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Author: Halvar Malmin

Halvar Malmin

(signature author)

Course coordinator: Daniella Müller

Supervisor(s):
Ashish Aeran (UIS)
Sigurd Næss (Blue Logic

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+ appendix*: Lifting through wave zone – simplified method.*

Stavanger, 15.05/2022
date/year

Forword

This bachelor thesis was determined after Blue Logic reached out an asked if I wanted to right a thesis for them. The assignment was to investigate their Subsea Docking Station and see if there were possibilities to do some optimizations of the joints. My supervisor from Blue Logic wanted to see if bolted joints were possible instead of welded.

It started with learning a new program Autodesk Inventor, and its calculation plugin called Nastran.

Here the structure was drawn in 3D and Nastran gave me the needed stresses and plots.

Thanks to Ashish Aeran for being my supervisor from University of Stavanger. And a special thanks to Sigurd Næss my supervisor from Blue Logic that I have worked closely to the whole period and provided what I needed. And thanks to Blue Logic for letting me write the thesis for them.

Thanks for the collaboration.

Sandnes, 15.05.2022,

Halvar Malmin

Abstract

The project consists of two concepts, which discuss the possibilities and drawbacks of different profiles and joints. The selection of concept is done so the structure is suitable to be installed on the seabed for 25 years. The joints on the Blue Logic original design were welded joints, so the concepts looked at possibilities to change the welds to bolts.

The bolting suggestion of bolting a joint in the structure made it so the whole structure needed a redesign, since the original design consisted of Rectangular Hollowed Sections which are not suitable for bolting. A full redesign of the original design where done, with respect to bolting joints but also the low weight problem the original structure had.

The concept structure was checked for different failures in profiles and joints, and the problem with corrosion was discussed and proposed some preventive methods to help against it. A bolted joint can have more difficulties than a welded joint, hence welds are more suitable for subsea structures. Blue Logic must do a risk vs reward analysis before deciding on the concept.

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1. INTRODUCTION

1.1. PROJECT DESCRIPTION

Blue Logic have produced the first series of universal open-standard Subsea Docking Station also known as SDS, which will enable subsea charging and communication transfer. The docking station design is a predominantly a welded structure. The SDS consists of two modules; a foundation “Subsea Docking Base” (SDB) and a “Subsea Docking Module” (SDM) which includes all necessary electronic [1].

This thesis will do a redesign of the SDB in order to optimize the beams and joints based on criteria listed in chapter 1.2 from Blue logic. Two concepts will explore different beam cross sections and joints solutions.

1.2. OBJECTIVS

The following objectives have been defined:

1. Loads on SDB

    Ultimate limit state: Determine hydrodynamic loads on SDB when lifting through the splash zone using simplified method according to DNV-RP-N103.

    NOTE: Assume that SDB and SDM will be lifted as one system

2. Discuss system weight limitations with respect to lifting through the splash zone when selecting steel profiles.

3. Discuss joint criticality.

    a. Propose bolted joint connections were deemed relevant

    b. Dimension connections according to Eurocode 3

    NOTE: Subsea structures will require different gamma factors (see e.g. DNV-OS-C101 or NORSOK N-004)

4. Discuss longevity with respect to corrosion in joints.

2. SDS

The SDS is designed to be transported and deploy together or separate. The SDS is a charging and data transfer station for underwater drone or ROVs and will be installed on the ocean floor. [Blue logic,2019].

The structure is protected from the environment with coating and cathodic protection using sacrificial anodes and has a design life of 25years. Currently the longest installed SDS has been subsea for approximately two years (*S.Næss Blue Logic, personal communication. 05.05.2022).*

There are currently three different inductive connector options, 2kW, 250W and 50W that all have the possibility to supply both power, data transfer and communication. When it is charging the drone can receive and upload data [1].

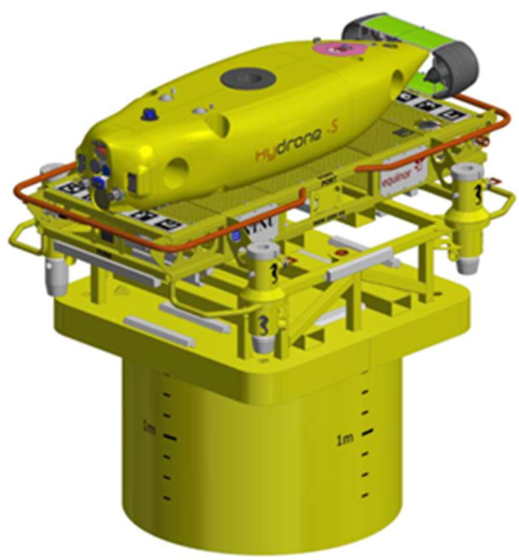


Figure 2-1 Illustrates the SDS with a ROV on it [1]

The individual modules can be installed separately or together as one single entity. Current experience has shown that the SDS is difficult to deploy through the wave zone due to its light weight. Blue Logic is in the development of a weighted plate to add additional weight when lifting through the wave zone (*S.Næss Blue Logic, personal communication. 05.05.2022)*.

Figure 2-2 Weighted plated in development for Blue Logic

Installation of the SDS can be performed either by using a four-point lifting sling system, or by using Multidog lifting technology a Blue Logic dedicated lifting tool that acts as a quick release connector [2].

Figure 2-3 Illustration of a Multidog, this gets placed in the reciver and locks in place[2]

2.1. SDM

The SDM is a retrievable plate that has a junction box that includes all the electronics. The plate is approximately 4.5m x 3.0m. Figure 2.3 is an overview of the SDM. The SDM is outside the scope of this thesis, only the weight will be added as mass when doing calculations. [2].

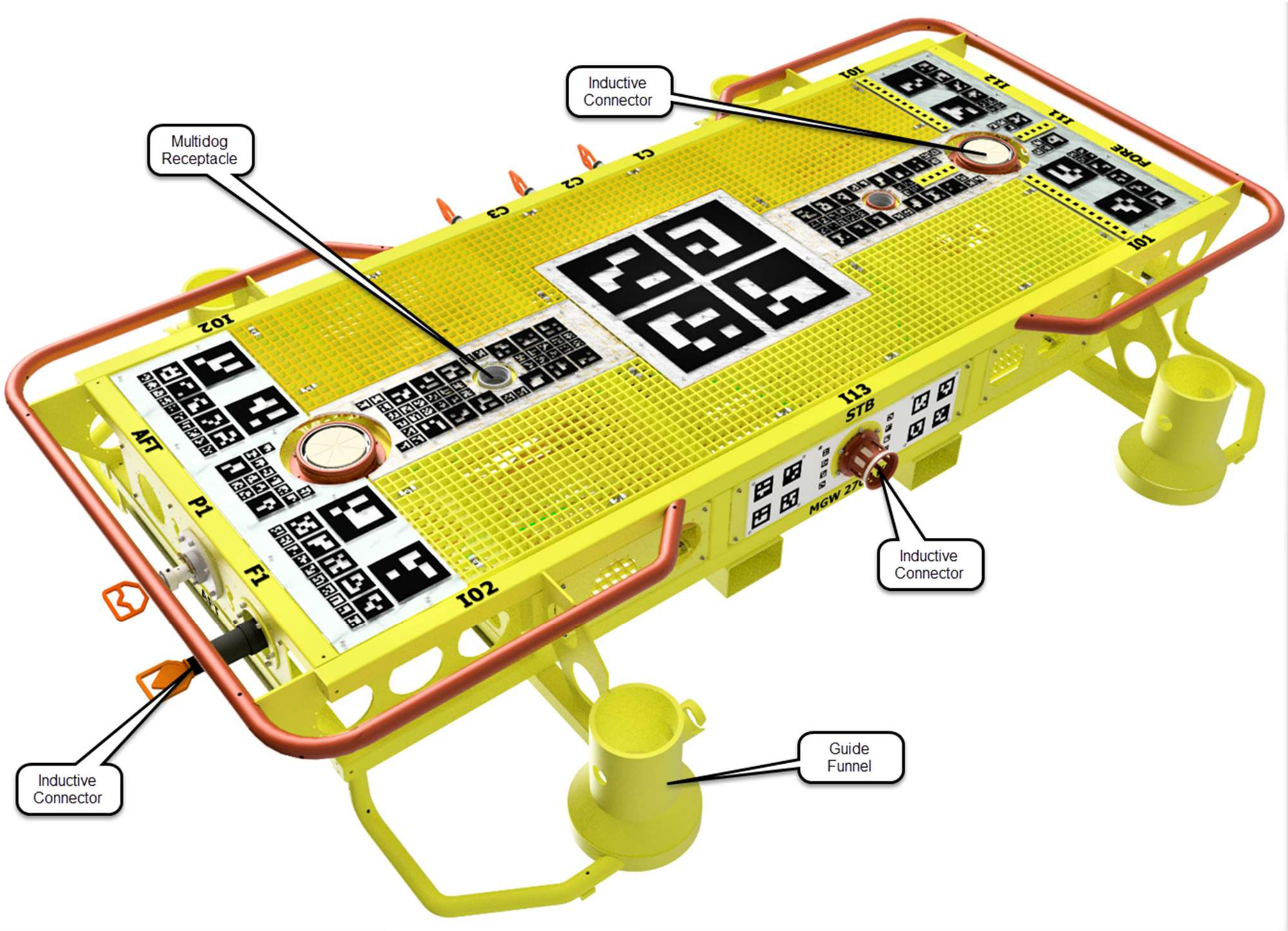


Figure 2-4 Shows the SDM that is the charging plate for the underwater drones and is fitted on top of the SDB [2].

2.2. SDB

The SDB is the foundation to the SDM. Blue logic has developed two variants of the SDB:
A suction anchor solution (see figure 2.1) and a gravity base solution. The suction anchor solution is outside the scope of this thesis.

Once installed on the seabed, four torque tool operated jacks can be used to level the structure, to ensure on-bottom stability.

The current Blue Logic design, consist of welded RHS profiles, that is displayed in Table 2.1(*S.Næss Blue Logic, personal communication. 05.05.2022)*.

The base is expected to have a design life of 25 years, and the anodes made from zinc-aluminium will help preserve it due to corrosion [3]. There are four pad eyes on top and bottom of the structure, that can be used for lifting the base. Current experience favours a four-point lifting arrangement solution, that will be the base case for this thesis with respect to calculations.

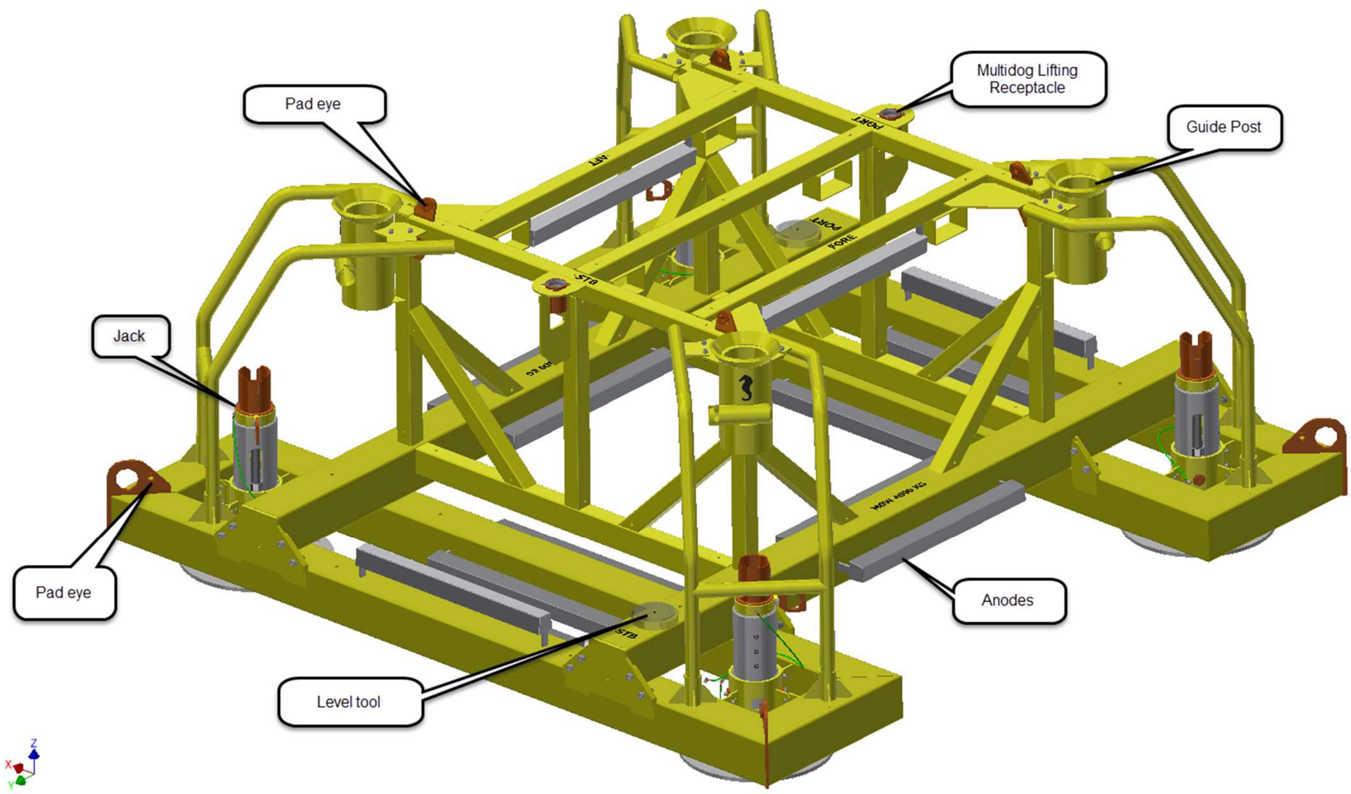


Figure 2-5 Shows the different extra equipment on the SDB.

As illustrated in figure 2.4 the highlighted equipment will not be projected in the concepts. The weight of the equipment will be added to the calculations by using a mass factor that will be developed.

Figure 2.5 below is an overview of the SDB. The base is symmetrical so that the mirrored beams will experience the same stress magnitude. The original Blue Logic design has a total of nine individual beams labelled in figure 2.5, and its data is displayed in table 2.1.

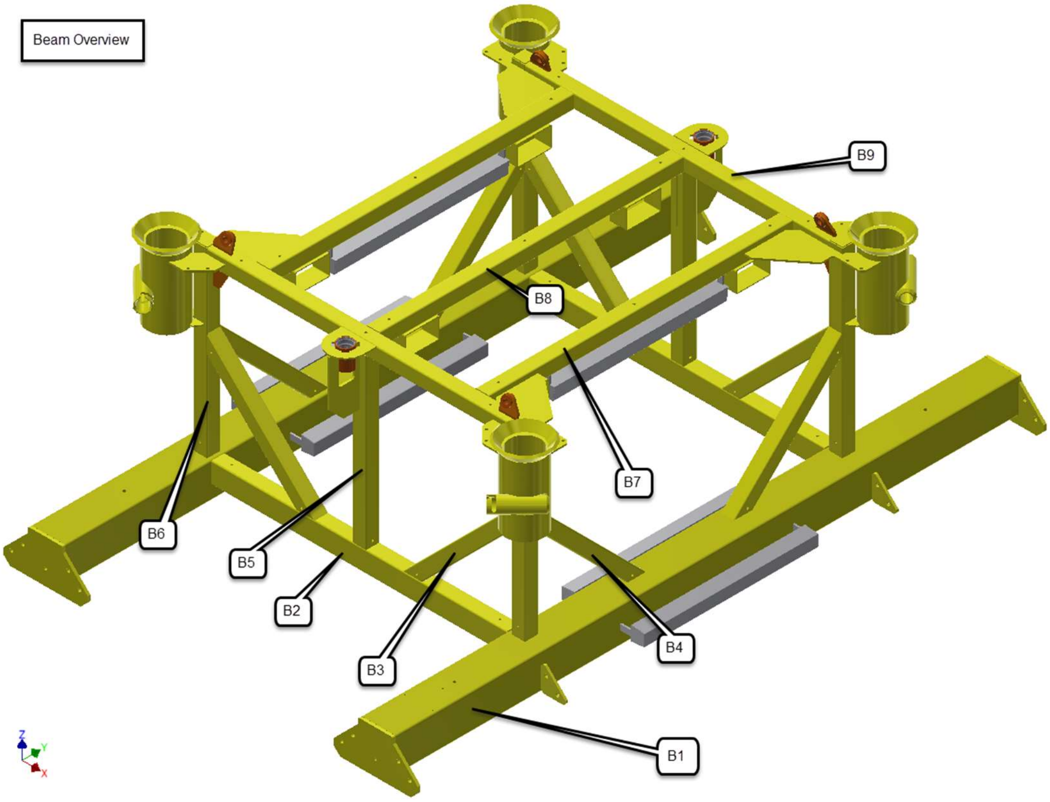


Figure 2-6 The structure is symmetrical; the numberers represent the symmetrical beams.

Table 2-1 The different beams on the SDM

Number of beams	Profile (mm)	Weight kg/m	Second moment of area (I) x10^6mm^4
B1	250x250x8	60	74.0
B2	150x100x8	29.1	5.77
B3	100x100x8	22.9	4.08
B4	100x100x8	22.9	4.08
B5	100x100x8	22.9	4.08
B6	100x100x8	22.9	4.08
B7	100x100x8	22.9	4.08
B8	100x100x8	22.9	4.08
B9	100x100x8	22.9	4.08

Figure 2.5 is the main body of the original Blue Logic design is bolted on top of two “pontoons” illustrated in figure 2.6. The pontoons are the “feet” of the structure and the size of the RHS is equal to 250x250x8mm. One individual pontoon is welded together and bolted to the top section. This is the only place where bolts are used on the original design.

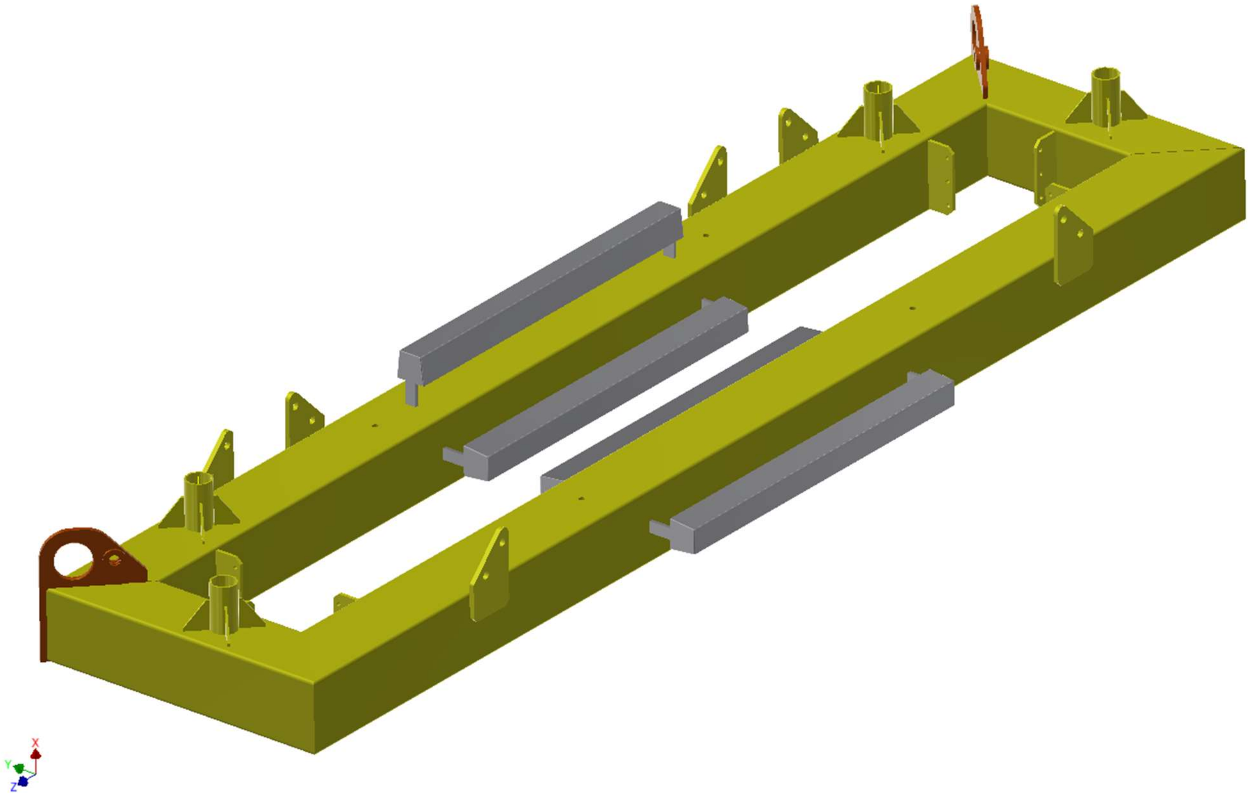


Figure 2-7 Pontoon, that the main body of the structure is placed on

.

2.2.1. Joint overview and criticality

Figure 2.9 displays all joints with a uniqe number. The SDB is symmetric and all loads are assumed to be symmetric, hence the load in any given joint will be mirrored. The joints are listed in Table 2.2 and discussed with respect to joint criticality.

Each joint has an associated criticality, this criticality can be assesed by assigning a Design Class according to NOROSK N-004, Table 1. The criticality is base on how complicated and stressed the joint is.

The joint complexity is base on the original design report with respect to the stress pattern.

Table 1 — Classification of structural joints and components

Design Class 1)	Joint complexity 2)	Consequences of failure
DC1	High	Applicable for joints and members where failure will have substantial consequences 3) and the structure possesses limited residual strength. 4).
DC2	Low	
DC3	High	Applicable for joints and members where failure will be without substantial consequences 3) due to residual strength. 4).
DC4	Low	
DC5	Any	Applicable for joints and members where failure will be without substantial consequences. 3)

1) Guidance for classification can be found in Annex B, Annex C, Annex D and Annex E.

2) High joint complexity means joints where the geometry of connected elements and weld type leads to high restraint and to triaxial stress pattern, e.g., typically multiplanar plated connections with full penetration welds.

3) "Substantial consequences" in this context means that failure of the joint or member will entail;
— danger of loss of human life;
— significant pollution;
— major financial consequences.

4) Residual strength means that the structure meets requirements corresponding to the damaged condition in the check for accidental damage limit states, with failure in the actual joint or component as the defined damage.

Figure 2-8 Table 1 from NOROSK N-004[4]

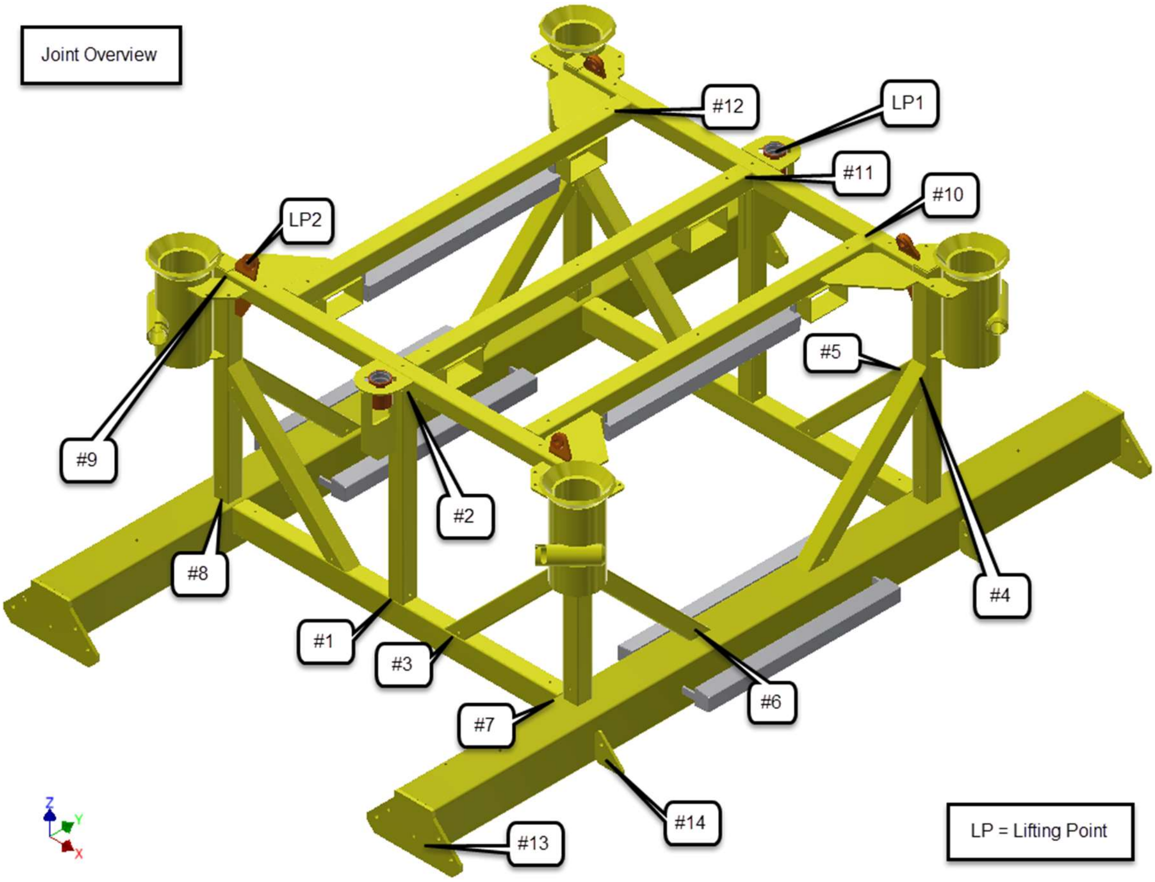
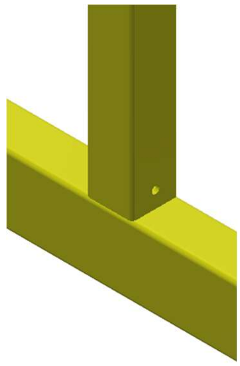
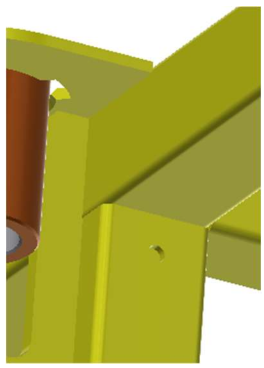
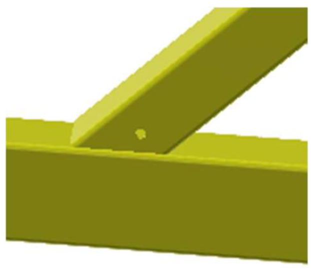
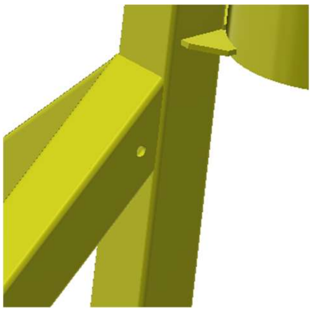
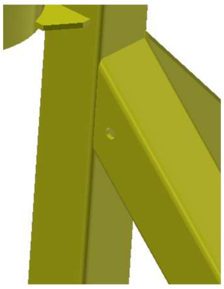
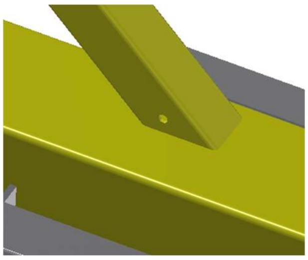
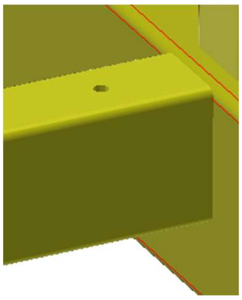
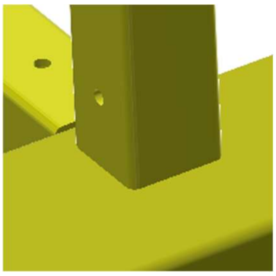
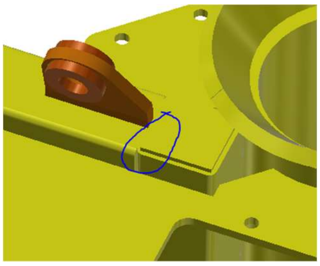
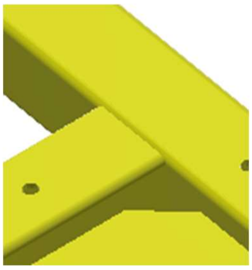
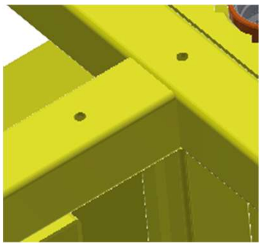


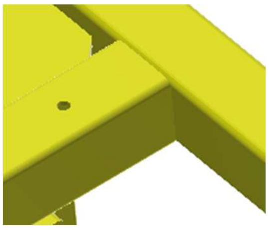
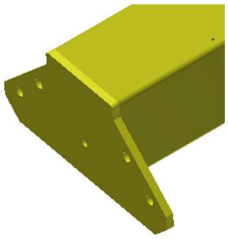
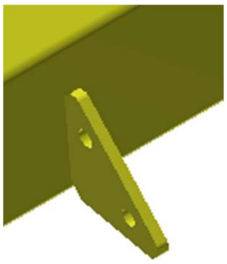
Figure 2-9 Illustration and numerating of the different beams and lifting points.

Table 2-2 Joints of the original SDM model

Joint number	Description	Criticality	Picture
1	Welded joint Criticality defined assuming a worst-case lift using a two-point lift. Stress will be uniaxial hence low joint complexity. No out of plane bending assuming lift using spreader beam.	DC2	
2	Welded joint Criticality defined assuming a worst-case lift using a two-point lift. Stress will be uniaxial hence low joint complexity. No out of plane bending assuming lift using spreader beam.	DC2	
3	Welded joint Criticality defined assuming a worst-case lift using a four-point lifting arrangement. Out of plane bending is present Triaxial stress is present hence high joint complexity.	DC1	

4	Welded joint Criticality defined assuming a worst-case lift using a four-point lifting arrangement. Out of plane bending is present Triaxial stress is present hence high joint complexity.	DC1	
5	Welded joint Criticality defined assuming a worst-case lift using a four-point lifting arrangement. Out of plane bending is present Triaxial stress is present hence high joint complexity.	DC1	
6	Welded joint Criticality defined assuming a worst-case lift using a four-point lifting arrangement. Out of plane bending is present Triaxial stress is present hence high joint complexity.	DC1	
7	Welded joint Criticality defined assuming a worst-case two point lifting with spreader beam. In-plane bending is present Stress will be uniaxial hence low joint complexity	DC2	

8	Welded joint Criticality defined assuming a worst-case lift using a four-point lifting arrangement. Out of plane bending is present Triaxial stress is present hence high joint complexity.	DC1	
9	Welded joint Criticality defined assuming a worst-case lift using a four-point lifting arrangement. Out of plane bending is present Triaxial stress is present hence high joint complexity.	DC1	
10	Welded joint Criticality defined assuming a worst-case lift using a four-point lifting arrangement. Out of plane bending is present Low triaxial stress is present hence low joint complexity.	DC2	
11	Welded joint Criticality defined assuming a worst-case lift using a four-point lifting arrangement. Out of plane bending is present No triaxial stress is present hence low joint complexity.	DC2	

12	Welded joint Criticality defined assuming a worst-case lift using a four-point lifting arrangement. Out of plane bending is present Low triaxial stress is present hence low joint complexity.	DC2	
13	Welded plate Criticality defined assuming a worst-case lift using a four-point lift. Stress will be uniaxial hence low joint complexity. No out of plane bending assuming lift using spreader beam.	DC2	
14	Welded plate Criticality defined assuming a worst-case lift using a four-point lift. Stress will be uniaxial hence low joint complexity. No out of plane bending assuming lift using spreader beam.	DC2	

2.2.2. Governing standards

The safety factors for offshore structures are provided by NORSOK, NORSOK is the Norwegian standards for the Norwegian Continental Shelf. The safety factors in table 2.3 below are used in calculations. The SDB will be verified according to NS-EN-1993-1-1 or NS-EN-1993-1-8.

Table 2-3 Safety factors from NORSOK N-004

Type of calculation	Material factor (1)	Value
Resistance of class 1,2 or 3 cross sections	γ_{m0}	1.15
Resistance of class 4 cross sections	γ_{m1}	1.15
Resistance of member to buckling	γ_{m1}	1.15
Resistance of net section at bolt holes	γ_{m2}	1.3
Resistance of fillet and partial penetration welds	γ_{m2}	1.3
Resistance of bolted connections	γ_{m2}	1.3
1) symbols according to NS-EN-1993-1-1 and NS-EN-1993-1-8. 2) All profiles considered will be classification 1.		

Table 2.3 Safety factors from NORSOK N-004 [4].

Material grade for SDB. Assuming S355 Like the original Blue Logic design. The properties are displayed in table 2.4[5]

Table 2-4 Table for steel tensile strength and correlation factor found in Eurocode. EN1993-1-1

Steel type	Yield strength	Ultimate strength f_u	Correlation factor β_w
S 355	355	510	0.9

3. DESIGN CRATIERIA FOR MEMBERS AND JOINTS

In this chapter all the required equations and data for doing the calculation will be discussed. It is found in Eurocode 3 EN-1993-1-1.

3.1. SHEAR

Shear is deformation of a material by slippage along a plane to the stress [9]. The shear is calculated by the following formula from Eurocode 3 EN-1993-1-1, chapter 6.2.6.

Initial check using elastic resistance, should this prove insufficient design using plastic resistance can be explored.

The design value of the shear V_{Ed} at each profile shall satisfy: $\frac{V_{Ed}}{V_{c,Rd}} \leq 1.0$ [5]

Where $V_{c,Rd}$ is design shear resistance [5].

For plastic design $V_{c,Rd}$ is the design plastic shear resistance $V_{pl,Rd}$ as:

$$V_{pl.Rd} = \frac{A_v\left(f_y/\sqrt{3}\right)}{\gamma_{M0}}$$ [5]

A_y is the shear area. The shear area A_y can be as followed:

Table 3-1 Cross section and areas respectably *[5]*

Cross section type	**A_y**
Rolled I and H section, load parallel to web	$A - 2bt_f + (t_w + 2r)t_f$, but not less than $\eta h_w t_w$
Rolled channel sections, load parallel to web	$A - 2bt_f + (t_w + 2r)t_f$
Welded I, H and box sections, loaded parallel to web	$\eta\sum(h_w t_w)$
Welded I, H channel and box sections, load parallel to flanges	$A-\sum(h_w t_w)$

Table 3-2 Symbol for equation [5]

Symbol		**Description**
A	=	Cross sectional area
b	=	Overall breadth
h	=	Overall depth
h_w	=	Depth of the web
r	=	Radius
t_f	=	Flange thickness
t_w	=	Minimum thickness of web
η	=	Value from EN 1993-1-4, can be taken to equal to 1

For elastic design, $V_{c,Rd}$, is calculated using formula for a critical point of the cross section [5]:

$\frac{\tau_{Ed}}{f_y/(\sqrt{3}\,\gamma_{M0})} \leq 1.0$ Where: $\tau_{Ed} = \frac{V_{Ed}\,S}{It}$

Table 3-3 Symbols for τ_{Ed} [5]

Symbol		Description
V_{Ed}	=	Design value of shear force
S	=	First moment of area about the centroidal axis at the point of the cross-section between the point where shear is required and boundary of Cross-section
I	=	Second moment of area of the cross section
t	=	Thickness of examined point

In chapter 6.2 the equation $V_{pl.Rd} = \frac{A_v \left(f_y / \sqrt{3} \right)}{\gamma_{M0}}$ is used to check the shear for each beam and is inserted in the table 6.1. The check $\frac{V_{Ed}}{V_{c,Rd}} \leq 1.0$ is also done in chapter 6.2 [5].

3.2. TENSION

Tension is the act of stretching/straining a member. Eurocode 3 EN-1993-1-1 chapter 6.2.3 gives the tension resistance by the following criteria.

The design value of the tension force N_{Ed} shall satisfy: $\frac{N_{Ed}}{N_{t,Rd}} \leq 1.0$ [5].

For sections with holes the design tension resistance $N_{t,Rd}$ is the smallest of

(1) $N_{pl,Rd} = \frac{Af_y}{\gamma_{M0}}$ or (2) $N_{u,Rd} = \frac{0.9 A_{net} f_u}{\gamma_{M2}}$ [5]

In slip-resistance at ultimate connections, the design tension resistance $N_{pl.Rd}$ of the net section at holes for fasteners should be taken as $N_{net,Rd}$: $N_{net,Rd} = \frac{A_{net} f_y}{\gamma_{M0}}$ where A_{net} is area - hole diameter [5].

Table 3-4 Symbols for $N_{pl,Rd}$ [5]

Symbol		Description
A or A_{net}	=	Area of cross section
F_y	=	Yield strength of material
γ	=	Safety factor (see table 2.3)

3.3. COMPRESSION

Compression is the opposite of tension. Eurocode 3 EN 1993-1-1 chapter 6.2.4 gives the following criteria.

The design value of the compression force N_{Ed} at each profile shall satisfy: $\frac{N_{Ed}}{N_{c,Rd}} \leq 1.0$
The design resistance is determined between class 1-3 or class 4
Class 1-3: $N_{c,Rd} = \frac{Af_y}{\gamma_{M0}}$ or class 4: $N_{c,Rd} = \frac{A_{eff}f_y}{\gamma_{M0}}$ [5]

Table 3.4 for symbol description.

$N_{c,Rd}$ is used in chapter 6.2 to check $\frac{N_{Ed}}{N_{c,Rd}} \leq 1.0$ for different beams [5].

3.4. MOMENT

Moment is rotation of a member around a single point and is calculated by the formulas from Eurocode 3 EN-1993-1-1 chapter 6.2.5.

The design value of the bending moment M_{Ed} at each profile shall satisfy [5]:

$$\frac{M_{Ed}}{M_{c,Rd}} \leq 1.0$$

The design resistance for bending is determined:

Table 3-5 Design resistance of moment by class of cross section [5]

Class	Equation
1 & 2	$M_{c,Rd} = M_{pl.Rd} = \frac{W_{pl}f_y}{\gamma_{M0}}$
3	$M_{c,Rd} = M_{pl.Rd} = \frac{W_{el,min}f_y}{\gamma_{M0}}$
4	$M_{c,Rd} = \frac{W_{eff,min}f_y}{\gamma_{M0}}$

Fastener holes in the tension flange may be ignored provided that for the tension flange:
$\frac{A_{f,net}0.9f_u}{\gamma_{M2}} \geq \frac{A_f f_y}{\gamma_{M0}}$ [5]

3.5. TORSION

Torsion is twisting of a member about the axial direction. The Eurocode 3 EN-1993-1-1 chapter 6.2.7 gives following way to calculate.

For member subject to torsion for which distortional deformations may be disregarded the design value of the torsional moment T_{Ed} at each cross-section should satisfy: $\frac{T_{Ed}}{T_{Rd}} \leq 1.0$ [5]

The total torsional moment at any cross-section should be considered as the sum of: $T_{Ed} = T_{t,Ed} + T_{w,Ed}$

- The shear stress $\tau_{t,Ed}$ due to St. Venant $T_{t,Ed}$
- The direct stresses, $\sigma_{w,Ed}$, due to bi moment B_{Ed} and shear stresses $T_{w,Ed}$ due to warping torsion [5].

For combined shear force and torsional moment the plastic shear resistance accounting for torsional effects should be reduced from $V_{pl,Rd}$ to $V_{pl,T,Rd}$ and the design shear force should satisfy: $\frac{V_{Ed}}{V_{pl,T,Rd}} \leq 1.0$ In which $V_{pl,T,Rd}$ may be derived as follows:
Where $V_{pl,Rd}$ is given in 2.1 [5].

Table 3-6 Design resistance for torsion for different Cross-sections [5].

For an I or H section	$V_{pl,T,Rd} = \sqrt{1 - \frac{\tau_{Ed}}{1.25(f_y/\sqrt{3})/\gamma_{M0}}}\, V_{pl,Rd}$
For a channel section	$V_{pl,T,Rd} = \left[\sqrt{1 - \frac{\tau_{t,Ed}}{1.25(f_y/\sqrt{3})/\gamma_{M0}}} - \frac{\tau_{w,Ed}}{(f_y/\sqrt{3})/\gamma_{M0}}\right] V_{pl,Rd}$
For a structural hollow section	$V_{pl,T,Rd} = \left[1 - \frac{\tau_{t,Ed}}{1.25(f_y/\sqrt{3})/\gamma_{M0}}\right] V_{pl,Rd}$

3.6. FAILURE MODES FOR BOLTS

There are 3 different failures from bolts.

1) Tension failure
2) Shear failure
3) And a combination of shear and tension

Design for tension failure: $F_{t,Ed} \leq F_{r,Rd} = 0.9\, f_{ub}A_s/\gamma_{M2}$ where [6]:

Table 3-7 Symbol description for tension resistance [6]

Symbol		Description
$F_{t,Ed}$	=	Design tensile stress
$F_{r,Rd}$	=	Design tensile resistance
f_{ub}	=	Ultimate tensile strength of bolt
A_s	=	Tensile stress area of the bolt
γ_{M2}	=	Safety factor

Design for shear stress: $F_{v,Ed} \leq F_{v,Rd} \frac{a_v f_{ub} A}{\gamma_{M2}}$ [6]

Table 3-8 Symbol description for shear resistance [6]

Symbol		Description
$F_{v,Ed}$	=	Design shear force
$F_{v,Rd}$	=	Design shear resistance
f_{ub}	=	Ultimate tensile strength of bolt from table 2.4
a_v	=	0.6 for class 4.6, 5.6 and 8.8 0.5 for class 4.8, 5.8, 6.8 and 10.9
A	=	Gross Area where shear plane passes through untreaded portion
γ_{M2}	=	Safety factor from table 2.3

Bolts have more than one shearing plane so $F_{v,Ed} \leq F_{v,Rd} = \frac{f_{ub}}{\gamma_{M2}} \sum_n a_{vn} A_n$ where n = Number of shear planes.

Design for combination of shear and tension $\frac{F_{v,Ed}}{F_{v,Rd}} + \frac{F_{r,Ed}}{1.4F_{r,Rd}} \leq 1$ [6]

3.7. BOLTED BRACKET

A bolted joint will in some circumstances require a bracket(s) to transfer loads. The bracket must be designed to withstand bolt tear out.

Bearing $F_{b,Ed} \leq F_{b,Rd} = \frac{k_i a_b f_u d t}{\gamma_{M2}}$ [6]

Table 3-9 Symbol description for bearing resistance [6]

Symbol		Description
$\mathbf{F_{b,Ed}}$	=	Design bearing force action on bracket
$\mathbf{F_{b,Rd}}$	=	Design bearing resistance of bracket
$\mathbf{f_u}$	=	Ultimate tensile strength from table 2.4
d	=	Nominal bolt diameter
t	=	thickness of plate.
$\boldsymbol{\gamma_{m2}}$	=	safety factor from table 2.3
$\mathbf{K_1 \alpha_b}$	=	Coefficients describe bolt end details and spacing limits

Where α_d: $\frac{f_{ub}}{f_u}$ or 1.0.
In the direction of load transfer:

- For end bolts: $\alpha_b = e_i/3d_0$. For inner bolts: $\alpha_b = p_1/3d_0 - 0.25$

Perpendicular to the direction of load transfer:

- For edge bolts k_1 is the smallest of $2.8\frac{\theta_2}{d_0} - 1.7$, $1.4\frac{p_2}{d_0}$-1.7 or 2.5
- For inner bolts $\mathbf{k_1}$ is the smallest of $1.4\frac{p_2}{d_0}$—1.7 or 2.5

For shear and tension failure, it is required to check for yielding and fracture.
For yielding of the plate $\sigma_y^2 + \sigma_z^2 - \sigma_y\sigma_z + 3\tau^2_{yz} \leq f_y^2$ where [6]:

Table 3-10 Symbol description for tension and shear failure [6].

Symbol		Description
$\boldsymbol{\sigma_y \sigma_z}$	=	Design normal stress
$\boldsymbol{\tau_{yz}^2}$	=	Design shear stress
$\mathbf{f_y}$	=	yield strength of plate
For fracture near the holes $\sigma_y^2 + \sigma_z^2 - \sigma_y\sigma_z + 3\tau^2_{yz} \leq f_u^2$		
$\mathbf{f_u}$	=	Ultimate strength of material

Table 3.11 is an overview over minimum distance for holes in a bracket

Table 3-11 Table for minimum distance for holes in a bracket [6].

Distances and spacings, see Figure 3.1	Minimum	Maximum[1) 2) 3)]		
		Structures made from steels conforming to EN 10025 except steels conforming to EN 10025-5		Structures made from steels conforming to EN 10025-5
		Steel exposed to the weather or other corrosive influences	Steel not exposed to the weather or other corrosive influences	Steel used unprotected
End distance e_1	$1{,}2d_0$	$4t + 40$ mm		The larger of $8t$ or 125 mm
Edge distance e_2	$1{,}2d_0$	$4t + 40$ mm		The larger of $8t$ or 125 mm
Distance e_3 in slotted holes	$1{,}5d_0$ [4)]			
Distance e_4 in slotted holes	$1{,}5d_0$ [4)]			
Spacing p_1	$2{,}2d_0$	The smaller of $14t$ or 200 mm	The smaller of $14t$ or 200 mm	The smaller of $14t_{min}$ or 175 mm
Spacing $p_{1,0}$		The smaller of $14t$ or 200 mm		
Spacing $p_{1,i}$		The smaller of $28t$ or 400 mm		
Spacing p_2 [5)]	$2{,}4d_0$	The smaller of $14t$ or 200 mm	The smaller of $14t$ or 200 mm	The smaller of $14t_{min}$ or 175 mm

3.8. WELDS

When designing a weld there are two methods that can be used, according to Eurocode 3 EN 1993-1-8: The Directional Method and The Simplified Method

The directional method is used if you have a specific direction of the force and is the most accurate method.

In the Simplified Method the resultant force of the weld is compared to the design resistance for the weld.

The Simplified Method:
$F_{w,Ed} \leq F_{w,Rd}$ where $F_{w,Ed}$ is the value of the weld force pr. unit length and $F_{w,Rd}$ is the weld resistance [6].

Weld resistance is independent from orientation of the weld throat. $F_{w,Rd}$ is is the design resistance per unit length and is given by:
$F_{w,Rd} = f_{vw,d}\, a$ [6]
Were a is throat thickness for weld and $f_{vw,d}$ is the design shear strength of the weld and is determined from [6]:
$f_{vw,d} \frac{f_u/\sqrt{3}}{\beta_w \gamma_{M2}}$, where β_w is the correlation factor and f_u is found in table 2.4, and γ_{M2} is the safety factor found in table 2.3 [6]
).

3.9. ASSMENT OF DESING CRITERIA

Not all the forces are equally relevant in the SDB. Some forces are so small that they can be neglected while other are the more dominant once. This will be reviewed in this chapter, but first there are some assumptions made.

- Force is mass distributed force according to DNV-ST-E273
- Four-point lifting

There are not that many loading problems for the SDB when it is sitting on the ocean floor, therefore the critical moments, and where it has most force applied to it is when lifting it through the wave zone. When lifting through the waves we assume that there is an even force applied to the SDB.

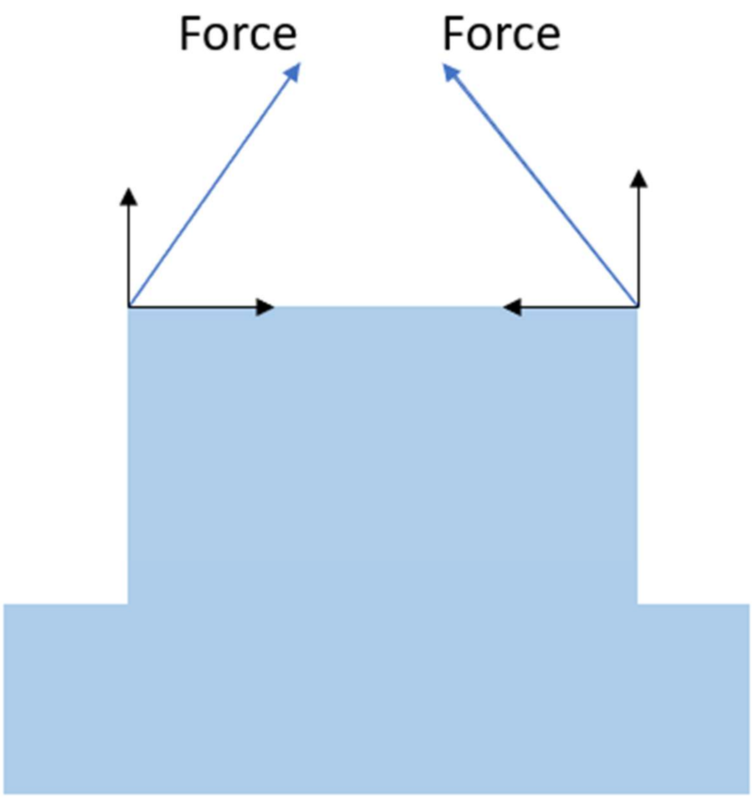


Figure 3-1 Sketch of the figure and its force applied to it.

Figure 3.1 display a sketch of the SDB, and it is visible here that there is compression and tension from how the SDB is lifted. When lifted the SDB is hanging and therefore is subjected to gravity. Table 3.12 displays the different stresses of the SDB.

Table 3-12 Table over different stresses of the SDB.

Failure type	Influence on SDB
Tension	The SDB is subjected to gravity when lifted, which means the vertical beams will have tension subjected to them.
Compression	The projection of the force shown in figure 3.1 shows to forces working against each other, which means there are compression in the horizontal beams.
Shear	Shear force is present in every SDB. Shear works in the perpendicular axis that force is applied to.
Moment	The SDB is subjected to gravity and when lifting it will have a bending moment.
Torsion	There are no forces that will twist the SDB to a big extent. This can be in this case neglected in the checks since it is so small.

The free body diagram of the SDB is displayed in figure 3.2. In the figure 3.2 there is compression in the vertical beams as shown in the figure 3.1

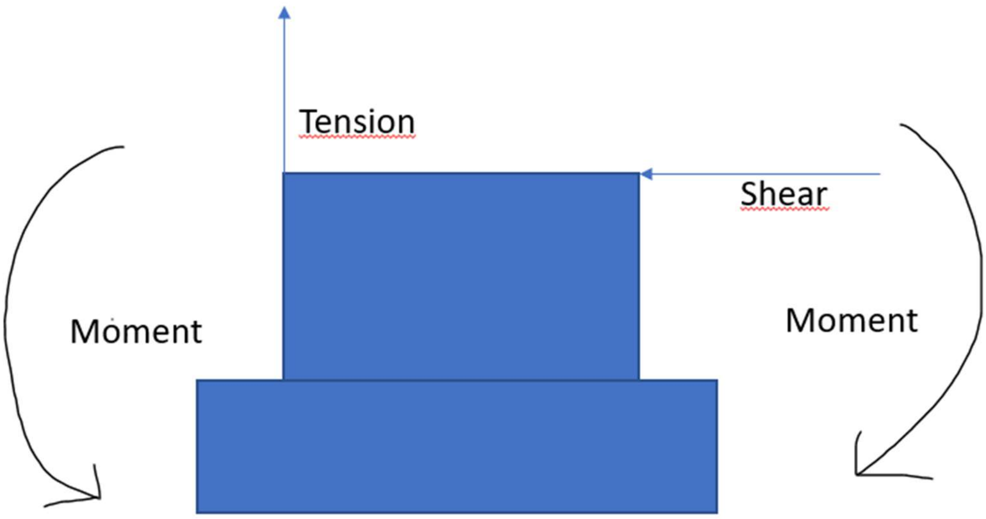


Figure 3-2 Free body diagram

4. EXTERNAL LOADS

The SDS will be installed on the seabed. The manner of installation will be determined by the location and contractors involved. Typically, one will have the option of simply lifting the object over the side of the vessel or through a moonpool, ref blue logic.

The hydrodynamic loads associated with these types of lifts are defined in DNV-RP-N103, Calculation of a moon pool installation is beyond the scope of this thesis as it involves specific vessel data. The simplified approach as defined in DNV-RP-N103 involves the calculation of the following hydrodynamic loads:

- Slamming force
  - $F_{slam} = 0.5 \cdot \rho \cdot C_s \cdot A_s \cdot v_s^2$
- Buoyancy force
  - $F_\rho = \rho \cdot \delta V \cdot g$
- Drag force
  - $F_D = 0.5 \cdot \rho \cdot C_D \cdot A_{Pi} \cdot V_r^2$
- Mass force
  - $F_M = \sqrt{\left((M + A_{33})a_{ct}\right)^2 + \left((\rho \cdot V + A_{33})\right)^2}$

These forces will all contribute to the total hydrodynamic force:

- $F_{hyd} = \sqrt{(F_D + F_{slam})^2 + \left(F_M - F_\rho\right)^2}$

The buoyancy force is assumed to be negligible for the SDS, because of the low displaced volume and relatively small size of the SDS.

The hydrodynamic load F_{hy} is characteristic and will be used to calculate the resultant sling loads, as discussed in Section **Feil! Fant ikke referansekilden.**[19]

See appendix I for calculation and explanation of terms.

4.1. SLING LOADS

The sing load is based on the characteristic hydrodynamic load and will be mass distributed in a Finite Element program to acquire the internal stress in the profiles and joints.

Resultant Sling Force as defined by DNV-ST-E273: $RSF = \frac{1.2 \cdot SKL \cdot PL \cdot F}{\cos(v)}$ [7]

Table 4-1 Description for equation for sling loads [7]

Symbol		Description
SKL	=	Skew Load Factor due to sling length tolerances. SKL shall be taken as minimum 1.33 (assuming sling sets made of matched slings) for a 4-leg lifting set.
PL	=	Percentage loading of F (quasi-static calculations) in the most loaded pad eye, taking into consideration most extreme location of CoG.
F	=	Hydrodynamic Loads
V	=	Angle of sling from vertical

The sling is assumed to be 4 meters from the lifting point, and is used in the calculations in Appendix I

4.2. GEOMETRIC CONSTRAINTS

Constraint that needs to be fulfilled in the SDB are as follows:

- The SDM guideposts forms a standard square whose dimensions are defined in API 17D (*S.Næss Blue Logic, personal communication. 05.05.2022)*.
- The four levelling jacks also forms a defined square limit the overall size of the structure, see figure 4.1.

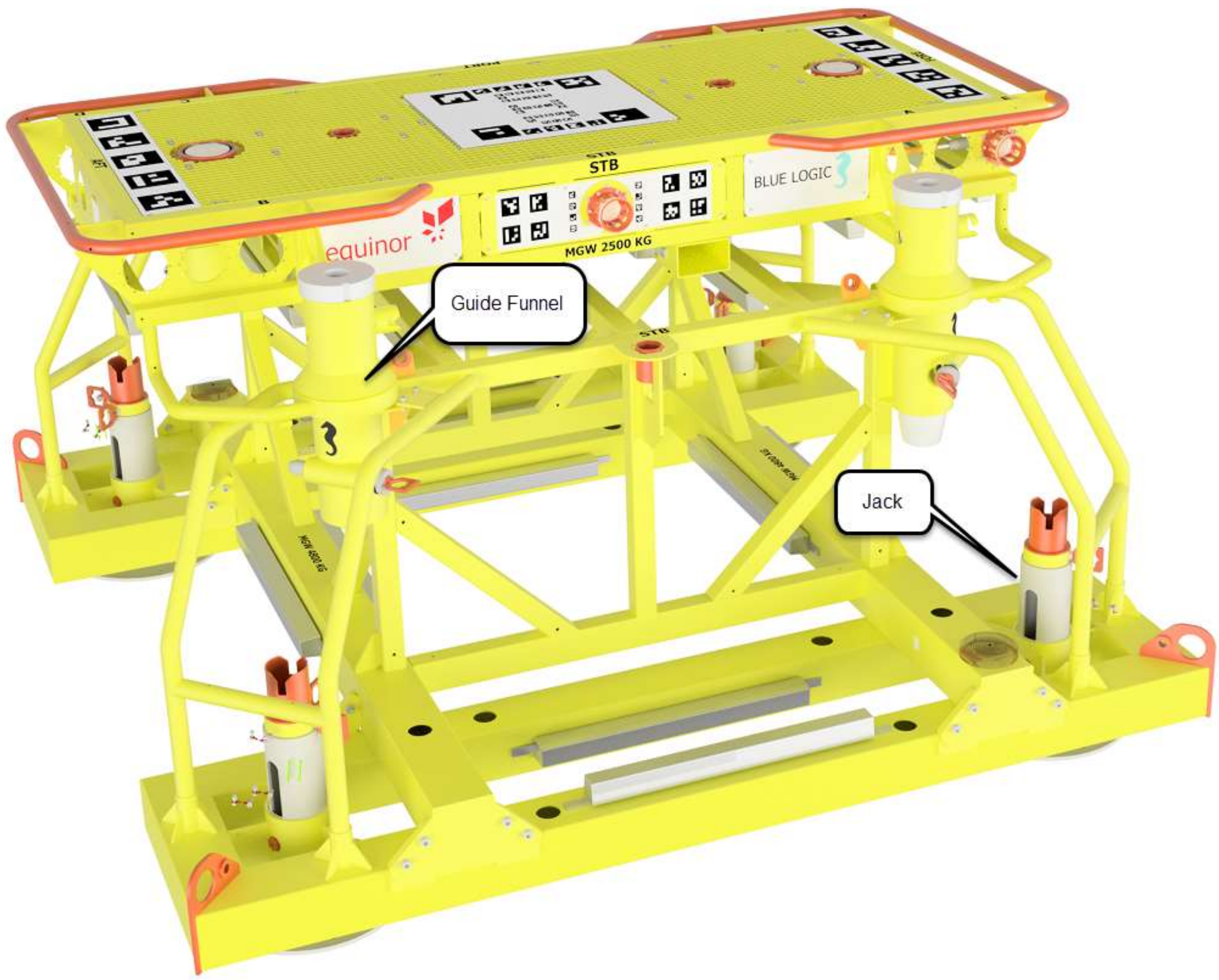


Figure 4-1 SDB and SDM together, the jacks on the bottom and the guidepost on top.

5. CONCEPT SELECTION FOR SDS DESIGN

5.1. CONCEPT 1

5.1.1. Beams

The first concept consists of HE-B profiles. HE-B profiles can be used in most structures. The conservation of steel is higher than RHS profiles, and since its widely used there are a lot of defined data already on the HE-B profiles. The HE-B can support all forces and is compatible to all kind of connectors [11]. This makes HE-B a good candidate to replace the RHS from the original Blue Logic design.

HE-B can be coated on the entire surface which will mitigate corrosion to a larger extent than RHS. RHS cannot practically be coated internally with NORSOK SYSTEM7 *(S.Næss Blue Logic, personal communication. 05.05.2022)*. The figure 5.1 shows a picture of the structure with HE-B profiles in different sizes.

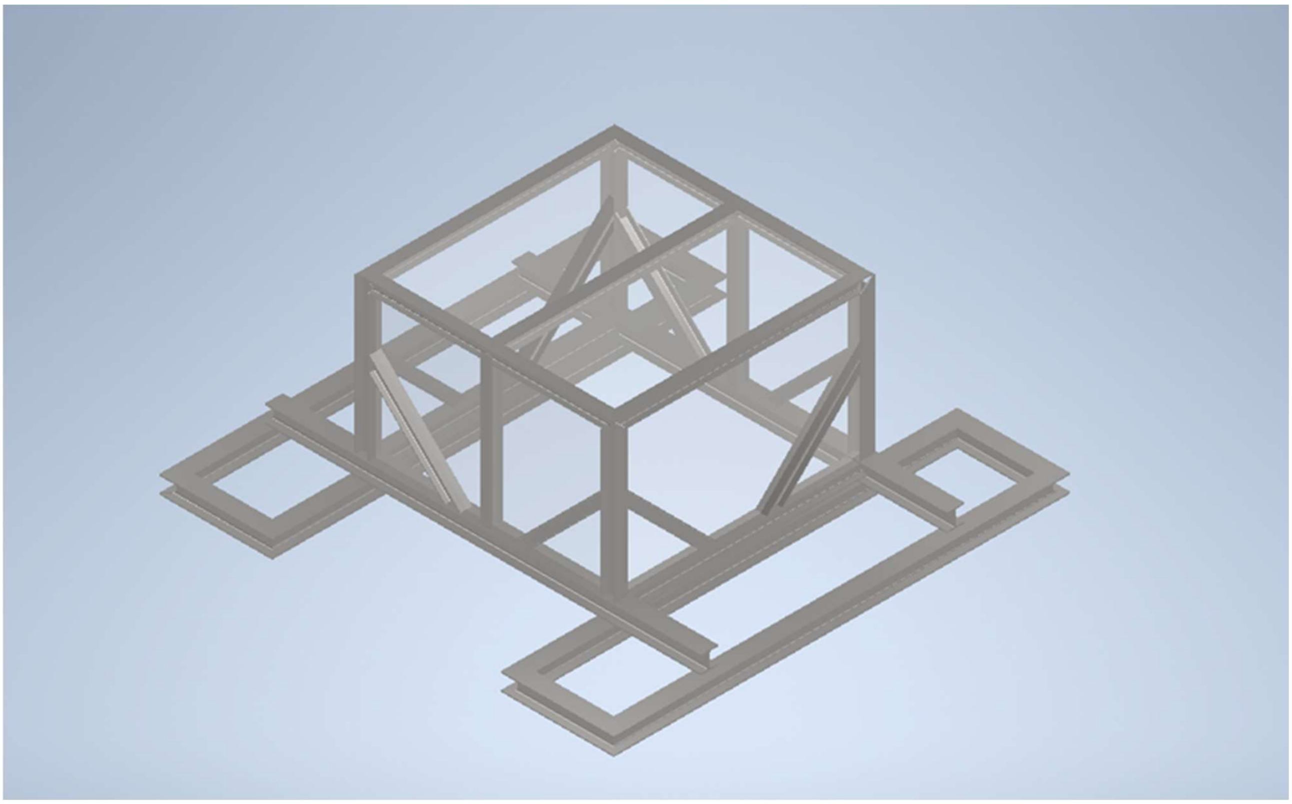


Figure 5-1 Figure of the base with HE-B profiles made in Autodesk Inventor.

The selection of beams was based on comparison of the original Blue Logic design by comparing the second moment of inertia of the RHS beams to HEB beams. The different beams are put into table 5.1 which compare the original to the new concept. The pontoons are not included in the table and is put here to be same size as B1.

Table 5-1 Table of beams on original and new design of the SDB

Number	Original dimension (mm)	Original I ($x10^6mm^4$)	Original weight (Kg/m)	New dimension (mm)	New I ($x10^6mm^4$)	New weight (Kg/m)
B1	250x250x8	74.0	60	HE-B 300	85.6	83.2
B2	150x100x8	5.77	29.1	HE-B 140	5.50	33.7
B3	100x100x8	4.08	22.9	HE-B 120	3.18	26.7
B4	100x100x8	4.08	22.9	HE-B 120	3.18	26.7
B5	100x100x8	4.08	22.9	HE-B 120	3.18	26.7
B6	100x100x8	4.08	22.9	HE-B 120	3.18	26.7
B7	100x100x8	4.08	22.9	HE-B 120	3.18	26.7
B8	100x100x8	4.08	22.9	HE-B 120	3.18	26.7
B9	100x100x8	4.08	22.9	HE-B 120	3.18	26.7

In this concept C-beams can also be a replacement for the RHS. The C-beams can also be coated to a bigger extend than RHS, because of its open profile. C-profiles are also compatible with all connectors and is a very conservative steel profile [11]. Figure 5.2 display an alternate structure with more C-sections

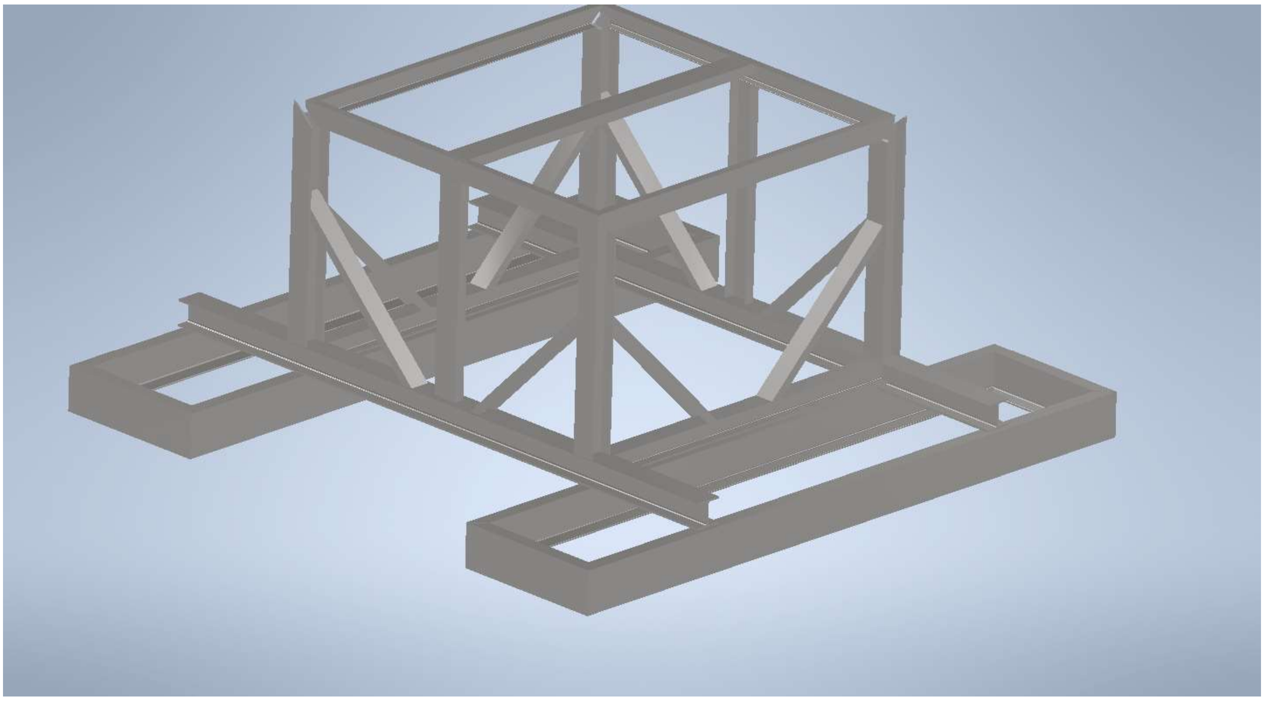


Figure 5-2 SDB with C and HE-B sections.

. The second moment of inertia is much lower in the C-beams, see table 5.2, and the weight pr meter is significantly lower than RHS and HE-B, which makes it more difficult to launch the structure through the waves.

Table 5-2 Table over beams on original and new design of SDB

Number	Original dimension (mm)	Original I ($x10^6mm^4$)	Original weight (Kg/m)	New dimension (mm)	New I ($x10^6mm^4$) y-y	New I ($x10^6mm^4$) z-z	New weight (Kg/m)
B1	250x250x8	74.0	60	HE 300x11	251.7	85.6	117
B2	150x100x8	5.77	29.1	HE 140x7	15.1	5.50	33.7
B3	100x100x8	4.08	22.9	C 280x95	62.8	3.99	41.8
B4	100x100x8	4.08	22.9	C 280x95	62.8	3.99	41.8
B5	100x100x8	4.08	22.9	C 280x95	62.8	3.99	41.8
B6	100x100x8	4.08	22.9	HE120x6.5	8.64	3.18	26.7
B7	100x100x8	4.08	22.9	C 280x95	62.8	3.99	41.8
B8	100x100x8	4.08	22.9	C 280x95	62.8	3.99	41.8
B9	100x100x8	4.08	22.9	C 280x95	62.8	3.99	41.8

5.1.2. Joints

In the first Concept bolted joints were considered instead of welds. Bolts will save a lot of time since the welding process is several steps, while a bolt is roughly drilling a hole in the correct place. The costs of bolts are also smaller than welding *(Tobias, 2019).* Under is a proposed joint involving a bracket. The size and number of bolts are for illustration only.

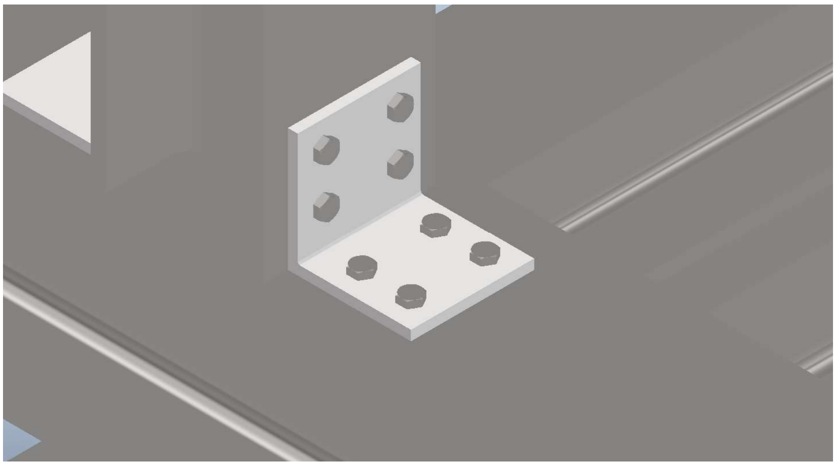


Figure 5-3 The bolted connection can be done made in Autodesk Inventor

The structure is symmetrical so we can only look at one quarter of the structure. Under in figure 5.4, there is an overview of one quarter, every place with a bracket will be bolted., which needs to be design correctly if the concept will be developed. The brackets are bolted as seen in figure 5.3 on both sides of the profile, where it is possible, to maximize the strength of the joint. When bolting on the top of the profile it is important to bolt on both side if the web to ensure more equal loading. There is also a possibility to just bolt directly in the flange or web. There are also brackets that are welded to one side and bolted to the other. In the case of concept one only regular angles will be used, part from the bolted joints from the original Blue Logic design.

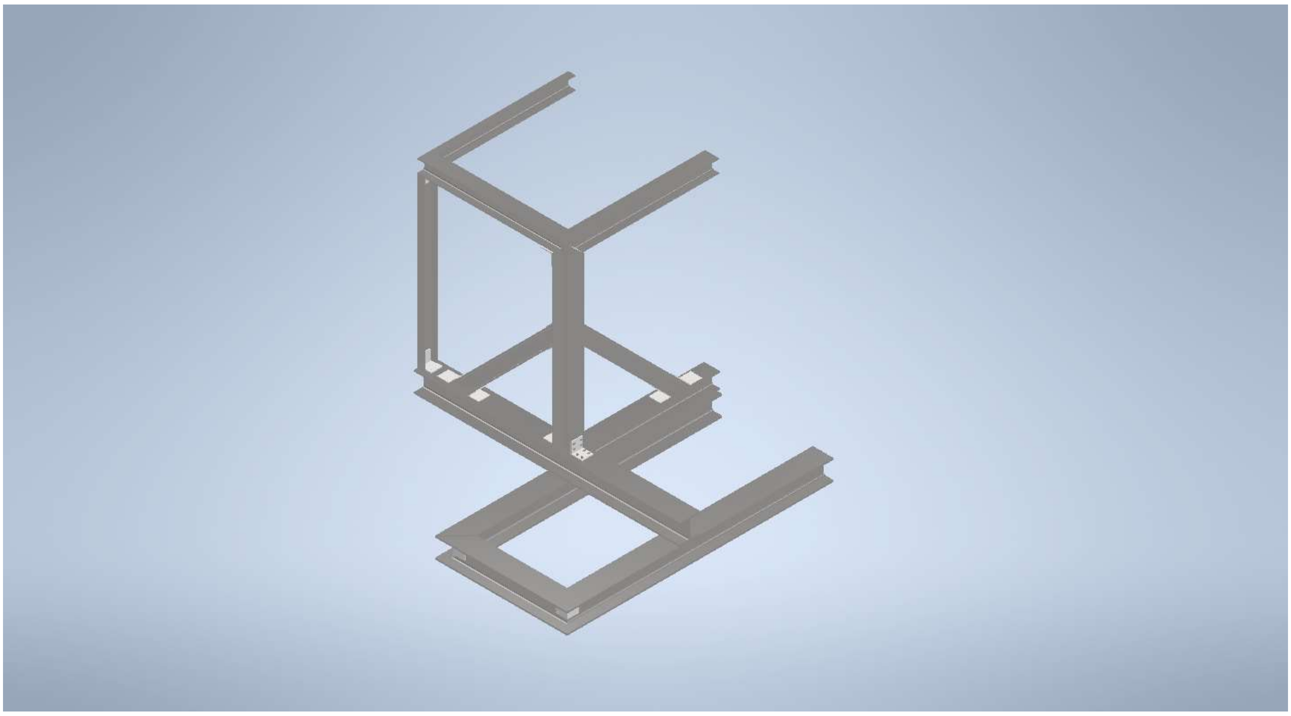


Figure 5-4 Overview over how the joints can be placed.

5.1.3. Challenges

The sharp ends of a HE beams creates snagging points that can do damage on cables and ROV's that gets in contact with the structure. The C-beams will have fewer sharp edges therefore there will be fewer snagging points and there is less chance of damaging ROVs and cables. The challenge with C-profiles is the weight. The weight of the Blue Logic original design is already to light. The consequence of a light structure is that the waves can lift the structure and when the wave is breaking, the slings will get a snap load on them, see chapter 4.1. The C profiles have an unsymmetrical geometry and can be unstable if loading on the top flange without bracing [11]. The C-profiles usually are a secondary structural member [11].

The I, HE and C beams can have a problem when bolting to close to the edge, due to the rounding off near corners [11].

Bolted joints are more exposed for corrosion then welded, due to more places where water can penetrate and start corroding. Critical points should have a lower risk of corrosion so that the structure can be retrieved after its service. The lifetime of the SDB is 25 years, which make it less ideal to use bolts in critical points, therefore welds will be superior in critical points.

DNV have done an investigation, and from the data collected, most incidents from bolts were in the lifting/dropping stage. The report was done by checking all incidents related to bolts in offshore structures. The investigation went through the incident database and found the most common problems with bolts. The most frequently incident with bolts were linked to dropping objects. The report found out that there were not good enough routines and rules related to bolted structures, which need to be followed if the bolting of joints will be considered [10].

5.2. CONCEPT 2

5.2.1. Beams

Second concept is considering HE beams since these are stronger and more versatile than the C-profiles that if loaded on top flange due to its unsymmetrical geometry will be unstable if heavy loaded [11]. HE-B are commonly used and are a good profile for connection between members. This makes it more accessible to use due to hight availability of manuals from optimal structures [11].

The locations where there are a lot of the stress will also be welded, due to corrosion forming on bolts, and the critical points needs to be intact to retrieve the structure. Square or rectangular hollow sections also have a high strength, but since its hollow corrosion can be forming on the non-visible surface, since the coating on the inside is harder to do to maximal extend. HE-B has a visible surface, so coating and testing the coating is easier. Figure 5.7 is an example of how the SDB could look.

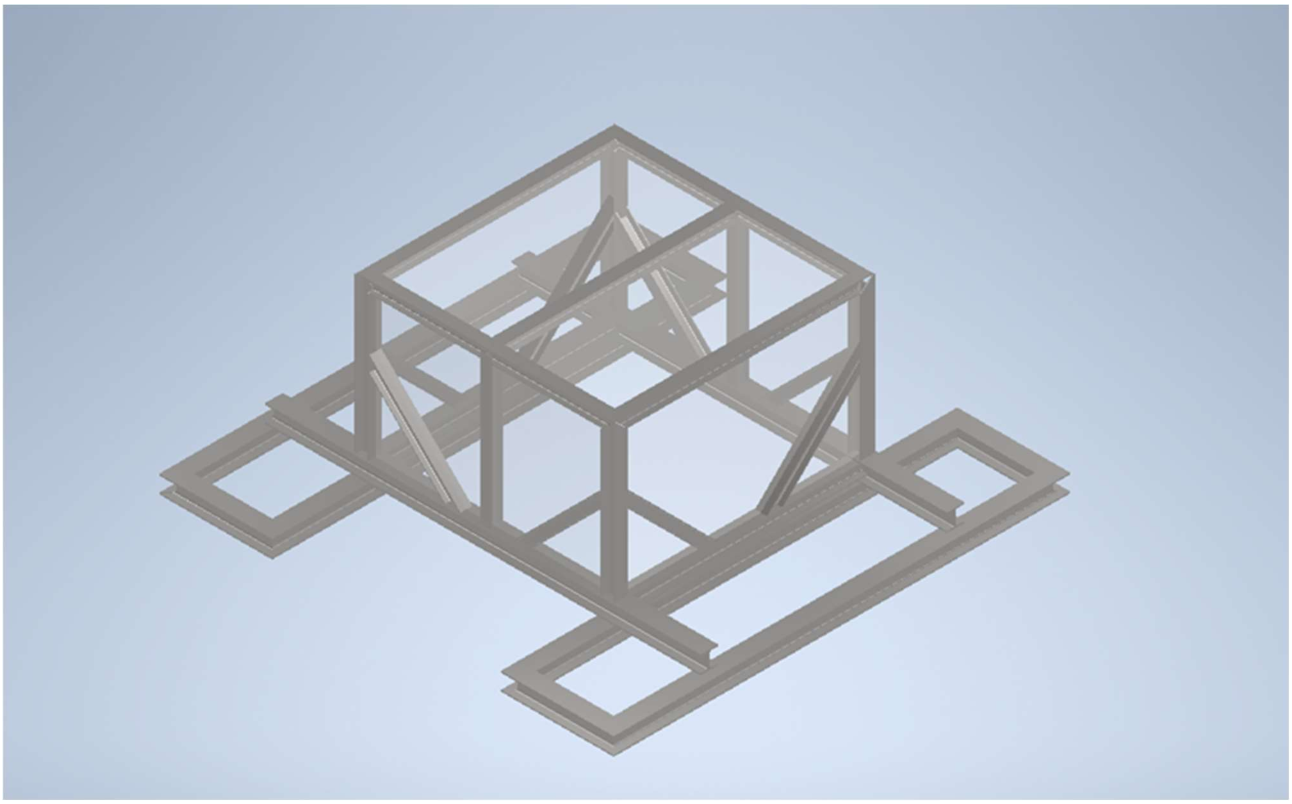


Figure 5-5 Structure for concept two.

When selecting the size of the cross sections the second moment of inertia, I, is compared to the original. The properties are put in table 5.3 for and compared [21]. The pontoon here is HE-B 220, and the others are found in table 5.3.
The weight does also have a factor in the structure. The original Blue Logic design is to light so choosing bigger profiles to increase the weigh to lower the center of gravity should be considered.

In this concept the smallest beams will be check, and as displayed in table 5.3 the weight of all the beams is higher than the original design.

Table 5-3 Table of Cross-sections and properties

Number	Original dimension (mm)	Original I ($x10^6mm^4$)	Original weight (Kg/m)	New dimension (mm)	New I ($x10^6mm^4$) y-y	New I ($x10^6mm^4$) z-z	New weight (Kg/m)
B1	250x250x8	74.0	60	200	80.9	28.4	71.5
B2	150x100x8	5.77	29.1	200	57.0	20.0	61.3
B3	100x100x8	4.08	22.9	140	15.1	5.5	24.7
B4	100x100x8	4.08	22.9	140	15.1	5.5	24.7
B5	100x100x8	4.08	22.9	180	25.1	9.25	30.4
B6	100x100x8	4.08	22.9	180	25.1	9.25	30.4
B7	100x100x8	4.08	22.9	160	16.7	9.25	30.4
B8	100x100x8	4.08	22.9	160	16.7	9.25	30.4
B9	100x100x8	4.08	22.9	160	16.7	9.25	30.4

5.2.2. Joints

Bolts have more problems with corrosion, and since the lifetime of the SDB is 25 years, the concept will consider welds in the critical points. The critical joints can be seen in table 2.2. Welds usually have a higher resistance than the steel itself due to weldment with higher material properties. This means that welding a joint make the joint rigid, and capable of supporting moment loads.

In concept two there will only be considered bolts on the stiffeners and the original bolted joints. The stiffeners take so little force so even if bolts are little loose the SDB can retrieve. The problem is that the force will then have to find another way. The original bolts may also be a problem when retrieving the SDB, since these are the joints connecting the base to the pontoons. Figure 5.6 shows a bolted bracket and a weld, the illustration is only a example and needs to be design after correct loads.

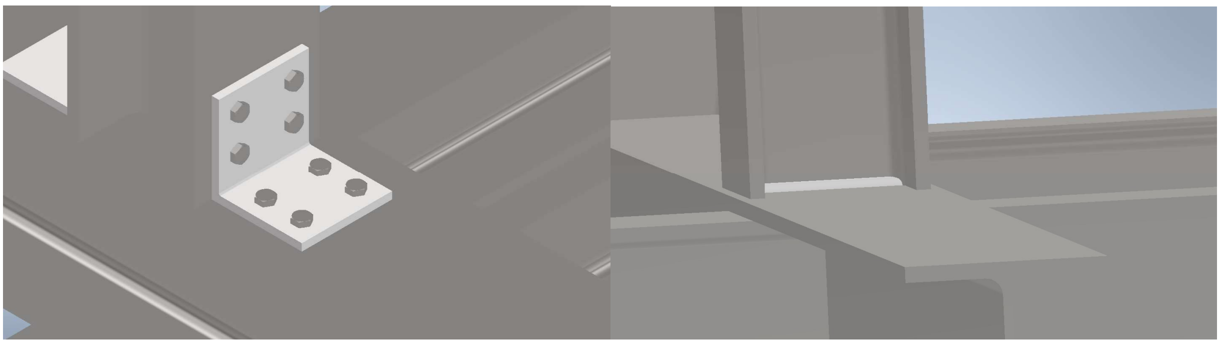


Figure 5-6 Figure of a bolted plate and a weld. Made in Inventor

5.2.3. Challenges

The challenges with the HE-B profiles are already discussed in 5.1.3.

Bolting will always have problem with corrosion. Welding critical points will make the SDB more likely to be retrieved after its service. Welding cost more than bolts, therefore the problem becomes finding a cost efficient joint [8].

If bolting the stiffeners there will be a problem with corrosion and the stiffeners can loosen and this will make it, so the force needs to find another way. If the SDB is unsymmetrical there can be a problem with torsion. The original Blue Logic design already have some bolts, which can also be a problem when retrieving it after 25 years.

5.3. DISCUSION

5.3.1. Beam profiles

The profiles that are considered are the C-profiles and the HE-B profiles. This is because they have a completely visible surface which have the advantage of visual inspections on the seabed, but the visual inspection only checks the integrity. It is impossible to see the electrical insulation. RHS profiles have a non-visible surface that can corrode without knowing the degree of corrosion forming.

C-profiles are more exposed for torsion if loaded on the top. The C-profiles also have a lighter weight per meter than both RHS and HE-B. The Blue Logic original design is already to light. The consequence of a light structure is that the waves can lift the structure and when the wave is breaking the slings will get a snap load on them.
Blue Logic are in development of a lifting plate, see figure 2.2 to add more mass so they can lift the structure through wave zones, and to negate the snap load on the slings.

The HE-B profiles have a higher weight and it’s an overall stronger option than C-profiles. problem with snagging» can be overcome by installing “cable rejectors” as illustrated in the original concept, see figure 2.4. Therefore, the design SDB for the concept is made of HE-B.

5.3.2. Joints

The original Blue Logic design is mainly welded part from two bolted joints joining the main body to the pontoons, see figure 5.7.

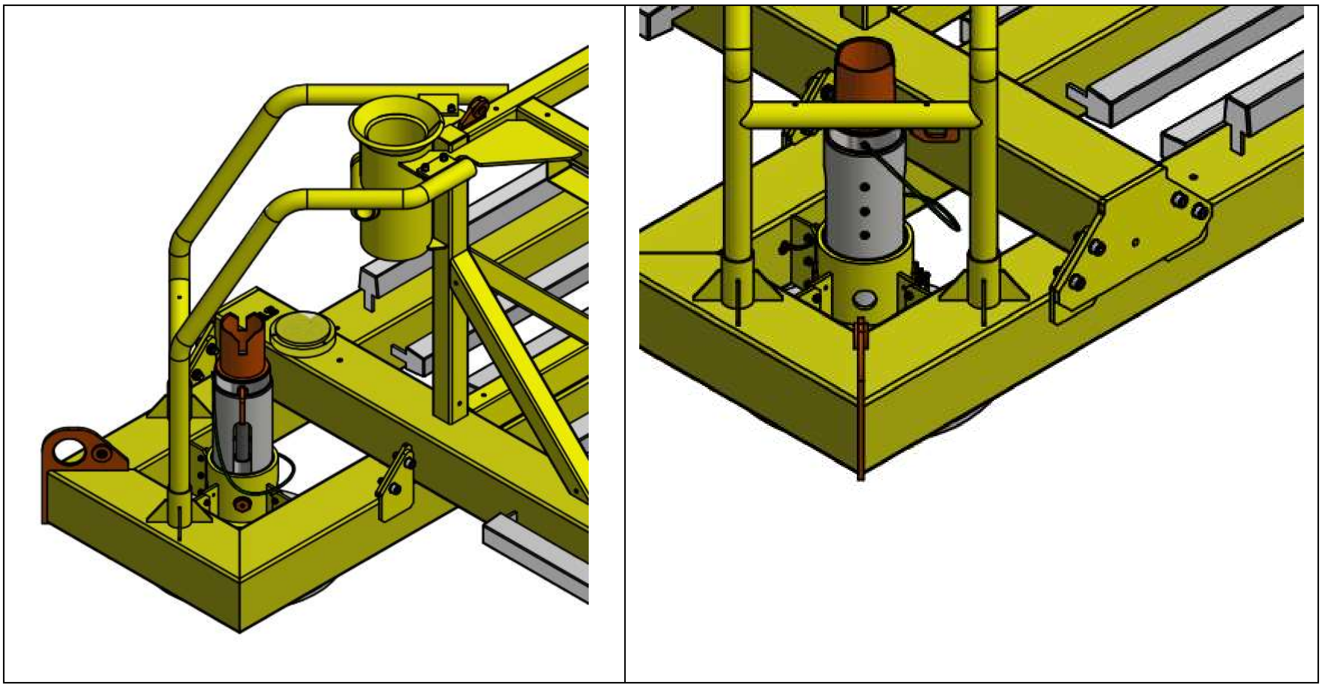


Figure 5-7 Figure shows the bolted connections for the Blue Logic original design

Welds are more complex and more expansive than bolting but will have Less risk associated with weld concerning corrosion. The lifetime of the SDB is 25 years and is sitting on the ocean floor, which means only ROVs can inspect it. This means that the joint needs to be intact until retrieved after 25 years, if there are visible damage to the SDB or there is need for it another place, the SDB can be retrieved before its design life. If the SDB gets retrieved before it should go through Non-Destructive Testing (NDT) on it before installed again. Welding is the best possible connector, but it needs to be done correctly and done NDT on it. Some typical NDT that is done is:

- Visual inspection
- Penetrant inspection
- Ultrasonic inspection on lifting points [23]

This makes the price of a weld much higher than bolting.

If bolting shall be considered, there are different methods to strengthen the bolts against corrosion. The material of the bolt should match the steels properties to reduce the electrochemical difference between bolts and beams and/or brackets. This will reduce the galvanic corrosion forming.

The biggest problem for a bolted joint is crevice corrosion. Crevice corrosion is the most common local corrosion and is the main problem for bolts. There are methods to reduce the crevice corrosion that is discussed in chapter 6.6, but the problem with new methods is that they aren't tested for 25 years. The bolted joint also needs to be aware of crevice corrosion which is the most common local corrosion around bolts.

Concept two is more consideration towards corrosion. The only joints that have bolts are the original brackets to the pontoons and the stiffeners. This way the most stressed members are welded and are more protected for corrosion. The bolted joints are only the stiffeners, this will make the joint connectors a less expansive vs the original Blue Logic design.

6. STRUCTUAL ANALYSIS OF PROPOSED CONCEPT

The prevailing concept is a welded SDB, with bolted stiffeners, consisting of HE-B profiles. Welds on the more stressed joints, and bolts on the stiffeners, and the original bolted joints. Use of HE-B beams instead of C-beams, since the second moment of inertia in the weak direction is much higher on, HE-B sections then on C sections. The chosen concept must be checked for different failures.

- Design Checks of the cross sections:
  - Shear
  - Tension/compression
  - Torsion
  - Moment

- Design checks joints
  - Welds
  - Bolts
  - Brackets

Before preforming these checks the internal forces are required. The external force that the SDB will experience for is the hydrodynamic force, see chapter 4.1 for equation. The full calculation is in appendix I.

The forces are put into Autodesk Inventor Nastran. The raw data is extracted and post-processed in excel.

6.1. INVENTOR NASTRAN

Autodesk Inventor Nastran is a Finite Element Analysis program, the model drawn in the Inventor modelling environment is automatically passed on to the Nastran environment for analysis.

To prepare the analysis the following steps will be performed.

6.1.1. Material definition

The following properties must be defined.

a. S355 has been chosen in line with Blue Logic material selection.
b. E-modules = 210 GPa
c. Yield strength 355 MPa
d. Mass density multiplied with the mass factor (1.94) (see chapter 6.1.4)
e. Poisson's ratio 0.3

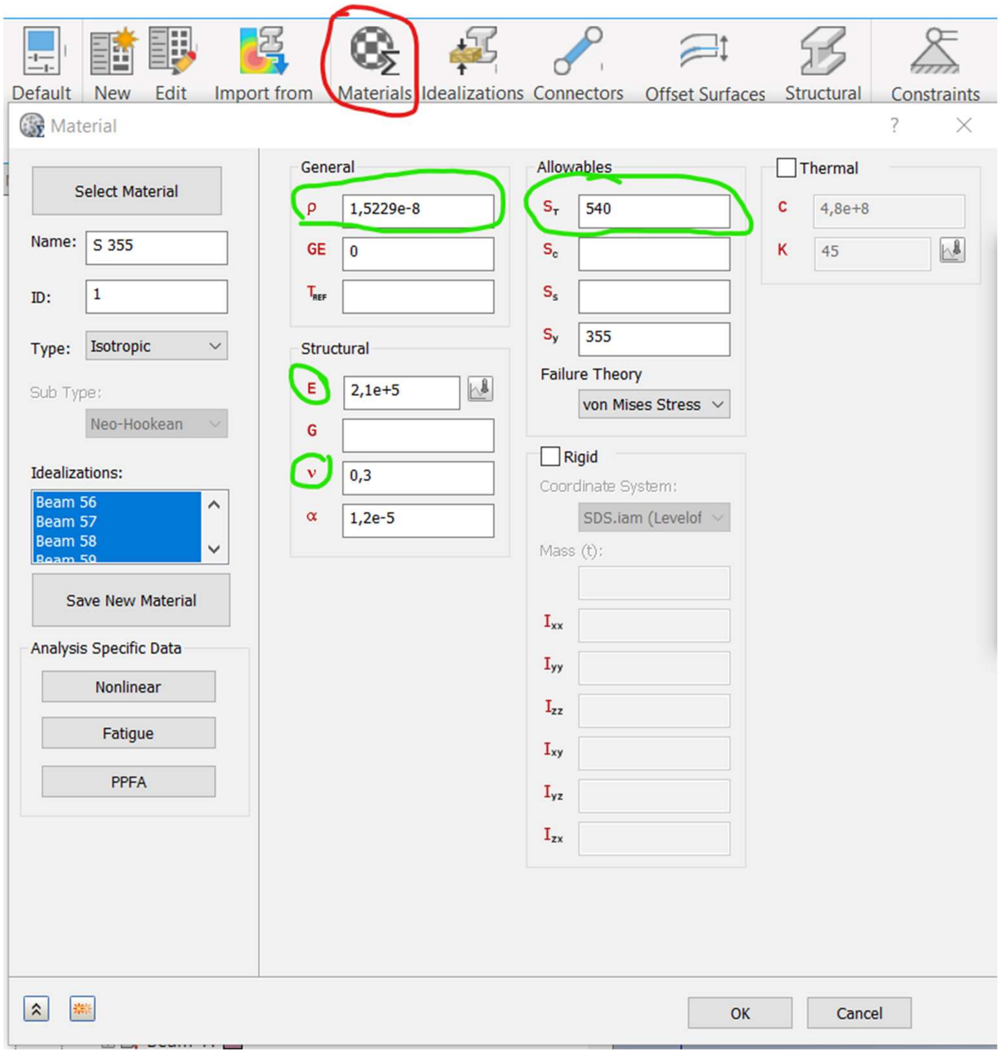


Figure 6-1 Figure over the different parameters that needs to be changed

6.1.2. Idealization

a. This step defines the element types used for each beam. For a simple truss like structure, 2D line elements are computationally beneficial and will yield realistic results.

6.1.3. Connectors

Connectors must be defined where load transfer is required. E.g. to transfer the load from the top structure to the pontoons a set of rigid connectors are defined at the joints. A rigid connector is essentially an infinitely stiff element

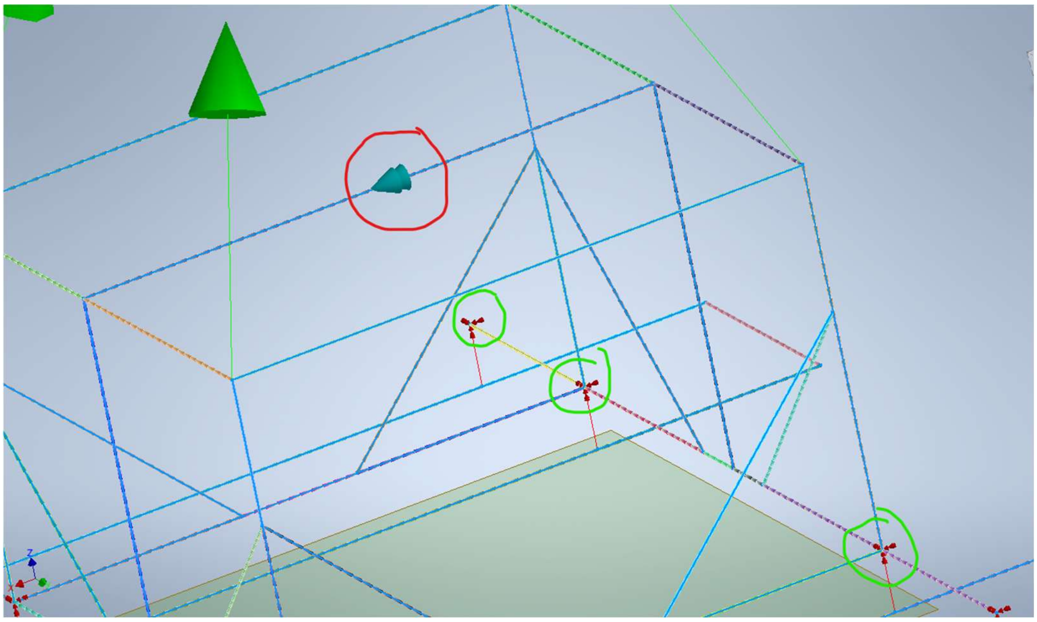


Figure 6-2 Figure over constraints and connectors.

6.1.4. Modelling

Modelling of constraints. Because the critical load case is during lifting operation the internal force balance will be controlled by the "interial relief" functionality in NASTRAN: the inertial relief will basically generate an acceleration field to balance the structure and prevent rigid body motion. One consequence of this method is that any additional acceleration loads such as gravity will be cancelled out. To ensure the contribution from self-weight the steel density is increased to create the effect of additional mass. mass factor added is $\frac{Total\ weight\ of\ SDB+all\ equiment}{Weight\ of\ SDB}$ = 1.94.

6.1.5. Adding load

The resultant sling load is added at every pad eye, see chapter 4. The total load is projected into the x, y and z direction, and the calculations can be found in appendix I.

6.1.6. Meshing

The final step before running the analysis meshing.

a. The shortest individual beam is 250mm. This is a consequence of the program that currently does not allow the creation of custom nodes at a specific point. Hence, the program relies on splitting beams into smaller sections where the node is required. The smallest beam is in reality one part of a solid beam measuring 4.5 meters in total length.
b. To ensure sufficient resolution across all beams the minimum element size is set to 250mm/4 = 62.5mm
c. Further refinement yields a final element size of minimum 50mm

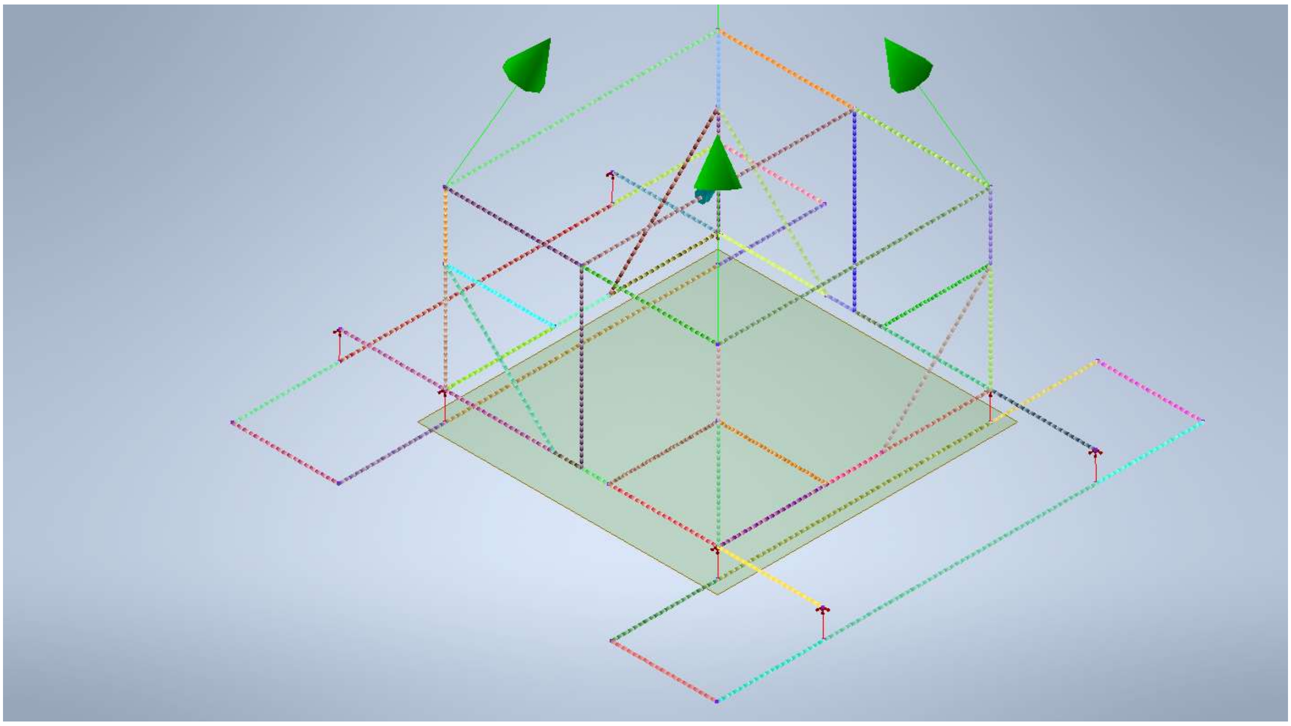


Figure 6-3 Picture of the mesh generated

After all these steps are complete, it is ready for analysis
The raw data is processed in excel and displayed in different tables and figures in the following chapter.

6.2. CHECK FOR FAILURE

6.2.1. ULS

Ultimate limit state is the ultimate stress that can be put on a SDB before it collapses. It is check by the formula found in Eurocode 3 EN 1993-1-1:2005 chapter 6.2.1[5]:

$$\left(\frac{\sigma_{x,Ed}}{f_y/\gamma_{M0}}\right)^2 + \left(\frac{\sigma_{z,Ed}}{f_y/\gamma_{M0}}\right)^2 - \left(\frac{\sigma_{x,Ed}}{f_y/\gamma_{M0}}\right)\left(\frac{\sigma_{z,Ed}}{f_y/\gamma_{M0}}\right) + 3\left(\frac{\tau_{Ed}}{f_y/\gamma_{M0}}\right)^2 \leq 1$$

Where:

$\boldsymbol{\sigma_{x,Ed}}$ = $M_{y,Ed}$

$\boldsymbol{\sigma_{z,Ed}}$ = $M_{z,Ed}$

$\boldsymbol{\tau_{Ed}}$ = V_{Ed}

The maximum of these value is chosen to check, the f_y and γ_{M0} is found in table 2.3 and 2.4

0.177 ≤ 1 so ULS is satisfied [15].

6.2.2. SLS

Serviceability limit state is associated with deformation, deflection and/or vibrations.
Vibration is the most relevant, with the underwater current inducing vibrations. Excessive vibrations could impact the functional use of the SDS, and overtime will affect the fatigue damage, see Section **Feil! Fant ikke referansekilden.**. To avoid excessive vibrations the natural frequency of the SDB must not equal the current frequency. A modal analysis including the effect of added mass is beyond the scope of this thesis.

Morrison equation is a simplified expression that can be used to estimate the effect of current load with respect to deflections.

Morrison equation: $F = F_I + F_D = \rho \cdot C_m \cdot V \cdot \dot{u} + \frac{1}{2} \cdot \rho \cdot C_d \cdot A \cdot u|u|$ [12]

The two terms in the equation are associated with inertial load and drag load, respectively.

6.2.3. FLS

Fatigue limit state is associated with alternating stress.

Fatigue will only be relevant once the SDS has been installed, and will be determined by shifting currents, hence the problem will be location specific.

West Africa is known to have challenging current patterns [22].

6.3. DATA AND FIGURES

When the analysis is done Nastran displays a different of plots. The plot in figure 6.4 is the plot of the Von Mises stress, this gives a good indication on how well the structure can handle the stresses.

As a simplified check to determine resistance against yielding, the von Mises stress from figure 6.4 is used. The max von Mises stress is $\sigma_{\emptyset,max}$ = 169.5 MPa. The yielding stress defined as $\frac{fy}{\gamma mo} = \frac{355\ MPa}{1.15}$ = 308MPa. Thus, the utilization is $\frac{\sigma_{\emptyset,max}}{\frac{fy}{\gamma m0}} = 0.55 < 1.0$ OK!

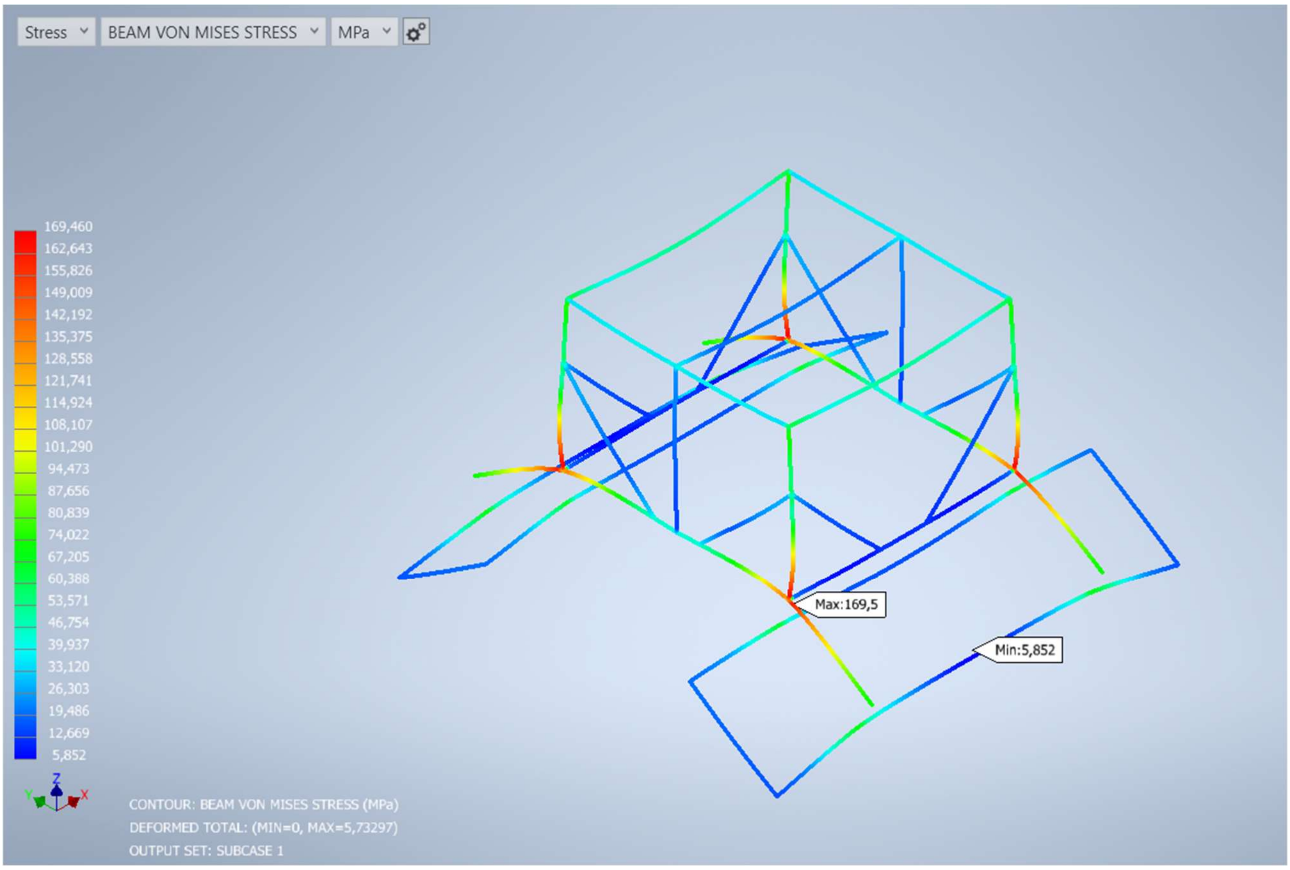


Figure 6-4 Von Mises stress on the structure

The deformation is another plot received from Nastran and is displayed in figure 6.5. The forces applied in the Nastran analysis is the hydrodynamic force from chapter 4, which are only applied when lifting through wave zones. This is only for a short period of time, and the maximum deformation is 5.733mm, which means that the deformation can be neglected, and the profiles are stiff enough.

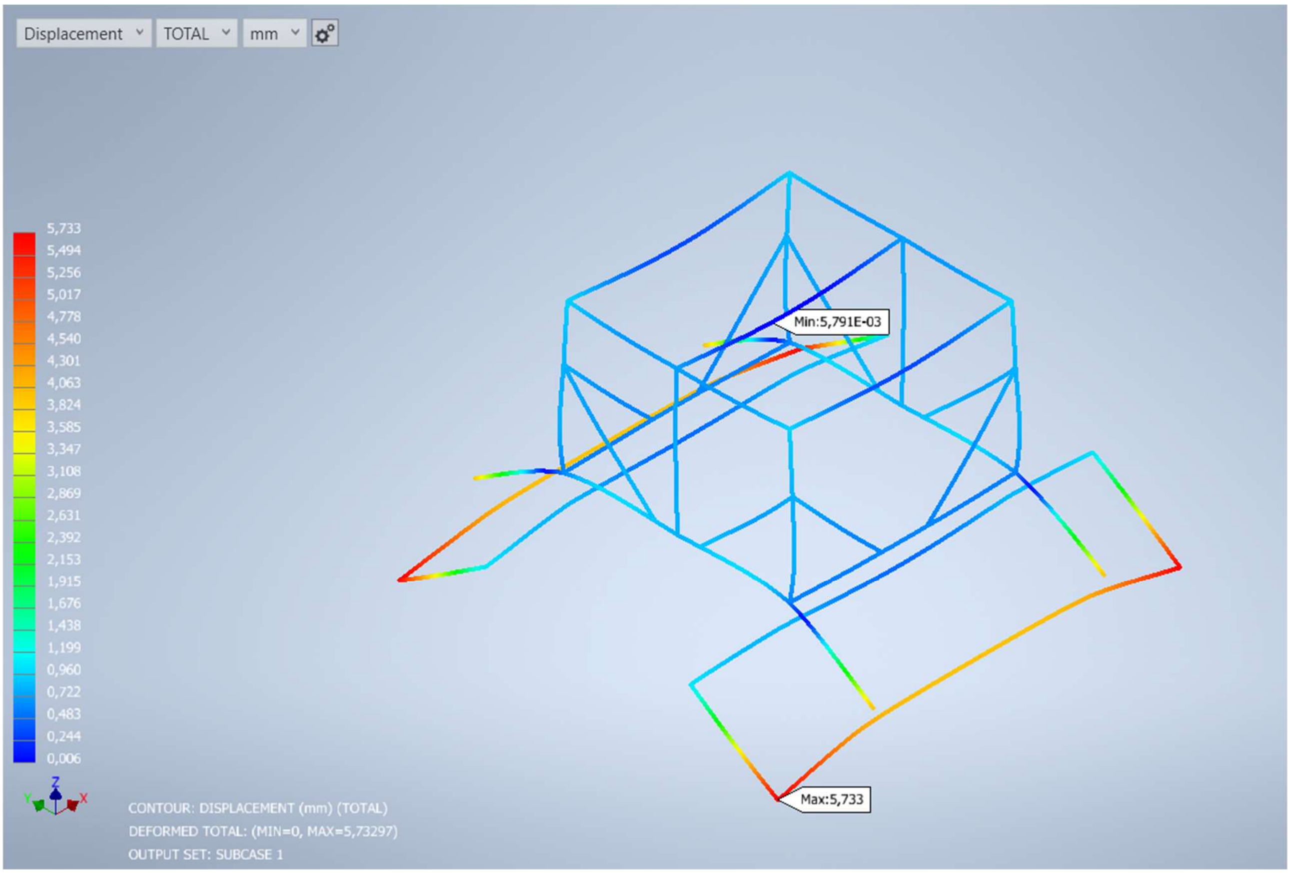


Figure 6-5 Displacement of structure

To check if the joints and the members satisfy their criteria in chapter 3, the calculated N_{Rd}, V_{Rd}, T_{Rd} and M_{Rd} are displayed in the table 6.1. The data collected from Nastran should not exceed these resistances. From the raw data we extract the max value from each stress. This is displayed in table 6.2.

Table 6-1 Table resistance forces for each profile from the equations in chapter 3.

Size beam	Area (A) Mm^2	Second moment of inertia (I) mm^4	Ay from table # mm2	N_{Rd} (kN)	V_{Rd} (kN)	T_{Rd} (kNm	$M_{y,Rd}$ (kNm)	$M_{z,Rd}$ (kNm)
HE-B 200	$7{,}81*10^3$	$Y=57*10^6$ $Z=20*10^6$	2485	2410	442	437	198	94
HE-B 180	$6.53*10^3$	$Y=38.3*10^6$ $Z=13.6*10^6$	2029	2015	361	358	148	71
HE-B 160	$5{,}43*10^3$	$Y=24.9*10^6$ $Z=8.89*10^6$	1764	1676	314	311	109	52
HE-B 140	$4{,}30*10^3$	$Y=15.1*10^6$ $Z=5.5*10^6$	1312	1327	233	231	75.76	24

Table 6-2 Table of the different max values of the forces and stresses on the figure.

Force/stress	Max value	Resistance of smallest beam from table 6.1	Check
N_{Ed}	329,95 kN	1312 kN	OK!
V_{Ed}	91,09 kN	233 kN	OK!
$M_{y,Rd}$	75,40 kNm	75.76 kNm	OK!
$M_{z,Rd}$	18,93 kNm	24 kNm	OK!
T_{Ed}	0.172 kNm	231	OK!

Can see from table over that there is no problem with the selected profiles. The closest stress is bending, but the resistance is for the smallest beam. A local overview over the joints is found in table 6.3.

Table 6.3 Table over every element max stress and force acting on them.

Joint	Element No.	N_{Ed} [N]	V_{Ed} [N]	T_{Ed} [Nmm]	$M_{y,Ed}$ [Nmm]	$M_{z,Ed}$ [Nmm]
	480	-2691,81	-41294,2305	24575,6504	4143133,75	-380364,625
1	481	-2691,92	41262,6602	-24562,0977	6204112	-491331,813
	841	-80779,28	-4439,33398	-1,24962592	-49123,3867	3733,37158
	872	-48158,7422	-4435,19678	-1,25177932	6872128,5	-4348,4043
2	1129	-144635,578	12505,4316	-1821,23926	-1002529,31	-688615,375
	1130	-144646,828	-12520,4668	1820,62793	-1632524,13	-728786,75
	485	-2692,21924	46268,5625	-24562,9688	-2423862	-47267,0977
3	386	-6422,55713	-4026,01563	-43070,7227	2423224,5	2770544,75
	1322	14656,7412	12515,5908	-1264,79504	-4079536,25	46423,9492
	828	264632,344	22204,3867	15818,9854	-138103,359	-2159758
4	829	318255,063	-15797,6328	689,769287	-2167657,75	680093,813
	1295	27932,5117	-763,005615	-1259,68652	3598812,75	460840,906
	828	264632,344	22204,3867	15818,9854	-138103,359	-2159758
5	829	318255,063	-15797,6328	689,769287	-2167657,75	680093,813
	1210	36718,2813	-7945,33594	7885,07617	1712485	-474695,313
	692	30936,4004	4686,37158	-1,02658784	-665508,063	864404,875
6	693	10588,7119	-6725,44141	-69482,8516	-632905,938	806080,25
	1183	23442,5996	5333,22461	7879,96729	266920,75	-90384,75
	505	-21908,0117	70132,5391	-1736,79053	-54762040	2484916,25
7	711	10587,2422	12098,4844	-69487,7734	-2580100,5	551159,063
	505	-21908,0117	70132,5391	-1736,79053	-54762040	2484916,25
8	506	6431,75098	-91108,3359	44583,9453	-75430160	974379,563
	809	244761,766	22202,3848	15818,9863	4468691,5	18933300
	840	329950,969	-15795,7441	689,768372	6665383	-836878,625
9	955	-162383,969	-21298,666	7,81184959	-7466515	245069,188
	955	-162383,969	-21298,666	7,81184959	-7466515	245069,188
10	1154	-144650,266	8348,89844	1813,4574	1392280,88	206682,094
	1005	-5987,43066	-21302,416	3,66E-12	-7098907,5	1436,02234
11	1129	-144635,578	12505,4316	-1821,23926	-1002529,31	-688615,375
	1130	-144646,828	-12520,4668	1820,62793	-1632524,13	-728786,75
	1004	-162376,484	21307,75	-6,82741356	-6413775	239805,172
12	1104	-144656,484	8348,75098	-1843,25146	1391518,38	-202103,438
	20	978,775208	35764,41	22942,61	-21809792	-3840880,25
13	21	-4189,80811	-30657,1074	26,6890106	-22169368	-125647,781
	437	6420,30957	68291,9844	-44570,0586	1206579,75	-3995570
	200	-974,294189	36168,6172	171622,234	-22270734	2898409
14	201	-8708,41602	-30656,5527	14,609766	-13763739	1036185,75
	456	-21943,8867	-70114,5	1734,28162	-58257544	2610107,25

In concept 1 the strong points will be welded and only the dark blue areas are bolted. That means the pontoons together and the connection for the top structure to the platoons are as normal. Table 6.3 will show the different joints and if it is welds or bolts. The bolts need to be attached to a plate and we choose this to be a steel S355 bracket, and dimension is 100 wide and long 80mm on each side, see figure 5.2 for example of bracket.

6.4. BOLT CHECKS

The force considered in the joint is only axial force, therefore we will use the shear force from table 6.3 to do the check. The Cross sections of the profiles are relatively small; therefore, the bolt size will matter, and shouldn't be to big. The class of the bolt is therefore chosen to be 8.8 which gives:
f_{yb} =640 n/mm^2
f_{ub} = 800 n/mm^2
from table 3.1 in Eurocode 3[Eurocode 3 EN-1993-1-8, 2005].

Design of bolts is following the formula in chapter 3.6 for flexible joints: $A_s \geq \frac{f_{t,Ed}\,\gamma_{M2}}{0.72 f_{ub}}$

Table 6.4 displays the different joints, the largest N_{Ed}, which joint and if bolts number and the size.

Table 6.4 Table of joints and what kind of fastener used, and some properties for bolts.

Joint number (from table #)	N_{Ed} (kN)	Joint	Bolts	A_S	$A_s \geq \frac{f_{t,Ed}\,\gamma_{M2}}{0.72 f_{ub}}$	Joint info (Number of bolts, bolt and hole diameter in mm)
1	80.78	Bolts with plate	M 14	115	115 ≤ 182	2 bolts, d=14, d_0 = 16
2	144.65	Weld				
3	14.66	Bolts with plate	M 12	84	84≥ 33	1 bolt d=12 , d_0 = 14
4	318.26	Weld				
5	318.26	Weld				
6	30.94	Bolts with plate	M 12	84	84≥69.83	1 bolt d=12, d_0 = 14
7	21.91	Bolts with plate	M 12	84	84 ≥49.45	1 bolt d=12, d_0 = 14
8	244.76	Weld				
9	329,95	Weld				
10	144.65	Weld				
11	144.65	Weld				
12	144.66	Weld				
13	6.42	Bolts	As before			
14	21.94	Bolts	As before			
Platoons corner	6.42	Bolts with plate	M 12	84	84≥14.49	1 bolt, d=14, d_0 = 16

For safety measure two bolts are chosen, in the case of one getting rusted and is unusable, there is still one that can hold the joint together. Failure checks will be done with two bolts. The bolted bracket has each bolt 30mm from the middle which gives 40mm between them, see figure 6.6. The bracket is set to be 80x100 mm on each bolted section.

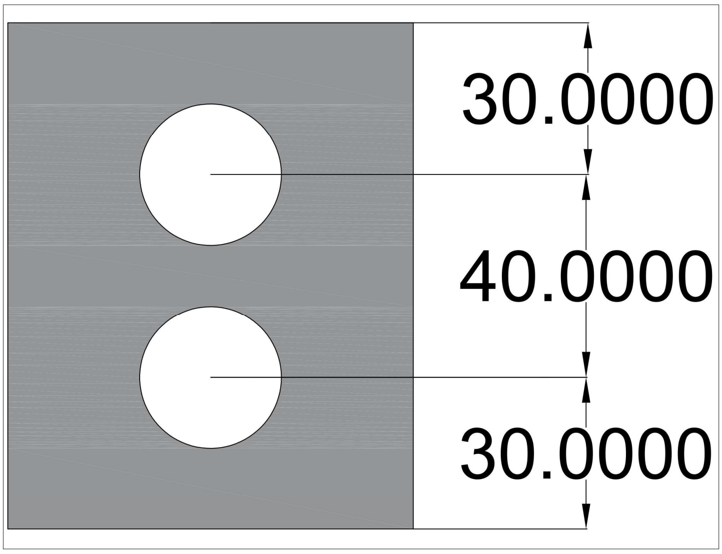


Figure 6-6 Bracket with bolt holes

From chapter 3.6 $F_{y,Rd}$ is calculated and inserted in table 6.5 and checked if the selected bolt is satisfying the criteria: $F_{v,Rd}/N_{Ed} > 1$.

Table 6.5 Table of bolt checks.

Joint number	**Bolt**	**N_{Ed} (kN)**	**$F_{v,Rd}$ (kN)**	**Check**
1	M14	80.78/2 = 40.39	44.2	OK!
3	M12	14.66/2 = 7.33	32.3	OK!
6	M12	30.94/2 = 15.47	32.3	OK!
7	M12	21.91/2 = 10.96	32.3	OK!
Platoon	M12	6.42/2 = 3.21	32.3	OK!

Chapter 3.7 gives us α_d and k_1 and the bolts are end and edge bolts. This gives:

For plate with M14 bolts: **α_d is 0.83** since this is smallest, and **k_1 is 2.5**
For plate with M12 bolts **α_d is 0.95** and **k_1 is 2.5**

The design minimum thickness of the bracket is found by using equations in 3.7 with the inputs over and is displayed in table 6.6.

Table 6.6 Table for design of bolted plate

Number of joints	N_{Ed} (kN)	Tickness (mm)	Fracture near hole thickness	Gross yielding σ ≤ fy thickness
1	40.39	3.69	3.17	2.84
3	7.33	0.78	0.54	0.51
6	15.47	1.65	1.13	1.09
7	10.96	1.17	0.80	0.77
Platoon	3.21	0.34	0.24	0.23

Chose to set the thickness of the bracket to 10mm as the size for each of the joints. Table 6.6 confirms that all thicknesses for different scenarios are smaller than 10 mm this means thickness of 10mm is acceptable for the design SDB. Last check for the bolts is to see placement of the holes are satisfied according to table 6.7 in chapter 3.8.

Table 6.7 Table for minimum distance for bolts in bolted plate

Type of bolt	Distance minimum distance for M14 since biggest	Check
Edge	1.2 x 16 = 19.2	30 > 19.2 OK!
End	1.2 x 16 = 19.2	30> 19.2 OK!
Spacing	2.2 x 16 = 35.2	40 > 35.2 OK!

6.5. WELD CHECKS

The welds are checked by doing the simplified method that is explained in chapter 3.8 and values is displayed in the table 6.8. $F_{w,Rd} = F_{wv,Rd}$ x a, where a is the throat thickness and $F_{wv,Rd}$ is $\frac{f_u/\sqrt{3}}{\beta_w \gamma_{M2}}$. In this case the throat thickness is set to 5mm, and $F_{wv,Rd}$ is with s355 steel 251.67 MPa [6]. The different joint values are the maximum values for each joint from table 6.3 and is displayed and checked in table 6.8

Table 6.8 Table over weld checks

Joint number	$F_{y,Ed}$ (kN)	$F_{y,rd}$ (kN)	Check
2	144,65	1258	$F_{y,Ed} \leq F_{y,rd}$ OK!
4	318.26	1258	$F_{y,Ed} \leq F_{y,rd}$ OK!
5	318.26	1258	$F_{y,Ed} \leq F_{y,rd}$ OK!
8	244.76	1258	$F_{y,Ed} \leq F_{y,rd}$ OK!
9	329.95	1258	$F_{y,Ed} \leq F_{y,rd}$ OK!
10	144.65	1258	$F_{y,Ed} \leq F_{y,rd}$ OK!
11	144,65	1258	$F_{y,Ed} \leq F_{y,rd}$ OK!
12	144,65	1258	$F_{y,Ed} \leq F_{y,rd}$ OK!

6.6. CORROSION

There are two different corrosion challenges, galvanic corrosion, and crevice corrosion of particular interest for subsea steel structures.

6.6.1. Galvanic corrosion

Galvanic corrosion occurs when different metals with different electrochemical potential are in contact with each other. The resulting ion transfer will prefer the higher electrochemical metal and start corroding it [13].

The size surface of the different metal's matters, the bigger the surface the more it will corrode. Therefore, if there is a place where two different steels meet there should be a non-metallic plate in between to try mitigating galvanic corrosion [15]. Table 6.9 shows difference between some common metals, the more noble metal the less potential it has. The importance is to have a big difference, it should be less than 250 milliVolt [24], but the closer the potential the better.
In the designed SDB the profiles are Carbon steel, and the bolts and nuts are class 8.8 and is a medium carbon steel [25].

Table 6.9 Table for potential electrochemical difference between different steels [14].

Alloy combinations	Potential difference (mV)
Al-stainless steel	850
Al-Carbon steel	240
Carbon steel – Stainless steel.	610

If the SDB is made of the same steel there will no galvanic corrosion, but the junction box and USB connectors are all made from duplex/super duplex steel (*S.Næss Blue Logic, personal communication. 05.05.2022)*. This is the reason for using cathodic protection to mitigate galvanic corrosion in the SDB. There are sacrificial anodes on the SDB, these work in the way that the anodes are drawing the loaded electrons to it, instead of the other member. In bolted joints if the bolt is a different steel, CP is required to avoid galvanic corrosion in bolts.

6.6.2. Crevice corrosion

Crevice corrosion is a localized attack in a place where liquid gets trapped and can't flow [26]. In these crevices the chloride from the saltwater has a higher electrochemical concentration than the concentration cell on the outside of the crevice [26]. When this happens acids are formed, see figure 6.6.

Crevice corrosion is a known problem in bolted joints where there is a gap between bolt and the metal, in the bolt hole. This makes the crevice corrosion difficult to discover by visual inspections.

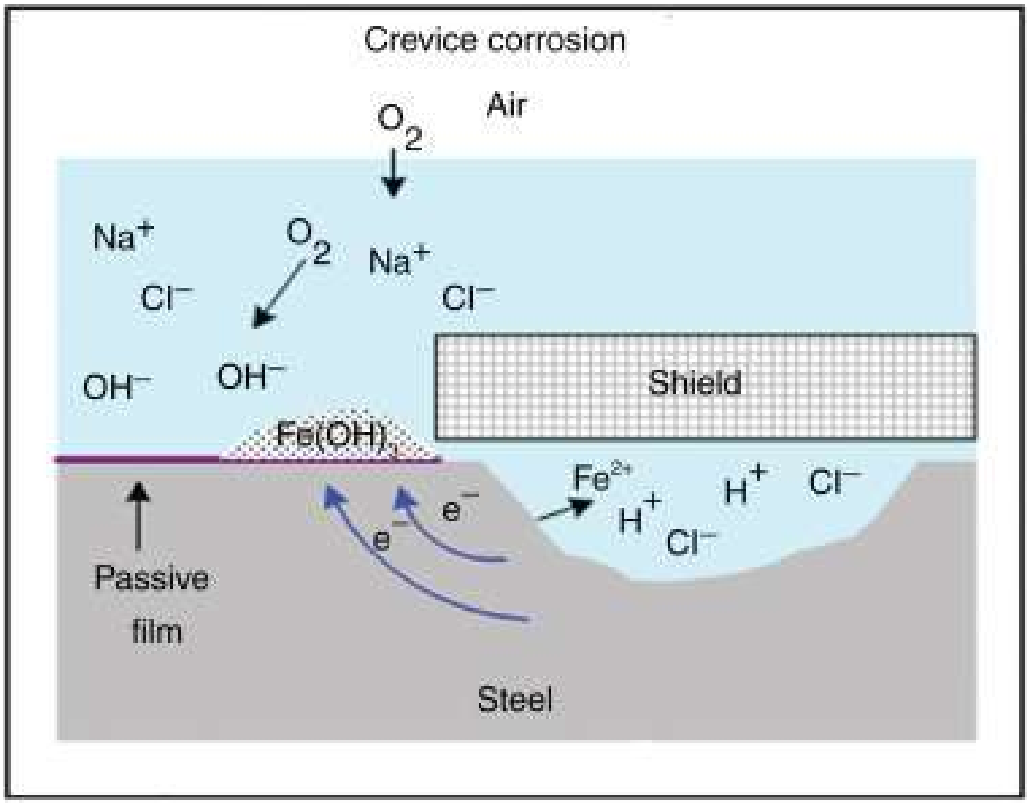


Figure 6-7 Crevice corrosion [27].

In a proper welded joint, there is no crevice corrosion assuming no trapped water during fabrication. Bolted joints are open joints, therefore more exposed for this type of corrosion. In the concept there is only the stiffeners that are bolted. These are one of the least stressed parts in the SDB, see figure 6.4.

For best chance of reduce the crevice corrosion every mating surface should be coated with a zinc rich primer before assembly [28]. There is also a new study on adding stripe coats and caulking for added protection [28].

Stripe coat is an added extra layer of coating to bolts and knobs. Caulking is a sealing member that will keep the moisture away [28].

An experiment done by Pete Ault and Eric Shoyer showed that doing striped coating to galvanized bolts and caulking the bracket so it is fully covered and will not let water inn and therefore reduce crevice corrosion. The experiment showed that the full caulked brackets showed little sign of crevice corrosion [28]. Galvanized bolts showed the best results, but the results for not galvanized bolts showed that the joint should be striped coated and full caulked.

The original Blue Logic design has sacrificial anodes attached to it. The concept SDB also needs anodes, and the joints needs to be protected from corrosion.

7. CONCLUSION

With respect to joint optimization this thesis has considered welded joints and bolted joints for a subsea structure.
To summarize the pros and cons the following categories are defined:

- Strength and stiffness of a joint
- Material selection and Beam dimensioning
- Corrosion

7.1. STRENGTH AND STIFFNESS OF A JOINT

Loosely defined a joint can be said to be a connection between to members that share a stiffness. The loss of stiffness will result in the members coming apart. For a welded joint the stiffness is maintained by melting the metal between two surfaces, creating a seamless connection between the members. Typically, when welding a stronger weldment is added such that the actual weld is not the weakest point. Therefore, stiffness will always be maintained as long as there is no crack growth that physically separates the members.

A bolted joint on the other hand will always require a non-zero stiffness to maintain its function, e.g. prevent excessive relative movement in the joint. The magnitude of stiffness will be determined by the loading. In the case of the SDS, there are two scenarios; lifting through the wave zone and loading after installation (which is predominantly static).

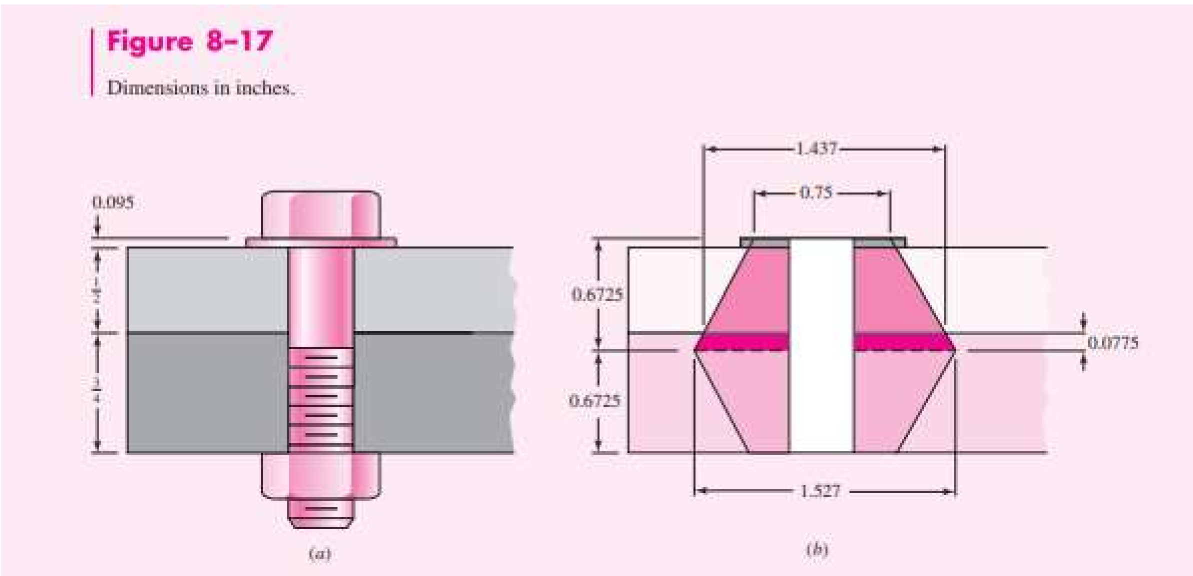


Figure 7-1 Figure over stiffness distribution in bolted joints [18. s. 431].

When lifting through the wave zone, it is assumed that an even force is pushing on the SDB, however this load case is relatively brief typically 30 minutes [19] so any potential failure modes are unlikely to develop due to the preload.

For the static on bottom case loss of preload over time can occur due to corrosion, see chapter 7.3.

In this case it is important to have a correct preload of the bolt. A rule of thumb is to preload the bolt for 2/3 of yielding strength [18].

Table 7.1 gives us the accuracy of preloading a bolt with different tools. Special tools are required to preload the bolts with less accuracy than 10%, this means it is difficult to do preload outside the workshop [11]. When transporting the bolted joints will need to keep its preload, since it is difficult to do an accurate preload right before instalment.

Table 7-1 Preload uncertainty [11]

Tightening Method	Accuracy
By feel	$\pm 35\ \%$
Torque wrench	$\pm 25\%$
Turn-of-the-nut	$\pm 15\%$
Load indicating washer	$\pm 10\%$
Bolt elongation	$\pm 3 - 5\%$
Strain gages	$\pm 1\%$
Ultrasonic sensing	$\pm 1\%$

All welds shall be inspected after welding. Depending on the criticality and type of the weld i.e. a lifting point is a critical point that requires substantial NDT, typically if fillet welds are used 100% visual and liquid penetrant tested is required [7]. If full penetration welds are used additional ultrasonic testing will be required [7]. Once installed on the seabed any inspection is unlikely to be practical, all subsea structures are coated hence the weld are obscured.

DNV with help of Petroleum Safety Authority, have had an investigation of bolt incidents offshore [10]. The investigation was frequently linked to dropped and/or lifting of an object, caused by vibration. The investigation gathered data from the incident data base, and found that the three biggest pre-defined failure modes where in following order:

Table 7-2 Table of incidents discovered from the pre-determined failure modes [10].

Incident type	Number of incidents
Moment (torque)	15
Assembly (tightening)	10
Corrosion	6
Fatigue	4
Crack	3
HISC	1
Overload	1
Tension	1
Total	41

For a total of 331 failures as reported in the DNV report, 41 incidents were linked to the pre-defined failure modes. Most of the incident didn't describe the root of the problem [10].

The DNVGL has published investigations reports from 2008 to 2018 with data of fracture of bolts. The common failure from these reports where mainly fatigue, brittle fracture and HISC (Hydrogen Induced Stress Cracking). Reoccurring factors for this where overloading and tightening. HISC is a frequent failure for carbon steel with high strength and hardness, and the reports have no conclusion for this, so it needs more research on HISC [10].

A review of selected subsea failures on bolts from 2002 to 2013 concluded that it is required to develop a standard of using bolts in joints, and a standardize laboratory tests of bolts susceptibility to HE, both with and without coating of the bolts [10].

The investigation did not give a clear conclusion to investigation of bolting failures, but DNV discovered that there should be better routines and rules around bolts to make it safe [10].

If bolted joints are correctly preformed and follow the routines and rules around them, there should not be a problem with bolting for less critical areas. Concept 2 is only bolted in the least stressed areas. The bolted are the stiffeners and the bolted joints from the Blue Logic original design. Bolts can be used where recommended in concept 2, but there are risks since there are not enough research on bolted joint on subsea structures. The design lifetime of the SDB is 25 years. It is difficult to predict the outcome after 25 years subsea.

All the checks for the bolts and the brackets are OK! Therefore, Blue Logic will need to decide if they want to take the risk of bolting 16 new joints of a total of 50 joints, which is 32%.

7.2. MATERIAL SELECTION AND BEAM DIMENSIONING

Material selection follows established standards, such as NORSOK M-001.

The HE-B that are chosen for the design, are strong enough to withstand all the stress and force applied during lifting stages proven in chapter 6.2.

When the SDB is just sitting on the ocean floor it is not exposed to any large environmental forces. Minor current is likely to be present however this is location dependent. Self-weigh is the main contributing factor once installed. Lifting through waves is the case that exposes the SDB to the maximal force exerted on it. HE-B varies from 140 to 200, and the weight of these beams can be larger since the total mass will make it difficult to lift through waves due to potential slack slings, which could lead to snap loads, see figure 7.2[19].

In the case of lifting, blue logic has a concept lifting plate, whose main purpose is to add more weight so the lifting can be performed.

$$\begin{bmatrix} 4 & -89.811 & -190.941 & -295.578 \\ -18.672 & -72.467 & -132.49 & -196.804 \\ -15.19 & -58.751 & -107.83 & -160.941 \\ -10.562 & -46.834 & -87.956 & -132.767 \\ -6.039 & -36.895 & -72.009 & -110.463 \\ -1.968 & -28.669 & -59.118 & -92.579 \\ 1.597 & -21.833 & -48.578 & -78.037 \\ 4.694 & -16.107 & -39.853 & -66.051 \\ 7.386 & -11.264 & -32.546 & -56.048 \\ 9.734 & -11.354 & -35.971 & -65.185 \\ 8.646 & NaN & NaN & NaN \end{bmatrix}$$

Figure 7-2 Table over interval for lifting through wave zone. Only values bigger than 0 is acceptable, full calculation in appendix: lifting through wave zone - simplified method.

The material should be consistent, so it does not generate electrochemical difference. S 355 steel is used on the original model, therefore in the concepts, this is the material as well. S 355 is a very common steel and is passing every check in chapter 6. HE-B are an open cross section; hence the entire surface can be coated for protection against corrosion.

7.3. CORROSION

There are two main types of corrosions on the SDB, galvanic corrosion, and crevice corrosion.
Galvanic corrosion is the easiest to discover since it is forming around the connection of two different galvanic loaded members. There are anodes on the SDB, these work by using anodes to draw the loaded electrons to them instead of the other members.

The bolts and washers in the concept 2 are carbon steel, hence they should have a low electrochemical difference between the bolts and base material, to reduce galvanic corrosion. There is however no guarantee that even the two carbon steels have the exact same chemical composition, so a minor difference is likely to exist.

In the welded joints the metals are joint together, therefore galvanic corrosion is not forming in welded joints.

Crevice corrosion is a common corrosion problem in bolted joints. It forms where water gets trapped, and forms hydrochloric acid which attacks the metal. Methods to reduce the chance of this happening are by using stripe coat before assembly and caulk the joint so the joint is sealed off. When the caulking is done it is important that there is no moisture in the joint, if that is the case it still can corrode [28].

The DNV report about bolted joint incidents concluded that there required to be more research on crevice corrosion, and a standard for crevice corrosion protection and testing should be developed. This will help against crevice corrosion problems in the future, but at the time, sealing of or electrical isolation of the joint is used to reduce the chance of crevice corrosion [10].

Corrosion is the main problem for the SDB, due to a lifetime of 25 years.

Mitigating measures will include coating schemes that themselves are not necessarily able to provide adequate protection for the duration of the lifetime, hence more research is required.

7.4. SUMMARY CONCLUSION

Strength and stiffness of a weld will have no problem over time if done correctly
The SDB is not subjected to alternating loading, hence no fatigue problems.
Strength and stiffness of a bolt can be difficult due to loss in preload over time.
DNV has discovered that there need to be better standards and testing for bolts offshore.
Material selection for existing standards is OK!
Can consider heavier profiles to help against slack slings.
Inherent corrosion challenges in bolted joints for long lifetime
Welds are overall better than bolts over its lifetime in the underwater environment, due to no fatigue problems
Blue Logic need to check the risk vs reward if bolted joints are to be considered, welds are safer but more expansive.

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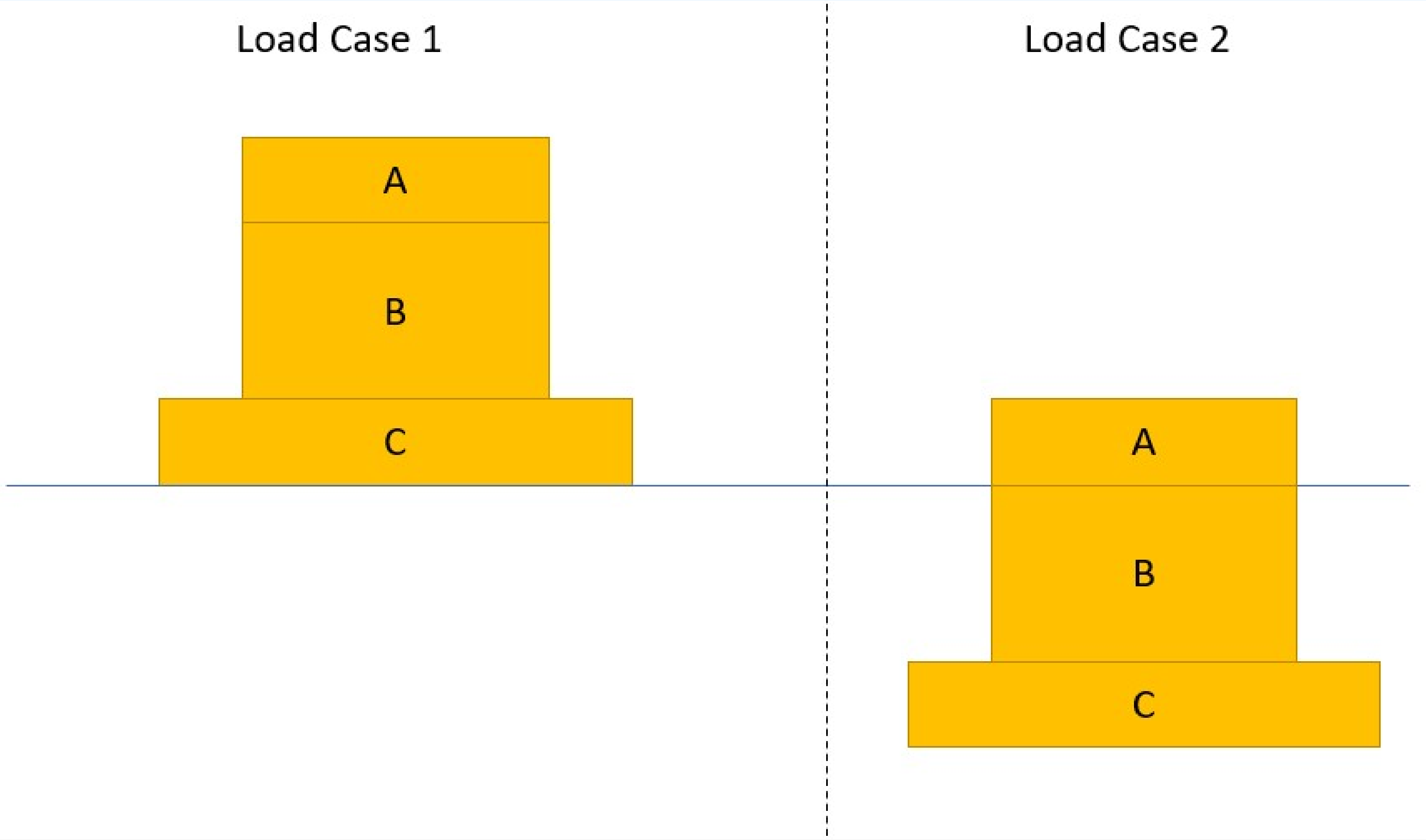
Load Cases

Load Case 1:

Includes only the contribution of slamming force

Load Case 2:

Includes slamming of A + mass and drag of B and C



Variable Coefficients:

$C_S := 3$ Slamming coefficient, between 3-5

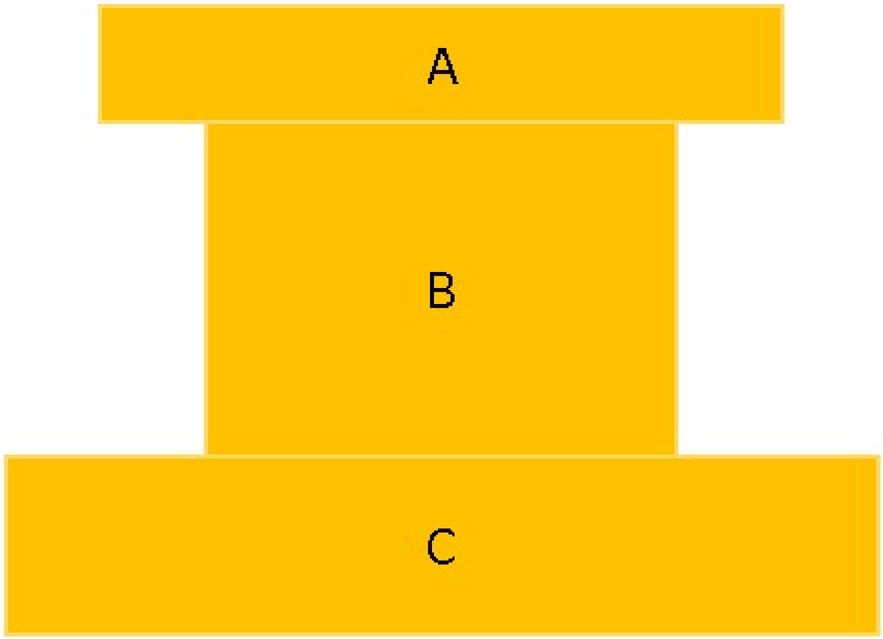
$C_D := 2$ Drag coefficient

Lifting Through Wave Zone - Simplified Method

Geometry and Mass:

$d1 := 0\ m$ Distance from water plane to center of gravity of submerged part of object

$d2 := 1\ m$ Distance from water plane to center of gravity of submerged part of object



$M_a := 2115\ kg$ Mass part "a" of object in air

$M_b := 2300\ kg$ Mass part "b" of object in air

$M_c := 1200\ kg$ Mass part "c" of object in air

$M_{tot} := M_a + M_b + M_c$ Total mass of object in air

$V_a := 0.358\ m^3$ Volume of part "a"

$V_b := 0.4\ m^3$ Volume of part "b"

$V_c := 0.3\ m^3$ Volume of part "c"

$V_{tot} := V_a + V_b + V_c$ Total volume of object in air

$A_{pa} := 4.5\ m \cdot 3\ m$ Projected area of part "a"

$A_{pb} := (2.6\ m)^2$ Projected area of part "b"

$A_{pc} := 2 \cdot (1\ m \cdot 4.5\ m)$ Projected area of part "c"

Sea State:

$$H_s := \begin{bmatrix} 1.5 \\ 2 \\ 2.5 \\ 3 \end{bmatrix} \cdot m$$

$T_{z1.5}$ (s)	$T_{z2.0}$ (s)	$T_{z2.5}$ (s)	$T_{z3.0}$ (s)
3.48	4.02	4.49	4.92
5.48	6.02	6.49	6.92
6.48	7.02	7.49	7.92
7.48	8.02	8.49	8.92
8.48	9.02	9.49	9.92
9.48	10.02	10.49	10.92
10.48	11.02	11.49	11.92
11.48	12.02	12.49	12.92
12.48	13.02	13.49	13.92
13.48	13.00	13.00	13.00
13.00	NaN	NaN	NaN

Zero up-crossing periods for Hs between 1.5m to 3.0m in the range:

$$8.9 \cdot \sqrt{\frac{H_s}{g}} \le T_z \le 13$$

Water partical velocity:

$$v_w\left(d, T_z, H_s\right) := \left\| \begin{array}{l} \zeta_a \leftarrow 0.9 \cdot H_s \\ v_w \leftarrow \overrightarrow{\zeta_a \cdot \left(\dfrac{2 \cdot \pi}{T_z}\right) \cdot e^{-\frac{4 \cdot \pi^2 \cdot d}{\left(T_z\right)^2 \cdot g}}} \end{array} \right.$$

$$v_{w.LC1} := \text{augment}\left(v_w\left(d1, T_{z1.5}, H_{s_0}\right), v_w\left(d1, T_{z2.0}, H_{s_1}\right), v_w\left(d1, T_{z2.5}, H_{s_2}\right), v_w\left(d1, T_{z3.0}, H_{s_3}\right)\right) = \begin{bmatrix} 2.437 & 2.813 & 3.149 & 3.448 \\ 1.548 & 1.879 & 2.178 & 2.452 \\ 1.309 & 1.611 & 1.887 & 2.142 \\ 1.134 & 1.41 & 1.665 & 1.902 \\ 1 & 1.254 & 1.49 & 1.71 \\ 0.895 & 1.129 & 1.348 & 1.554 \\ 0.809 & 1.026 & 1.23 & 1.423 \\ 0.739 & 0.941 & 1.132 & 1.313 \\ 0.68 & 0.869 & 1.048 & 1.219 \\ 0.629 & 0.87 & 1.087 & 1.305 \\ 0.652 & NaN & NaN & NaN \end{bmatrix} \frac{m}{s}$$

$$v_{w.LC2} := \text{augment}\left(v_w\left(d2, T_{z1.5}, H_{s_0}\right), v_w\left(d2, T_{z2.0}, H_{s_1}\right), v_w\left(d2, T_{z2.5}, H_{s_2}\right), v_w\left(d2, T_{z3.0}, H_{s_3}\right)\right) = \begin{bmatrix} 1.748 & 2.193 & 2.579 & 2.92 \\ 1.354 & 1.681 & 1.98 & 2.254 \\ 1.189 & 1.485 & 1.757 & 2.009 \\ 1.055 & 1.325 & 1.575 & 1.808 \\ 0.946 & 1.193 & 1.425 & 1.642 \\ 0.856 & 1.084 & 1.299 & 1.502 \\ 0.78 & 0.993 & 1.193 & 1.383 \\ 0.717 & 0.915 & 1.103 & 1.282 \\ 0.662 & 0.848 & 1.025 & 1.194 \\ 0.615 & 0.85 & 1.062 & 1.274 \\ 0.637 & NaN & NaN & NaN \end{bmatrix} \frac{m}{s}$$

Water partical acceleration:

$$a_w\left(d, T_z, H_s\right) := \left\| \begin{array}{l} \zeta_a \leftarrow 0.9 \cdot H_s \\ v_w \leftarrow \overrightarrow{\zeta_a \cdot \left(\frac{2 \cdot \pi}{T_z}\right)^2 \cdot e^{-\frac{4 \cdot \pi^2 \cdot d}{\left(T_z\right)^2 \cdot g}}} \end{array} \right.$$

$$a_{w.LC1} := \text{augment}\left(a_w\left(d1, T_{z1.5}, H_{s_0}\right), a_w\left(d1, T_{z2.0}, H_{s_1}\right), a_w\left(d1, T_{z2.5}, H_{s_2}\right), a_w\left(d1, T_{z3.0}, H_{s_3}\right)\right) = \begin{bmatrix} 4.401 & 4.397 & 4.406 & 4.403 \\ 1.775 & 1.961 & 2.109 & 2.226 \\ 1.269 & 1.442 & 1.583 & 1.699 \\ 0.953 & 1.105 & 1.232 & 1.34 \\ 0.741 & 0.873 & 0.986 & 1.083 \\ 0.593 & 0.708 & 0.807 & 0.894 \\ 0.485 & 0.585 & 0.673 & 0.75 \\ 0.404 & 0.492 & 0.569 & 0.639 \\ 0.342 & 0.419 & 0.488 & 0.55 \\ 0.293 & 0.42 & 0.526 & 0.631 \\ 0.315 & NaN & NaN & NaN \end{bmatrix} \frac{m}{s^2}$$

$$a_{w.LC2} := \text{augment}\left(a_w\left(d2, T_{z1.5}, H_{s_0}\right), a_w\left(d2, T_{z2.0}, H_{s_1}\right), a_w\left(d2, T_{z2.5}, H_{s_2}\right), a_w\left(d2, T_{z3.0}, H_{s_3}\right)\right) = \begin{bmatrix} 3.156 & 3.428 & 3.609 & 3.729 \\ 1.552 & 1.755 & 1.917 & 2.046 \\ 1.153 & 1.329 & 1.474 & 1.594 \\ 0.886 & 1.038 & 1.165 & 1.274 \\ 0.701 & 0.831 & 0.943 & 1.04 \\ 0.567 & 0.68 & 0.778 & 0.864 \\ 0.468 & 0.566 & 0.653 & 0.729 \\ 0.392 & 0.478 & 0.555 & 0.623 \\ 0.333 & 0.409 & 0.477 & 0.539 \\ 0.287 & 0.411 & 0.513 & 0.616 \\ 0.308 & NaN & NaN & NaN \end{bmatrix} \frac{m}{s^2}$$

Slamming Force:

$\rho := 1025 \dfrac{kg}{m^3}$ Density of seawater

$v_c := 0.5 \dfrac{m}{s}$ Lowering velocity

$v_{ct} := 0.1 \dfrac{m}{s}$ Crane tip velocity

$v_{s.LC1} := v_c + \overrightarrow{\sqrt{{v_{ct}}^2 + {v_{w.LC1}}^2}}$ Slamming impact velocity

$v_{s.LC2} := v_c + \overrightarrow{\sqrt{{v_{ct}}^2 + {v_{w.LC2}}^2}}$ Slamming impact velocity

$A_{s.LC1} := (4.5\ m)^2 = 20.25\ m^2$

$A_{s.LC2} := A_{pa} = 13.5\ m^2$

$$F_{slam.LC1} := \overrightarrow{0.5 \cdot \rho \cdot C_S \cdot A_{s.LC1} \cdot {v_{s.LC1}}^2} = \begin{bmatrix} 269.02 & 342.172 & 414.828 & 485.661 \\ 130.982 & 176.558 & 223.719 & 271.603 \\ 102.316 & 139.162 & 177.86 & 217.706 \\ 83.575 & 114.026 & 146.359 & 180.005 \\ 70.544 & 96.204 & 123.673 & 152.485 \\ 61.052 & 83.04 & 106.717 & 131.705 \\ 53.882 & 72.992 & 93.662 & 115.578 \\ 48.307 & 65.118 & 83.36 & 102.773 \\ 43.867 & 58.81 & 75.064 & 92.41 \\ 40.26 & 58.924 & 78.915 & 101.864 \\ 41.902 & NaN & NaN & NaN \end{bmatrix} kN$$ Slamming force

$$F_{slam.LC2} := \overrightarrow{0.5 \cdot \rho \cdot C_S \cdot A_{s.LC2} \cdot {v_{s.LC2}}^2} = \begin{bmatrix} 105.169 & 150.785 & 196.978 & 242.988 \\ 71.605 & 99.018 & 127.893 & 157.664 \\ 59.53 & 82.037 & 105.979 & 130.905 \\ 50.512 & 69.389 & 89.617 & 110.833 \\ 43.705 & 59.809 & 77.161 & 95.468 \\ 38.469 & 52.405 & 67.483 & 83.465 \\ 34.36 & 46.568 & 59.818 & 73.913 \\ 31.076 & 41.883 & 53.64 & 66.183 \\ 28.405 & 38.06 & 48.583 & 59.833 \\ 26.201 & 38.13 & 50.939 & 65.629 \\ 27.208 & NaN & NaN & NaN \end{bmatrix} kN$$ Slamming force

Added Mass:

$a_a := 3\ m$ Width of A

$b_a := 4.5\ m$ Length of A

$a_b := 2.6\ m$ Width of B

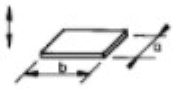
$b_b := 2.6\ m$ Length of B

$a_c := 4.5\ m$ Width of C

$b_c := 4.5\ m$ Length of C

$$C_A(a,b) := \begin{array}{l} \text{if } \frac{b}{a} = 1.00 \\ \quad C_A \leftarrow 0.579 \\ \text{else if } \frac{b}{a} = 1.25 \\ \quad C_A \leftarrow 0.642 \\ \text{else if } \frac{b}{a} = 1.50 \\ \quad C_A \leftarrow 0.690 \\ \text{else if } \frac{b}{a} = 1.59 \\ \quad C_A \leftarrow 0.704 \\ \text{else if } \frac{b}{a} = 2.00 \\ \quad C_A \leftarrow 0.757 \\ \text{else if } \frac{b}{a} = 2.50 \\ \quad C_A \leftarrow 0.801 \\ \text{else if } \frac{b}{a} = 3.00 \\ \quad C_A \leftarrow 0.830 \\ \text{else if } \frac{b}{a} = 3.17 \\ \quad C_A \leftarrow 0.840 \\ \text{else if } \frac{b}{a} = 4.00 \\ \quad C_A \leftarrow 0.872 \\ \text{else if } \frac{b}{a} = 5.00 \\ \quad C_A \leftarrow 0.897 \\ \text{else if } \frac{b}{a} = 6.25 \\ \quad C_A \leftarrow 0.917 \\ \text{else if } \frac{b}{a} = 8.00 \\ \quad C_A \leftarrow 0.934 \\ \text{else if } \frac{b}{a} = 10.00 \\ \quad C_A \leftarrow 0.947 \\ \text{else if } \frac{b}{a} = \infty \\ \quad C_A \leftarrow 1.00 \\ \text{else} \end{array}$$

V_R

		b/a	C_A	b/a	C_A	
Rectangular plates 	Vertical	1.00	0.579	3.17	0.840	$\frac{\pi}{4}a^2b$
		1.25	0.642	4.00	0.872	
		1.50	0.690	5.00	0.897	
		1.59	0.704	6.25	0.917	
		2.00	0.757	8.00	0.934	
		2.50	0.801	10.00	0.947	
		3.00	0.830	∞	1.000	

$C_{A.a} := C_A(a_a, b_a) = 0.69$ Mass coeffficient of A

$C_{A.b} := C_A(a_b, b_b) = 0.579$ Mass coeffficient of B

$C_{A.c} := C_A(a_c, b_c) = 0.579$ Mass coeffficient of C

$V_{R.a} := \frac{\pi}{4} \cdot a_a^{\ 2} \cdot b_a = 31.809\ m^3$ Refernce volume of A

$V_{R.b} := \frac{\pi}{4} \cdot a_b^{\ 2} \cdot b_b = 13.804\ m^3$ Refernce volume of B

$V_{R.c} := \frac{\pi}{4} \cdot a_c^{\ 2} \cdot b_c = 71.569\ m^3$ Refernce volume of C

4.6.3.3 The following simplified approximation of the added mass in heave for a three-dimensional body with vertical sides may be applied:

$$A_{33} \approx \left[1 + \sqrt{\frac{1-\lambda^2}{2(1+\lambda^2)}}\right] \cdot A_{33o} \quad [\text{kg}]$$

$$\text{and} \lambda = \frac{\sqrt{A_p}}{h+\sqrt{A_p}} \quad [-]$$

where:

A_{33o} = added mass for a flat plate with a shape equal to the horizontal projected area of the object [kg]

h = height of the object [m]

A_p = area of submerged part of object projected on a horizontal plane [m^2].

4.6.3.4 A structure that contains a partly enclosed volume of water moving together with the structure may be taken as a three-dimensional body where the mass of the partly enclosed water volume is included in the added mass.

$A_{33oa} := \rho \cdot C_{A.a} \cdot V_{R.a} = 22496.65\ kg$ Added mass of A

"Check Geometry"

$A_{33ob} := \rho \cdot C_{A.b} \cdot V_{R.b} = 8192.42\ kg$ Added mass of B

$A_{33oc} := \rho \cdot C_{A.c} \cdot V_{R.c} = 42474.65\ kg$ Added mass of C

$h_a := 0.68\ m$ height of object

$h_b := 1.65\ m$ height of object

$h_c := 0.18\ m$ height of object

$$\lambda_a := \frac{\sqrt{A_{pa}}}{h_a + \sqrt{A_{pa}}} = 0.844$$

$$\lambda_b := \frac{\sqrt{A_{pb}}}{h_b + \sqrt{A_{pb}}} = 0.612$$

$$\lambda_c := \frac{\sqrt{A_{pc}}}{h_c + \sqrt{A_{pc}}} = 0.943$$

$$A_{33a} := \left(1 + \sqrt{\frac{1 - \lambda_a^2}{2 \cdot (1 + \lambda_a^2)}}\right) \cdot A_{33oa} = \left(2.902 \cdot 10^4\right)\ kg$$

$$A_{33b} := \left(1 + \sqrt{\frac{1 - \lambda_b^2}{2 \cdot (1 + \lambda_b^2)}}\right) \cdot A_{33ob} = \left(1.21 \cdot 10^4\right)\ kg$$

$$A_{33c} := \left(1 + \sqrt{\frac{1 - \lambda_c^2}{2 \cdot (1 + \lambda_c^2)}}\right) \cdot A_{33oc} = \left(4.972 \cdot 10^4\right)\ kg$$

$p_a := 10$ Per cent perforation of A

$p_b := 50$ Per cent perforation of B

$p_c := 50$ Per cent perforation of C

4.6.4 Effect of perforation

4.6.4.1 The effect of perforation on the added mass may roughly be estimated by the following guidance:

$$A_{33} = A_{33s} \quad \text{if} \quad p \le 5 A_{33} = A_{33s} \cdot \left(0.7 + 0.3 \cdot \cos\left[\frac{\pi (p-5)}{34}\right]\right) \quad \text{if} \quad 5 < p < 34 \text{and} A_{33} = A_{33s} \cdot e^{\frac{10-p}{28}} \quad \text{if} \quad 34 \le p \le 50$$

where:

$A_{33S} =$ solid added mass (added mass in heave for a non-perforated structure) [kg]

p = perforation rate (percentage) [-].

Enclosed water:

$V_{enclosed.a} := (a_a \cdot b_a \cdot h_a) \cdot 0.75 = 6.885\ m^3$ Enclosed or "trapped" water volume of A (assumed to be a percentage of the projected volume)

$V_{enclosed.b} := (a_b \cdot b_b \cdot h_b) \cdot 0.95 = 10.596\ m^3$ Enclosed or "trapped" water volume of B (assumed to be a percentage of the projected volume)

$V_{enclosed.c} := (a_c \cdot b_c \cdot h_c) \cdot 0.9 = 3.281\ m^3$ Enclosed or "trapped" water volume of C (assumed to be a percentage of the projected volume)

$M_{enclosed.a} := \rho \cdot V_{enclosed.a} = 7057.13\ kg$ Enclosed masss of A

$M_{enclosed.b} := \rho \cdot V_{enclosed.b} = 10861.208\ kg$ Enclosed masss of B

$M_{enclosed.c} := \rho \cdot V_{enclosed.c} = 3362.513\ kg$ Enclosed masss of C

$$A_{33p}(p, A_{33}) := \left\| \begin{array}{l} \text{if } p \le 5 \\ \quad \| A_{33} \leftarrow A_{33} \\ \text{else if } 5 < p < 34 \\ \quad \left\| A_{33} \leftarrow A_{33} \cdot \left(0.7 + 0.3 \cdot \cos\left(\frac{\pi \cdot (p-5)}{34}\right)\right) \right. \\ \text{else if } 34 \le p \le 50 \\ \quad \left\| A_{33} \leftarrow A_{33} \cdot e^{\frac{10-p}{28}} \right. \\ \text{else} \\ \quad \| \text{“Check Geometry”} \end{array} \right.$$

$A_{33ap} := A_{33p}(p_a, A_{33a}) + M_{enclosed.a} = 35164.898\ kg$

$A_{33bp} := A_{33p}(p_b, A_{33b}) + M_{enclosed.b} = 13761.318\ kg$

$A_{33cp} := A_{33p}(p_c, A_{33c}) + M_{enclosed.c} = 15278.076\ kg$

Mass Force:

$a_{ct} := 0\ \frac{m}{s^2}$ Crane tip acceleration

$$F_{Ma.LC1} := \overrightarrow{\sqrt{\left(\left(M_a + A_{33ap}\right) \cdot a_{ct}\right)^2 + \left(\left(\rho \cdot V_a + A_{33ap}\right) \cdot a_{w.LC1}\right)^2}} = \begin{bmatrix} 156.37 & 156.242 & 156.555 & 156.463 \\ 63.059 & 69.672 & 74.933 & 79.091 \\ 45.098 & 51.236 & 56.26 & 60.38 \\ 33.846 & 39.256 & 43.787 & 47.601 \\ 26.334 & 31.034 & 35.045 & 38.487 \\ 21.071 & 25.149 & 28.682 & 31.761 \\ 17.242 & 20.792 & 23.907 & 26.656 \\ 14.369 & 17.476 & 20.232 & 22.689 \\ 12.159 & 14.895 & 17.343 & 19.546 \\ 10.422 & 14.94 & 18.676 & 22.411 \\ 11.205 & NaN & NaN & NaN \end{bmatrix} kN$$

$$F_{Ma.LC2} := \overrightarrow{\sqrt{\left(\left(M_a + A_{33ap}\right) \cdot a_{ct}\right)^2 + \left(\left(\rho \cdot V_a + A_{33ap}\right) \cdot a_{w.LC2}\right)^2}} = \begin{bmatrix} 112.147 & 121.79 & 128.217 & 132.491 \\ 55.148 & 62.347 & 68.102 & 72.714 \\ 40.976 & 47.217 & 52.364 & 56.626 \\ 31.496 & 36.874 & 41.408 & 45.252 \\ 24.9 & 29.536 & 33.513 & 36.945 \\ 20.148 & 24.16 & 27.652 & 30.707 \\ 16.622 & 20.114 & 23.189 & 25.911 \\ 13.937 & 16.996 & 19.716 & 22.148 \\ 11.848 & 14.545 & 16.964 & 19.144 \\ 10.193 & 14.589 & 18.236 & 21.883 \\ 10.942 & NaN & NaN & NaN \end{bmatrix} kN$$

$$F_{Mb.LC1} := \overrightarrow{\sqrt{\left(\left(M_b + A_{33bp}\right) \cdot a_{ct}\right)^2 + \left(\left(\rho \cdot V_b + A_{33bp}\right) \cdot a_{w.LC1}\right)^2}} = \begin{bmatrix} 62.366 & 62.315 & 62.44 & 62.403 \\ 25.15 & 27.788 & 29.886 & 31.544 \\ 17.987 & 20.435 & 22.438 & 24.081 \\ 13.499 & 15.656 & 17.464 & 18.985 \\ 10.503 & 12.377 & 13.977 & 15.35 \\ 8.404 & 10.03 & 11.439 & 12.667 \\ 6.877 & 8.292 & 9.535 & 10.631 \\ 5.731 & 6.97 & 8.069 & 9.049 \\ 4.849 & 5.94 & 6.917 & 7.796 \\ 4.156 & 5.959 & 7.448 & 8.938 \\ 4.469 & NaN & NaN & NaN \end{bmatrix} kN$$

$$F_{Mb.LC2} := \overrightarrow{\sqrt{\left(\left(M_b + A_{33bp}\right) \cdot a_{ct}\right)^2 + \left(\left(\rho \cdot V_b + A_{33bp}\right) \cdot a_{w.LC2}\right)^2}} = \begin{bmatrix} 44.728 & 48.574 & 51.137 & 52.842 \\ 21.995 & 24.866 & 27.162 & 29.001 \\ 16.342 & 18.832 & 20.885 & 22.585 \\ 12.562 & 14.707 & 16.515 & 18.048 \\ 9.931 & 11.78 & 13.366 & 14.735 \\ 8.036 & 9.636 & 11.028 & 12.247 \\ 6.629 & 8.022 & 9.248 & 10.334 \\ 5.558 & 6.778 & 7.864 & 8.834 \\ 4.726 & 5.801 & 6.766 & 7.635 \\ 4.065 & 5.818 & 7.273 & 8.728 \\ 4.364 & NaN & NaN & NaN \end{bmatrix} kN$$

$$F_{Mc.LC1} := \overrightarrow{\sqrt{\left(\left(M_c + A_{33cp}\right) \cdot a_{ct}\right)^2 + \left(\left(\rho \cdot V_c + A_{33cp}\right) \cdot a_{w.LC1}\right)^2}} = \begin{bmatrix} 68.59 & 68.534 & 68.671 & 68.63 \\ 27.66 & 30.561 & 32.868 & 34.692 \\ 19.782 & 22.474 & 24.678 & 26.485 \\ 14.846 & 17.219 & 19.207 & 20.879 \\ 11.551 & 13.613 & 15.372 & 16.882 \\ 9.243 & 11.031 & 12.581 & 13.932 \\ 7.563 & 9.12 & 10.486 & 11.692 \\ 6.303 & 7.666 & 8.874 & 9.952 \\ 5.333 & 6.533 & 7.607 & 8.574 \\ 4.571 & 6.553 & 8.192 & 9.83 \\ 4.915 & NaN & NaN & NaN \end{bmatrix} kN$$

$$F_{Mc.LC2} := \overrightarrow{\sqrt{\left(\left(M_c + A_{33cp}\right) \cdot a_{ct}\right)^2 + \left(\left(\rho \cdot V_c + A_{33cp}\right) \cdot a_{w.LC2}\right)^2}} = \begin{bmatrix} 49.192 & 53.422 & 56.241 & 58.115 \\ 24.19 & 27.348 & 29.872 & 31.895 \\ 17.973 & 20.711 & 22.969 & 24.838 \\ 13.815 & 16.174 & 18.163 & 19.849 \\ 10.922 & 12.955 & 14.7 & 16.205 \\ 8.838 & 10.598 & 12.129 & 13.469 \\ 7.291 & 8.823 & 10.171 & 11.366 \\ 6.113 & 7.455 & 8.648 & 9.715 \\ 5.197 & 6.38 & 7.441 & 8.397 \\ 4.471 & 6.399 & 7.999 & 9.599 \\ 4.799 & NaN & NaN & NaN \end{bmatrix} kN$$

$$F_{M.LC1} := F_{Ma.LC1} + F_{Mb.LC1} + F_{Mc.LC1} = \begin{bmatrix} 287.325 & 287.09 & 287.666 & 287.496 \\ 115.87 & 128.02 & 137.686 & 145.328 \\ 82.867 & 94.145 & 103.375 & 110.946 \\ 62.191 & 72.131 & 80.457 & 87.465 \\ 48.388 & 57.024 & 64.394 & 70.719 \\ 38.718 & 46.21 & 52.702 & 58.36 \\ 31.682 & 38.204 & 43.928 & 48.979 \end{bmatrix} kN$$

Total mass force

$$\begin{bmatrix} 26.403 & 32.112 & 37.175 & 41.69 \\ 22.341 & 27.368 & 31.868 & 35.916 \\ 19.149 & 27.453 & 34.316 & 41.179 \\ 20.589 & NaN & NaN & NaN \end{bmatrix}$$

$$F_{M.LC2} := F_{Ma.LC2} + F_{Mb.LC2} + F_{Mc.LC2} = \begin{bmatrix} 206.066 & 223.786 & 235.595 & 243.448 \\ 101.333 & 114.561 & 125.136 & 133.61 \\ 75.291 & 86.76 & 96.217 & 104.049 \\ 57.874 & 67.755 & 76.087 & 83.149 \\ 45.754 & 54.271 & 61.579 & 67.885 \\ 37.022 & 44.394 & 50.809 & 56.423 \\ 30.542 & 36.958 & 42.609 & 47.611 \\ 25.608 & 31.229 & 36.228 & 40.697 \\ 21.771 & 26.726 & 31.171 & 35.177 \\ 18.73 & 26.806 & 33.508 & 40.21 \\ 20.105 & NaN & NaN & NaN \end{bmatrix} kN$$

Total mass force

Drag Force:

$$v_{r.LC1} := \overrightarrow{v_c + \sqrt{{v_{ct}}^2 + {v_{w.LC1}}^2}} = \begin{bmatrix} 2.939 & 3.315 & 3.65 & 3.95 \\ 2.051 & 2.381 & 2.681 & 2.954 \\ 1.813 & 2.114 & 2.39 & 2.644 \\ 1.638 & 1.914 & 2.168 & 2.404 \\ 1.505 & 1.758 & 1.993 & 2.213 \\ 1.4 & 1.633 & 1.851 & 2.057 \\ 1.316 & 1.531 & 1.734 & 1.927 \\ 1.246 & 1.446 & 1.636 & 1.817 \\ 1.187 & 1.374 & 1.553 & 1.723 \\ 1.137 & 1.376 & 1.592 & 1.809 \\ 1.16 & NaN & NaN & NaN \end{bmatrix} \frac{m}{s}$$

Characteristic vertical relative velocity between object and water particles

$$v_{r.LC2} := \overrightarrow{v_c + \sqrt{{v_{ct}}^2 + {v_{w.LC2}}^2}} = \begin{bmatrix} 2.251 & 2.695 & 3.081 & 3.422 \\ 1.857 & 2.184 & 2.482 & 2.756 \\ 1.694 & 1.988 & 2.26 & 2.511 \\ 1.56 & 1.828 & 2.078 & 2.311 \\ 1.451 & 1.698 & 1.928 & 2.145 \\ 1.361 & 1.589 & 1.803 & 2.005 \\ 1.287 & 1.498 & 1.698 & 1.887 \\ 1.224 & 1.421 & 1.608 & 1.786 \\ 1.17 & 1.354 & 1.53 & 1.698 \\ 1.124 & 1.355 & 1.567 & 1.778 \\ 1.145 & NaN & NaN & NaN \end{bmatrix} \frac{m}{s}$$

$$F_{Da.LC1} := \overrightarrow{0.5 \cdot \rho \cdot C_D \cdot A_{pa} \cdot {v_{r.LC1}}^2} = \begin{bmatrix} 119.565 & 152.077 & 184.368 & 215.849 \\ 58.214 & 78.47 & 99.431 & 120.713 \\ 45.474 & 61.85 & 79.049 & 96.758 \\ 37.145 & 50.678 & 65.049 & 80.002 \\ 31.353 & 42.758 & 54.966 & 67.771 \\ 27.134 & 36.907 & 47.43 & 58.536 \\ 23.948 & 32.441 & 41.627 & 51.368 \\ 21.47 & 28.941 & 37.049 & 45.677 \\ 19.496 & 26.138 & 33.362 & 41.071 \\ 17.893 & 26.188 & 35.073 & 45.273 \\ 18.623 & NaN & NaN & NaN \end{bmatrix} kN$$

"

Drag force of A

$$F_{Da.LC2} := \overrightarrow{0.5 \cdot \rho \cdot C_D \cdot A_{pa} \cdot {v_{r.LC2}}^2} = \begin{bmatrix} 70.113 & 100.524 & 131.319 & 161.992 \\ 47.737 & 66.012 & 85.262 & 105.109 \\ 39.686 & 54.691 & 70.653 & 87.27 \\ 33.675 & 46.26 & 59.744 & 73.889 \\ 29.137 & 39.873 & 51.44 & 63.645 \\ 25.646 & 34.937 & 44.989 & 55.643 \\ 22.907 & 31.045 & 39.878 & 49.275 \\ 20.717 & 27.922 & 35.76 & 44.122 \\ 18.937 & 25.373 & 32.388 & 39.889 \\ 17.467 & 25.42 & 33.959 & 43.753 \\ 18.139 & NaN & NaN & NaN \end{bmatrix} kN$$

$$F_{Db.LC1} := \overrightarrow{0.5 \cdot \rho \cdot C_D \cdot A_{pb} \cdot v_{r.LC1}^{\ 2}} = \begin{bmatrix} 59.871 & 76.151 & 92.321 & 108.085 \\ 29.15 & 39.293 & 49.789 & 60.446 \\ 22.771 & 30.971 & 39.583 & 48.451 \\ 18.6 & 25.377 & 32.573 & 40.06 \\ 15.7 & 21.41 & 27.524 & 33.936 \\ 13.587 & 18.481 & 23.75 & 29.311 \\ 11.992 & 16.245 & 20.845 & 25.722 \\ 10.751 & 14.492 & 18.552 & 22.872 \\ 9.763 & 13.088 & 16.706 & 20.566 \\ 8.96 & 13.114 & 17.563 & 22.67 \\ 9.325 & NaN & NaN & NaN \end{bmatrix} kN$$

$$F_{Db.LC2} := \overrightarrow{0.5 \cdot \rho \cdot C_D \cdot A_{pb} \cdot v_{r.LC2}^{\ 2}} = \begin{bmatrix} 35.108 & 50.336 & 65.757 & 81.116 \\ 23.904 & 33.055 & 42.694 & 52.633 \\ 19.873 & 27.386 & 35.379 & 43.7 \\ 16.862 & 23.164 & 29.916 & 36.999 \\ 14.59 & 19.966 & 25.758 & 31.87 \\ 12.842 & 17.494 & 22.528 & 27.863 \\ 11.47 & 15.546 & 19.969 & 24.674 \\ 10.374 & 13.982 & 17.906 & 22.094 \\ 9.482 & 12.706 & 16.218 & 19.974 \\ 8.747 & 12.729 & 17.005 & 21.909 \\ 9.083 & NaN & NaN & NaN \end{bmatrix} kN$$

$$F_{Dc.LC1} := \overrightarrow{0.5 \cdot \rho \cdot C_D \cdot A_{pc} \cdot v_{r.LC1}^{\ 2}} = \begin{bmatrix} 79.71 & 101.384 & 122.912 & 143.899 \\ 38.809 & 52.314 & 66.287 & 80.475 \\ 30.316 & 41.233 & 52.699 & 64.506 \\ 24.763 & 33.785 & 43.366 & 53.335 \\ 20.902 & 28.505 & 36.644 & 45.181 \\ 18.089 & 24.604 & 31.62 & 39.024 \\ 15.965 & 21.627 & 27.752 & 34.245 \\ 14.313 & 19.294 & 24.699 & 30.451 \\ 12.997 & 17.425 & 22.241 & 27.381 \\ 11.929 & 17.459 & 23.382 & 30.182 \\ 12.415 & NaN & NaN & NaN \end{bmatrix} kN$$

$$F_{Dc.LC2} := \overrightarrow{0.5 \cdot \rho \cdot C_D \cdot A_{pc} \cdot v_{r.LC2}^{\ 2}} = \begin{bmatrix} 46.742 & 67.016 & 87.546 & 107.994 \\ 31.824 & 44.008 & 56.841 & 70.073 \\ 26.458 & 36.461 & 47.102 & 58.18 \\ 22.45 & 30.84 & 39.83 & 49.259 \\ 19.425 & 26.582 & 34.294 & 42.43 \\ 17.097 & 23.291 & 29.992 & 37.095 \\ 15.271 & 20.697 & 26.586 & 32.85 \\ 13.811 & 18.614 & 23.84 & 29.415 \\ 12.625 & 16.916 & 21.592 & 26.593 \\ 11.645 & 16.946 & 22.64 & 29.168 \\ 12.093 & NaN & NaN & NaN \end{bmatrix} kN$$

$$F_{D.LC1} := F_{Da.LC1} + F_{Db.LC1} + F_{Dc.LC1} = \begin{bmatrix} 259.145 & 329.612 & 399.601 & 467.833 \\ 126.174 & 170.077 & 215.506 & 261.633 \\ 98.561 & 134.054 & 171.332 & 209.715 \\ 80.508 & 109.84 & 140.987 & 173.398 \\ 67.955 & 92.673 & 119.133 & 146.888 \\ 58.811 & 79.991 & 102.8 & 126.871 \\ 51.904 & 70.313 & 90.224 & 111.335 \\ 46.533 & 62.728 & 80.3 & 99 \\ 42.256 & 56.652 & 72.309 & 89.018 \\ 38.782 & 56.761 & 76.018 & 98.124 \\ 40.364 & NaN & NaN & NaN \end{bmatrix} kN$$

Total drag foce

$$F_{D.LC2} := F_{Da.LC2} + F_{Db.LC2} + F_{Dc.LC2} = \begin{bmatrix} 151.962 & 217.875 & 284.622 & 351.102 \\ 103.465 & 143.075 & 184.798 & 227.815 \\ 86.017 & 118.538 & 153.133 & 189.15 \\ 72.987 & 100.264 & 129.491 & 160.148 \\ 63.151 & 86.421 & 111.492 & 137.945 \\ 55.585 & 75.722 & 97.509 & 120.601 \\ 49.649 & 67.288 & 86.433 & 106.799 \\ 44.903 & 60.518 & 77.506 & 95.63 \\ 41.044 & 54.995 & 70.199 & 86.456 \\ 37.859 & 55.095 & 73.604 & 94.83 \\ 39.315 & NaN & NaN & NaN \end{bmatrix} kN$$

Hydrodynamic Force:

$F_\rho := 0$ Assuming buoyancy is zero

$$F_{hyd.LC1} := \overrightarrow{\sqrt{\left(F_{D.LC1}+F_{slam.LC1}\right)^2+\left(F_{M.LC1}-F_\rho\right)^2}} = \begin{bmatrix} 601.261 & 730.558 & 863.739 & 995.894 \\ 282.054 & 369.52 & 460.3 & 552.686 \\ 217.298 & 288.982 & 364.172 & 441.585 \\ 175.474 & 235.199 & 298.398 & 364.066 \\ 146.709 & 197.298 & 251.2 & 307.612 \\ 125.961 & 169.453 & 216.044 & 265.08 \\ 110.429 & 148.31 & 189.059 & 232.139 \\ 98.446 & 131.817 & 167.83 & 206.036 \\ 88.973 & 118.661 & 150.78 & 184.948 \\ 81.329 & 118.898 & 158.688 & 204.183 \\ 84.803 & NaN & NaN & NaN \end{bmatrix} kN$$

Hydrodynamic force

4.3.9 Hydrodynamic force

4.3.9.1 The characteristic hydrodynamic force on an object when lowered through water surface is a time dependent function of slamming impact force, varying buoyancy, hydrodynamic mass forces and drag forces.

4.3.9.2 The following combination of the various load components is acceptable in this Simplified Method:

$$F_{hyd} = \sqrt{(F_D + F_{slam})^2 + (F_M - F_\rho)^2} \quad [N]$$

where:

F_D = characteristic hydrodynamic drag force [N]

F_{slam} = characteristic slamming impact force [N]

F_M = characteristic hydrodynamic mass force [N]

F_ρ = characteristic varying buoyancy force [N].

Guidance note:

During lowering through the water surface, the structure may have both fully submerged parts and items in the splash zone. The slamming force acting on the surface crossing item is then in phase with the drag force acting on the fully submerged part. Likewise, the mass and varying buoyancy forces are 180° out of phase.

---e-n-d---of---g-u-i-d-a-n-c-e---n-o-t-e---

$$F_{hyd.LC2} := \overrightarrow{\sqrt{\left(F_{D.LC2}+F_{slam.LC2}\right)^2+\left(F_{M.LC2}-F_\rho\right)^2}} = \begin{bmatrix} 329.515 & 431.266 & 536.137 & 642.035 \\ 202.281 & 267.83 & 336.8 & 407.978 \\ 163.867 & 218.535 & 276.399 & 336.543 \\ 136.387 & 182.682 & 231.942 & 283.451 \\ 116.24 & 155.977 & 198.449 & 243.084 \\ 101.079 & 135.6 & 172.638 & 211.723 \\ 89.388 & 119.704 & 152.331 & 186.879 \\ 80.178 & 107.056 & 136.058 & 166.852 \\ 72.782 & 96.817 & 122.804 & 150.459 \\ 66.742 & 97.002 & 128.972 & 165.42 \\ 69.495 & NaN & NaN & NaN \end{bmatrix} kN$$

Slack Sling:

$M_{final} := M_{tot} + 2500\ kg$

The final mass includes the additional mass from equipement such as jacks, anodes and cable deflectors

Slack sling criterion:

$M_{final} \cdot g + F_M - \left(F_{slam} + F_D\right) > 0$

$$M_{tot} \cdot g + F_{M.LC1} - \left(F_{slam.LC1} + F_{D.LC1}\right) = \begin{bmatrix} -185.776 & -329.629 & -471.699 & -610.934 \\ -86.221 & -163.551 & -246.474 & -332.844 \\ -62.946 & -124.007 & -190.752 & -261.411 \\ -46.828 & -96.67 & -151.825 & -210.874 \\ -35.046 & -76.789 & -123.347 & -173.589 \\ -26.08 & -61.757 & -101.75 & -145.151 \\ -19.04 & -50.037 & -84.893 & -122.87 \\ -13.373 & -40.67 & -71.421 & -105.019 \\ -8.717 & -33.029 & -60.441 & -90.448 \\ -4.828 & -33.168 & -65.553 & -103.745 \\ -6.612 & NaN & NaN & NaN \end{bmatrix}\ kN$$

$$M_{tot} \cdot g + F_{M.LC2} - \left(F_{slam.LC2} + F_{D.LC2}\right) = \begin{bmatrix} 4 & -89.811 & -190.941 & -295.578 \\ -18.672 & -72.467 & -132.49 & -196.804 \\ -15.19 & -58.751 & -107.83 & -160.941 \\ -10.562 & -46.834 & -87.956 & -132.767 \\ -6.039 & -36.895 & -72.009 & -110.463 \\ -1.968 & -28.669 & -59.118 & -92.579 \\ 1.597 & -21.833 & -48.578 & -78.037 \\ 4.694 & -16.107 & -39.853 & -66.051 \\ 7.386 & -11.264 & -32.546 & -56.048 \\ 9.734 & -11.354 & -35.971 & -65.185 \\ 8.646 & NaN & NaN & NaN \end{bmatrix}\ kN$$

Design Load:

$DAF := 2.5$ According to DNV-ST-E273

$$F_{hyd.rel} := \text{submatrix}\left(F_{hyd.LC1}, 3, 6, 0, 3\right) = \begin{bmatrix} 175.474 & 235.199 & 298.398 & 364.066 \\ 146.709 & 197.298 & 251.2 & 307.612 \\ 125.961 & 169.453 & 216.044 & 265.08 \\ 110.429 & 148.31 & 189.059 & 232.139 \end{bmatrix} \; kN$$

Load Case 1 is worst case

$F_{design} := DAF \cdot \max\left(F_{hyd.rel}\right) = 910.164 \; kN$ Design load

$SKL := 1.33$

Skew Load Factor due to sling length tolerances. SKL shall be taken as minimum 1.33 (assuming sling sets made of matched slings) for a 4-leg lifting set.

$PL := 0.25$

Percentage loading of F (quasi-static calculations) in the most loaded pad eye, taking into consideration most extreme location of CoG.

$\nu := 30 \; deg$ Angle of sling from vertical

$$RSF := \frac{1.2 \cdot SKL \cdot PL \cdot F_{design}}{\cos\left(\nu\right)} = 419.336 \; kN$$

Resultant sling force

$F_{projected} := RSF \cdot \cos\left(2 \cdot \nu\right) = 209.668 \; kN$ Projected force to the horizontal plane

$fx := F_{projected} \cdot \cos\left(45 \; deg\right) = 148.258 \; kN$ Force in X-direction in the horizontal plane (input to NASTRAN)

$fy := fx = 148.258 \; kN$ Force in Y-direction in the horizontal plane (input to NASTRAN)

$fz := RSF \cdot \sin\left(2 \cdot \nu\right) = 363.156 \; kN$ Force in Z-direction in the vertical plane (input to NASTRAN)