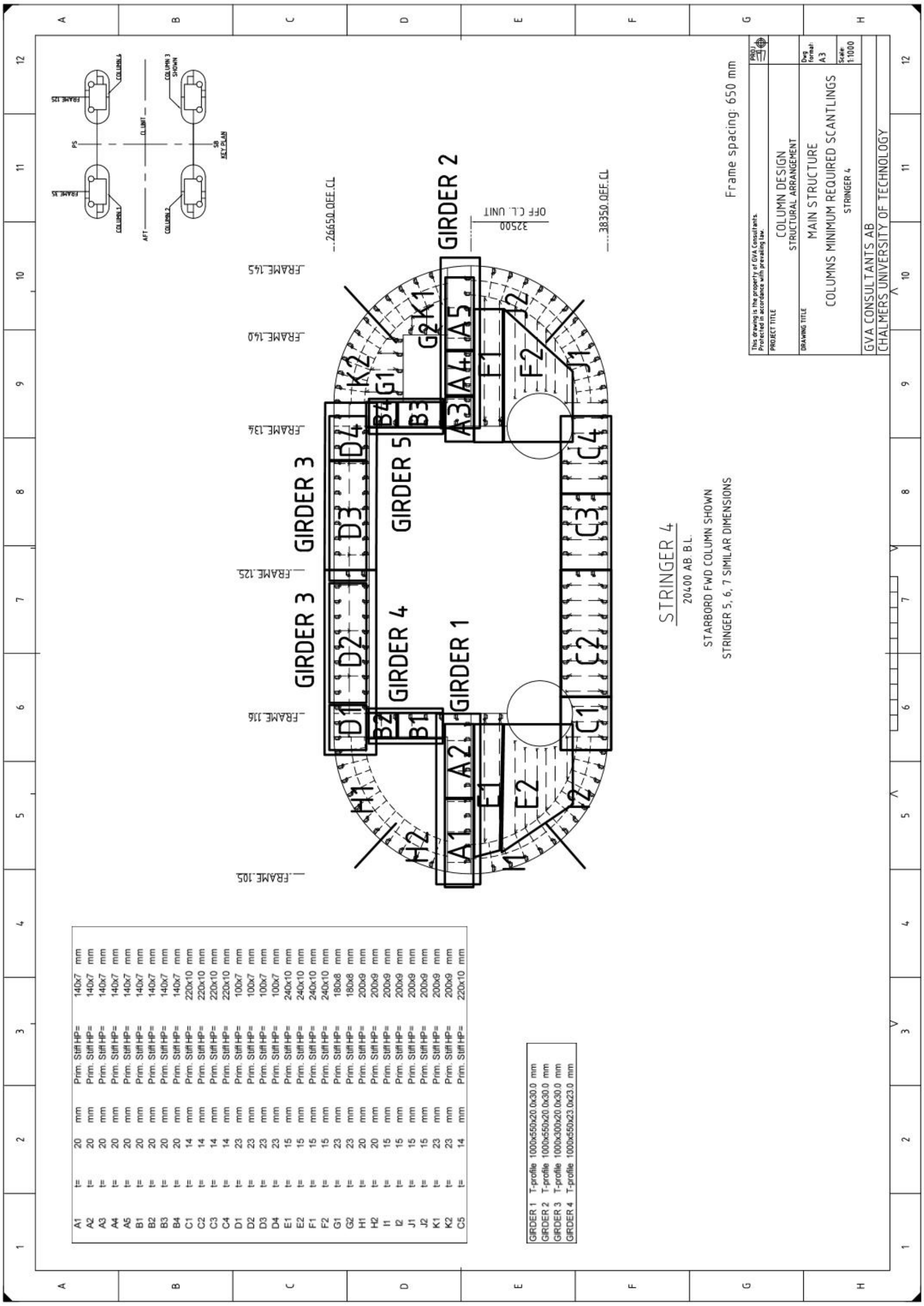
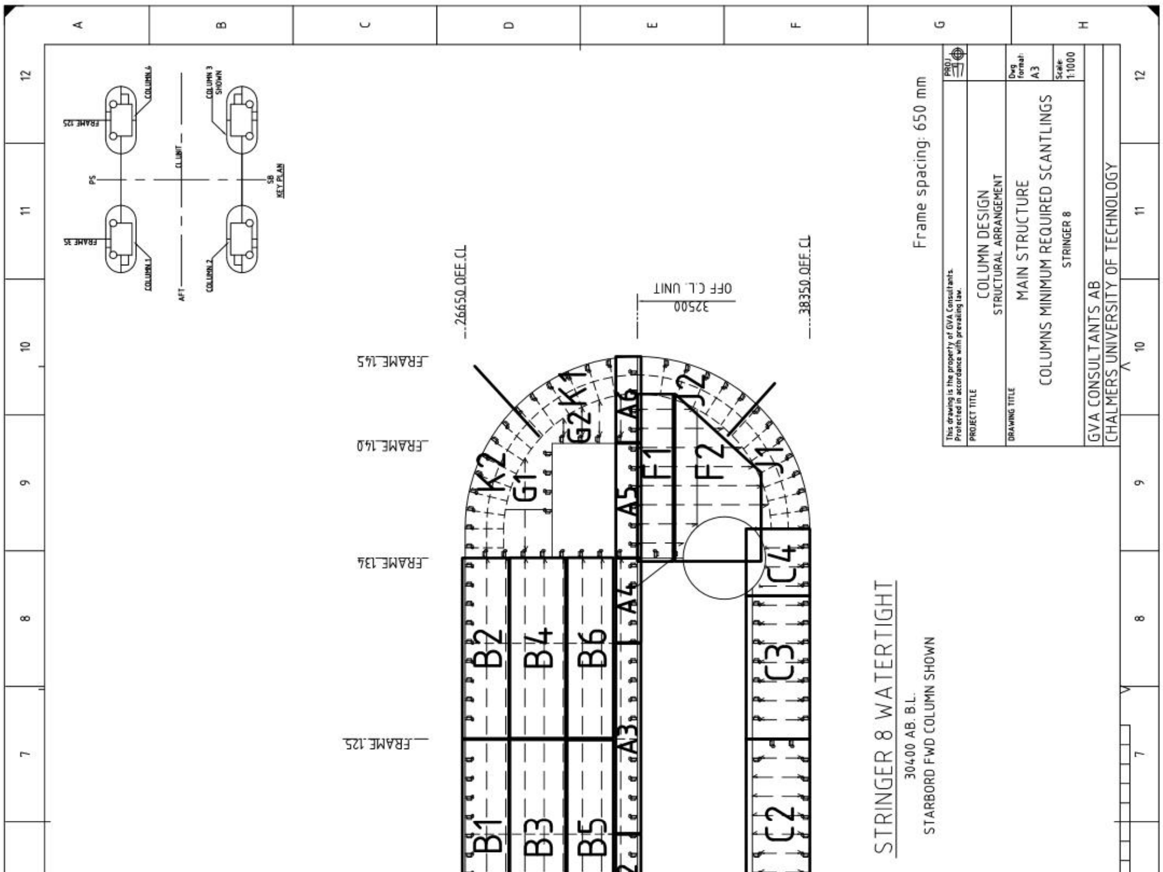
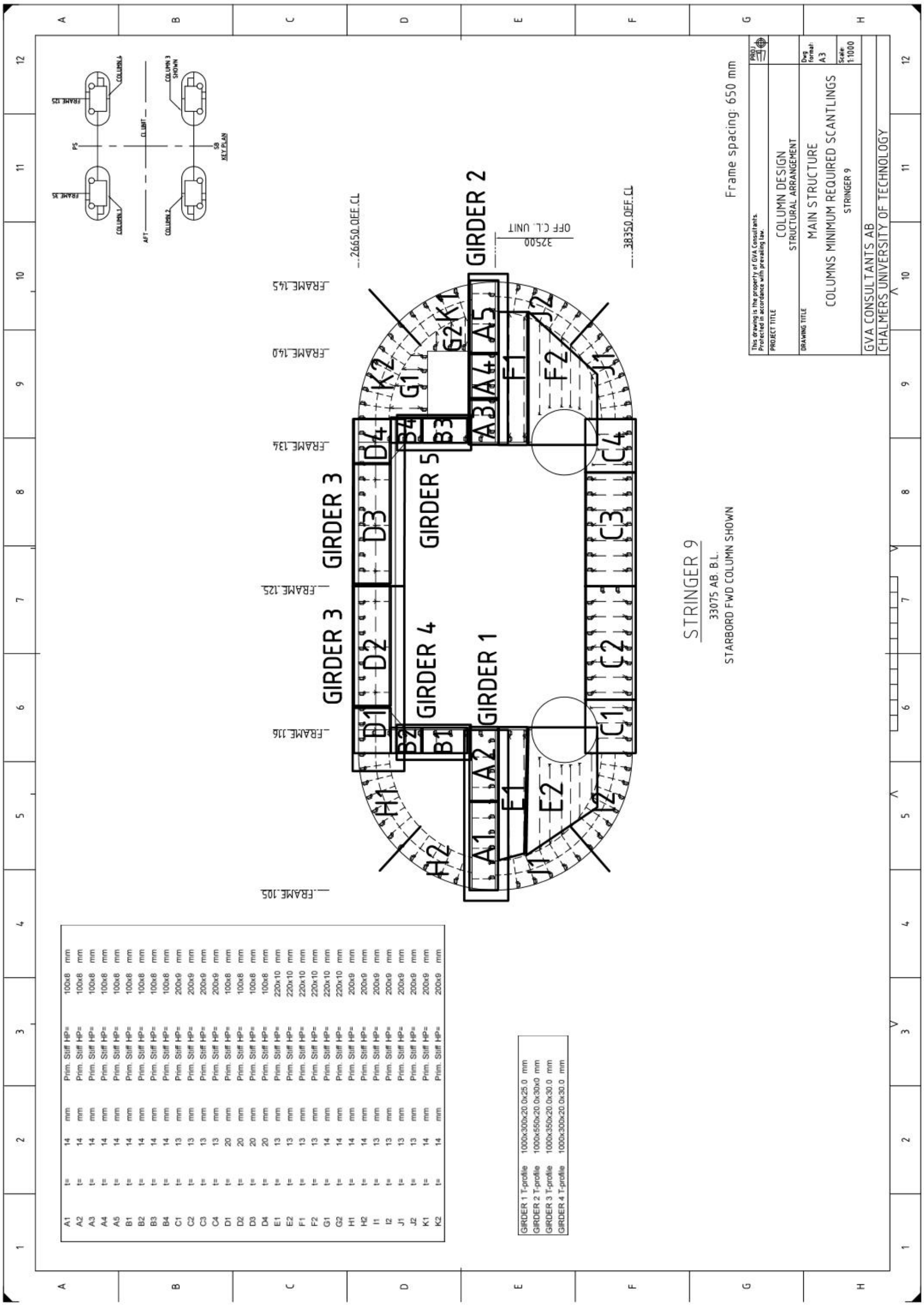


Figure J.7: Stringer 4 minimum required scantlings



A1	t=	14	mm	Prim. Stiff HP=	260x10	mm
A2	t=	14	mm	Prim. Stiff HP=	260x10	mm
A3	t=	14	mm	Prim. Stiff HP=	260x10	mm
A4	t=	14	mm	Prim. Stiff HP=	260x10	mm
A5	t=	14	mm	Prim. Stiff HP=	260x10	mm
A6	t=	14	mm	Prim. Stiff HP=	260x10	mm
B1	t=	11	mm	Prim. Stiff HP=	240x10	mm
B2	t=	11	mm	Prim. Stiff HP=	240x10	mm
B3	t=	10	mm	Prim. Stiff HP=	220x10	mm
B4	t=	10	mm	Prim. Stiff HP=	220x10	mm
B5	t=	10	mm	Prim. Stiff HP=	220x10	mm
B6	t=	10	mm	Prim. Stiff HP=	220x10	mm
C1	t=	10	mm	Prim. Stiff HP=	240x10	mm
C2	t=	10	mm	Prim. Stiff HP=	180x8	mm
C3	t=	10	mm	Prim. Stiff HP=	180x8	mm
C4	t=	10	mm	Prim. Stiff HP=	220x10	mm
E1	t=	10	mm	Prim. Stiff HP=	220x10	mm
E2	t=	11	mm	Prim. Stiff HP=	240x10	mm
F1	t=	10	mm	Prim. Stiff HP=	220x10	mm
F2	t=	11	mm	Prim. Stiff HP=	240x10	mm
G1	t=	11	mm	Prim. Stiff HP=	240x10	mm
G2	t=	11	mm	Prim. Stiff HP=	240x10	mm
H1	t=	10	mm	Prim. Stiff HP=	260x10	mm
H2	t=	10	mm	Prim. Stiff HP=	220x10	mm
I1	t=	11	mm	Prim. Stiff HP=	220x10	mm
I2	t=	11	mm	Prim. Stiff HP=	220x10	mm
J1	t=	11	mm	Prim. Stiff HP=	220x10	mm
J2	t=	11	mm	Prim. Stiff HP=	220x10	mm
K1	t=	11	mm	Prim. Stiff HP=	220x10	mm
K2	t=	11	mm	Prim. Stiff HP=	220x10	mm
L1	t=	11	mm	Prim. Stiff HP=	220x10	mm
L2	t=	11	mm	Prim. Stiff HP=	220x10	mm

Figure J.8: Stringer 8 minimum required scantlings



A1	t=	14	mm	Prim. Stiff HP=	100x8	mm
A2	t=	14	mm	Prim. Stiff HP=	100x8	mm
A3	t=	14	mm	Prim. Stiff HP=	100x8	mm
A4	t=	14	mm	Prim. Stiff HP=	100x8	mm
A5	t=	14	mm	Prim. Stiff HP=	100x8	mm
B1	t=	14	mm	Prim. Stiff HP=	100x8	mm
B2	t=	14	mm	Prim. Stiff HP=	100x8	mm
B3	t=	14	mm	Prim. Stiff HP=	100x8	mm
B4	t=	14	mm	Prim. Stiff HP=	100x8	mm
C1	t=	13	mm	Prim. Stiff HP=	200x9	mm
C2	t=	13	mm	Prim. Stiff HP=	200x9	mm
C3	t=	13	mm	Prim. Stiff HP=	200x9	mm
C4	t=	13	mm	Prim. Stiff HP=	200x9	mm
D1	t=	20	mm	Prim. Stiff HP=	100x8	mm
D2	t=	20	mm	Prim. Stiff HP=	100x8	mm
D3	t=	20	mm	Prim. Stiff HP=	100x8	mm
D4	t=	20	mm	Prim. Stiff HP=	100x8	mm
E1	t=	13	mm	Prim. Stiff HP=	220x10	mm
E2	t=	13	mm	Prim. Stiff HP=	220x10	mm
F1	t=	13	mm	Prim. Stiff HP=	220x10	mm
F2	t=	13	mm	Prim. Stiff HP=	220x10	mm
G1	t=	14	mm	Prim. Stiff HP=	220x10	mm
G2	t=	14	mm	Prim. Stiff HP=	220x10	mm
H1	t=	14	mm	Prim. Stiff HP=	200x9	mm
H2	t=	14	mm	Prim. Stiff HP=	200x9	mm
I1	t=	13	mm	Prim. Stiff HP=	200x9	mm
I2	t=	13	mm	Prim. Stiff HP=	200x9	mm
J1	t=	13	mm	Prim. Stiff HP=	200x9	mm
J2	t=	13	mm	Prim. Stiff HP=	200x9	mm
K1	t=	14	mm	Prim. Stiff HP=	200x9	mm
K2	t=	14	mm	Prim. Stiff HP=	200x9	mm

GIRDER 1 T-profile	1000x300x20.0x25.0	mm
GIRDER 2 T-profile	1000x550x20.0x30x0	mm
GIRDER 3 T-profile	1000x350x20.0x30.0	mm
GIRDER 4 T-profile	1000x300x20.0x30.0	mm

Figure J.9: Stringer 9 minimum required scantlings

Appendix K: Yield and Buckling Check

The results regarding the yield and buckling can be found on CD attached to this report.

Appendix L: Structural Steel Weight Breakdown

The information under this section is subject to confidentiality agreement with GVA Consultants, therefore required to be hidden.