Terra Nova Calcium Nitrate Storage Tank

Prepared for:

Tim Matthews, P. Eng., Wood Group PSN

Completed by:

Stephen Lundrigan
Helena Greene
Bradley Burton
Sarah Mapplebeck

April 3, 2013

Engineering 8700: Civil Engineering Project

Justin Skinner, P. Eng
Amgad Hussein, P. Eng.
Stephen Bruneau, P. Eng.

BHS Consultants
Faculty of Engineering and Applied Science
Memorial University of Newfoundland
St. John’s, NL
A1B 3X5
BHSconsulting@live.com

Wednesday April 3, 2013

Tim Matthews, P. Eng.
Wood Group PSN
227-281 Water Street
St. John’s, NL
A1C 6L3

Subject: Terra Nova Calcium Nitrate Module Design

Dear Mr. Matthews,

BHS Consultants is pleased to present the enclosed design report for the Terra Nova calcium nitrate module. This report displays the design of the calcium nitrate storage tank and supporting platform design. This report is also a requirement for the Engineering 8700 project course.

The enclosed report presents the detailed design of the structures, including modelling images and calculations as completed by BHS Consultants. As part of the project, the design for seafastening during transportation and lifting onto the Terra Nova FPSO is also included. Finally, this report displays the cost estimate that was completed for the structures.

If you have any questions or concerns regarding this design report, we would be glad to discuss them with you at your convenience.

Sincerely,

BHS Consultants

Stephen Lundrigan | Helena Greene

Bradley Burton | Sarah Mapplebeck

Executive Summary

The Terra Nova FPSO is located southeast of Newfoundland in the Terra Nova oil field. In 2010 hydrogen sulfide was encountered in the field slowing production. After consideration it was decided that nitrate injection into the field would be used to counter the effects of the sulfide. To do this, a tank must be designed to store aqueous calcium nitrate solution on board the Terra Nova deck. This project was undertaken by BHS Consultants.

The objective of this project was to create an efficient, safe and economical design for a tank capable of storing 100 cubic meters of calcium nitrate solution to be located at Module Four, starboard. The design process began with preliminary designs in order to complete load calculations. The models for the platform and tank were then completed and optimized.

Various materials were investigated for the tank. 316L stainless steel was chosen based on life expectancy and cost. The tank was designed as a rectangle to facilitate simpler connection design and maintenance. The design loads that were considered to act on the tank included self weight, hydrostatic force due to fluid in the tank, vessel acceleration due to wave action on the tank and fluid, and blast force on the tank. The forces were calculated and factored according to ISO 19902 Offshore Code. The tank was modeled using Abaqus Finite Element Analysis software. In this program the loads were applied appropriately as distributed forces on the inside walls of the tank. Stiffeners were added to reinforce the tank walls and to minimize thickness requirements. Bulkheads were modeled inside the tank, splitting it into four compartments, to minimize the effects of fluid sloshing inside the tank. The final tank design is 5 x 5 x 4 m, with a wall thickness of 8 mm. The stiffeners are 8 mm thick, tube members, spaced at 750 mm intervals and extend around the tank in the x, y, and z directions.

The platform was designed to support the full tank and all loads applied to both the tank and the platform. Restrictions on the platform included the existing equipment at Module Four that dictated where the columns and bracing would be located. The loads that were considered to act on the platform were self weight, a full tank, personnel, wind, snow, ice, waves and blast loading. The platform was modeled using S-Frame. The loads were applied and structural members were chosen. The platform was optimized to create the most economical and functional structure. The final design employs hollow sections for the columns and cross bracing, and W sections for the beams. The platform is equipped with a steel deck walkway, two exits with ladders, and hand railing all around.

Bolted connections were designed to connect the tank to the platform and the platform to the primary steel of the FPSO. It was found that the tank would be bolted through the stiffeners to the platform beams in six locations using one M36 high strength A325M bolt. The platform was designed to connect to the primary steel of the deck through a plate using eight M36 high strength A325M bolts. The primary steel was also checked to ensure its integrity to carry the new structures.

The platform and tank will be transported to the Terra Nova on a supply boat, and therefore required a seafastening design to secure these structures to the boat. The design resulted in the tank and platform being equipped with eight chains for a total resistance of 16 tons during shipment. To transfer the platform and tank onto the Terra Nova a lifting design was completed. The lifting assembly consists of slings shackled through padeyes that are attached in four locations on top of both the platform and the tank. Both are lifted using an existing crane on the Terra Nova.

A cost estimate was done using RS Means and researched data. It resulted in a total cost of $261,600.21 for the tank, and $181,638.31 for the platform.

The storage tank and supporting platform were designed in an efficient, safe and economical manner and are capable of successful implementation offshore on the Terra Nova FPSO.

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1.0 Project Description

This project involved the design of a storage tank to hold and dispense aqueous calcium nitrate solution from the Terra Nova FPSO. The tank must store 100 cubic meters of fluid, and must be located at Module Four (MO4), starboard, which is approximately in the middle of the vessel. A drawing of MO4 on the Terra Nova deck is displayed in Figure 1.1, as taken from the Terra Nova Alliance Topsides Structural Design Brief (Design Brief). The tank must be equipped with a ladder and nozzles for maintenance and use. Due to the location of the tank, a platform is required to hold the tank approximately 4.5 meters above the deck surface to clear existing equipment. The platform must be equipped with two exit ladders and railings and walkways around the tank for maintenance. The equipment under the platform will affect the position of structural columns and bracing.

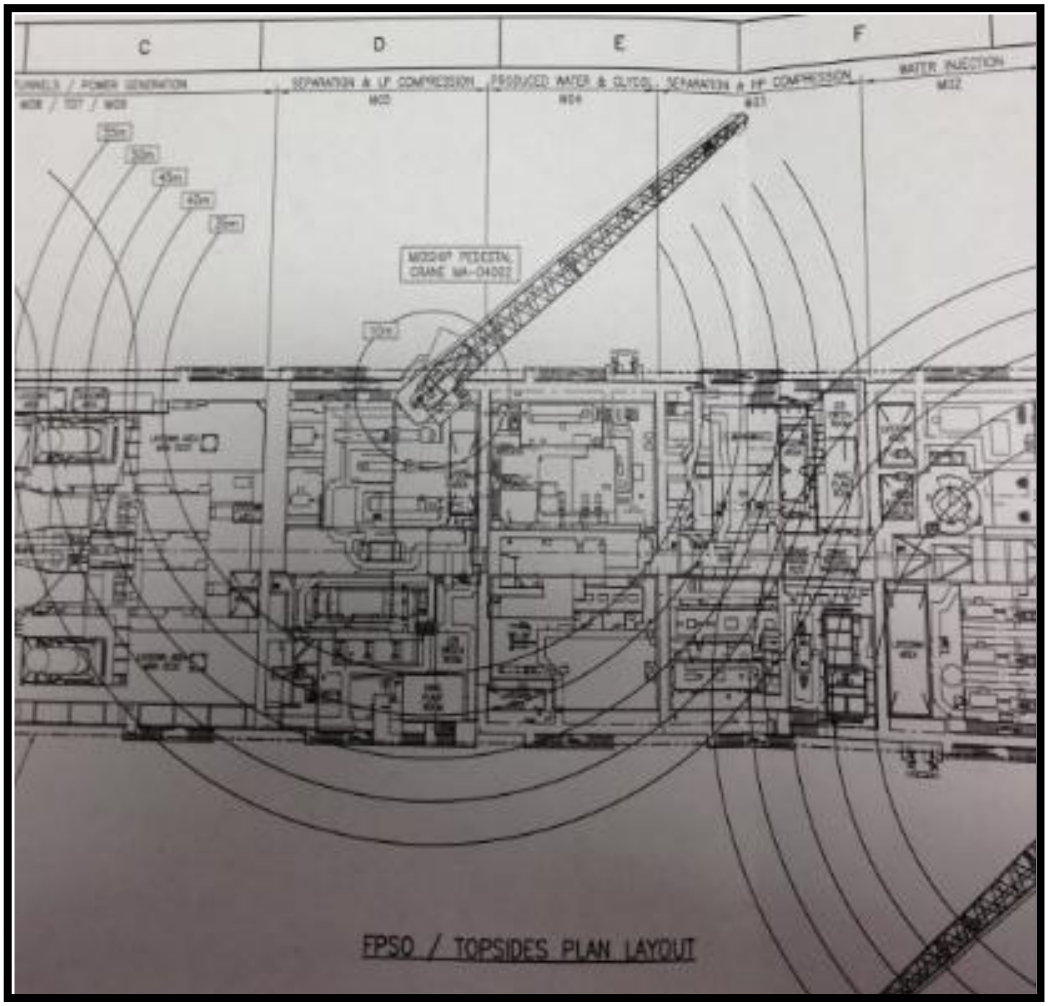


Figure 1.1 Terra Nova FPSO Deck Drawing

2.0 Background

Prior to beginning the design process for the calcium nitrate storage tank, research was conducted to familiarize the project team with the topic. The areas that were explored were the Terra Nova oil field, environmental concerns and fatigue design.

2.1 The Terra Nova

The Terra Nova is a floating production storage and offloading (FPSO) vessel that is located approximately 350 kilometers southeast of Newfoundland in the Terra Nova oil field. This FPSO is 292.2 meters long and 45.5 meters wide, and can store 960,000 barrels of oil. There is more than 40 kilometers of flexible pipe that conveys hydrocarbons between the wells and the vessel. Once on the FPSO, the crude oil is offloaded onto shuttle tankers for shipment (Suncor Energy).

The Terra Nova FPSO was designed specifically for the North Atlantic environment, which included ice-reinforcement, and a global dynamic positioning system. This system allows the vessel to position itself for more favorable wave headings (Suncor Energy).

Figure 2.1: Terra Nova Floating Production Storage and Offloading Vessel (Suncor Energy).

In 2010 hydrogen sulfide gas was detected in the Terra Nova field, slowing production. Hydrogen sulfide is a flammable gas that occurs due to the decay of substances containing protein resulting from bacterial reduction of sulfates in rocks. It can result when water is injected into a reservoir due to microbial populations mixing with nutrients. Hydrogen sulfide is dangerous due to its toxicity upon contact and flammability. This chemical is also extremely corrosive to all equipment, including safety equipment, and can cause "sulfide stress cracking" and failure (Pinheiro).

Solutions for hydrogen sulfide presence in oil fields include biocide treatment or microbiological competition. After consideration, the solution proposed for the Terra Nova field was the injection of calcium nitrate into the field. This process encourages nitrate reduction thereby reducing sulfate reduction (Statoil).

2.2 Environmental Concern

As part of the duty of an engineer, environmental concern with regards to design and practice is of the utmost importance to BHS Consultants. Keeping with this, BHS Consultants is energy and waste efficient with respect to our day to day activities, and our engineering practice. For the calcium nitrate storage tank and platform design, BHS Consultants has completed the design using methods and materials that we believe are sustainable and economical. Research was completed when choosing structural materials in order to minimize resources and maximize economics and sustainability.

2.3 Fatigue

Fatigue is mechanical failure that is caused by the repeated loading of time varying stresses on the structure, or cyclic loading. For offshore structures, National Standard of Canada ISO 19902-09 (ISO 19902) states that this action is predominantly caused by waves hitting the structure. ISO 19902 also describes the importance of stress range (S) and the number of cycles (N) relating to fatigue. The storage tank and supporting platform were designed for a minimum wave return period of one year. Over the twenty year design life, that would cause approximately twenty cycles. In ISO 19902, cycles for fatigue design are of the order of 10^5 or greater, which is significantly higher than the expected number of cycles for the structures. Furthermore, the load combination factors decrease the stress range, which in turn lessons the effects of fatigue. Therefore, fatigue failure of the storage tank and platform will not be considered as part of the module design (ISO 19902).

3.0 Methodology

The purpose of this project was to create an efficient, safe and economical design for a tank capable of storing 100 cubic meters of calcium nitrate solution, and a platform that can support the tank. Both will be installed offshore on the deck of the Terra Nova FPSO.

The design had to take into account a number of constraints. It had to accommodate a number of vessel deck obstructions, which affected the height of the platform and position of the columns and bracings of the platform. It also had to consider challenging offshore loading conditions. The corrosive nature of calcium nitrate influenced tank material selection. Furthermore, safety considerations, such as multiple exits routes from the platform, played a role in the design.

Preliminary designs were completed in order to begin load calculations. These designs were based on the required inside volume of the storage tank, and support required of the platform. These preliminary designs were used to compute dead load forces of the two structures. Next, the load calculations were completed for both the tank and the platform. Individual load cases considered dead loads, live loads, environmental loads and blast loads. These individual load cases were factored and combined to generate a number of load combinations that were to be used for modeling. The tank and the platform were modeled in S-Frame and Abaqus, respectively, and the loads were applied. Then, the models were used to optimize the size of the structures and obtain a final design.

After the structures were fully designed, seafasting and lifting designs were completed for the transportation onto the Terra Nova deck. As hot work on the operating Terra Nova FPSO was unacceptable, the structures would have to be bolted in place. These connections were completed using the Handbook of Steel Construction.

Finally, a cost estimate was completed for the construction of the two structures. This estimate was done using RS Means and research.

4.0 Tank Design

The storage tank is required to hold 100 cubic meters of calcium nitrate and will be refilled approximately every two weeks. The tank will be constructed of stainless steel, and will be designed in accordance with ISO 19902. A ladder will be provided to reach the top of the tank for calcium nitrate loading and maintenance purposes. The loading events on the tank were computed based on the requirements set out in the standards, and are described in detail in section 4.3. The tank was modeled using Abaqus Finite Element Analysis. The lifting, seafastening and bolted connection designs were completed in accordance with DNV Standard for Certification, No. 2.7-1, Offshore Containers and the Steel Code, CSA-S16.

4.1 Material Selection

Various materials were investigated for the storage tank. This tank is required to be resistant to corrosion. First, exotic steels were ruled out due to cost and availability. Next, carbon steel was investigated. It was found that it would need corrosion protection inside the tank. Through contact with Construction System Supply, it was found that the life of a corrosion liner is seven years. From this information it was concluded that carbon steel with the corrosion liner would not be feasible for the tank for two main reasons. First, the design life of the tank is to be twenty years, and therefore would require shut downs in order to reapply the corrosion coating, and second, the combined cost of the carbon steel material and the corrosion liner would be greater than that of stainless steel. It was concluded that 316L stainless steel would be used for the tank.

4.2 Preliminary Design

In the preliminary stages of the tank design two options were considered, keeping in mind the minimization of overall load effects. One option was a vertical cylindrical tank, and the second was a rectangular tank.

Considering the design criteria, various conclusions were drawn with respect to the two frame shapes. First, a rectangular frame creates a more manageable design process with regards to load calculations and load application during the modeling stage. The connection of the tank to the platform and maintenance of the tank during its lifetime would be simpler for a rectangular tank. It was also considered that fabrication of a circular tank with stiffeners and interior bulkheads could pose more difficulty than that of a rectangular tank, potentially adding cost. Considering these conclusions, a rectangular frame was chosen to proceed in the design phase.

The preliminary design of the stainless steel rectangular tank was chosen to have inside dimensions of 5 m long, by 5 m wide, by 4 m high. The wall thickness was set at 50 mm. The overestimation of wall thickness was justified because the stiffeners and bulkheads were not considered and it was deemed conservative to overdesign and then use the models to optimize. The tank has rectangular stiffeners that extend around the tank in all directions to reinforce the tank and to minimize wall thickness requirements. The size and spacing of these stiffeners was set to 10 mm and 500 mm respectively. Bulkheads were placed inside the tank, dividing the tank into four compartments to reduce the effect of fluid sloshing.

4.3 Design Loads

The calcium nitrate storage tank was designed to resist the various loads that will act on it during its operation. Waves acting on the Terra Nova cause an acceleration of the structures on board of the vessel. For the tank this includes the stainless steel structure, as well as the calcium nitrate fluid inside. The acceleration of the fluid will cause pressures on the inside walls of the tank. These, as well as the hydrostatic fluid pressures are the most extreme loads that the tank will experience.

Environmental loads including wind, snow and ice, and live loads such as personnel will not be considered in the load cases for the tank. The rationale for this is that the hydrostatic forces act out from the inside of tank, meaning that the environmental and live loads would counter these forces. Therefore the only forces modeled on the tank are:

- hydrostatic force due to the calcium nitrate fluid,
- vessel acceleration on the tank caused by the wave action,
- vessel acceleration on the calcium nitrate fluid caused by the wave action, and
- blast force

It is important to note that the self-weight of the tank does not have to be included as a force. The density of the stainless steel tank is modeled, which accounts for the self-weight. The forces discussed are factored based on their wave conditions. This is done because the modeling program, Abaqus, uses individual factored load cases to make combinations of loads that will act simultaneously. The factors that are used are the same as those used for the calculation of the platform load combinations. A summary of the tank load cases can be seen in Table 4.1.

Table 4.1: Factored tank load cases

		Load (kN)		
Load Cases	Load Factor	x (long.)	y (trans.)	z (heave)
Hydrostatic force due to fluid (kN)				
Unfactored		0.0596	0.0596	0.0596
Wave 1 (10 yr)	1.5	0.0894	0.0894	0.0894
Wave 2 (100 yr)	1.1	0.0656	0.0656	0.0656
Wave 3 (1 yr all yr)	1.1	0.0656	0.0656	0.0656
Wave 4 (1 yr all yr)	1	0.0596	0.0596	0.0596
Wave 5 (1 yr all yr)	1	0.0596	0.0596	0.0596
Vessel acceleration on tank (kN)				
Wave 1 (10 yr)	1.215	26.8066	38.6331	37.5818
Wave 2 (100 yr)	1.35	30.2231	49.6711	43.8893
Wave 3 (1 yr all yr)	1.35	11.8264	135.6100	90.4066
Wave 4 (1 yr all yr)	1	30.7488	144.2827	43.3636
Wave 5 (1 yr all yr)	1	16.2942	202.3637	90.4066

Vessel acceleration on fluid (Pressure, MPa)				
Wave 1 (10 yr)	1.215	0.0094	0.0135	0.0132
Wave 2 (100 yr)	1.35	0.0118	0.0193	0.0171
Wave 3 (1 yr all yr)	1.35	0.0046	0.0528	0.0352
Wave 4 (1 yr all yr)	1	0.0089	0.0416	0.0125
Wave 5 (1 yr all yr)	1	0.0047	0.0583	0.0261
Blast Force (kN)				
Blast in x direction		1431.68	0.00	0.00
Blast in y direction		0.00	1431.68	0.00

The pressure that the fluid exerts on the tank due to the force of gravity is the hydrostatic pressure. This pressure on the side of tank increases proportionately with depth from zero at the fluid surface to a maximum pressure at the tank bottom, as a result of the increased weight of the fluid. There is also a constant hydrostatic pressure exerted on the bottom surface of the tank that is equal to this maximum pressure. Figure 4.1 shows the pressure distributions. The maximum hydrostatic pressure was calculated as follows:

$$P_{hydrostatic} = \rho g h$$

Where: $P_{hydrostatic}$ = hydrostatic pressure [MPa]
ρ = density of the fluid [kg/m^3] = 1500
g = force of gravity [m/s^2] = 9.81
h = height of the fluid [m] = 4.05

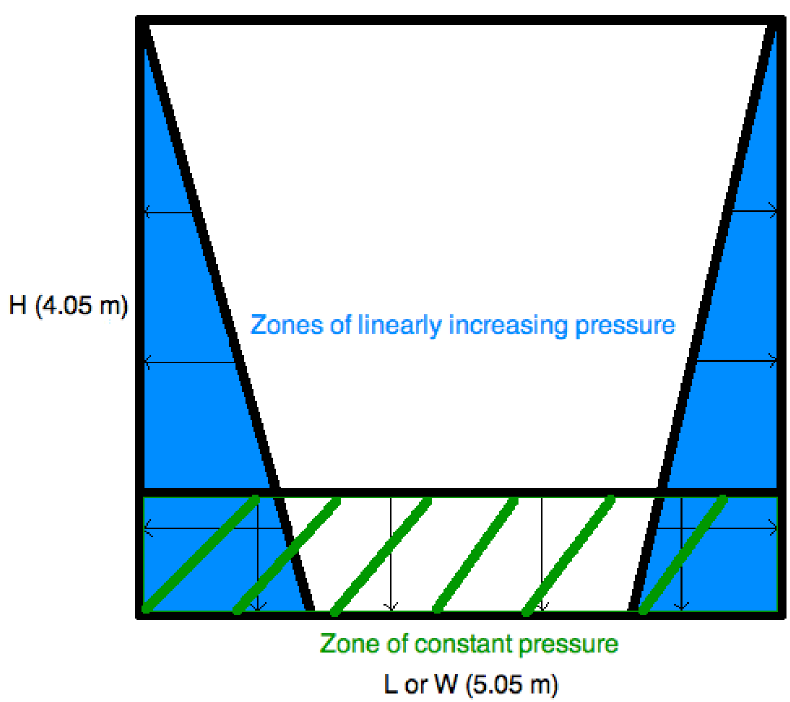


Figure 4.1: Hydrostatic pressure distribution along walls and bottom of tank

Vessel accelerations cause directional forces on the tank. Each wave causes a vessel acceleration in the x, y and z directions, therefore a force on the tank was calculated for each of these directions for each wave as follows:

$$F_{\text{tank, vessel acceleration}} = a_{\text{vessel}} * m_{\text{tank}}$$

Where: $F_{\text{tank, vessel acceleration}}$ = force caused by vessel accelerations on the tank [kN]
a_{vessel} = vessel acceleration, which is wave and directional dependant [m/s^2]
m_{tank} = mass of tank [kg] = 26,281

There is a pressure caused by the vessel accelerations on the fluid. Each wave causes a vessel acceleration in the x, y and z directions, which results in a pressure exerted by the fluid. As a wave causes the fluid to accelerate toward a particular surface, several different pressure distributions are generated. The pressure increases proportionately with distance from zero to a maximum at the surface the fluid is accelerating toward. There is also a constant pressure exerted on the surface that the fluid is accelerating toward. Figure 4.2 shows the pressure distributions. Both the distributed pressure maximum and the constant pressure were calculated as:

$$P_{\text{fluid, vessel acceleration}} = \rho * a_{\text{vessel}} * h$$

Where: $P_{\text{fluid, vessel acceleration}}$ = pressure cause by the vessel accelerations on the tank [MPa]
ρ = density of the fluid [kg/m^3] = 1500
a_{vessel} = vessel acceleration, which is wave and directional dependant [m/s^2]
h = height of the fluid, which is dependent on the direction of fluid acceleration [m]

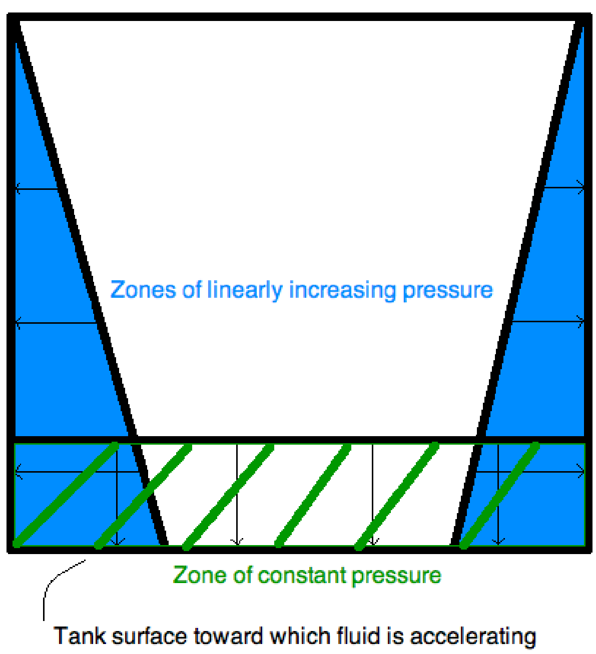


Figure 4.2: Pressure distribution along different surfaces of the tank caused by vessel acceleration on the calcium nitrate fluid

Blast loading is also considered as a force on the tank. This is the load that is exerted on the tank in the event of a blast or explosion. The force on the tank as a result of blast loading is calculated as follows:

$$F_{blast} = P_{blast} * A$$

Where: F_{blast} = force caused by blast loading [kN] = 1431.68
P_{blast} = pressure caused by blast [kPa] = 70 (Hamdan, pg.1, 2006)
A = projected area [m^2] = 20.45

4.4 Abaqus Model

Abaqus is a finite element analysis modeling software with capabilities for both static and dynamic modeling. For the purpose of the tank design, only static analysis was completed. The tank was built using shell elements for the tank walls, stiffeners and bulkheads. Figure 4.3 displays the outside shell of the tank and the four compartment division created by the bulkheads.

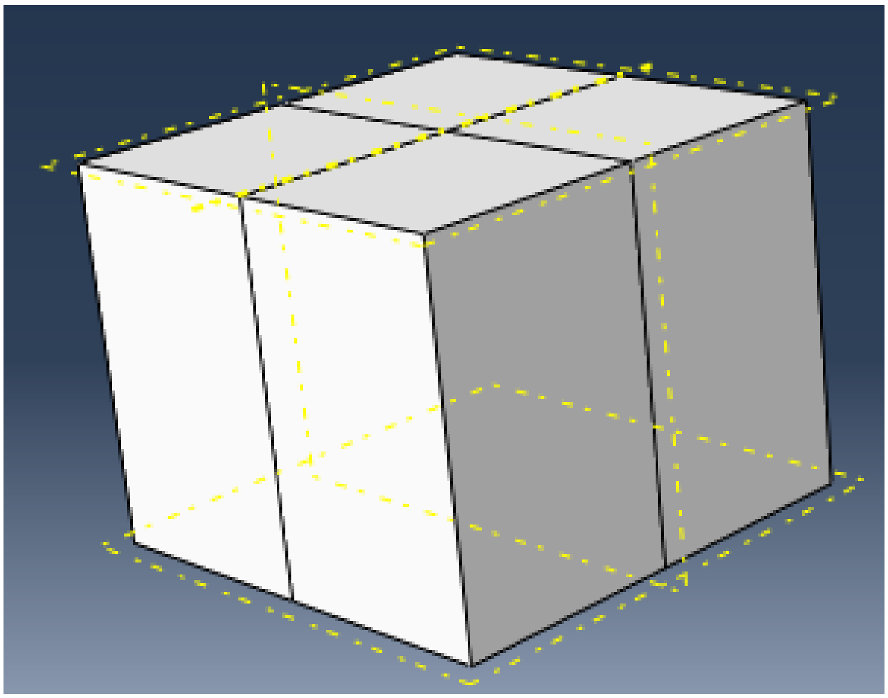


Figure 4.3: Outside view of tank from Abaqus

The bulkheads were modeled with various holes for the fluid to pass between the compartments without causing too much fluid sloshing. Each bulkhead was modeled with one 600 mm hole and six 300 mm holes. Figure 4.4 displays the bulkheads inside the tank.

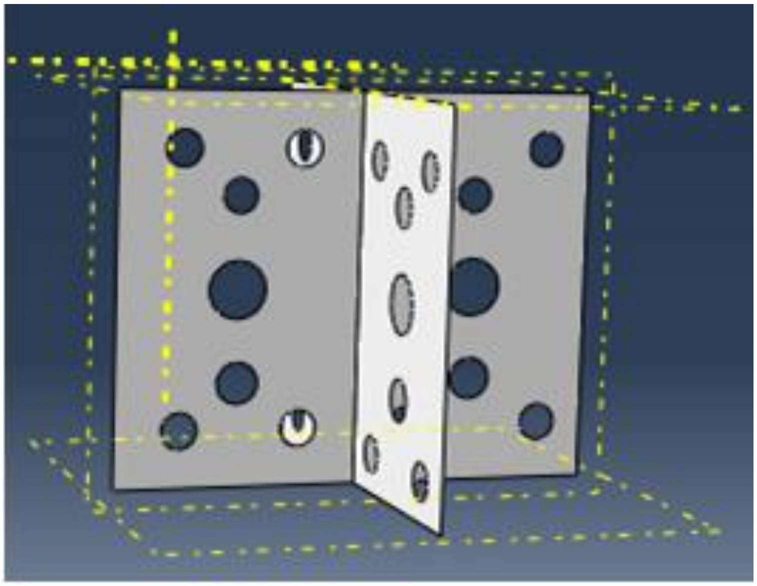


Figure 4.4: Bulkheads inside tank from Abaqus

The stiffeners travel around the outside of the tank in all directions, and provide reinforcement to the tank walls. The Abaqus view of the outside of the tank is displayed in Figure 4.5.

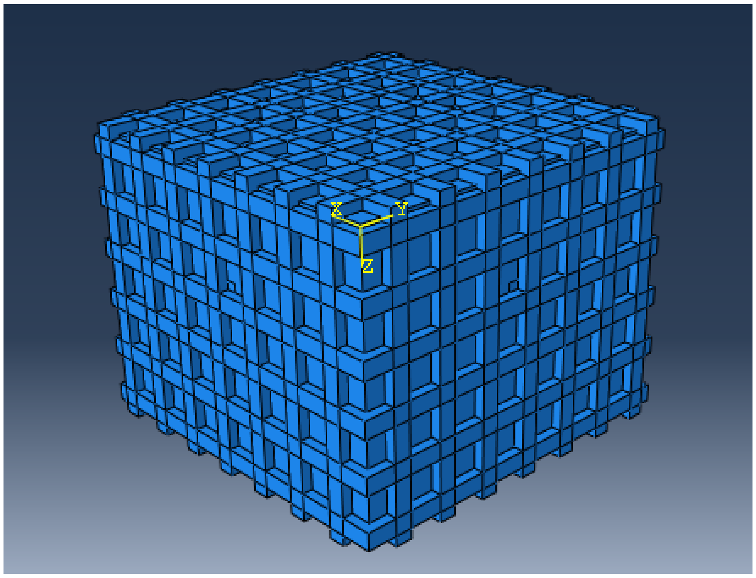


Figure 4.5: Outside view of tank and stiffeners from Abaqus model

4.4.1 Application of Loads

The calculated loads that would act on the tank were input to the Abaqus model in order to design and optimize the tank, stiffeners and bulkheads. The design loads were applied to the model as combinations of the load cases. Each combination considered the hydrostatic force due to the fluid, the vessel acceleration on the tank and the fluid, as well as the self weight of the tank to act at one time. Blast load was applied alone. The loads were input as appropriate distributed forces as described in section 4.3.

4.4.2 Tank Optimization

After applying the loads it was concluded that the preliminary tank was overdesigned, and the wall thickness could be reduced. Optimization of the tank was completed to create an economical and functional design. By reducing the wall thickness and stiffener spacing and re-running the software, the wall thickness was finalized at 8 mm. The stiffener thickness was 8 mm, and they were placed at 750 mm intervals in all directions around the tank. Figure 4.6 displays the stress distribution on the final tank design. The colors signify the stress intensity throughout the tank, where dark blue is very low stress, yellow/green is medium stress, and red shows the high stress areas. It is important to note that these colors do not signify failure of the tank in any location. The mix of colors does display that the tank is not completely over or under designed.

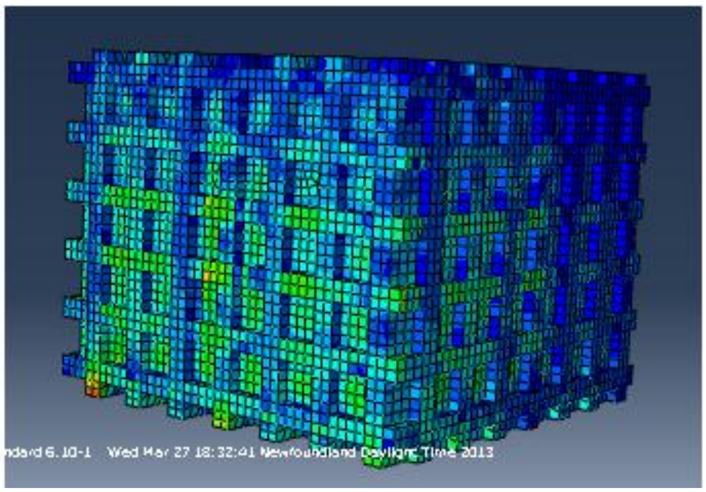


Figure 4.6: Stress distribution on final tank design from Abaqus

4.5 Tank Design Summary

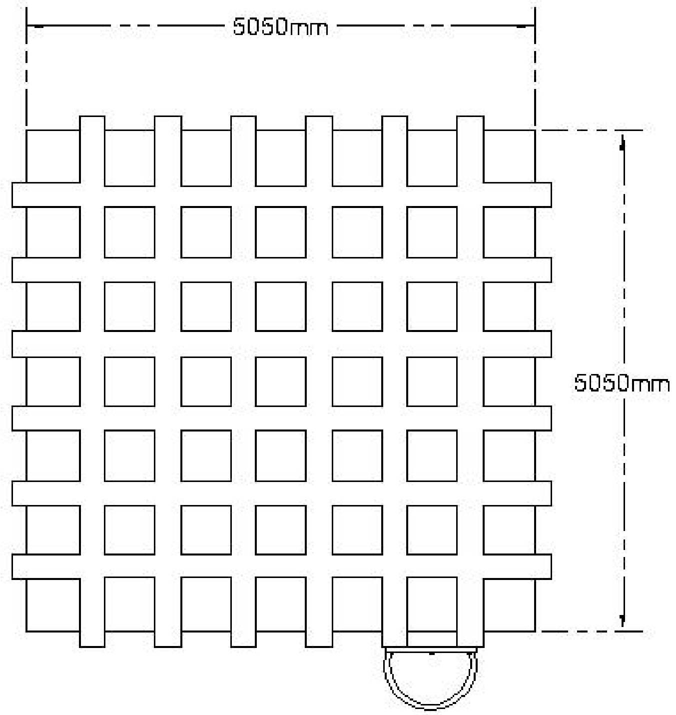
After completing the tank model in Abaqus, the final stainless steel tank design had dimensions as displayed in Table 4.2. Figure 4.7 displays the drawing that was completed for the tank design.

Table 4.2: Tank dimensions

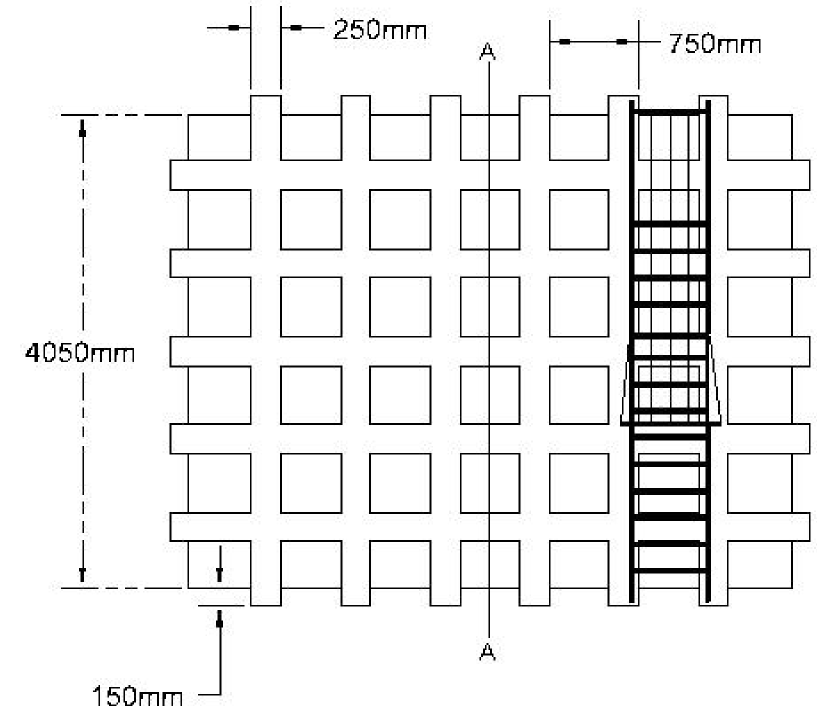
Parameter	Measurement
Inside Width/Length	5000 mm
Inside Height	4000 mm
Wall Thickness	8.0 mm
Stiffener Thickness	8.0 mm
Stiffener Spacing	750 mm
Bulkhead Hole Diameter	1 – 600 mm, 6 – 300 mm
Total Weight	17, 139 kg

Figure 4.7: AutoCAD Drawing of the Tank (See next page)

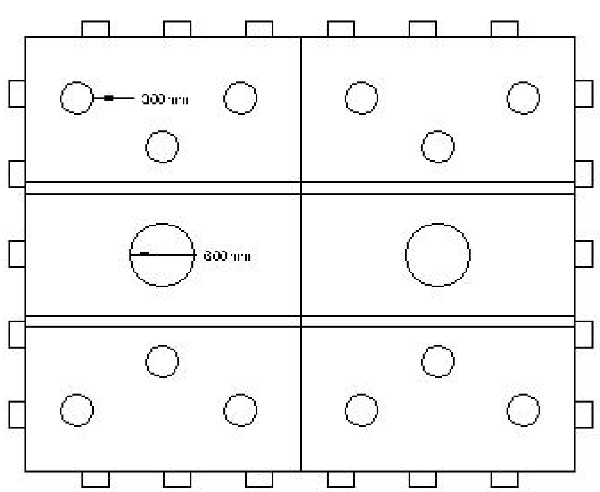
Top View



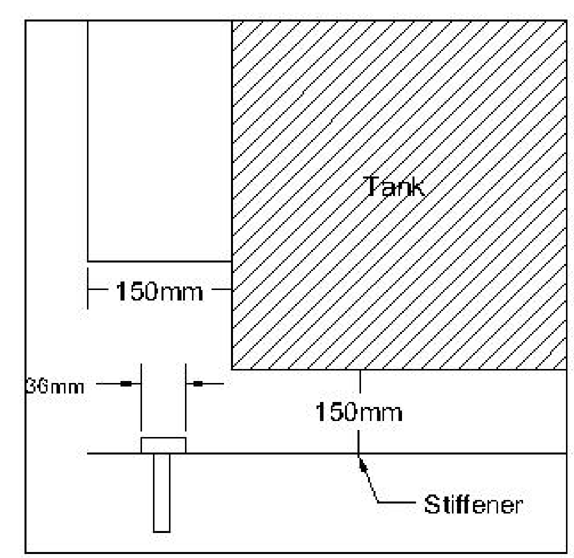
Side View



Section A-A



Bolted Connection (NTS)



Notes

1. All connections are full penetration welds.

Materials:

Tank
-M316L Stainless Steel
-8 mm thick
-Full tank is made of shell elements

Stiffeners
-M316L Stainless Steel
-8 mm thick
-Stiffeners are 250 X 150 X 8 mm

Bulkheads
-M316L Stainless Steel
-8 mm thick
-Include 2 stiffeners on each, same material

1	DWG	24/03/13	BTB

BHS Consultants

Terra Nova
Calcium Nitrate Module Design
Client: Tim Mathews, P. Eng., Wood Group PSN

March 29, 2013
BTB | BTB | 2013–002
1mm=800mm | 1

5.0 Platform Design

The platform will be constructed of steel with a yield strength of 350 MPa and it is required to hold the storage tank filled with 100 cubic meters of calcium nitrate solution. It will be located on MO4, which is a fully operating section of the Terra Nova FPSO. Therefore it was necessary for the platform to be designed around the existing topside infrastructure. The platform will be erected on MO4, starboard, which has multiple restrictions to overcome. The platform needed to be at least 4.5 m high. Therefore, there were only four appropriate positions for the columns and the stern side of the platform could not be fully braced due to underlying pipes.

The platform was designed in accordance with ISO 19902, and also the Steel Code, CSA-S16. The platform will be equipped with a walkway and railing, as well as two exits with ladders, to allow access for maintenance. The design process began with a preliminary outline.

5.1 Preliminary Design

The preliminary design of the platform was rectangular, with dimensions of 7.7 m (starboard-port) x 7.05 m (bow-stern) . At each corner there is a square hollow column extending 4.5 m in height. The columns will be connected together by W sections at the top inside faces and square hollow cross bracing connected 0.5 m and 3.85 m above the deck. However, the connections at the side closest to the stern will be connected by W sections at the top inside faces and corner bracing at 3.85 m above the deck due to the aforementioned restrictions. The platform will also be equipped with a steel mesh deck, two ladders on the stern side and hand railing around the full perimeter of the topside.

5.2 Design Loads

The platform is designed to resist the various loads that could potentially act on the structure during its design life. The loading calculations were done in accordance with ISO 19902. The platform was designed to resist dead loads, such as self weight, and the weight of the tank; live loads, such as personnel and the calcium nitrate; environmental loads, such as wind, ice, snow and waves; and blast loads.

5.2.1 Dead Loads

The dead loads acting on the platform include the weight of the tank and the platform self weight. The weight of both the empty tank and the platform were calculated as:

$$F_{DL} = V_{steel} * \rho * g$$

Where: V_{steel} = Volume of steel in the tank [m^3] = 2.15
ρ = density of steel [kg/m^3] = 8000 for stainless steel, and 7850 for steel
$g = 9.81\ m/s^2$

In order to complete the load computations and modeling, the empty tank weight and platform weight were estimated, and then were updated when the design was complete. The initial estimated value of the tank weight acting on the platform was 258 kN. This was based on a 50 mm thickness of a tank with an inside volume of 100 cubic meters, which is equal to the volume of calcium nitrate to be stored. The initial estimated value of the platform was 162 kN, which was based on the required height of the platform and required size based on initial tank dimensions.

5.2.2 Live Loads

The live loads acting on the platform include personnel who may be working on the structure and the calcium nitrate in the tank. The force used for personnel was 1.962 kN, and the force from the calcium nitrate was calculated as follows:

$$F_{\text{Calcium Nitrate}} = V * \rho * g$$

Where: V = Volume of fluid [m^3] = 100
ρ = density of fluid [kg/m^3] = 1500
$g = 9.81\ m/s^2$

5.2.3 Environmental Loads

The environmental conditions that exist on the Terra Nova include wind, snow, ice and waves. These conditions cause consequent loading on structures on the vessel, including the platform and tank.

5.2.3.1 Wind

The wind loads exerted on the platform were calculated using wind velocities for 15 second gust values, as recommended in the Design Brief. A wind speed factor was applied to the given wind speeds to capture the speed at the center of gravity of the tank, which is at 22.03 m above still water level. Factors of 1.077 and 1.124 were provided in the Design Brief for still water heights of 20 m and 30 m, respectively. A factor of 1.087 was interpolated for 22.03 m. The wind speed factor was multiplied by the given 15 s gust velocity for the five return periods to obtain the actual wind velocity. The total force from the wind was calculated using the following equation:

$$F_{wind} = 0.5*\rho*v^2*Cs*A$$

Where: ρ = wind density [kg/m^3] = 1.225
v = wind velocity [m/s]
Cs = shape coefficient = 1.5, which accounts for suction and drag forces
A = Area of face [m^2] = 20.45

Table 5.1 displays the results of this calculation for the various return periods. The total wind force was broken into x and y components. It was assumed that the headwind acted at 20 degrees to the bow of the vessel because the Terra Nova spins to optimize conditions.

Table 5.1: Wind loads components

	F_{wind} (kN)		
	Total	x component	y component
1 yr ice	17.39	7.10	15.88
1 yr all yr	29.72	12.13	27.13
10 yr	35.85	14.63	32.73
50 yr	50.47	20.60	46.08
100 yr	57.25	23.36	52.26

5.2.3.2 Ice

The forces that result from ice accumulation were calculated for the tank and for the platform, as they will both contribute to the load on the platform. The Design Brief describes the effects of sea spray icing, but because the height of the tank is greater than 25 meters above water level, the effect of sea spray will not be considered. It is important to note that an additional volume of ice would accumulate at the corners of the tank and this is accounted for in the force calculation. The force due to ice accumulation on the platform and the tank was calculated using the following formula:

$$F_{ice} = \rho * t * A * g$$

Where: ρ = density of ice [kg/m^3] = 900
t = thickness of ice [m] = 0.01
A = surface area of tank or platform [m^2] = 132.815 or 24.2, respectively

Therefore, the total force due to ice acting on both the tank and the platform are as follows:

$$F_{ice\ tank} = 11.762 \text{ kN}$$
$$F_{ice\ platform} = 2.137 \text{ kN}$$

5.2.3.3 Snow

The force on the platform and tank due to snow accumulation was calculated using the pressure of snow given in the Design Brief, section 3.3.6. This force was calculated as follows:

$$F_{snow} = P * A$$

Where: P = pressure of snow from the Design Brief [kg/m^2]= 204
A = top surface area of tank or platform [m^2] = 25.50 or 24.2, respectively

Therefore, the total force on the tank and platform due to snow are:

$$F_{\text{snow tank}} = 51.037 \text{ kN}$$
$$F_{\text{snow platform}} = 48.43 \text{ kN}$$

5.2.3.4 Waves

Sea conditions involving waves cause different accelerations of the Terra Nova, hereafter referred to as vessel accelerations. These accelerations are given in Table 5.2.

Table 5.2: Consequent vessel accelerations due to wave conditions

Design Condition	Sea State	Unit Function	Max single amplitude acceleration		
			x, long	y, trans	z, vert
			m/s^2	m/s^2	m/s^2
1, Operating	10 bow year	Running	1.02	1.47	11.24
2, Survival Bow	100 bow year	Stopped	1.15	1.89	11.48
3, Survival Beam	1 year beam	Stopped	0.45	5.16	13.25
4, Vessel Damaged	1 year oblique	Stopped	1.17	5.49	11.46
5, Vessel Damaged	1 year beam	Stopped	0.62	7.7	13.25

The vessel accelerations cause accelerations and subsequent forces on the platform, tank and calcium nitrate fluid in the x, y and z direction. Roll forces are caused in the x or longitudinal direction; pitch forces are caused in the y or transverse direction; and heave forces are caused in the z or vertical direction. The equation used to convert the vessel accelerations into forces on the platform, tank and fluid is as follows:

$$F_{\text{wave}} = m * a$$

Where: m = mass of the tank, fluid or platform [kg]
a = given vessel acceleration [m/s^2], as seen in Table 5.2

Table 5.3 displays the resulting forces that were considered to act on the tank, platform and fluid as a result of the vessel accelerations.

Table 5.3: Forces on the platform, tank and fluid resulting from the vessel accelerations

Design condition	Sea state	Forces on tank [kN]			Forces on platform [kN]			Forces on fluid [kN]		
		x	y	z	x	y	z	x	y	z
Operating	10 bow year	27	39	38	17	24	24	153	221	215
Survival Bow	100 bow year	30	50	44	19	31	28	173	284	251
Survival Beam	1 year beam	12	136	90	7	85	57	68	774	516
Vessel Damaged	1 year oblique	31	144	43	19	91	27	176	824	248
Vessel Damaged	1 year beam	16	202	90	10	127	57	93	1155	516

5.2.3.5 Blast Loading

Blast loading on a vessel includes explosions caused by hydrocarbon fires and acts of violence. ISO 19902, section 10.4 states that generally steel framed structures on vessels are not designed against explosion. However, on request of the Client, a blast pressure of 0.7 bar was modeled on all sides of the tank. The resulting force from a blast was found as follows:

$$F_{blast} = A * P_{blast}$$

Where: A = projected area of tank [m^2] = 24.4525
P_{blast} = pressure of the design blast [kPa] = 70 (Hamdan 1)

This calculation resulted in a blast force of 1431.675 kN in both the x and y directions, on the side of the tank.

5.2.4 Load Combinations

The calculation of the individual dead loads, live loads, environmental loads and blast loads are referred to as load cases. These load cases are combined to create a number of load combinations that consider appropriate cases to be acting simultaneously. Therefore, each load combination has a single x, y and z force component. Load combination factors specific to the individual load cases were found in ISO 19902, section 9, and were applied to the load case forces when they were added together to calculate the load combination forces. The combination factors for the different cases are based on the specific conditions under which loading occurred. This depends on whether the vessel was in operating, survival, damaged or still water mode, the return rate of the wave, and where the force was acting. Table 5.4 is a summary of the combination factors that were used.

Table 5.4: Load combination factors

		Load Combination Factors					
		DL	LL	Wave	Wind	Snow	Ice
Wave 1	Compression	1.3	1.5	1.215	1.215	1.215	1.215
	Uplift	1.1	1.1	1.215	1.215	0	0
Wave 2	Compression	1.1	1.1	1.35	1.35	1.35	1.35
	Uplift	0.9	0.8	1.35	1.35	0	0
Wave 3	Compression	1.1	1.1	1.35	1.35	1.35	1.35
	Uplift	0.9	0.8	1.35	1.35	0	0
Wave 4	Compression	1	1	1	1	1	1
	Uplift	1	1	1	1	0	0
Wave 5	Compression	1	1	1	1	1	1
	Uplift	1	1	1	1	0	0
Still		1.3	1.5	0	1.35	1.5	1.5
Blast		1	1	1	1	1	1

For each of the five waves there were four compression and four uplift load combinations. Compression combinations accounted for the maximum downward force, and therefore considered a full tank, the platform, all live loads, and wave, wind, snow and ice forces. The heave force, which is the vertical wave component, was considered to be working downward in a negative direction. Conversely, uplift combinations accounted for the maximum upward force, and considered only an empty tank, the platform, wave and wind forces. In this case, the heave force was considered to be working upwards in a positive direction. All other forces were not considered as they act downward and would minimize uplift. To maximize the x and y components of the force for each load combination, wave and wind loads were always assumed to act in the same direction when they were both present. Still water combinations and blast loading combinations were also considered. It is important to note that the wind return period used in each combination was equal to that of the wave return period. In total, there are forty load combinations for the different waves, five for still water and two for blasting. The total load acting on the platform for each combination was calculated by adding the appropriate load cases in the x, y, and z directions. Table 5.5 displays all forty-seven load combinations that were modeled on the platform in order to design the structure.

Table 5.5: Load combinations

	Load Type	Load Case	Fx [kN]	Fy [kN]	Fz [kN]
Wave 1, Operating, 10 Year Bow	Max Compression 1	1001	257	384	-3324
	Max Compression 2	1002	257	-384	-3324
	Max Compression 3	1003	-257	384	-3324
	Max Compression 4	1004	-257	-384	-3324
	Max Uplift 1	1005	71	76	-468
	Max Uplift 2	1006	71	-76	-468
	Max Uplift 3	1007	-71	76	-468
	Max Uplift 4	1008	-71	-76	-468
Wave 2, Survival Bow, 100 Year Bow	Max Compression 1	2001	331	562	-2751
	Max Compression 2	2002	331	-562	-2751
	Max Compression 3	2003	-331	562	-2751
	Max Compression 4	2004	-331	-562	-2751
	Max Uplift 1	2005	98	180	-347
	Max Uplift 2	2006	98	-180	-347
	Max Uplift 3	2007	-98	180	-347
	Max Uplift 4	2008	-98	-180	-347
Wave 3, Survival Beam, 1 Year Bow	Max Compression 1	3001	129	1,370	-3212
	Max Compression 2	3002	129	-1,370	-3212
	Max Compression 3	3003	-129	1,370	-3212
	Max Compression 4	3004	-129	-1,370	-3212
	Max Uplift 1	3005	38	325	-245
	Max Uplift 2	3006	38	-325	-245
	Max Uplift 3	3007	-38	325	-245
	Max Uplift 4	3008	-38	-325	-245
Wave 4, Vessel Damaged, 1 Year Oblique	Max Compression 1	4001	238	1,085	-2398
	Max Compression 2	4002	238	-1,085	-2398
	Max Compression 3	4003	-238	1,085	-2398
	Max Compression 4	4004	-238	-1,085	-2398
	Max Uplift 1	4005	62	235	-423
	Max Uplift 2	4006	62	-235	-423
	Max Uplift 3	4007	-62	235	-423
	Max Uplift 4	4008	-62	-235	-423
Wave 5, Vessel Damaged, 1 Year Beam	Max Compression 1	5001	132	1,512	-2743
	Max Compression 2	5002	132	-1,512	-2743
	Max Compression 3	5003	-132	1,512	-2743
	Max Compression 4	5004	-132	-1,512	-2743
	Max Uplift 1	5005	39	329	-346
	Max Uplift 2	5006	39	-329	-346
	Max Uplift 3	5007	-39	329	-346
	Max Uplift 4	5008	-39	-329	-346
Still Water	Still Water 1	6001	9.58	21.43	-3021
	Still Water 2	6002	16.37	36.62	-3021
	Still Water 3	6003	19.75	44.18	-3021
	Still Water 4	6004	27.81	62.21	-3021
	Still Water 5	6005	31.54	70.55	-3021
Blast	Blast Loading 1	7001	1431.675	0	-1967
	Blast Loading 2	7002	0	1431.675	-1967

5.3 S-Frame Model

S-Frame and S-Steel were chosen as the computer software to model and optimize the preliminary design of the platform. The primary steel of MO4 was included in the modeled version of the platform to ensure that the loads caused from the platform and the tank did not cause the primary steel to fail. Figure 5.1 displays the platform in S-Frame.

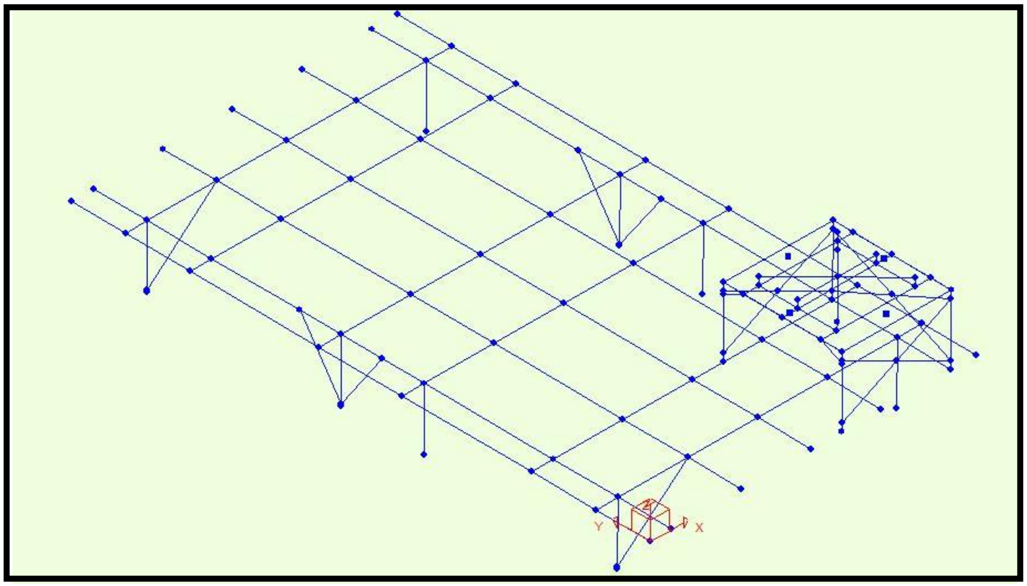


Figure 5.1: Platform model in S-Frame

5.3.1 Application of Loads

The platform had to be analyzed for the environmental, dead and live loads acting on the members, which were direct loads, as well as the loads created by and acting on the calcium nitrate tank, which were indirect loads.

For the direct loads, the platform was analyzed by applying uniform distributed loads (UDL) on each cross bracing, corner bracing, column and on the top deck. The UDLs consisted of horizontal wind forces and vertical snow and ice forces.

To analyze the platform for the indirect loading the storage tank needed to be represented. A node representing the center of gravity (CoG) of the tank was placed in the appropriate position above the platform model. An infinitely stiff member was extended vertically from the CoG to 0.5 m above the platform surface. From this point, six infinitely stiff beams were extended horizontally to the different tank connection positions. Vertical members 0.5 m in length were then added to complete the connection of the tank's CoG to the platform. At each of the six connections the moment was released to rid of unwarranted forces. The tank loads were applied to the tank CoG and with the infinitely stiff beams and moment releases, proper analysis of the indirect platform loading was completed. Figure 5.2 displays the method of applying the indirect loads from the tank to the platform, where the infinitely stiff beams are displayed in red.

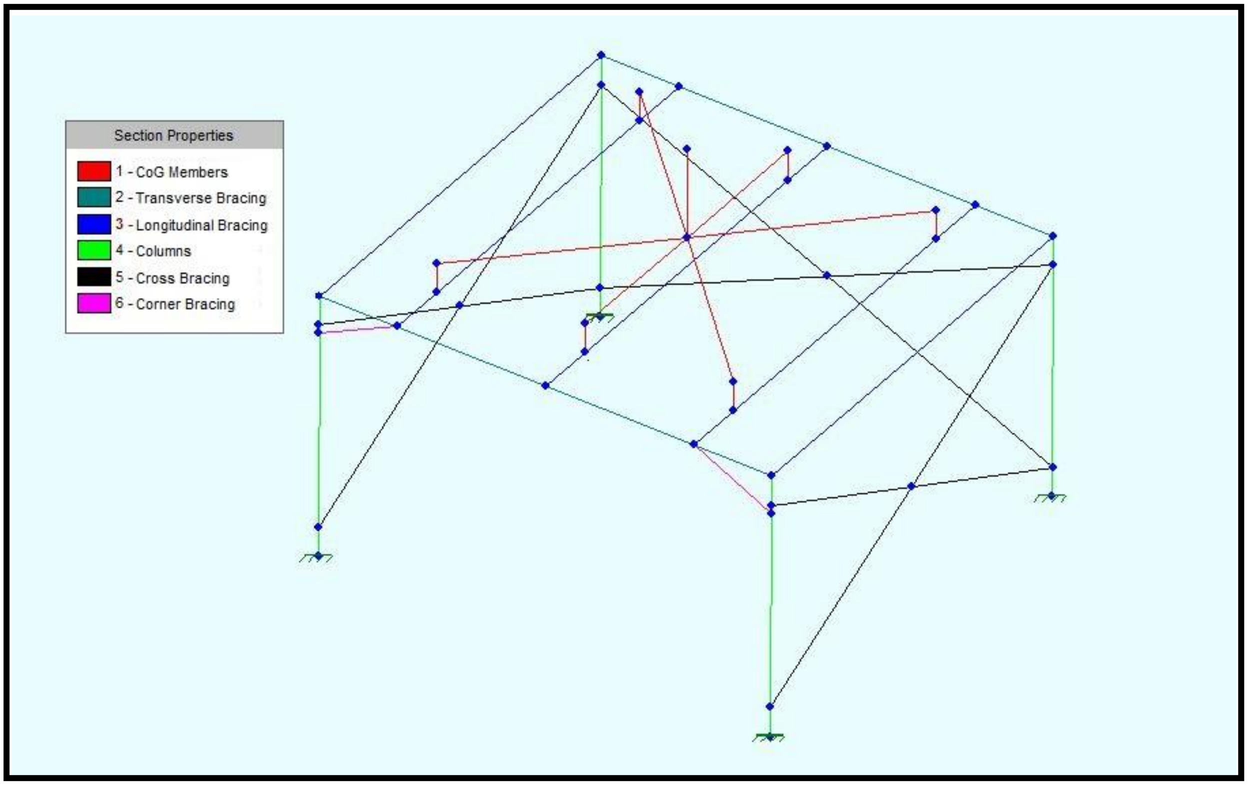


Figure 5.2: Tank load representation on platform

5.3.2 Platform Optimization

After completing and analyzing all load cases on the platform the section choices were altered until all utilizations were less than 1.0 and the platform was as light as possible. Table 5.6 outlines the sections chosen as well as the final utilizations for each member. Figure 5.3 displays the utilizations of the members from S-Frame.

Table 5.6: Platform sections and utilizations

Platform Member	Section	S-Steel Utilizations
Columns	HS600x600x16	0.611-0.614
Cross Braces	HS450x450x16	0.075-0.215
Corner Braces	HS200x200x16	0.57
Longitudinal Deck Beams	W457x191	0.466-0.601
Transverse Deck Beams	W533x210	0.572-0.573

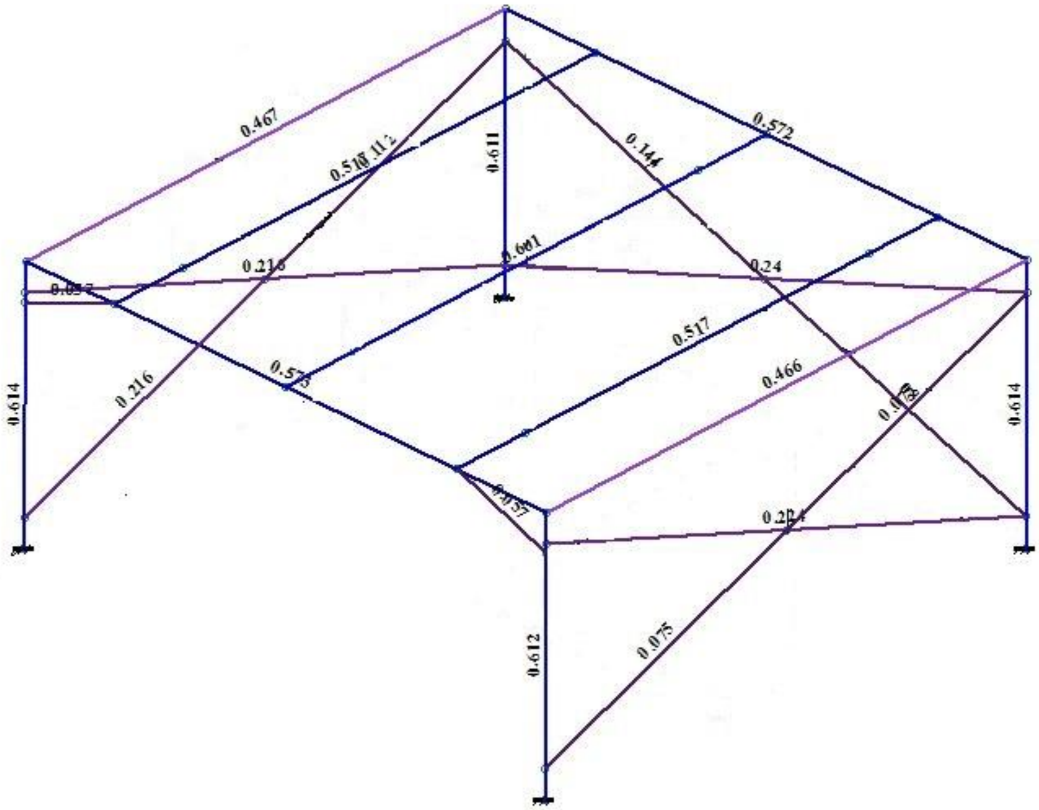
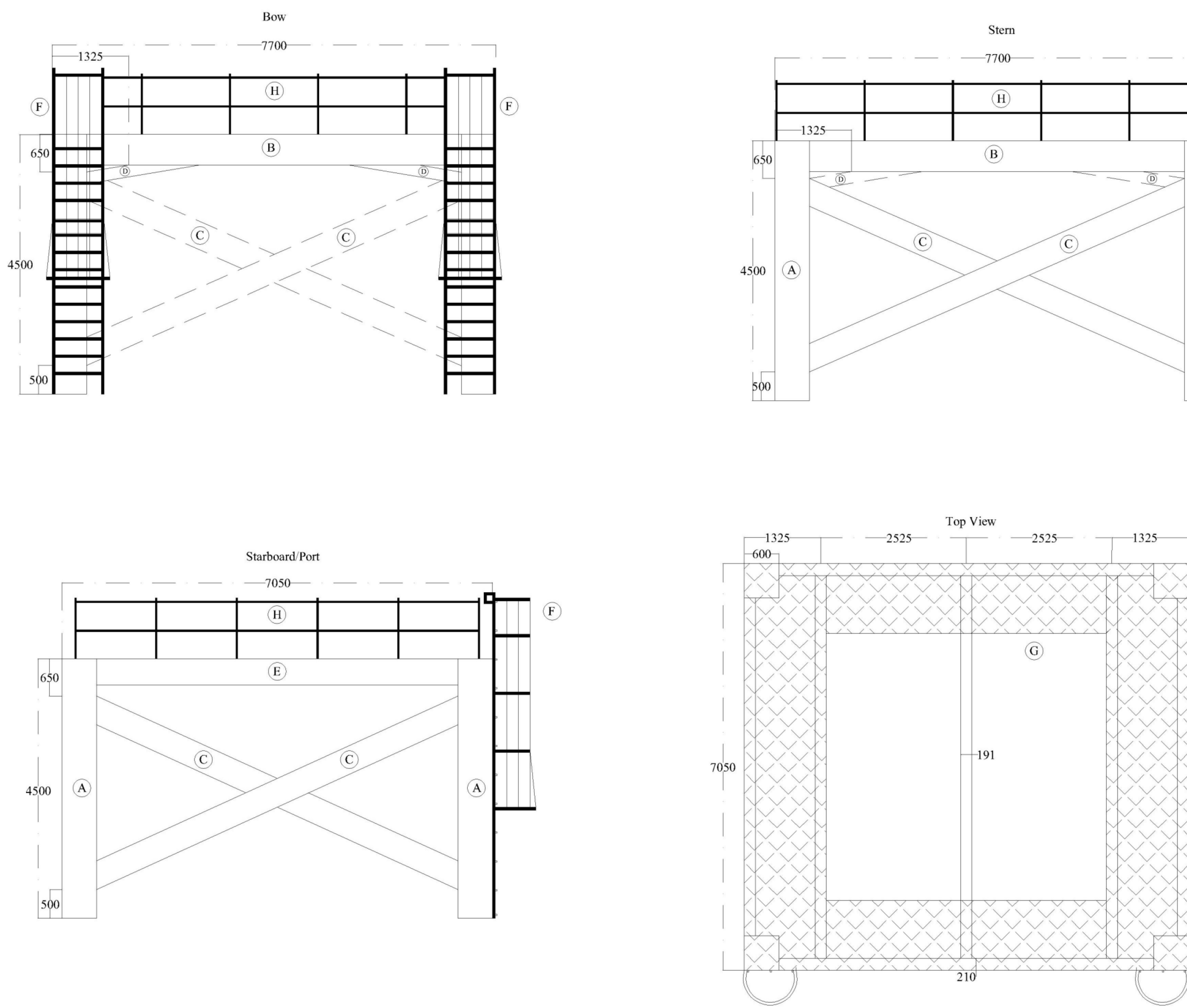


Figure 5.3: Platform Member Utilizations

5.4 Platform Design Summary

The preliminary design was optimized with no changes. The final dimensions of the platform are 7.7 m x 7.05 m x 4.5 m and it weighs approximately 24 tons. The platform meets all criteria set out by the Client. Figure 5.4 displays the completed platform design.

Figure 5.4: Final platform design (See next page)



Notes

1.All connections full penetation welds.

2. Back view does not display back of ladders for simplicity.

Materials:

A: 600x600x16 SHS
B: 533x210x138 UKB
C: 450x450x16 SHS
D: 200x200x16 RHS
E: 457x191x161 UKB
F: Ladder, shop fabricated, steel, 900 mm W, bolted to column, incl cage.
G: Steel mesh floor decking
H: Railings, pipe, steel, wall rail, 31 mm dia, 1.5 m high columns @ 1.4-1.5 m centre to centre, shop fabricated .

ENGINEER'S STAMP

No.	DESCRIPTION	DATE	BY
1	DWG	24/03/13	SAM

REVISION OR ISSUE

BHS Consultants

PROJECT:
Terra Nova
Calcium Nitrate Module Design
Client: Tim Mathews, P. Eng., Wood Group PSN

DATE	REF NO
March 24, 2013	

DRAWN BY	CHK	DWG NO
SAM	SAM	2013-001

SCALE	SHEET
1mm=800mm	1

6.0 Bolted Connections

Bolted connections must be designed to connect the tank to the platform, and the platform to the primary steel that exists under the deck on the vessel. The following subsections complete the design of these connections, as well as check the structural integrity of the primary steel beams.

High strength A325 bolts are to be used since A490 bolts often fail in fatigue. The design of bolted connections follows the Handbook of Steel Construction, 10^{th} Edition by the Canadian Institute of Steel Construction (CISC). All clauses referred to throughout this section are from this handbook.

6.1 Tank to Platform

The tank is to be bolted at six locations through the stiffeners to the platform deck. The maximum shear at the platform connections was determined to be 395 kN from the S-Frame model. The shear resistance is calculated according to clause 13.12.1.2.c of the handbook to ensure it is greater than the applied shear force.

$$V_r = 0.60\Phi_b n m A_b F_u$$

Where: V_r = shear capacity [kN] = 405.57
$\Phi_b = 0.8$
n = number of bolts = 1
m = number of shear planes = 1
A_b = area of bolt [mm^2] = 1018
F_u = specified minimum tensile strength [MPa] = 830

Using only one M36 high strength A325 bolt for each of the six connections, the shear capacity is 405.57 kN, which is greater than the maximum applied shear force of 395 kN.

The maximum uplift (tension force) experienced is compared to the calculated tensile resistance to determine whether the selected bolt type is sufficient. According to clause 12.12.1.3 of the handbook, the tensile resistance is:

$$T_r = 0.75\Phi_b A_b F_u$$

Where: T_r = tension capacity [kN] = 506.96
$\Phi_b = 0.8$
A_b = area of bolt [mm^2] = 1018
F_u = specified minimum tensile strength [MPa] = 830

The calculated tensile resistance of 506.96 kN is far greater than the maximum tension force of 53 kN, so the selected bolt design is acceptable.

The tank will be bolted to the platform deck through the stiffeners using one M36 high strength A325 bolt at each of the six connection locations.

6.2 Platform to Primary Steel

Bolted connections must be designed to connect the platform to the vessel deck at the four columns. For the design of the column's bolted connections, the maximum forces and moments are determined from the S-Frame model. They are summarized in Table 6.1.

Table 6.1: Maximum forces and moments on the platform as obtained from the S-Frame model

Maximum Forces and Moments (S-Frame)	
Largest x force [kN]	88.6
Largest y force [kN]	376.1
Largest z force, compression [kN]	135
Largest z force, tension [kN]	135
Largest Moment [kN m]	1203

6.2.1 Bearing, Shear and Tensile Resistance of Bolts

The bearing, shear and tensile resistances must be calculated and compared to the values from the platform model. The bolt number and size, as well as the base plate dimensions, are selected based on these resistance checks.

The bearing resistance is calculated according to clause 13.12.1.2.a of the handbook. To choose the number of bolts and the plate thickness, the applied bearing force was set to be half that of the applied shear force. Then a number of bolts were assumed to calculate the required plate thickness, and a plate thickness was assumed to calculate the required number of bolts.

$$B_r = 3\Phi_{br} ntdF_u$$

Where: B_r = bearing capacity [kN] = 193.2
$\Phi_{br} = 0.8$
n = number of bolts
t = thickness of plate [mm]
d = bolt diameter [mm] = 36
F_u = specified minimum tensile strength [MPa] = 450
Assuming n = 8, t = 1.11 mm
Assuming t = 10 mm, n = 0.89

An initial bolt diameter of 36 mm was assumed for the above calculations. Since the calculated number of bolts and plate thickness were quite small, larger values were assumed. These values will be decreased later if after all the checks show the resistances are much greater than the applied forces. The M36 A325M bolts have a diameter of 36 mm, an area of 1018 mm^2, and a specified minimum tensile strength of 830 MPa. The bolt parameters were used to determine both shear and tensile resistance.

The shear resistance was calculated according to clause 13.12.1.2.c of the handbook.

$$V_r = 0.60\Phi_b n m A_b F_u$$

Where: V_r = shear capacity [kN] = 3244.57
Φ_b = 0.8
n = number of bolts = 8
m = number of shear planes = 1
A_b = area of bolt [mm^2] = 1018
F_u = specified minimum tensile strength [MPa] = 830

The shear capacity of 3244.57 kN was larger than the applied shear force of 386.4 kN. Therefore, the selected number and size of bolts is sufficient.

The tensile resistance was calculated next. It was compared to the maximum tension in each bolt which is calculated when checking the primary steel in section 6.2.2. According to clause 12.12.1.3 of the handbook, tensile resistance is determined.

$$T_r = 0.75\Phi_b A_b F_u$$

Where: T_r = tension capacity [kN] = 506.96
Φ_b = 0.8
A_b = area of bolt [mm^2] = 1018
F_u = specified minimum tensile strength [MPa] = 830

6.2.2 Primary Steel Integrity

The platform and tank will be located on an operating section of the vessel. Therefore it was required to determine if the existing structural members that will be supporting the designed tank and platform would be able to handle the additional load. Both the web bearing and the flange bending were checked for the compression and tension cases, respectively. The web bearing resistance is the smaller of the two resistances calculated according to clause 14.3.2.a.

$$B_{r,1} = \Phi_b w(N+10t)F_y$$

$$B_{r,2} = \Phi_{bi} w^2\sqrt{(F_y E)}$$

Where: $B_{r,1}$ = bearing capacity [kN] = 5600.00
$B_{r,2}$ = bearing capacity [kN] = 3822.10
Φ_b, Φ_{bi} = 0.80
w = thickness of web [mm] = 20
N = length of plate [mm] = 700
t = thickness of flange [mm] = 30
F_y = specified minimum yield stress [MPa] = 350
E = modulus of elasticity [MPa] = 200,000

The applied bearing of 135 kN is far less than the bearing resistance of 3822.10 kN, therefore the design is acceptable.

The flange bending is checked assuming a pattern of circular yielding for a pair of bolts separated by a web in a flange. The effective length of the yielding zone was then calculated and used to calculate the moment resistance of the flange.

$$L_{eff} = 2\pi m$$

$$z = L_{eff}t^2 / 4$$

Where: L_{eff} = effective length [mm] = 439.82
m = distance from web edge to center of bolt hole [mm] = 70
z = [mm^3] = 98,960
t = thickness of flange [mm] = 30

$$M_r = \Phi z F_y$$

Where: Mr = moment resistance calculated as [kN m] = 31.17
Φ = 0.9
F_y = specified minimum yield stress [MPa] = 350

Now the factored moment applied to the flange can be calculated to ensure it is less than the moment resistance of the flange. Figure 6.1 shows the column and the base plate along with the location of the bolt holes on the base plate. The reactions at the bolts that cause consequent reactions on the flange of the primary steel beam are shown.

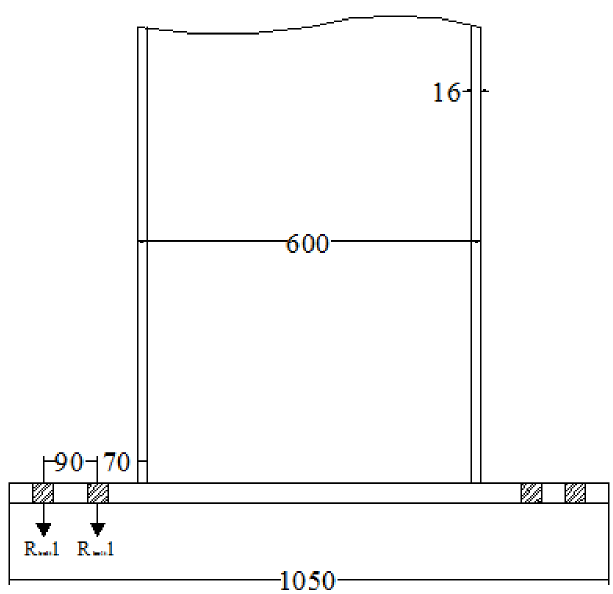


Figure 6.1: Diagram of column and base plate showing bolt reactions

The applied moment to the column is known and relates to the bolt reactions as follows.

$$M_{applied} = 2R_{bolt1}d_{bolt1} + 2R_{bolt2}d_{bolt2}$$

Where: $M_{applied}$ = applied moment to column [kN m] = 1203
R_{bolt1} = reaction at bolt 1 [kN]
R_{bolt2} = reaction at bolt 2 [kN]

Using ratios, R_{bolt1} and R_{bolt2} were calculated as 450.64 kN and 396.71 kN respectively.

The maximum tension force in a bolt must be determined next, which will be the bolt with the largest reaction force. The tension force in the column, divided by the number of bolts, is added to the bolt reaction force to find the maximum tension.

$$T_f = T_{column}/n + R_{bolt1}$$

Where: T_f = maximum tension in bolt calculated as [kN] = 467.51
T_{column} = largest z force (tension) applied to column [kN] = 135
n = number of bolts = 8

Returning briefly to the tensile resistance check in section 6.2.1, the tensile resistance of 567.72 kN is larger than the applied tension force of 467.6 kN. The tension capacity is not much larger than the applied tension force, so the bolted connections are not overdesigned and the choice of 8 M36 high strength A325M bolts was reasonable.

It is also necessary to ensure that the bolts are acceptable under combined shear and tension conditions. The check from Clause 13.12.1.3 must be satisfied. The values for shear resistance (assuming threads intercepted to be conservative) and tensile resistance are from Table 3-4 of the handbook.

$$(V_f/V_r)^2 + (T_f/T_r)^2 = 0.88 < 1$$

Where: V_f = factored shear for one bolt [kN] = 48.30
V_r = shear resistance [kN] = 284
T_f = maximum tension in bolt [kN] = 467.51
T_r = tensile resistance [kN] = 507

Because the calculated value was found to be less than 1, this check is satisfied.

Finally, the factored moment applied to the flange can be calculated and compared to the moment resistance. To do this, the required distance from the center of the web to the center of the bolt hole must be found. The required diameter of a plain circular washer for a M36 bolt is 72 mm according to a table on p. 6.64 of the handbook. Figure 6.2 shows the location of the bolt in relation to the web of the primary steel. Here, the minimum distance is represented by e_{min} and using the required weld and washer size it was found to equal 60 mm.

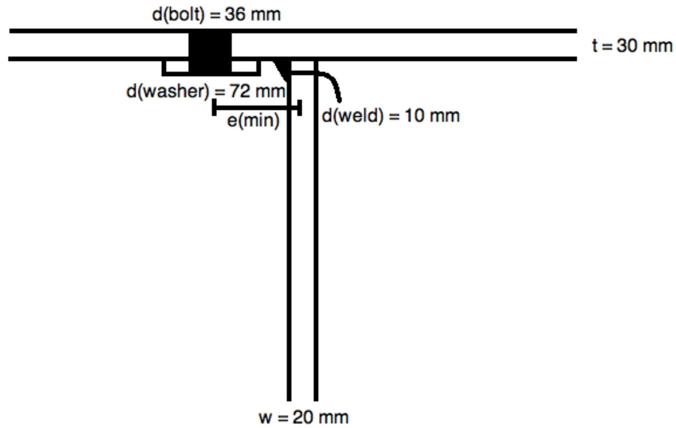


Figure 6.2: Primary steel beam as bolted to secure the platform

The factored moment was calculated using the distance and the maximum tension in the bolt as follows:

$$M_f = T_f * e$$

Where: M_f = factored moment calculated as [kNm] = 28.05
e = distance from web edge to center of bolt hole [mm] = 60

The factored moment of 28.05 kN m is less than the moment resistance of 31.17 kN m that was found above, and the web bearing is sufficient. Therefore, the primary steel capacity is adequate to support the designed platform, tank and connections.

6.2.3 Base Plate Bending

The bending of the base plate under the platform column must be checked to ensure it does not fail due to applied loads. The base plate is only bolted to the primary steel in the plane of the primary steel web. Therefore, the base plate in the direction perpendicular to the primary steel web is only required to be sized to accommodate the full penetration weld between the platform column and the plate. A size of 700 mm was selected.

In the direction of the primary steel beam web the base plate must be sized to accommodate the bolts as well. A size of 1050 mm is chosen based on calculation of the minimum size required in this direction, which is:

$$Length_{min} = Length_{column} + 2d_{web\ edge\ to\ bolt1} + 2d_{bolt1\ to\ bolt2} + 2(\text{edge distance})$$

Where: $Length_{min}$ = required length of base plate calculated as [mm] = 1048, use 1050
$Length_{column}$ = length of column [mm] = 600
$d_{web\ edge\ to\ bolt1}$ = distance from web edge to center of bolt 1 [mm] = 70
$d_{web\ edge\ to\ bolt2}$ = center to center distance between bolt 1 and 2 [mm] = 90
edge distance [mm] = 64, required for M36 bolts according to clause 22.3.2, Table 6

The factored moment was then determined as follows:

$$M_f = (2R_{bolt1}d_{bolt1} + 2R_{bolt2}d_{bolt2})(d_{web\ to\ bolt2})$$

Where: M_f = factored moment calculated as [kN m] = 194.89
R_{bolt1} = reaction at bolt 1 [kN] = 450.64
d_{bolt1} = distance from far column edge to center of bolt 1 [mm] = 752
R_{bolt2} = reaction at bolt 2 [kN] = 396.71
d_{bolt2} = distance from far column edge to center of bolt 2 [mm] = 662
$d_{web\ to\ bolt2}$ = distance from web edge to center of bolt hole 2 [mm] = 115

By setting the factored moment equal to the moment resistance, the following two equations were used to solve for z, and then for the required pate thickness.

$$M_r = M_f = \Phi z F_y$$

Where: $\Phi = 0.9$
z = [mm^3] = 618,696.46
F_y = specified minimum yield stress [MPa] = 350

$$z = bt^2 / 4$$

Where: b = length of plate [mm] = 700
t = thickness of plate, calculated as [mm] = 29.73, use 35

6.2.4 Platform to Primary Steel final design

Based on the above checks, the base plate and bolted connections between the platform and the primary steel were designed. Each base plate will be 1050 mm by 700 mm and 35 mm thick. The columns will be attached to the base plate with full penetration welds. The base plates will each have eight M36 high strength A325 bolts, which will be located as shown in Figure 6.3.

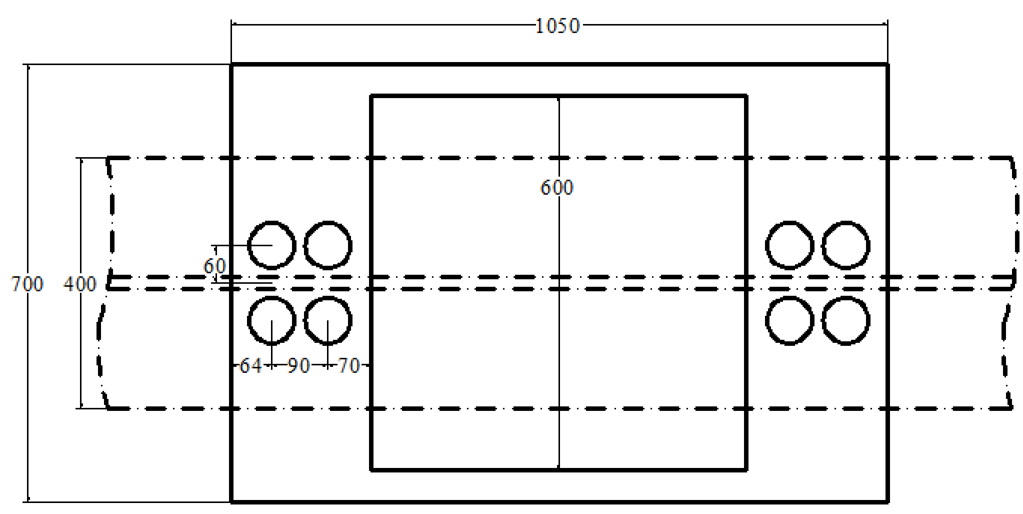


Figure 6.3: Bolt locations in the base plate

7.0 Seafastening Design

Seafastening is the act of securing objects that are being transported on a vessel so that they are not subject to movement. Movement during transportation is undesirable because it could cause instability of the vessel and potentially damage the object, the vessel, and endanger the lives of the crew. The design of seafastening is object and vessel specific based on vessel accelerations and available padeye capacities.

Both the tank and the platform will have an individual seafastening design. The Maersk Nascopie supply boat was used for the seasfastening design, as it will be shipping the tank and the platform to the Terra Nova FPSO. The supply boat is equipped with attachment padeyes, or lugs, on framelines every 5 m. Each lug can carry 2 tons of horizontal force.

It is assumed that the supply boat will be subject to a 0.5 g acceleration, which causes a 12 ton horizontal force on both the tank and the platform based on their respective masses. The tank and the platform will be equipped with eight chains for a total support of 16 tons during its transport to the Terra Nova FPSO. The connection layouts are shown in Figure 7.1.

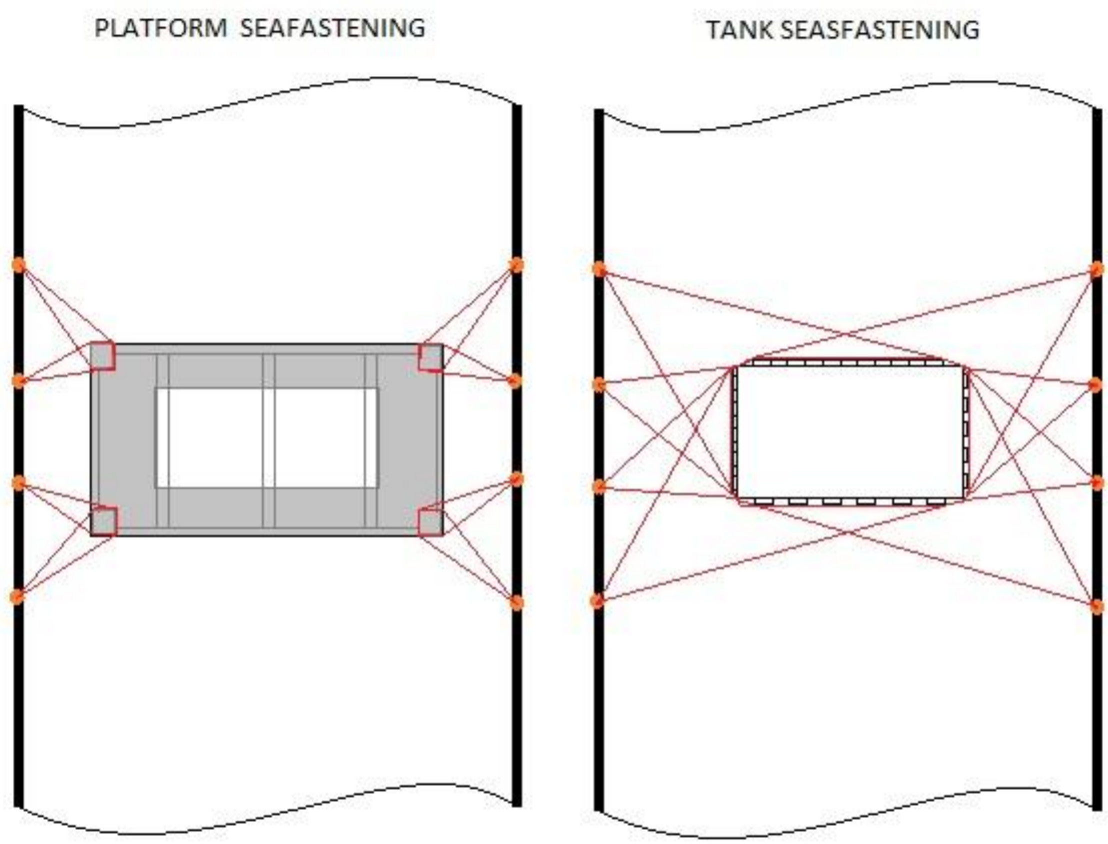


Figure 7.1: Tank and platform seafastening design

8.0 Lifting Design

Lifting assemblies are designed for the lift and transfer of the tank and platform from a supply vessel to the Terra Nova FPSO. A lift assembly is used for the safe and efficient transfer of objects offshore. The assembly consists of slings, master link, shackles and padeyes, and the design of all these components is called the lifting design. The lift system is named for the number of padeyes, and therefore liftpoints, on the object. Both the tank and the platform have four-point lift systems. A typical four-point wire sling lifting assembly is shown in Figure 8.1.

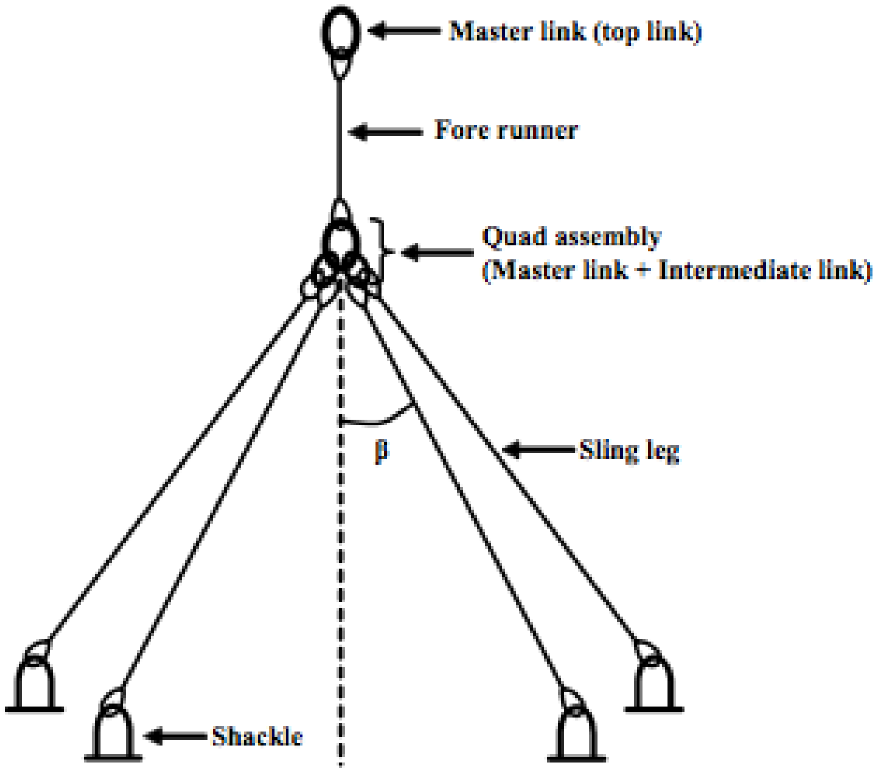


Figure 8.1: Typical four-point wire sling lifting assembly (Det Norske Veritas 39)

8.1 Tank Lifting Design

The proof load is calculated to determine the Working Load Limit (WLL) of the slings, master link and shackles for the purpose of their selection and the design of the lifting assembly. Two codes are used for the lifting design. For the design of the sling assembly, including slings, shackles and master link, Lloyd's Register Code for Lifting Appliances in a Marine Environment (July 2008) was used. The padeye design used DNV Standard for Certification No. 2.7-1 Offshore Containers (April 2006).

For the purpose of the proof load calculation, the Safe Working Load (SWL) is defined as the mass (in metric tons) of the object being lifted.

$$SWL_{tank} = m_{tank} = 17.14 \text{ t}$$

According to Table 9.1.1 of the Lloyd's Register Code, the proof load is calculated as follows for 10 < SWL < 160 t:

$$\text{Proof Load}_{tank} = (1.04 * SWL) + 9.6 = 27.42 \text{ t}$$

Based on note 4 from the same table, the proof load must be increased by the ratio of $F_h/1.6$ because the lift occurs offshore, where F_h is the hoisting factor. The sea state number was found to be 5-6 based on the significant wave height for the SWL obtained from the Terra Nova FPSO crane access drawing. The sea state number is used for Table 3.3.1 to determine the value of F_w as 21.7, where F_w is the wave factor dependant on the design operational sea condition. Then F_h is calculated as follows:

$$F_h = 0.83 + F_w * \sqrt{(K/L_1)} = 2.07$$

Where: F_h = hoisting factor
F_w = wave factor
K = the crane system stiffness [N/mm]
L_1 = live load [N]
$\sqrt{(K/L_1)} = 0.057$ as given in the Lloyd's code.

Once the factor of $F_h/1.6$ is applied to the proof loads, the new proof load for the tank becomes 35.43 t. The sling leg angle is assumed to be 60 degrees for the purpose of this design. The proof load is used to determine the WLL_{min} of the slings, shackles and master link and to make the component selection. A summary is in Table 8.1. The slings were chosen from the Hercules catalogue. The shackles and the master link were chosen from the Crosby catalogue.

Table 8.1: Minimum Working Load Limits for slings, shackles and master link for the tank lifting system and component selection

Component	WLL_{min} (Equation)	WLL_{min} [t]	Selection
Slings	(Proof Load/3)/sin60	13.64	6x36 Galvanized EIPS, diam. 1.25 in, Nominal Breaking Strength 79.9 t
Shackles	(Proof Load/3)/sin60	13.64	A-345 master link, WLL 38.5 t
Master Link	Proof Load	35.43	Bolt type anchor shackle G-2130, WLL 17 t

For sling length calculations it is assumed that the sling leg angle is 60 degrees and the center of gravity of the tank is located at the geometric center. The meeting point of the four slings is assumed to be located directly above the geometric center of the tank. The sling length is calculated as follows:

$$d_{LP\ to\ CoG} = 0.5(width_{tank}) = 0.5(length_{tank}) = 2525\ mm$$

Where: $d_{LP\ to\ CoG}$ = distance from any liftpoint to the center of gravity [mm]
$width_{tank} = length_{tank}$ = 5050 mm

$$L_{sling} = (d_{LP\ to\ CoG}) / \cos(\text{sling leg angle}) = 5050\ mm$$

Where: L_{sling} = length of sling at any liftpoint [mm]
$d_{LP\ to\ CoG}$ = distance from any liftpoint to the center of gravity [mm] = 2525
Sling leg angle [degrees] = 60

Finally, the padeyes located at each of the four lift points are designed. The padeye material is 350WT carbon steel, with a minimum yield strength of 350 MPa. The padeye dimensions were chosen, and both the tear out stress and the contact stress were checked.

$$\text{Tear out stress:} \quad Re \geq (3\ RSL) / (2Ht - D_H t)$$
$$\text{Contact stress:} \quad Re \geq 23.7 / \sqrt{(RSL / D_H t)}$$

Where: Re = minimum specified yield strength of padeye material [N/mm^2]
RSL = resulting sling load [N] = 133,769.24
H = shortest distance from bolt hole center to padeye edge [mm] = 100.00
D_H = bolt hole diameter [mm] = 40.00
t = padeye thickness [mm] = 50.00

The tear out and contact stress checks were satisfied so the proposed design is acceptable.

The tension at the weld is calculated to determine the design length. The tensile resistance is set equal to the tension force and the nominal area of the fusion face normal to the tensile force is found. Then the area is used to determine the minimum length of the padeye.

$$T_r = \Phi_x A_n F_u = RSL$$

Where: T_r = factored tensile resistance [kN] = 133.77
Φ_x = 0.67
A_n = nominal area of fusion face normal to tensile force [mm^2] = 570.44
F_u = specified minimum tensile strength [MPa] = 350

$$A_n = t * L$$

Where: A_n = nominal area of fusion face normal to tensile force [mm^2] = 570.44
t = thickness of padeye [mm] = 50.00
L = minimum length of padeye [mm] = 11.41

The minimum length of the padeye is far too small to be the actual length. Therefore, a reasonable assumption is made that the length is equal to twice the shortest distance from bolt hole center to padeye edge, which is 200 mm.

The moment resistance of the padeye was calculated to determine the height to the center of the padeye:

$$M_r = (1/SF)(bt^2/6)F_y = 9.72 \text{ kN m}$$

Where: M_r = moment resistance [kN m]
SF = safety factor = 3
b = length of the padeye [mm] = 200.00
t = thickness of padeye [mm] = 50.00
F_y = yield stress [MPa] = 350

Assuming the applied moment is equal to the moment resistance, the height to the center of the padeye is determined as follows.

$$M_{applied} = F_H * x,$$

$$x = H_c + 0.5D_H + (100 – D_H/2) /2, \text{ and}$$

$$H_c = 110 \text{ mm, use } 105 \text{ mm}$$

Where: $M_{applied}$ = applied moment [kN m] = M_r = 9.72
F_H = horizontal component of RSL [kN] = 66.88
x = moment arm [mm] = 160.00
H_c = height to center of padeye [mm]
D_H = bolt hole diameter [mm] = 40.00

A diagram showing the padeye dimensions is seen in Figure 8.2. The selected five dimensions that make up the padeye design that is to be fabricated are summarized in Table 8.2.

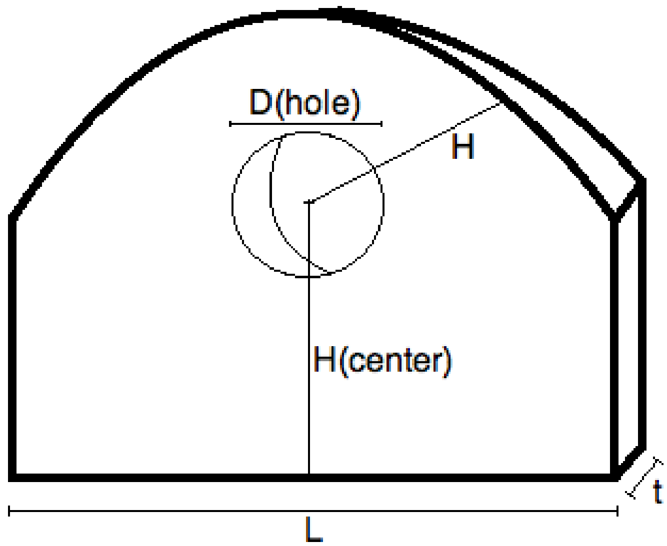


Figure 8.2: Padeye dimension diagram

Table 8.2: Padeye design dimensions for tank lifting system

Shortest distance from bolt hole center to padeye edge, H [mm]	100
Bolt hole diameter, D_H [mm]	40
Padeye thickness, t [mm]	50
Height to center of padeye, H_c [mm]	105
Length of padeye, L [mm]	200

8.2 Platform Lifting Design

The lifting design for the platform follows the same procedure as above. The following values are calculated.

$$SWL_{platform} = m_{platform} = 24 \text{ t}$$

$$\text{Proof Load}_{platform} = (1.04 * SWL) + 9.6 = 34.56 \text{ t}$$

$$F_h = 0.83 + F_w * \sqrt{(K/L_1)} = 2.07$$

Where: F_h = hoisting factor
F_w = wave factor
K = the crane system stiffness [N/mm]
L_1 = live load [N]
Assuming $\sqrt{(K/L_1)} = 0.057$ as given in the Lloyd's code

$$\text{Proof Load}_{platform} = (34.56 \text{ t})(F_h/1.6) = 44.65 \text{ t}$$

Table 8.3: Minimum Working Load Limits for slings, shackles and master link for the platform lifting system and component selection

Component	WLL_{min} (Equation)	WLL_{min} [t]	Selection
Slings	(Proof Load/3)/sin60	17.18	6x36 Galvanized EIPS, diam. 1.375 in, Nominal Breaking Strength 96 t
Shackles	(Proof Load/3)/sin60	17.18	A-345 master link, WLL 46.5 t
Master Link	Proof Load	44.65	Bolt type anchor shackle G-2130, WLL 25 t

For sling length calculations it is assumed that the sling leg angle is 60 degrees. The platform was modeled in S-Frame to find the center of gravity and the sling lengths that will yield the proper sling leg angle. The x and y coordinates of the center of gravity were found to be 4300 mm and 3850 mm, respectively, as seen in Figure 8.3.

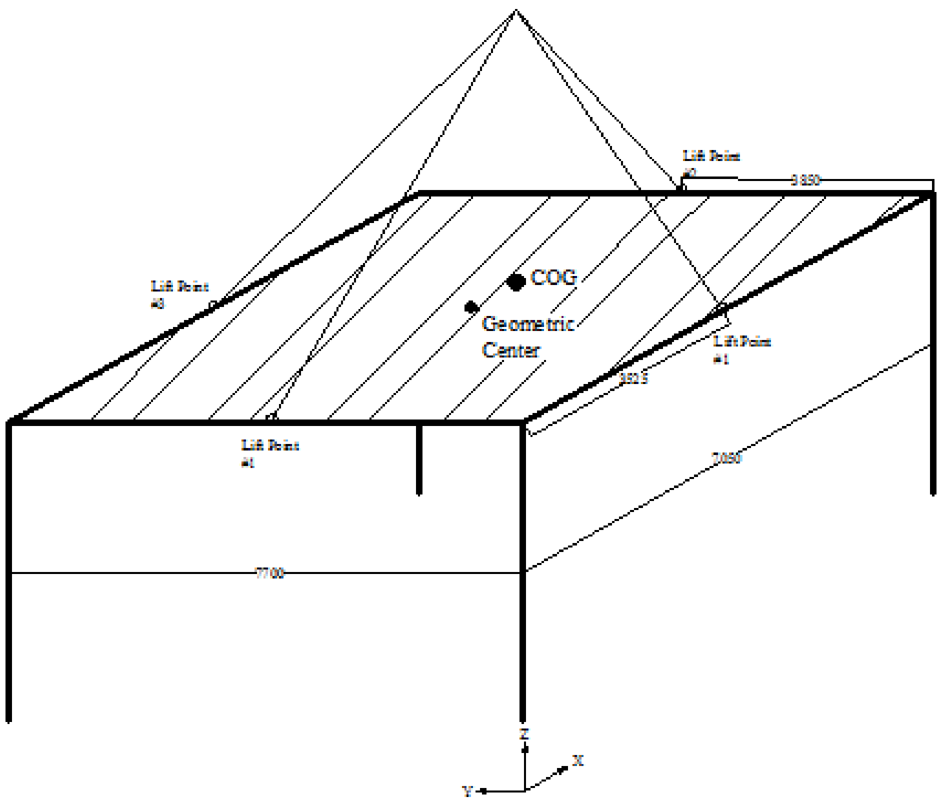


Figure 8.3: Platform diagram showing liftpoints, center of gravity and geometric center

Next, the distance from each liftpoint to the center of gravity was determined. Then sling lengths were calculated as follows:

$$L_{sling} = (d_{LP\ to\ sling}) / \cos 60$$

The distances from the liftpoints to the center of gravity and the sling lengths are summarized in Table 8.4.

Table 8.4: Sling lengths for platform lifting system

Liftpoint (LP)	Distance from LP to CoG, $d_{LP\ to\ sling}$ (mm)	Sling Length, L_{sling} (mm)
1	3927.23	7854.46
2	2750.00	5500.00
3	3927.23	7854.46
4	4300.00	8600.00

Finally, the padeyes that were designed for the tank are used for the platform as well. Once again, the padeye material is 350WT carbon steel, with a minimum yield strength of 350 MPa. The padeye dimensions were chosen, and both the tear out stress and the contact stress were checked.

Tear out stress: $Re \geq (3\ RSL) / (2Ht - D_H t)$

Contact stress: $Re \geq 23.7 / \sqrt{(RSL / D_H t)}$

Where: Re = minimum specified yield strength of padeye material [N/mm^2]
RSL = resulting sling load [N] = 180,139.94
H = shortest distance from bolt hole center to padeye edge [mm] = 100.00
D_H = bolt hole diameter [mm] = 45.00
t = padeye thickness [mm] = 55.00

The tear out and contact stress checks were satisfied so the proposed design is acceptable.

The tension at the weld is calculated to determine the design length. The tensile resistance is set equal to the tension force and the nominal area of the fusion face normal to the tensile force is found. Then the area is used to determine the minimum length of the padeye.

$$T_r = \Phi_x A_n F_u = RSL$$

Where: T_r = factored tensile resistance [kN] = 180.14
Φ_x = 0.67
A_n = nominal area of fusion face normal to tensile force [mm^2] = 768.19
F_u = specified minimum tensile strength [MPa] = 350

$$A_n = t * L$$

Where: A_n = nominal area of fusion face normal to tensile force [mm^2] = 768.19
t = thickness of padeye [mm] = 55.00
L = minimum length of padeye [mm] = 13.97

The minimum length of the padeye is far too small to be the actual length. Therefore, a reasonable assumption is made that the length is equal to twice the shortest distance from bolt hole center to padeye edge, which is 200 mm.

The moment resistance of the padeye was calculated to determine the height to the center of the padeye:

$$M_r = (1/SF)(bt^2/6)F_y = 11.76 \text{ kN m}$$

Where: M_r = moment resistance [kN m]
SF = safety factor = 3
b = length of the padeye [mm] = 200.00
t = thickness of padeye [mm] = 55.00
F_y = yield stress [MPa] = 350

Assuming the applied moment is equal to the moment resistance, the height to the center of the padeye is determined as follows.

$$M_{applied} = F_H * x,$$

$$x = H_c + 0.5D_H + (100 – D_H/2) /2, \text{ and}$$

$$H_c = 69.36 \text{ mm, use } 65 \text{ mm}$$

Where: $M_{applied}$ = applied moment [kN m] = M_r = 11.76
F_H = horizontal component of RSL [kN] = 90.07
x = moment arm [mm] = 130.61
H_c = height to center of padeye [mm]
D_H = bolt hole diameter [mm] = 45.00

A diagram showing the padeye dimensions is seen in Figure 8.2. The selected five dimensions that make up the padeye design that is to be fabricated are summarized in Table 8.5.

Table 8.5: Padeye design dimensions for tank lifting system

Shortest distance from bolt hole center to padeye edge, H [mm]	100
Bolt hole diameter, D_H [mm]	45
Padeye thickness, t [mm]	55
Height to center of padeye, H_c [mm]	65
Length of padeye, L [mm]	200

9.0 Cost

A cost estimate was completed for the tank and platform structures using RS Means, as well as researched data. The various members for the structures will be fabricated as designed, so steel unit weight was used to estimate the cost of the steel. In order to estimate the cost of 316L stainless steel, a unit cost was found as $4.9/kg, and the unit cost of steel was found to be $0.6/kg. Therefore the cost for steel bare material in RS Means was multiplied by a factor of eight (metal prices). The cost estimate for the tank resulted in a total cost of $261,600.61 and the breakdown is displayed in Table 9.1. The cost estimate for the platform resulted in a total cost of $181,638.31, and the breakdown is displayed in Table 9.2.

Table 9.1: Tank cost breakdown

Description	**Unit**	**Quantity**	**Cost**
316L Stainless steel	kg	17139	$ 78,668.01
Welding	m	200	$ 102,070.00
E-3A Crew	days	15	$ 80,862.60
Total			$ 261,600.61

Table 9.2: Platform cost breakdown

Description	**Unit**	**Quantity**	**Cost**
Structural tubing, heavy section, including fabrication labour, shop primer, cap and base plate, and bolts	kg	24013.81	$ 86,209.58
Welding	m	53.3	$ 5,615.16
Railing, pipe, steel, primed, 31 mm dia, shop fabricated	m	26	$ 2,585.44
Ladder, shop fabricated, steel, including cage	m	9	$ 3,846.60
High strength bolt, , including washer & nut	Each	32	$ 344.64
Metal floor steel decking	m2	49	$ 2,346.61
E-3A Crew	days	2	$ 80,862.60
Total			$ 181,638.31

10.0 Project Summary

Throughout the design of the calcium nitrate storage tank and the supporting platform the project constraints were considered and accommodated. All project deliverables were met.

Abaqus, which is a finite element analysis modeling software, was used to model the storage tank. The preliminary design was optimized to be most economical. The tank design included tank walls, stiffeners and bulkheads. The final wall thickness was 8 mm. The stiffener thickness was 8 mm, and they were placed at 750 mm intervals in all directions around the tank. The tank was designed to be 5.05 m by 5.05 m by 4.05 m. It has a weight of 17, 139 tons and a cost of $261,600.61 .

The platform was modeled in S-Frame and the preliminary design was optimized to meet all project criteria and to be most cost-efficient. The columns, cross-bracing and corner-bracing are hollow sections, and the deck is comprised of W sections. The design included the bolted connections through to the primary steel of the Terra Nova FPSO. The final platform dimensions were 7.7 m by 7.05 m by 4.5 m. The final platform has a weight of approximately 24 tons and a cost of $181,638.31.

The storage tank and supporting platform were designed in an efficient, safe and economical manner and are capable of successful implementation offshore on the Terra Nova FPSO.

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