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Master's degree thesis

IP501909 MSc thesis, discipline oriented master

An Innovative method for the installation of Offshore Wind Turbines

Prabhu Bernard

Number of pages including this page: 84

Aalesund, 06.06.2017

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MASTER THESIS 2016
FOR
STUD.TECHN. Prabhu Bernard

AN INNOVATIVE METHOD FOR THE INSTALLATION OF OFFSHORE WIND TURBINES

This project aims in developing a new concept which can install an entire Offshore Wind Turbine on top of a monopile using an unique approach which has never been tested before. This operation includes the possibility of carrying up to four or more wind turbines in one travel based on the size of the vessel. Huge catamaran installation vessels could provide more stability while carrying out the operation presented in the report

The project aims in coming up with a concept design, which is structurally stable and mathematically valid. The 3d design of the concept is done so as to check and validate the behavior of the system at sea. This model which is made using NX can be used for motion simulation. Studying the effects of wind and waves on the structure is the main objective of motion simulation. The final outcome of the design is expected to be a structurally stable design that could compensate for the effects of wave motions and reduce the time consumed for installing offshore wind turbines.

- Prestudy:
    - Different Installation methods for offshore wind turbines
    - Motion Analysis Using NX

- Model development:
    - 3D Concept development
    - Structral Analysis
    - Motion Analysis
    - Real time Simulation

- Perform motion simulations on selected cases with different operation profiles
- Ensuring the structural stability of the concept design

The work scope may prove to be larger than initially anticipated. Subject to approval from the supervisor, topics may be deleted from the list above or reduce in extent.

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Supervision at Ålesund UC.: Karl Henning Halse, Yael Pericard

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MASTER THESIS

CANDIDATE NO (S):				
10004 / PRABHU BERNARD				
DATE: 06-06-2017	SUBJECT CODE: IP501909	SUBJECT NAME: MSc THESIS, DISCIPLINE ORIENTED		
STUDY PROGRAMME: MASTER OF PRODUCT AND SYSTEM DESIGN			NO OF PAGES/APPENDIX 55 / 11	BIBL. NO: 22

SUPERVISOR(S):

Karl Henning Halse, Yael Pericard

TITLE:

AN INNOVATIVE METHOD FOR THE INSTALLATION OF OFFSHORE WIND TURBINES

ABSTRACT:

Bringing an offshore wind turbine to life is an inspiring task that demands great engineering precision and dedication. Transporting a fully assembled wind turbine to an offshore location for installation ensures that the time spend offshore is considerably minimized and the installation cost is significantly reduced. The objective of this thesis is to develop an innovative method for transporting and installing an offshore wind turbine in water depths above 200 meters. The concept developed is a piece of machinery that relies heavily on the existing technological advances in the field of motion compensation and heavy equipment installation. The thesis is structured into three phases. A design phase in which a new deployment mechanism is developed by considering manufacturability and material selection. An analysis phase that ensures the structural stability of the concept using NX Nastran and a simulation phase that verifies the kinematic stability of the design using NX motion simulation. All the 3D models associated with the design is developed using the software Siemens NX, animated using PTC Creo and rendered using Keyshot. The project focus mostly on the manufacturability of the product by carefully selecting the standards steel cross sections available in the European market and by selecting the equipment's from European suppliers. A detailed explanation on the various steps involved in the installation process along with a structural and motion analysis to support the claim is presented as a result of the study.

This thesis is handed in for evaluation and accreditation at NTNU i Ålesund.

Postadresse/Postaladdress
NTNU i Ålesund
Postboks 1517
N-6025 Aalesund
Norway

Besøksadresse/Main office
Larsgårdsvegen 2
Internett/Internet
www.ntnu.no/alesund

Telefon/Telephone
+47 73 59 50 00
Epostadresse/Emailaddress
postmottak@alesund.ntnu.no

Telefaks/Telefax
+47 70 16 13 00

Abstract

Bringing an offshore wind turbine to life is an inspiring task that demands great engineering precision and dedication. Transporting a fully assembled wind turbine to an offshore location for installation ensures that the time spend offshore is considerably minimized and the installation cost is significantly reduced. The objective of this thesis is to develop an innovative method for transporting and installing an offshore wind turbine in water depths above 200 meters. The concept developed is a piece of machinery that relies heavily on the existing technological advances in the field of motion compensation and heavy equipment installation.

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Preface

This thesis was written as a part of my Master of science degree program in Product and System design at NTNU (Norwegian University of Science and Technology), during the spring of 2017, under the supervision of Professor Karl Henning Halse in the Department of Ocean Operations and Civil Engineering.

The thesis aims to develop an innovative method for the installation of Offshore Wind Turbines. This study is conducted in three phases where a concept for a new installation equipment is developed using Siemens NX in phase one, the structural stability of the critical components are analyzed in phase two and the dynamic stability of the system in response to the ocean waves are verified using motion simulation in phase three.

I have been working as a Project Engineer in the Design of Construction and Mining Equipment's for 5 years before pursuing my mater degree at NTNU, which I strongly believe has helped me in structuring this thesis. I would like to acknowledge the support, patience and guidance of the following people without whom, this thesis would not have been completed. It is to them that I owe my deepest gratitude.

Firstly, I would like to express my sincere gratitude to my supervisor **Prof. Karl Henning Halse** for the continuous support, patience and motivation. He consistently allowed this paper to be my own work, but steered me in the right direction with his insightful comments and encouragement which had helped me to widen my research from various perspectives.

Besides my supervisor, I would like to thank my Co-Supervisor **Mr. Yael Pericard** for sharing his expertise in all the modules of NX and for his passionate participation and assistance in developing this concept.

My sincere thanks also goes to **Prof. Vilmar Æsøy,** who provided me an opportunity to join his team as an intern which in fact was the first and foremost step that led me into developing this thesis. Without whom, I would not be having an opportunity to conduct this research.

I would also like to acknowledge **Mr. Rodrigo Urbina,** my friend and class mate who has helped me in various stages of this thesis for solving the bottle necks that I dealt with.

Last but not the least, I would like to thank my wife, my parents and my brother for providing me with unfailing support and continuous encouragement throughout my years of study and through the process of researching and writing this thesis.

Prabhu Bernard
Ålesund, June 6th 2017

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1 Introduction

A large portion of our economy is based on fossil fuels, where oil powers majority of the transportation sector and coal along with natural gas powers most of the electricity. Now, in the first couple of decades of the twenty first century, we are relying on very extreme and devastating ways for finding and extracting new sources in order to sustain our dependence on fossil fuels. Every move that we make in this quest is destroying our planet by the second. It has become inevitable that the mankind has to switch from fossil fuels to renewable resources like wind and solar energy for the benefit of our planet and for the generations to come. By failing to do so will make us and all living things that we cherish on this planet, a history.

Among several sources of renewable energy resources available today, Offshore Wind Turbines (OWT) have proved to be extremely promising for the future of mankind. Currently there are several OWT installations around the world along with many upcoming projects which are in the initiation phase. Installation of these wind turbines are extremely expensive and time consuming owing to the complexities involved in erecting a huge structure out in the ocean. The statistics of the European offshore wind energy shows that only 182 turbines were erected during the first half of 2016 in 13 wind farms operated by four countries as shown in [Figure 1.1]

	BELGIUM	GERMANY	NETHER-LANDS	UNITED KINGDOM	TOTAL
Number of farms	1	6	2	4	13
Number of foundations installed	14	77	0	86	177
Number of turbines erected	0	56	126	0	182
Number of turbines grid connected	0	43	71	0	114
MW fully connected to the grid	0 MW	258 MW	253 MW	0 MW	511 MW

Figure 1.1 Offshore wind turbine installation between 1 January and 30 June 2016 in Europe [1]

Meteorological studies have proved that the average wind speed in the offshore area is less turbulent and more intense when compared to the onshore sites due to low surface shear. Installing a wind turbine out in offshore location has always been a challenge and it still remains to be one. A smart and efficient way of installing a 1000-ton wind turbine safely and efficiently in the middle of the ocean is still a prominent research question. This project aims in developing an innovative concept design for the installation of offshore wind turbines which could surpass the current limitations in the installation time and contribute towards a better future. Reducing the installation time could have a significant impact on the capital investments required for the project. The dynamic stability and structural integrity of the concept developed in this project is later verified using motion simulation and structural analysis with the help of a CAD (Computer Aided Design) software, Siemens NX.

1.1 Problem Definition

Most of the wind turbines in operation today are installed on monopiles which are driven deep in to the sea bed closer to the shore for a stable and reliable operation. The installation of these heavy wind turbine is often carried out in an effective manner using jack up vessels which are rooted to the sea bed for increased stability during assembly as shown in [Figure 1.2]. However, researchers have found that a more reliable wind speeds are recorded far into the ocean than near to the shore. Installing a wind turbine on a monopile far from shore has its limitations due to the depth of the sea bed and the unpredictability of the sea conditions.

Figure 1.2 Existing OWT installations using jack up vessel [2]

The concept developed in this project is inclined towards the installation of an OWT far in the deep oceans where the monopiles are either floating or moored to the sea bed. In this scenario, the jack up vessels shown in [Figure 1.2] cannot be used for the installation owing to the depth of the sea bed. Due to this reason, these heavy installation needs to take place in a constantly floating environment which questions the reliability of the existing technology in achieving a safe and quick installation. This project aims in developing a new concept which can install an entire OWT on top of a monopile using a unique approach which has never been tested before on a structure of this magnitude. This also includes the possibility of carrying up to six or more wind turbines in one travel based on the size of the vessel. Huge catamaran installation vessels could provide more stability while carrying out the operation presented in the report. The main objective behind installing a pre-assembled wind turbine on top of a monopile rather than carrying out a part by part installation out in the sea is to reduce the installation time. A quick and safe installation out in the sea require calm waves and wind conditions which are available only on rare intervals during a 24-hour period. The mechanism developed in this project is also equipped with a motion compensation system which could actively compensate for all the wave motions which would in turn make the installation at offshore condition possible without having to wait for calm sea conditions. In the absence of a technologically advanced motion compensation system, it has been proved in the past that the time required for installing an OWT is considerably high due to the short window of calm waves. This project proposal could significantly reduce the time required for the installation of an offshore wind turbine.

1.2 Scope of Work

After evaluating the current investments and projections in the field of offshore energy, it is evident that the total installation of wind turbines needs to increase in order to reduce the consumption of fossil fuels that induces global warming. To achieve the clean energy target projected by the European countries, a paradigm shift is required. The current industrial focus is towards increasing the production of fully assembled on shore wind turbine structures that can later be transferred to offshore sites, providing safety and stability while transporting and installing a fully assembled OWT, developing new technologies that could reduce the wind turbine installation time and increasing the operability at higher sea states by improving the wave and wind motion compensation systems currently available.

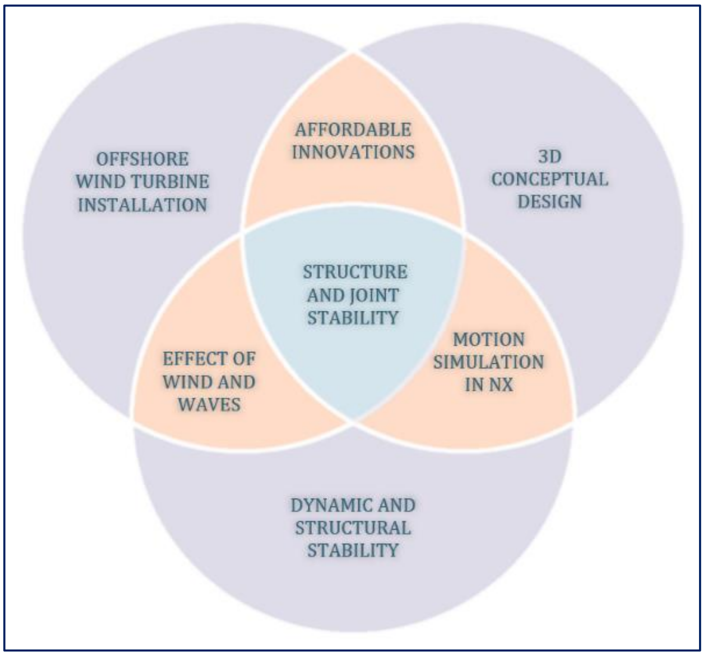


Figure 1.3 Scope of the work

These factors are to be addressed to meet the current requirements of the industry. Scope of this project is aligned towards tackling these existing challenges and to ensure a safe and reliable installation by implementing this concept.

The project aims in developing a concept design, which is structurally stable and mathematically valid. A 3d design of the concept is created so as to check and validate the behavior of the system at sea. This model, which is made using NX can be used for motion simulation. Studying the effects of waves on the structure is the main objective of motion simulation. The integrity of the concept design and the kinematic linkages can be verified using motion simulation. The final outcome of the design is expected to be a structurally stable model that could compensate for the effects of wave and reduce the time consumed for installing offshore wind turbines.

Structural stability of the concept is verified by finite element analysis using NX Nastran. The kinematics of the concept and the motion analysis is done using NX motion simulation to successfully analyze the dynamic stability of the system. A simulation is finally created to simulate the movement of the wind turbine with respect to the waves and the effect of motion compensation on the installation is illustrated with supporting animations using Siemens NX. The NX which is capable of analyzing the physics behind a 3D model could accurately simulate the response of the entire structure to the wave motions. The displacement and the velocities thus obtained can be considered for further study.

1.3 Motivation

The motivation behind choosing the project has two major aspects, an environmental aspect and a technical aspect. "We are running the most dangerous experiment in history right now, which is to see how much carbon dioxide the atmosphere can handle before there is an environmental catastrophe" (Elon Musk). The use of fossil fuels has a huge negative impact on the humanity and any effort to reduce it is a step closer to saving our planet. A shift from fossil fuels to renewable energy like wind power could save our future generations from the ill effects of global warming. This transition from nonrenewable energy to renewable energy is made smoother by introducing this concept design which could in turn boost the generation of electricity using wind power and encourage the decommissioning of existing coal power plants which poses a constant threat to mankind.

The technical aspect of choosing the project is to reduce the huge amount of capital investment required for chartering the OWT installation vessels. As per the statistics presented in the report published on offshore wind cost reduction [3]. It is shown that a significant 26% of the whole installation time is consumed by weather downtime as shown in [Figure 1.4]. The weather down time is expensive due to the cost involved in hiring the wind turbine installation vessels. In order to carry out a successful wind turbine installation out in the sea, significant wave height (Hs) is an important factor. For example, installation of a monopile required for mounting a wind turbine requires a significant wave height of 1.5m. However, the North Sea sites (located between UK, Scandinavia, Germany, Netherlands, Belgium and France) are typically dominated by sea states larger than 1.5m almost 40% time of the year

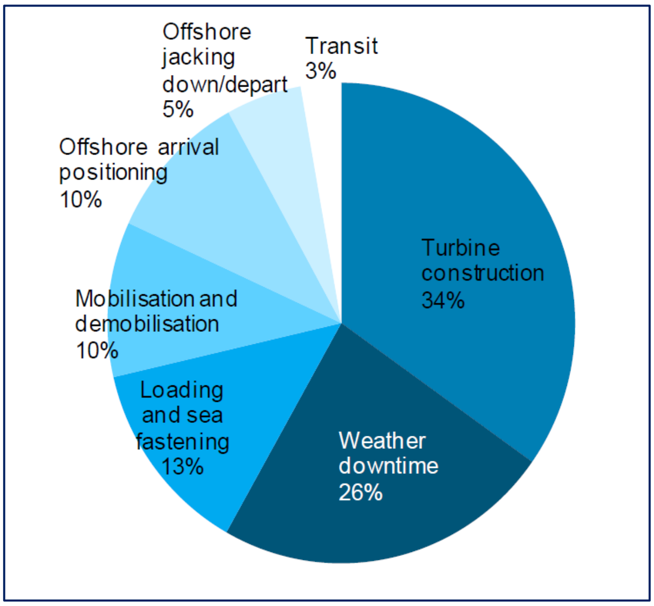


Figure 1.4 Turbine installation time in % [3]

Increasing the installation capabilities from a significant wave height of 1.4 m to 2.5 meter could reduce the weather downtime to less than one third of the existing time. The floating vessels with highly efficient dynamic positioning system could increase the maximum operating wave height to 2.5 as per the reports published by The Crown Estate [4]. However, these vessels have expensive charter rates per day. A comparison of the charter cost is shown in [Figure 1.5]. As per the report, the operating cost for a large installation vessel with highly advanced dynamic positioning system is around **2.3 Million Norwegian Kroners** a day. With this huge investment at stake, reducing weather downtimes could have a significant impact on the trade and strengthen our drive towards clean energy.

Vessel type	Length (m)	Deck area (m2)	Jacket carrying capacity (# jackets)	Maximum operating significant wave height	Operating day rate (£k)
Large floating DP	250	6500	6	2.5	220
Large jack-up	160	4300	3	1.4	150

Figure 1.5 Operating day rate for floating and Jack-up vessels [4]

In addition to using a floating vessel for installation of OWT, the project focuses on developing a fully functional wave compensation system to assist the installation. This could further increase the possibilities of installing the wind turbines at a much higher significant wave height, thereby reducing the downtime due to weather conditions further more. The most important challenge while designing a heave compensation system for this heavy lifting is to provide a safe and stable operation for the installation at these high sea states.

1.4 Objectives

The specific objectives of this project is summarized below.

1. To develop a support structure capable of carrying fully assembled wind turbines vertically on a vessel for transporting it to the installation site.
2. To develop a wind turbine deployment mechanism for installing the wind turbines on top of the foundation without using traditional high lift cranes.
3. To develop motion compensated clamping and lifting mechanism to aid wind turbine installation
4. To carry out a structural analysis and motion analysis of the structure developed for installation.
5. To ensure that heave, pitch and roll motions are primarily accounted for and ensure slight adjustments along sway, surge and yaw to provide a safe and secure installation
6. To explore the possibilities of using Siemens NX for motion simulation.

1.5 Research Questions

There are various uncertainties associated with the construction of a structure of this magnitude. Safety and reliability has to be the primary objective behind the concept. The research questions are summarized below.

1. Developing a mechanism that could carry a 1000-ton, 135-meter tall structure mounted on top of a motion compensated platform installed on a vessel which is exposed to waves and winds that questions the safety and reliability of the operation.
2. Understanding and implementing the concept of motion simulation on a 3d model and to ensure the stability of the structure by extracting and comparing the response of the model to prescribed wave motions.

2 State of the art

2.1 Existing OWT installation Methods

This section briefly explains the existing installation procedures associated with the scope of the work. The installation process has a more practical knowledge database and are not backed by equivalent academic research works. The information thus provided in this section is gathered from various industries which tried and succeeded in installing OWT's. The most prominent among this is the installation of the wind turbines using jack-up platforms as shown in [Figure 2.1].

Figure 2.1 Installation of OWT using jack-up platform [5]

This is the most stable method of installing an OWT available today. The reason behind the extra stability is that the vessel is lifted using jacks which are lowered on to the ocean floor. This will make the structure resistant to the effects of the waves there by making the installation easier by considering only the effects of wind during the operation. However, due to the lack of a stable and reliable wind availability near the shore. The industries have taken initiative in moving the wind farms further into the ocean. The strong winds that are received whole year round comes with the requirement for a more technologically advanced installation method.

The initial solution to this problem was to carry out a complicated and precise assembling of the wind turbines onshore and later carry them over to the wind farms located in offshore locations far from shore for installation as shown in [Figure 2.4]. These floating turbines are more expensive when compared to the normal wind turbines. These turbines are constructed on top of a jacket assembly which is then towed to the location of the wind farm for deployment since the installation of a wind turbine on top of a foundation in the ocean raises serious safety concerns. Few of the major drawbacks associated with these combined installations were the space required for each turbine and the construction cost and time involved in making them. This lead to a suggestion that new innovative installation process is required for installing the OWT's offshore. The solution has many constrains tied to it, owing to the huge capital investments required in manufacturing an offshore deployment structure. These jack up installations also had other disadvantages associated with the method. Depending on the sea state prevailing, the installation of the wind turbines using jack up vessel may induce heavy impact loads on the lifting system of a jack up vessel. In general, the jack up vessels are designed to withstand a sea state of 1.5 meters. However, the North Sea sites are dominated by sea states higher than 1.5 meters almost 40% of a year as shown in [Figure 2.2].

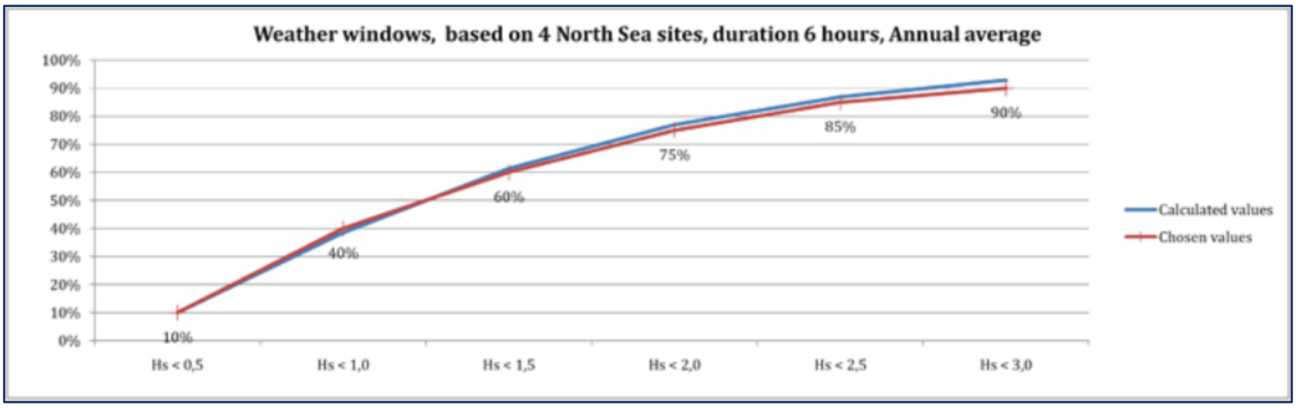


Figure 2.2 Available weather window in the North Sea [6]

While installing the upper structure of the wind turbine (tower, nacelle and blades), the most widely used method so far is a jack up vessel or a semi jack up crane vessel. A floating vessel is not preferred due to the involvement of large altitude and high precision. This is one of the reason that this project opted for the transportation of a wind turbine as a whole, instead of pieces while being installed in offshore locations where jack up vessels cannot be used. Apart from sea states, the wind speeds on these sites also limit the direct installation of upper structure. From the experience gained by A2SEA offshore wind turbine installation company, it is said that 10-12m/s wind speed is the limiting factor while installing the upper structures, tower and nacelle. However, while installing the blades, it needs to be as low as 8-10m/s.

It was also found that, using the existing method of installation, it will take 90 turbines around 1.5 to 2 years to complete the installation. However, the projections proposed by wind energy companies are as high as 500 turbines to be installed. Due to above said reasons, it is advisable to install the wind turbines as a full assembly thereby the risks involved in assembling out in the sea could be avoided. This has been previously tried in the Beatrice project [7], as shown in [Figure 2.3]. For such operation the allowable sea state is even less when compared to the ordinary sea state of 1.5 meters for jack up vessels.

Figure 2.3 Beatrice Project [7]

As per the reports from Scaldis, the allowable sea state for installation was around 0.5 meters. These vessels also have the natural frequencies in the range of 8-10 seconds, which increases the difficulties while installing the wind turbine as a full assembly.

2.2 Existing concepts developed on OWT installation

The requirement for a special installation vessel that can carry more than one integrated turbine to the site is a major requirement in the industry. These installation needs to be carried out in a safe and secure environment. Various industries are working on this concept and a fully functional multi turbine carrying installation vessel has not been made yet owing to the enormous capital investment and research needed for a project of this size. Some of the few concepts developed for this purpose till date is discussed below.

Figure 2.4 Onshore installation and towing of OWT [2]

The method shown in [Figure 2.4] is a 2MW wind turbine developed by principle power deployed 5km off the coast of Portugal in October 2011. The structure was completely assembled and commissioned onshore before being towed around 400km along the Portuguese shore before installation. This is a prototype design and the experience gained from this project can be used for commercial installation of heavy wind turbines. What makes this installation special is the decommissioning process done on July 2016. After the completion of the project objectives. The foundation was detached from its mooring lines and electric cable and then towed back to southern Portugal where the wind turbine was disassembled. This was the first time ever an offshore wind turbine had been dismounted from a floating structure and this demonstration has helped in developing a procedure that needs to be followed while carrying out this operation [9]. The inspections after the decommissioning has revealed that the foundation is in excellent condition after the decommissioning. More projects are since being developed by wind float. Till now they have encountered around 18 meters of wave height and 41 m/s of wind speed.

The stability of a floating structure depends on the distance between the center of gravity and the metacenter of the vessel. If the distance is higher, then the structure becomes more unstable. This is the major disadvantage of carrying a preinstalled turbine vertically on a vessel. The height of the turbine with nacelle on top will make the center of gravity of the structure to be far away from the metacenter. A wider vessel with multiple hull and special support structures are then required to keep the turbine from tipping the vessel as shown in [Figure 2.5]

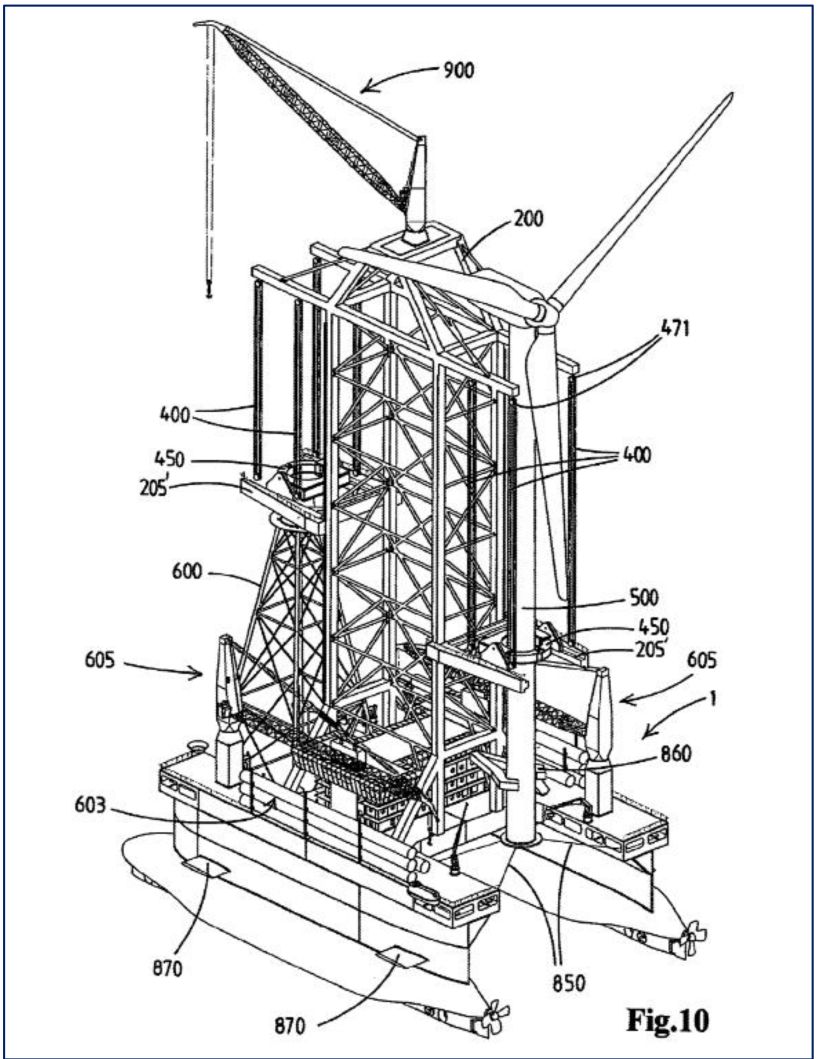


Figure 2.5 OWT installation patent (US 8701579 B2)

This is a patented method for installing an OWT. The structure along with its foundation is carried on top of a multi hull vessel. In normal cases, a wind turbine will be around 100 meters tall. The whole support structure is also made to be 100 meters tall. The major factors that are considered in this design is that, the vessel used is a catamaran vessel, which improves the stability of the vessel due to the width. The support structure used is also around 100 meters tall, which could reduce all problems related to stability since the center of gravity of the entire structure could be bought down to a great extent by using these tall support structures.

This method also claims about including a roll damping device that comprises of more than one mobile solid ballast bodies guided on a track on the hull which comes with an associated displacement drive and control system. The lower end of the mast is also said to be positioned above the foundation there by it can compensate the sea state induced by vertical motion by activating the heave compensation device available on board. The vessel is also meant to have sensors for detecting the vessel motions. These sensors are generally termed as motion reference units (MRU). These devices are capable of recording the existing sea state and generate control signals to compensate the motion using mechanical solutions.

Huisman, an operating company with extensive experience in the design and manufacturing of heavy construction equipment came up with a concept for the installation of the wind turbine effectively as shown in the [Figure 2.6]. This method of installation is claimed to improve efficiency of offshore wind turbine installation and to allow for increasing economies of scale. The product is named wind turbine shuttle, a dynamically positioned fast sailing wind turbine installation vessel. It can carry and install two fully assembled wind turbine by combining low vessel motions, compensating systems and an accurate dynamic positioning system. The wind turbine is kept stationary with respect to the foundation during the installation process. This method could improve to at least 80% workability in annual North Sea conditions. This vessel is also equipped with high transit speed and DP3 system for stability during installation. This vessel is also capable of installing and decommissioning a variety of offshore structures.

Figure 2.6 Huisman and Ulstein concpets [10], [11]

As a part of Statoil's Hywind installation challenge, many innovative concepts were considered for the installation of offshore wind turbines. Ulstein also developed concepts for transportation and installation of integrated wind turbines as shown in [Figure 2.6]. This method uses an existing platform supply vessel for the transportation and installation of fully assembled wind turbines. However, it has very low support structures and small installation mechanisms that may or may not be strong enough to support a 1000-ton wind turbine from tipping off. This design also uses a sliding concept instead of using lifting of the turbine using ropes. This could have a huge positive impact when the wind loads are considered. The installation mechanism travels between wind turbines as it is moved into position for installation. Heave compensation system is also introduced with the installation setup to compensate the wave motions. The structural and dynamic stability of the model is not mentioned in the proposal. The guide structures are used for sliding the wind turbine on top of the foundations. This type of installation also has limitations about the height of the foundation. Ulstein is one of the winners in the challenge and the concepts designed by other two winners are also discussed here.

The solution proposed in [Figure 2.7] is developed by Atkins. The concept has multiple turbines attached to a reusable transportation frame. This reduces the draught of the structure. This will allow the turbines to be assembled in regions where deep water inshore location is not readily available. This will also allow conventional quayside assembling possible. Multiple turbines can be towed simultaneously that will improve the efficiency of transportation by reducing the number of towing vessel required while constructing a huge wind farm. Semi-submersible platforms reduce weather restrictions for towing and increase the speed when compared to the towing of single wind turbines.

Figure 2.7 Atkins concept design for Hywind challenge [12]

Another solution developed is by MODEC, by foreseeing the potential of spars as one of the floating substructure for wind turbines. Spars concept and the installation method would further improve the advantages of spar by offering a broad selection of the assembly and installation sites. D-Spar concept and fork-on/Float-off installation methods are patented inventions of MODEC. The offshore assembled wind turbine, when on site can be held in position while pre-installed spar is pulled up between the twin forks and connected to the tower. The complete assembly will be floated off the forks during this operation. This operation can be reversed in an unlikely event of malfunction. This also covers the possibility of dismantling the wind turbines. These are the few existing concepts developed for the installation of Offshore wind turbines.

Figure 2.8 MODEC concept design [13]

2.3 Motion Simulation using NX

The concept of co-simulation is a way of combining different sub systems to solve a complex problem which are modeled and simulated in a distributed manner. Software and electronics are playing an ever increasing role in product design. However, combining a mechanical system and control system can be challenging. A mechanical engineer has the necessity to understand how an electronic control system will affect the performance of the mechanical system likewise a control system engineer need to know how a mechanical system affects their control design. Co-Simulation allows engineers to analyze motion mechanisms and control systems in one shot. Two examples are sited below which illustrates the possibilities of motion simulation using NX.

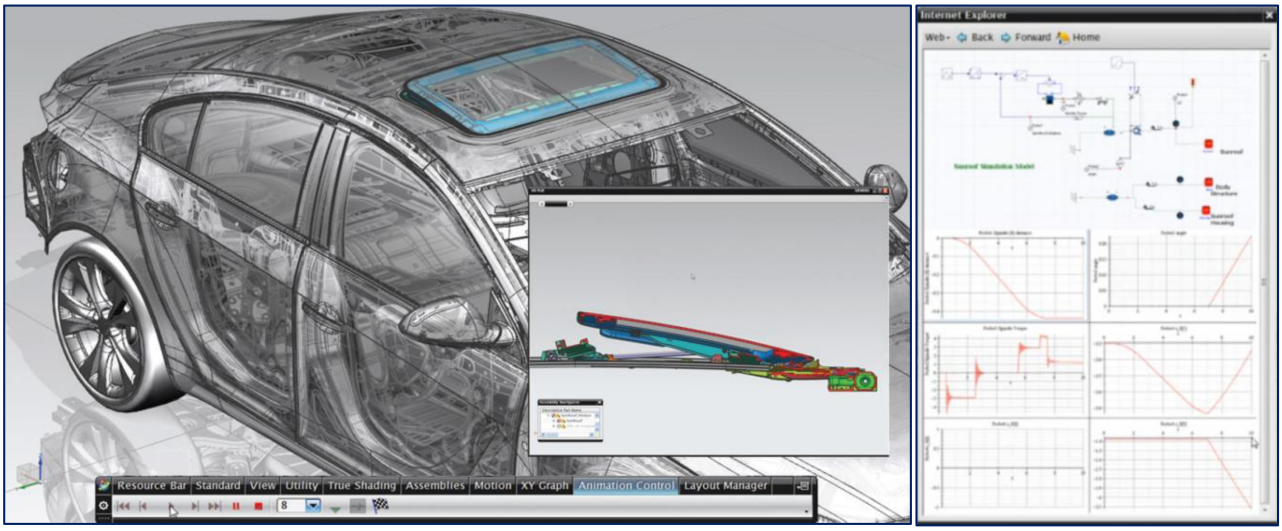


Figure 2.9 Mechanical motion integration with NX [14]

The first example shows an electronically controlled automated sun roof. The model shown in [Figure 2.9] shows a mechanical design of a sun roof created using NX that is paired with a control system model developed using Matlab. This can be co simulated to get required results. The NX has capabilities where in an engineer can launch Matlab within NX motion simulation and can integrate the model using a NX motion plant. NX creates a logic block that can be attached directly to the logic diagram in Matlab. It also develops input blocks with required interval that could be included along with the simulation to get the desired outputs as shown in [Figure 2.10]. In addition to this, variables in Matlab can also be controlled such as the motion timing. This method can help to verify the robustness of the control system design in controlling the dynamic mechanism and assist in avoiding expensive changes to the system during the final stages of development. At a specified sampling rate, the control system diagram receives information about the state of the mechanism (displacement, velocities and acceleration) at each time step. Control system feedback will provide inputs to the force or torque loads in the system. This will help to optimize the dynamics of the model. This will also assist in improving the productivity by concurrent optimization of both mechanical system and control system.

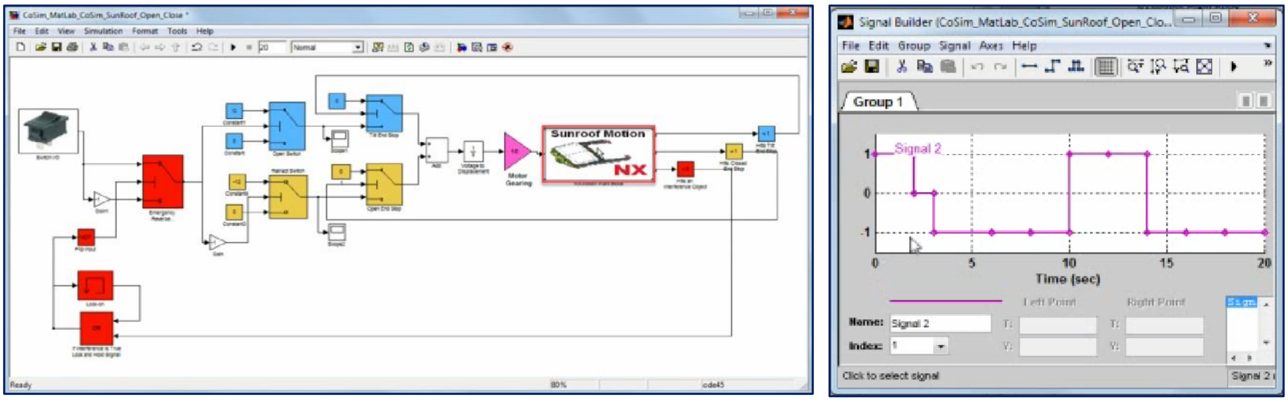


Figure 2.10 NX motion plant combined with Simulink [14]

The second example is based on the stand point of a control system engineer. In this example, an engineer is developing a control for an excavator as shown in [Figure 2.11]. The output from the motion model that the engineer need to consider are the bucket tip height relative to the ground surface and force from one of the hydraulic unit on the excavator. If the engineer is familiar with the mechanical design and more interested in developing the control. Then the motion simulation can be directly launched from Matlab. This has to incorporate the nx motion plant to the control design. An engineer can then set the desired bucket tip height that will be touching the ground and before the simulation, the bucket cylinder driving profile is defined.

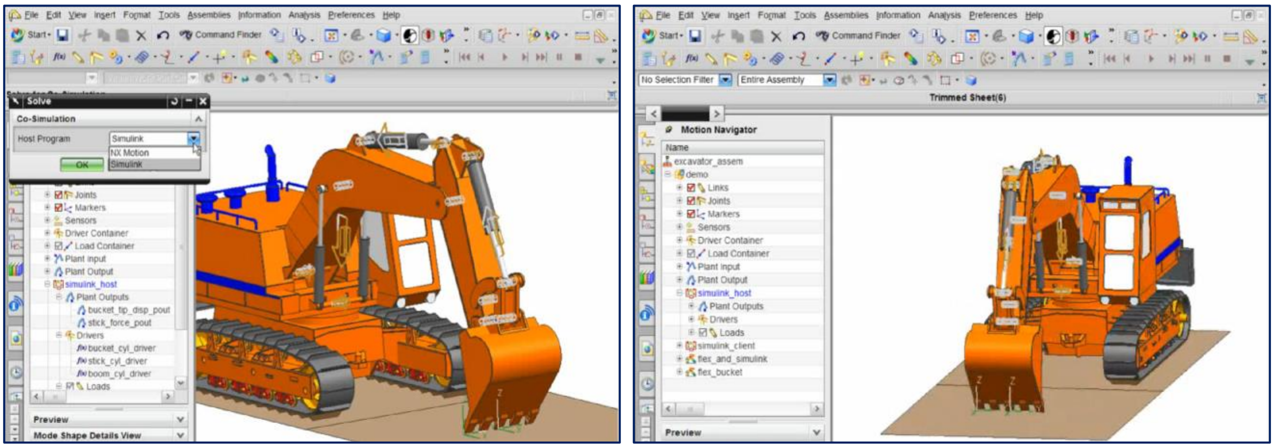


Figure 2.11 NX motion simulation [15]

The result of the simulation can evaluate the bucket cylinder displacement and the force on the stick cylinder as shown in [Figure 2.12]. In this result shows the interaction of the bucket tip with the ground. Co-simulation with NX enables rapid pre prototype of control system designs integrated with mechanical designs to achieve a faster understanding of the entire mechatronics system. This will help in accelerating the product development by reducing design and analysis cycles for new machine designs. This can assist in rapidly evaluating and validating processes and determine the best controller system. Expensive physical prototypes are not required further. It can also reduce installation time of new machines by controller pretuning done through simulation models.

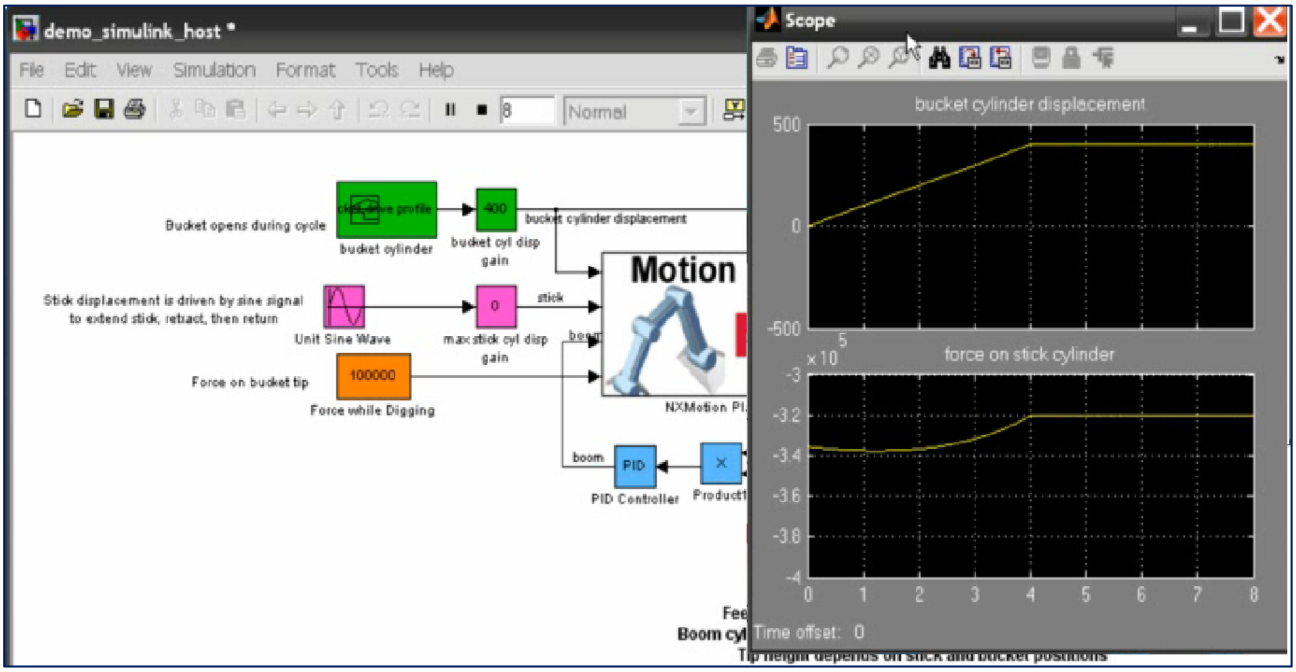


Figure 2.12 NX motion simulation results. [15]

Running a controller integrated simulation is easy and it requires the following steps.

- Define mechanical mode with NX motion based on geometric assembly.
- Define plant input and outputs and generate a plant block
- Define controller scheme in Simulink
- Drag and drop the plant block on to the scheme and connect the input and outputs
- Solve the co-simulation.

The advantages of using a co-simulation can be summarized as shown in the Venn diagram.

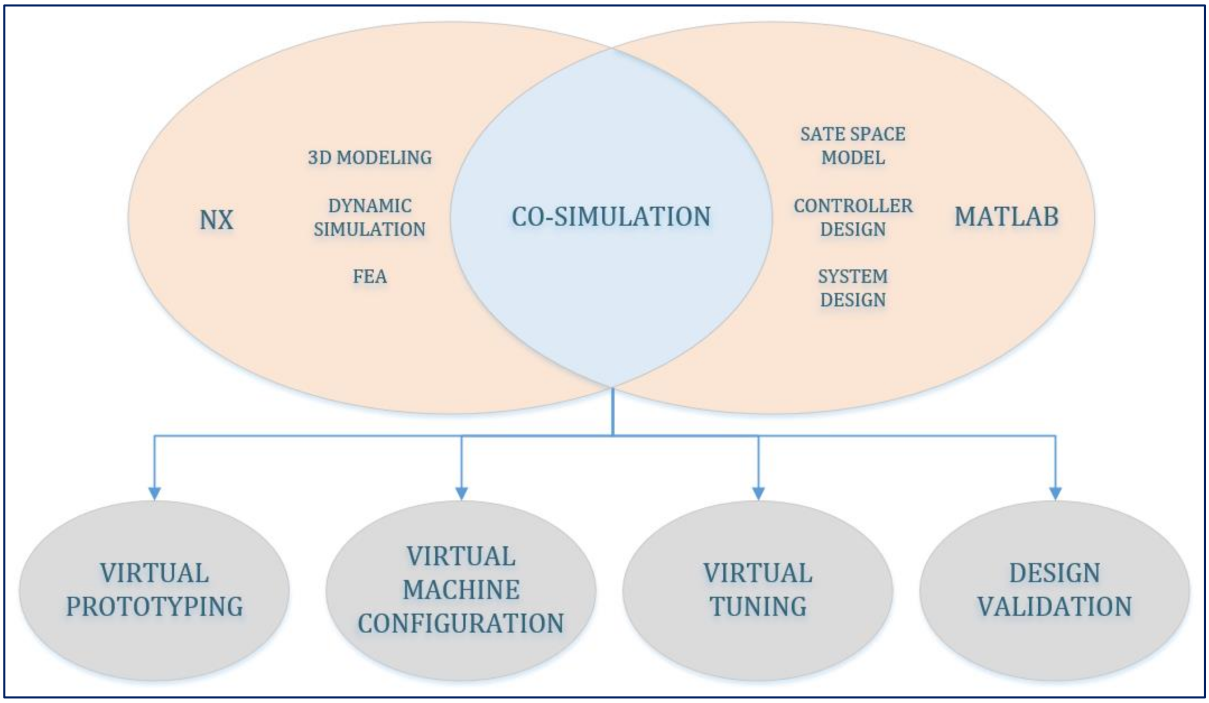


Figure 2.13 Venn Diagram to summarize co-simulation

3 Concept Design Overview

3.1 Methodology

This chapter explains the design flow chart laid out for the project. The project has mainly three phases which structure the whole process followed. The phases are summarized as shown below. A design flow chart is created to connect these phases as shown in [Figure 3.1].

- Design Phase : Where a concept of the new deployment mechanism is developed
- Analysis Phase : Where the structural design is analyzed for stability using FEA
- Simulation Phase : Where the motion response of the system is analyzed using NX

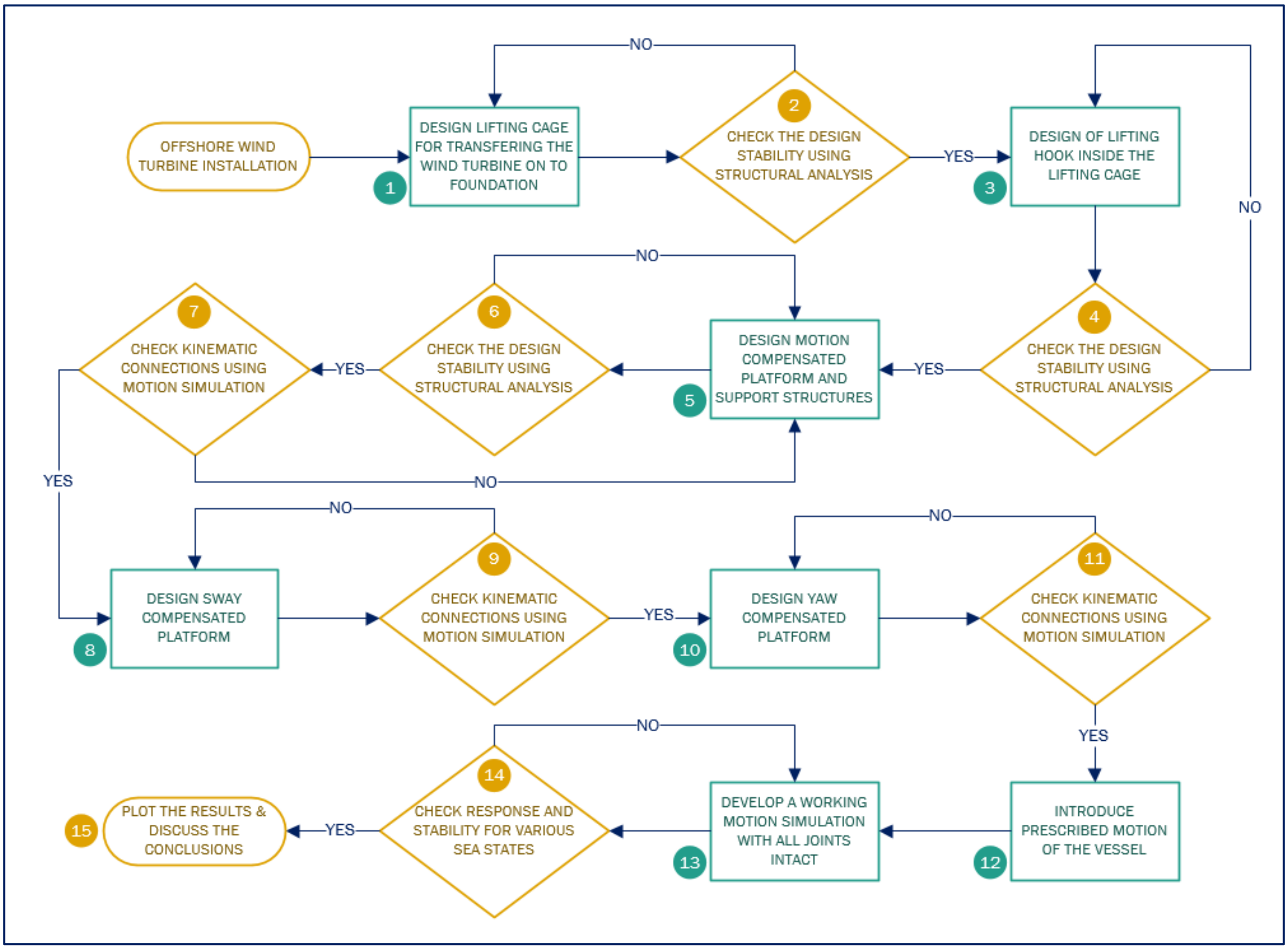


Figure 3.1 Design Flowchart for OWT Installation

The flow chart explains the steps followed during the completion of the project. It also summaries every step which needs to be validated with the respective analysis to be able to proceed to the next level. The layout shows that the design proposal could only be validated to be a successful one only after the completion of all these levels. Final plots and results are discussed in a separate chapter at the end.

- Design of Lifting cage for transferring wind turbine on to foundation: Usually the wind turbines are carried to the installation location as separate pieces. In this project the wind turbine is planned to be carried in the vessel vertically after assembling all the components together. However, for transferring the turbine assembly from the vessel the foundation requires utmost precision. In order to meet that, a special lifting and deploying cage is designed for this purpose.

- Design of lifting hook inside the lifting cage: The lifting hooks designed in this project is an attachment coming along with the lifting cage. These hooks are hydraulically actuated so that they can be folded in and out after the lifting process. This hook is a critical part which takes up the entire weight of the turbine. Hence a separate structural analysis is required to ensure the stability of the hook as well as the stability of the lifting cage along with the hook.
- Design of the motion compensated platform and support structures: The motion compensated platform is designed to compensate for the pitch, roll and heave motion alone. However, this platform has to be at a height almost half of that of the turbine so as to maintain the balance of the system. In order to achieve that, the entire structure is designed on a tall support structure which also compensate for the sway motion. This part is also analyzed for structural stability using FEA.
- Design of sway compensated platform: In this concept, in order to compensate the movement in the sway direction, a platform is designed which is actuated by hydraulic cylinders and supported on steel rollers. This will assist in achieving a safe and secure installation by compensating the sway motion.
- Design of Yaw compensated platform: Even though the yaw motion is compensated by the thrusters in the vessel, a compensation system is made so as to achieve precision while installation. These are actuated with the help of helical gears driven by electric motors.
- Introduce prescribed motion to the vessel: After completing the design face, the kinematic stability of the system needs to be analyzed using the motion simulation module. A prescribed motion is applied for the vessel to move in the direction of heave, pitch and roll. This is done so as to study the response of the joints to these motions.
- Develop a motion simulation model with all joints intact: The motion response from the joints are compared in relative to the motion of the turbine to ensure a perfectly synchronized motion simulation.
- The next step was to create an animation to explain the complex mechanisms involved in the installation. The 3d model created in NX is later moved to PTC creo for creating the motion animation explaining the installation process. This software is used only because of the compatibility of Creo with key shots for rendering.
- The final step was to create a realistic rendered video of the installation process using the software key shots. The animations also involve a separate section on the motion restrictions of the platform so as to explain the maximum possible motions possible by the platform. These steps were followed in the exact same order to complete the concept design presented in this report.

3.2 Rationale behind the concept

The primary objective was to design a heave compensated structure capable of lifting an entire wind turbine assembly. There is only one heave compensated structure available in the market which is capable of carrying up to 700 tones using vertically mounted hydraulic cylinders. It is the BM-T700 from barge master [16]. This structure is used as a base line for the concept design owing to the fact that, this design remains as a working proof of a fully functional heave compensation system of this magnitude driven by hydraulic cylinders. The structure of the system shown in [Figure 3.2] was carefully studied to understand the advantages and disadvantages of choosing the pivot points. The number of cylinders used, largely determine the degrees of freedom of the system and the support links contribute towards holding the structure along the desired axis.

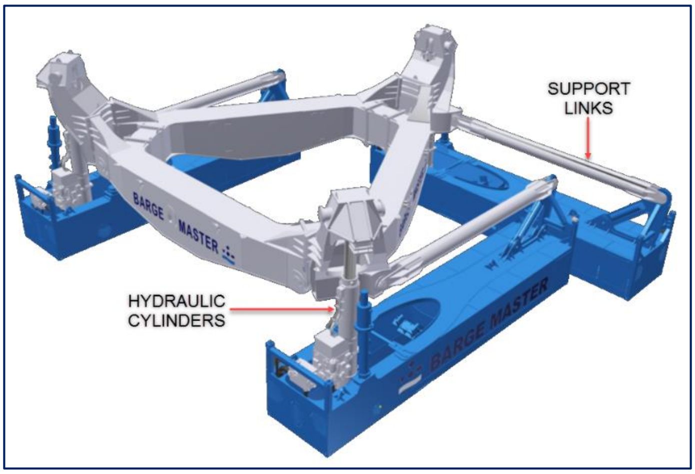


Figure 3.2 Barge Mater T-700 [16]

The secondary objective in the design process was to create a structure that could support this lifting mechanism and could also assist in moving this lifting mechanism in between the stacked up wind turbines. The idea is to deploy the wind turbines from the rear end of the vessel. The support structure can thus be extended from front to rear end. The height and the width of the support structure was only decided after carefully studying the effect of the center of gravity of the system on the stability of the vessel. The recommended vessel for this operation is a multi-hull catamaran vessel. The width of the vessel provides additional stability while carrying more than one wind turbines vertically. An example of catamaran vessel that can be used for this purpose is as shown in [Figure 3.3]. Pioneering spirit, the largest construction vessel in the world. Using a vessel of this size could reduce the stability issues arising due to stacking up of 7 to 8 wind turbine assemblies vertically.

Length overall (incl. stinger)	: 477 m
Length overall (excl. stinger)	: 382 m
Length btw perpendiculars	: 370 m
Breadth	: 124 m
Depth to main deck	: 030 m
Slot length	: 122 m
Slot width	: 059 m

Figure 3.3 Pioneering Spirit [17]

3.3 Concept Development

The proposal for the project started off with two sketches that combines the initial design idea. This was later tweaked into a working model after checking the feasibility of the kinematics behind the movements.

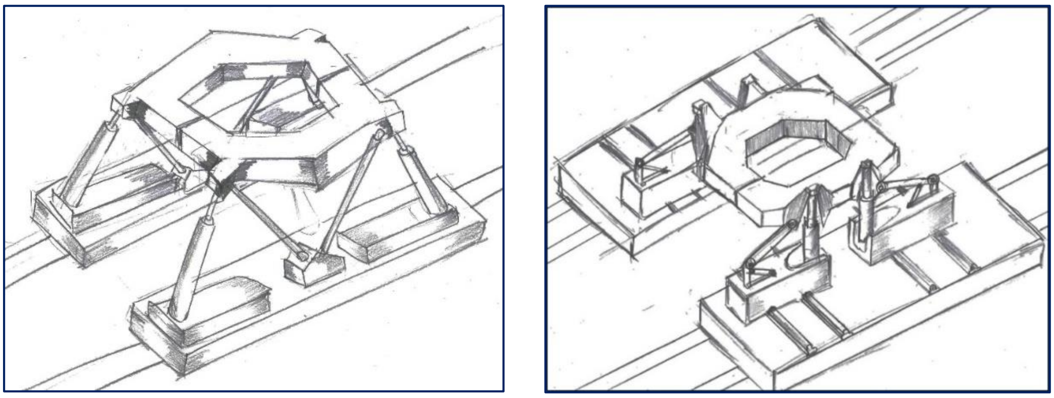


Figure 3.4 Concept Sketches

The sketches shown in [Figure 3.4] is made after studying the existing designs available in the market. It shows a lifting mechanism for a vertically mounted wind turbine on a vessel. This arrangement can then be moved back and forth between wind turbines for assembling each one of them. This is the reason why the center of the structure is split into two. This can be opened and closed by pulling the structure back through the tracks. However, the structure like this needs a lot of reinforcements to handle a wind turbine of 1000 tons or more. Stability of the entire concept model was later verified with structural and motion analysis using Siemens NX. Different configurations were tried to find the perfect setup that will provide the required motion.

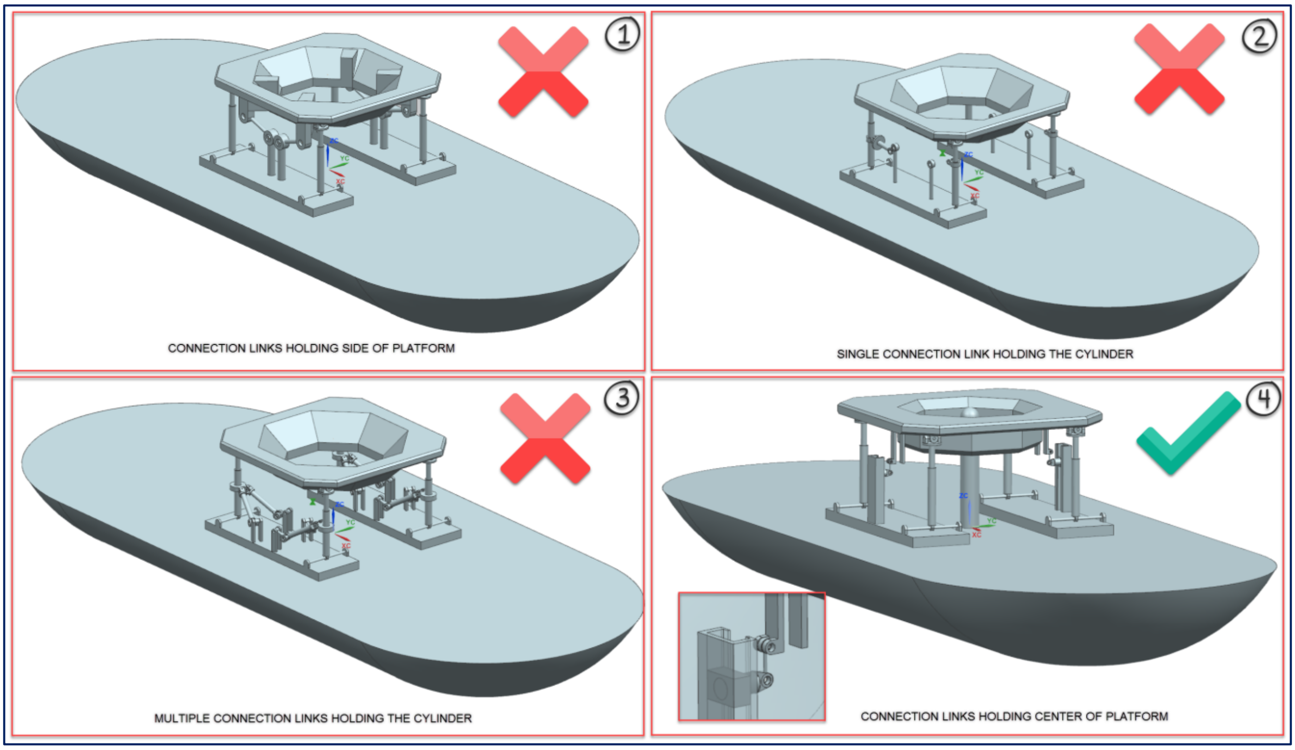


Figure 3.5 Kinematics verified using Siemens NX

After verifying the kinematics of several arrangements holding the hydraulic cylinder and the platforms at different angles using NX motion analysis as shown in [Figure 3.5], it was evident that the platform has to be connected at the center in order to prevent the entire structure from collapsing due to the motion of the waves. The heave compensation system is only designed to actively compensate the **roll, pitch and heave** movements of the ship. The **sway, surge and yaw** movements are constrained by the dynamic positioning system of the ship. However, the design has also considered movements along the sway, surge and yaw direction using actuators to assist a safe and secure installation. This is explained further in the coming chapters.

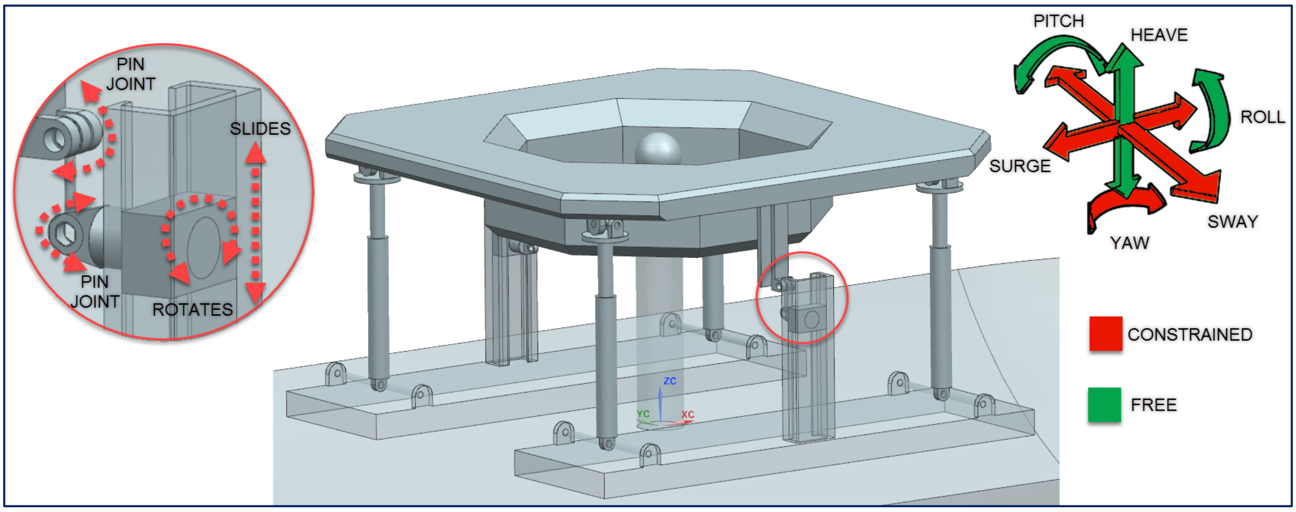


Figure 3.6 Motion compensation platform with 3 DOF

The degrees of freedom of the heave compensation system achieved by the hydraulic cylinders and the universal joint are as shown in [Figure 3.6]. The figure also shows a sliding l that keeps the platform from tipping off as the cylinders try to compensate for the ship motions. There are similar links used on all four sides of the platform to improve stability while lifting the wind turbine assembly. A detailed explanation of which is provided in the next chapter. The universal joints are used on top of the cylinder rod to achieve the roll and pitch motion of the platform. Spherical joints are used at the bottom end of the cylinder housing which allows the hydraulic cylinders to have a slight angular movement while compensating roll motion.

3.4 Design Proposal

The detailed design of the concept is developed as a **3d model in NX and rendered using key shots.** The most important factor considered in the entire design process is that, each and every single component used in the whole assembly can be made from standard cross sections of steel that is available in the European market. The components that needs to be forged and welded are separately explained along with structural analysis to claim the stability of the structure. The whole installation process is explained further in various steps to illustrate the complex mechanisms involved in the concept design. This is a summarized version of the entire process. A detailed explanation on the design is included in [Chapter 5].

❖ **Step 1: Arrangement of Wind turbines in the vessel**

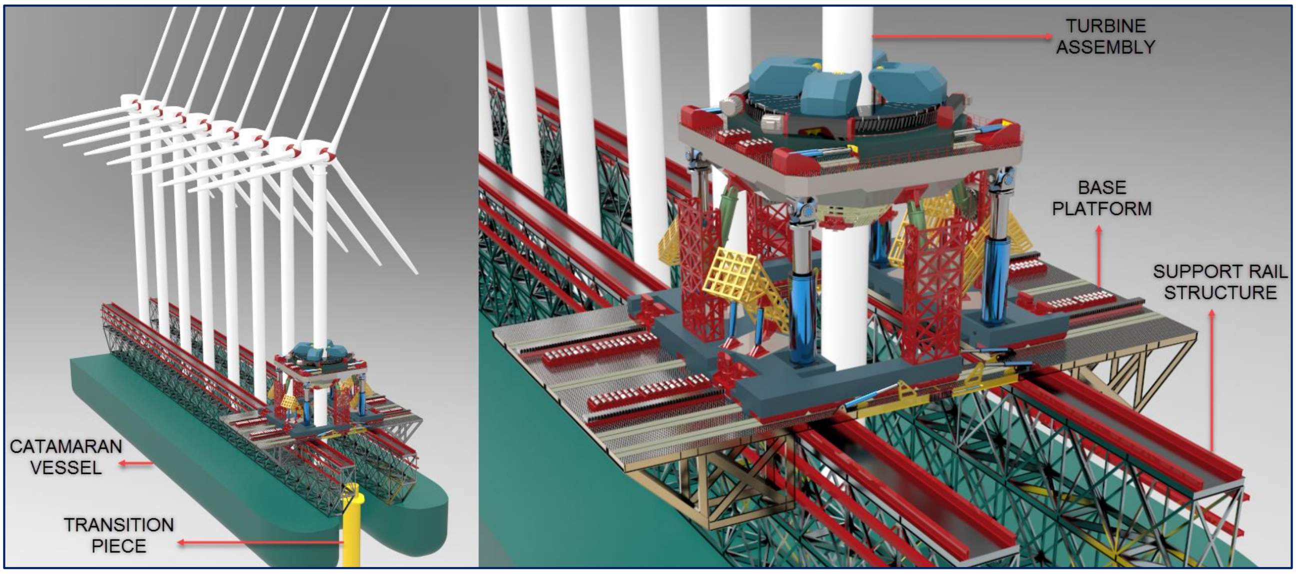


Figure 3.7 Concept Layout designed in NX and rendered in key shots

The **turbine assembly** considered in the concept is around **135 meters tall** and weighs close to a **1000 tons.** The turbine assemblies are stacked vertically on the vessel as shown in [Figure 3.7] using specially designed mounts and tie rods. The assumed vessel dimension used for the installation is of a length of **270 meters and a width of 100 meters**. The increased width and multi hull will contribute towards lowering the meta center of the whole vessel and thus improve the stability. This is almost similar in dimension to the **catamaran vessel** pioneering spirit as shown in [Figure 3.3]. The main intention behind this approach is to utilize the same vessel to implement this installation process which will minimize the capital investment required for the entire project. Building a construction vessel alone of this size would cost around 25 Billion Norwegian Kroners (NOK). The **transition piece** where the turbine is placed will be aligned in a slot in between the hulls. To have a more precise execution of the installation, there should be connection between the vessel and the transition piece that could record the motion of the transition piece with respect to that of the vessel. However, in this project it is assumed that the transition piece is fixed and the connection to the vessel is not taken into consideration.

A **support rail structure** which runs along the entire length of the vessel is used for sliding the **base platform** which moves between wind turbines. This platform houses the components required for the heave compensation system and the equipment's required for lowering the turbine assembly on top of the transition piece.

❖ **Step 2: Opening and closing of the Base Platform**

The base platform is designed so as to switch between wind turbines during installation. The hydraulic cylinders which are used for the heave compensation are assembled on a rolling platform (**Cylinder Platform**) that can move in and out as the base platform open and closes. The open and close conditions of the base platform is as shown in [Figure 3.8]. This step is required so as to ensure an easy switch between turbines after installation.

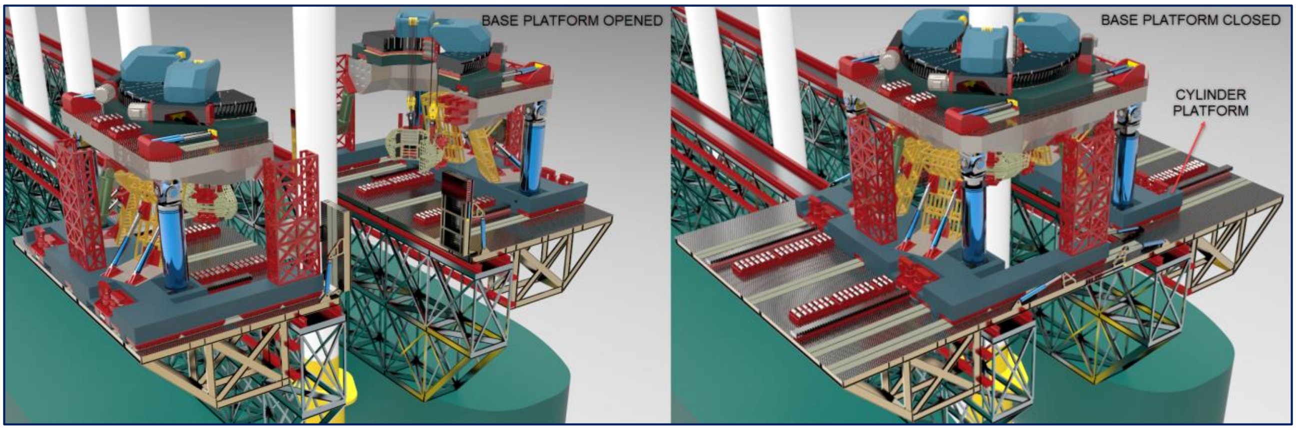


Figure 3.8 Opened and Closed condition of the base platform

The entire **cylinder platform** is moved with the help of steel rollers on a defined path. The actuators used for initiating the motion is a rack and pinion system which drives along a tooth on both the sides. A detailed description on each module is separately mentioned in the coming chapters.

- **Step 3: Opening and closing of the support structures**

The heave compensated platform is moved up and down using 4 hydraulic cylinders. The main heave compensated platform has a weight of around **2000 tons.** When the **cylinder platform** is retracted back after installation, weight of the structure needs to be supported on both sides using additional support structures. However, these support structures needs to be retracted back once the heave compensation is in operation for safety purposes. Hence a hydraulic actuated support structure is designed to extend and retract whenever required. Once closed, the weight of the heave compensated platform is distributed along the **4 platform support structures** and the **4 main hydraulic cylinders**. This will allow safe retraction of the platform by ensuring equal weight distribution along 8 points. There are also 4 additional guide mechanism which can take the weight of the structure. However, this is used as a redundant system to ensure more safety and stability during this operation. The platform is supported by support structures as shown in [Figure 3.9].

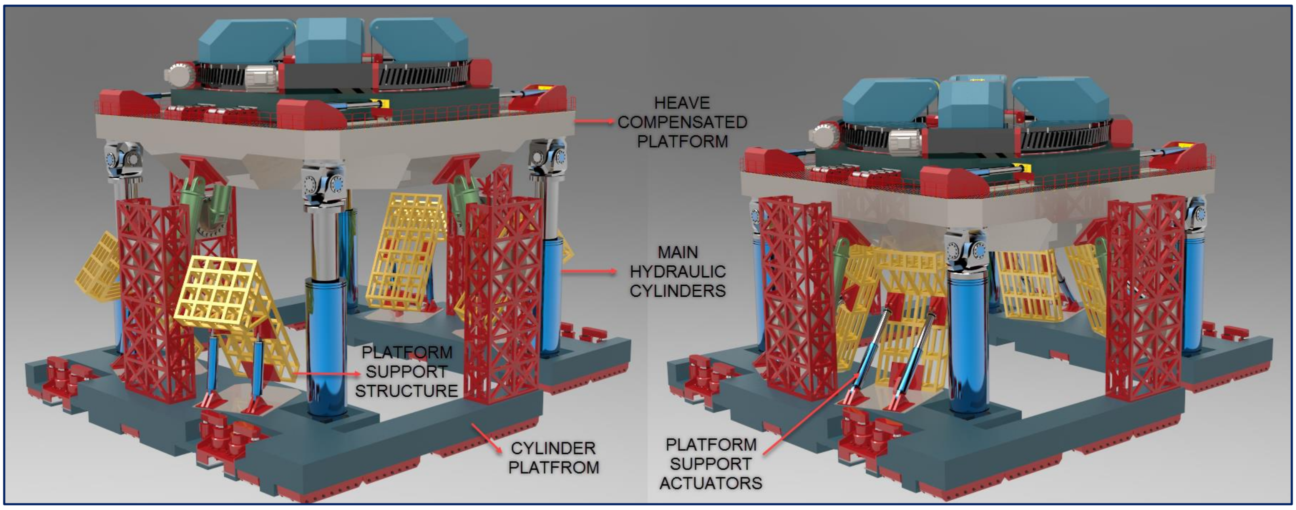


Figure 3.9 Opened and Closed condition of the platform support structures

- **Step 4: Pitch and roll movements of the platform**

The pitch and roll motion of the platform is achieved by **4 main joints** as shown in [Figure 3.10]. A universal joint that connects the hydraulic cylinder to the heave compensated platform, a fixed link with multiple pin joints along with a slide link and a rotating link that constraints the motion of the platform within the prescribed limits. There are 8 points on the heave compensated platform where these links are connected.

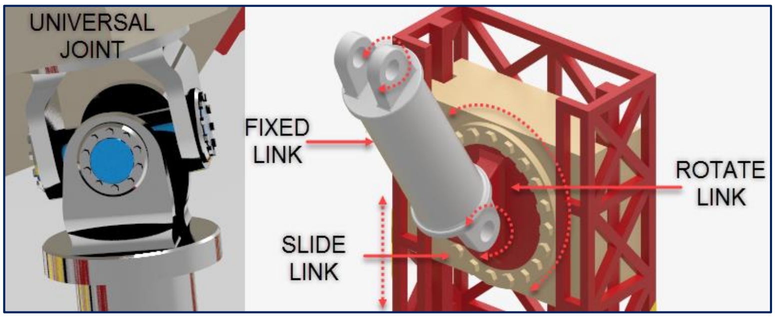


Figure 3.10 Main connection links

In fact, only two of the fixed link connections are enough to constraint the motion. However, 4 connections are installed for safety since there is a combined load of around **3000 tons.** As the motion compensation happens, the **slide link** will move up and down along the **vertical guides** and will restrict the motion beyond a certain point. This will allow the main hydraulic cylinders to stay upright. Swivel bearings are used at the base of cylinder housings to enable roll motion. The pitch and roll motion of the platform is as shown in [Figure 3.11].

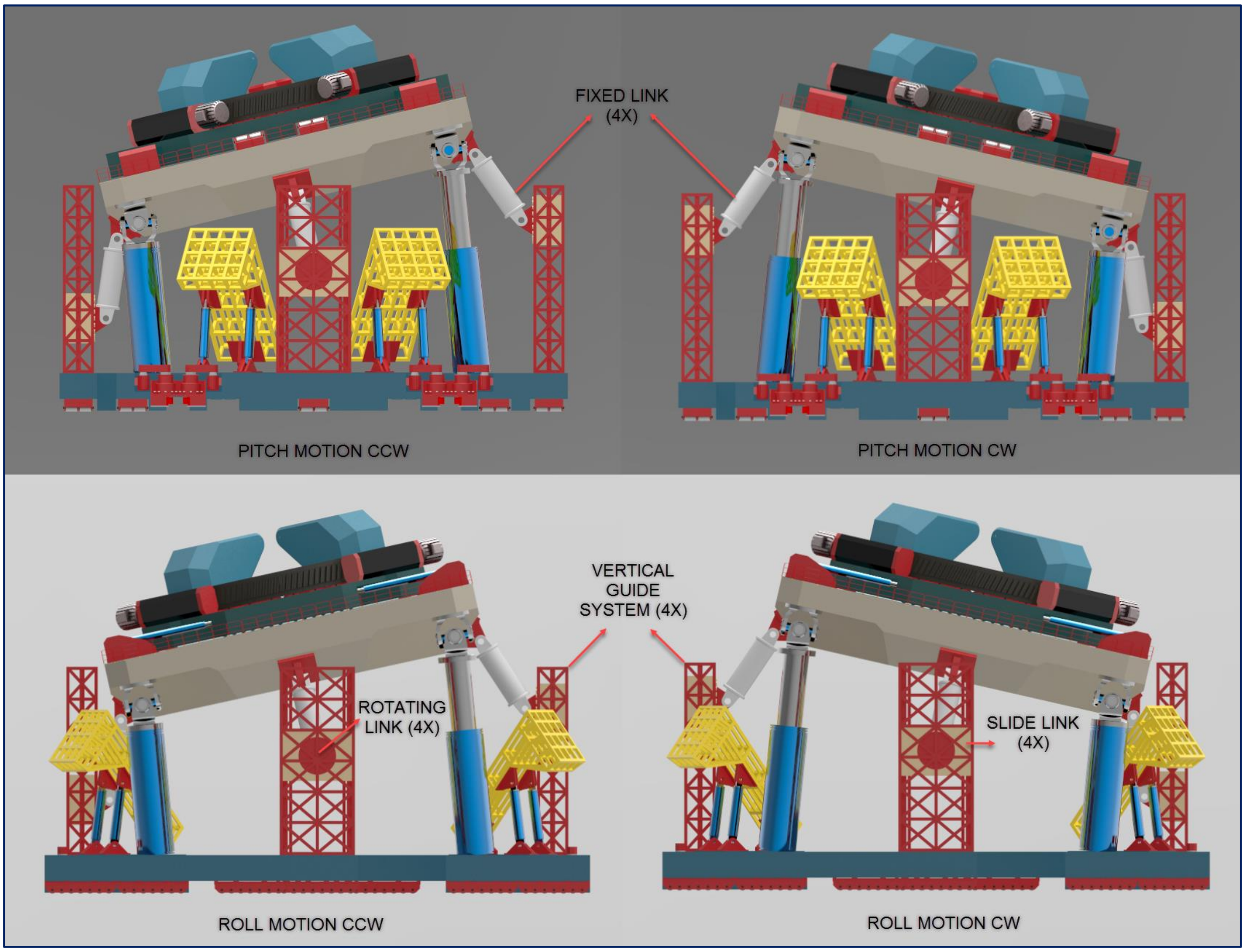


Figure 3.11 Pitch and roll motion of the platform

❖ **Step 5: Sway and Yaw movements of the platform**

As mentioned earlier in the [Chapter 3.3], the sway and yaw movements of the ship are controlled by the dynamic positioning system. However, while installing the wind turbine on top of the transition piece, some fine adjustments in the direction of yaw and sway in inevitable. Hence a system is developed to bring in the compensation for the sway and yaw on top of the heave compensation platform. The movement of the **sway platform** is achieved by using **8 Hydraulic Cylinders.** These cylinders propel the platform to move **3.5 meters** in both directions. The entire platform is supported on top of steel rollers to assist the motion. The movement of the **yaw platform** is achieved by a helical gear system driven by **4 Electrical Motors.** The yaw platform houses the winch system required to lift and lower the wind turbine. It also houses hydraulically actuated rolling grippers which are used to support the wind turbine as it is lowered down to the platform. These grippers are extended and retracted from within the yaw platform. The sway and yaw movements are as shown in [Figure 3.12]. A detailed explanation on the component selected is provided in the coming chapters.

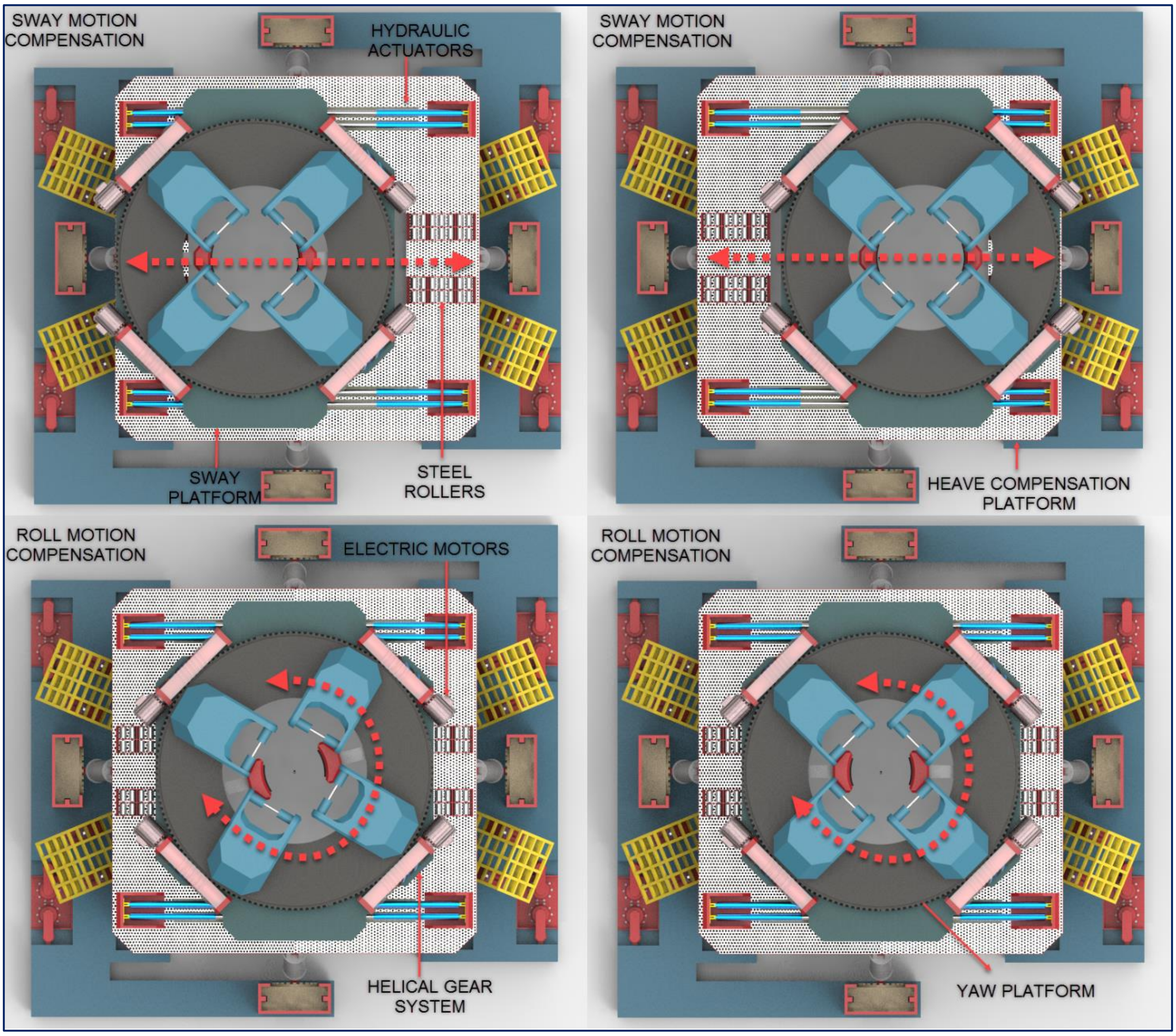


Figure 3.12 Sway and Yaw motion of the platform

- **Step 6: Lowering of the Lifting cage and hook**

A lifting cage is designed to lift a fully assembled wind turbine from the vessel and lower it down to a transition piece pre-installed in the ocean. There are **4 electric winches** that assist in lifting and lowering which makes the installation a little flexible. There are 2 hydraulic actuated **roller grippers** installed inside the **yaw platform** which can extend and retract while gripping the turbine assembly. These grippers contribute towards constraining and supporting the turbine walls as it is lowered down. Without the grippers, there is a high chance of turbine colliding with the yaw platform due to the wind conditions offshore. Rollers are horizontally arranged as the roller action is supposed to work only when the wind turbine is lowered. The crane hook is designed as a typical hook which are commonly used in heavy lifting operations. 4 **heavy ropes** are connected to **lifting hooks** inside the lifting cage which are extended and retracted using hydraulic cylinders. Lifting cage is designed to split into two parts as the installation is completed. The whole lifting assembly is as shown in [Figure 3.13] and [Figure 3.14]. These yaw platform is mainly there to assist in the precise turning of the turbine assembly.

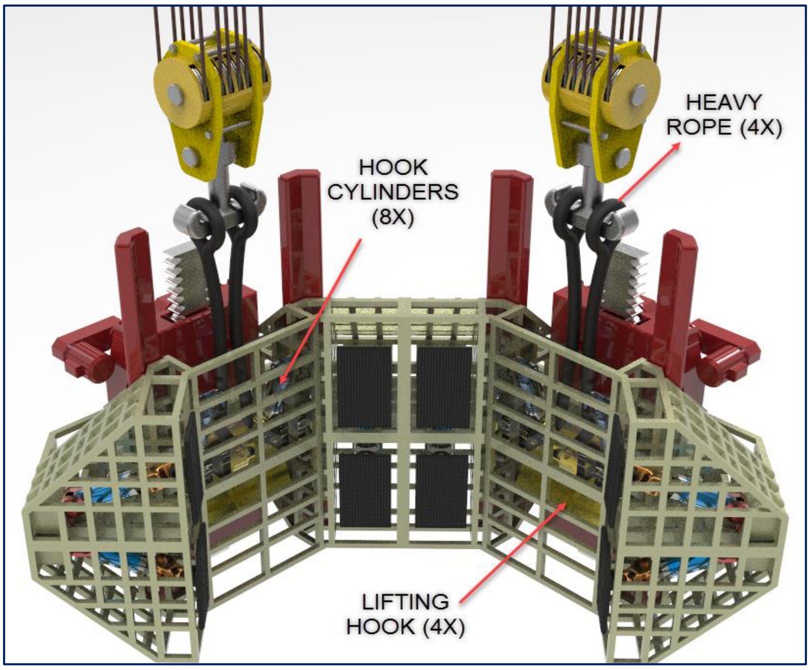


Figure 3.13 Lifting Hook

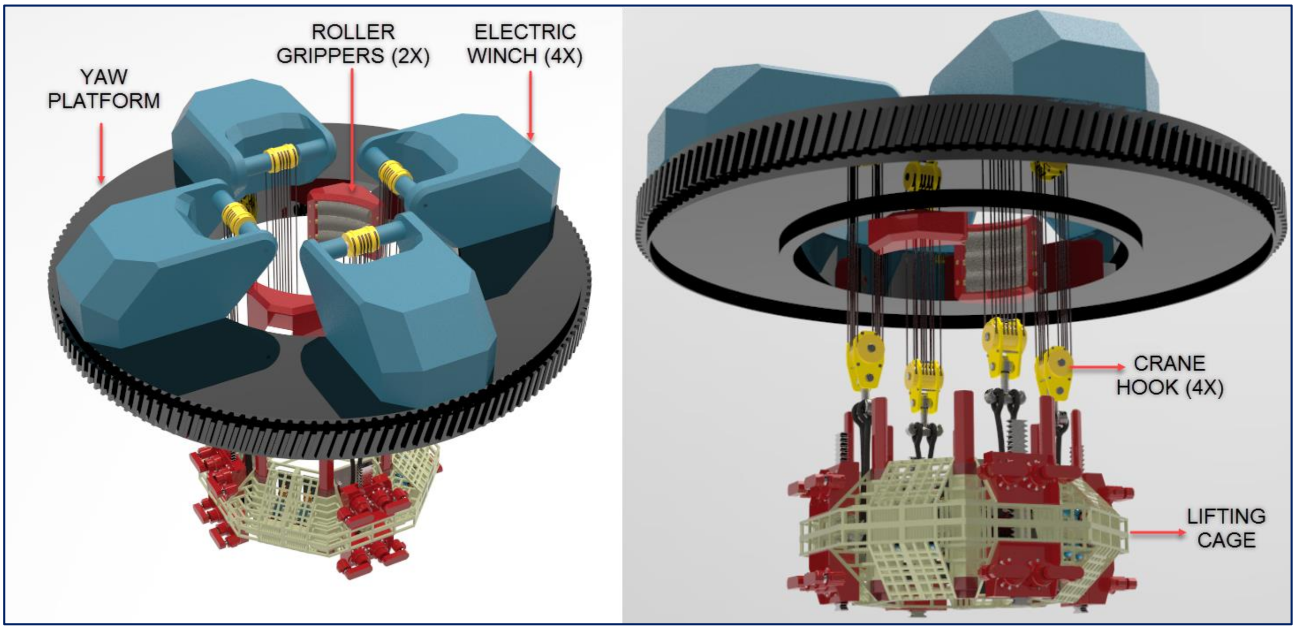


Figure 3.14 Lifting cage, Crane hook and winches

- **Step 7: Lifting and lowering the turbine assembly**

In order to lift the turbine assembly, the lifting cage has to be opened with the help of a rack and pinion system attached to it. The important part of lifting comes when the **upper half of the cage is aligned to the base of the wind turbine** as shown in [Figure 3.15]. Once the alignment is corrected, the lifting hooks are closed. This will then allow the ropes and the crane hook to take the entire load of the wind turbine as well as the lifting cage. The lifting points are designed in such a way that the load is distributed equally on all the four hooks.

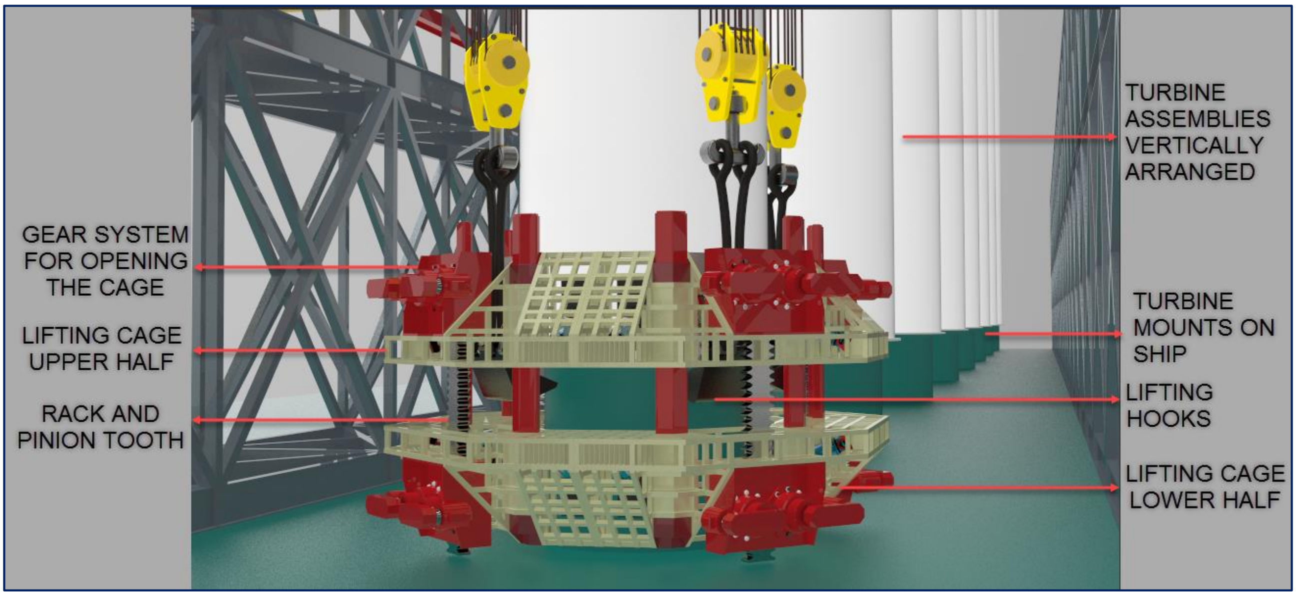


Figure 3.15 Lifting of turbine assembly from vessel

The lower half of the lifting cage is then aligned with the transition piece. The hydraulic grippers inside the cage is then activated and takes up the weight of the wind turbine on **16 Hydraulic Cylinders**. The hooks are opened and are allowed to pass through the space in between the lower and upper cage as the turbine is lowered on to the transition piece. The ropes are then changed to slacking mode and are relieved of the weight of the turbine.

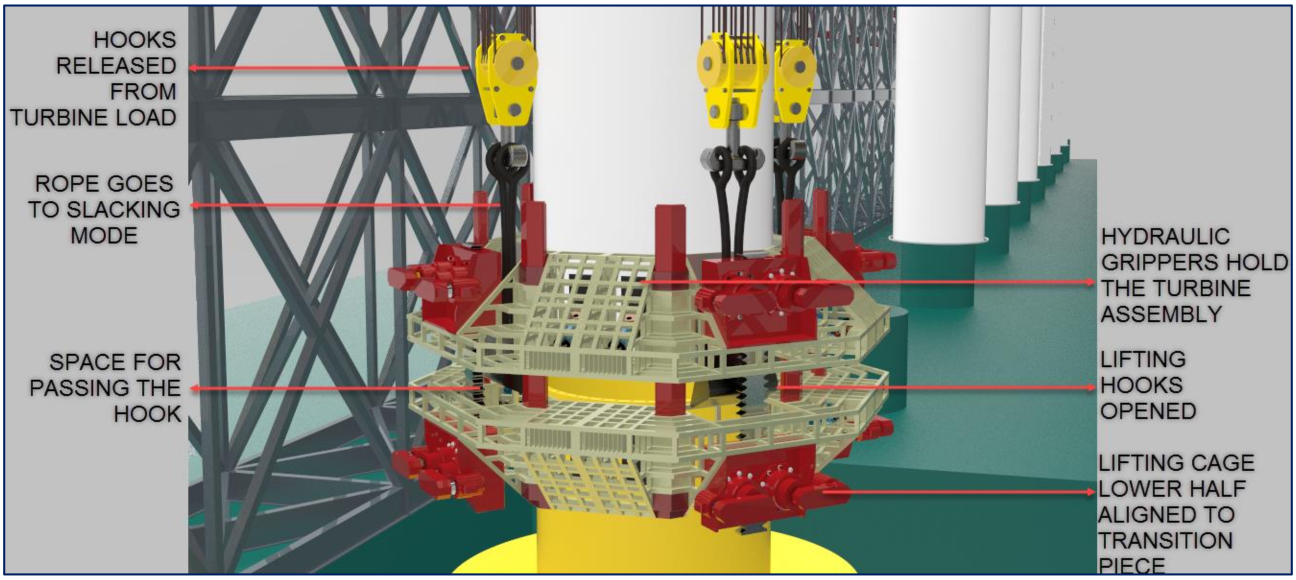


Figure 3.16 Lowering the turbine assembly on to the transition piece

- **Step 8: Detaching the cage after installation**

Once the installation is carried out, the lifting cage is pulled back to the top by keeping it in the closed condition. This will not cause interference with the turbine assembly owing to the tapered structure of the turbine tower. Once it is raised to a height almost up to **3 meters** below the heave compensated platform. The Cage is to be detached into two and pulled back to either sides of the installed turbine. The **detachment methods are not taken into consideration** for this project. This can be a hydraulic cylinder arrangement with locks that detaches the cage once it reaches the required height. Weight of the one half of the lifting cage is then distributed to the two **electrical winches** pulling it. There are also hydraulic actuators that moves inside the one half of the platform to improve the stability of the structure once in closed condition. These are as shown in [Figure 3.17]. The lifting cage once detached can be lowered down to the base platform floor and can rest there for inspection before starting the installation of the next turbine.

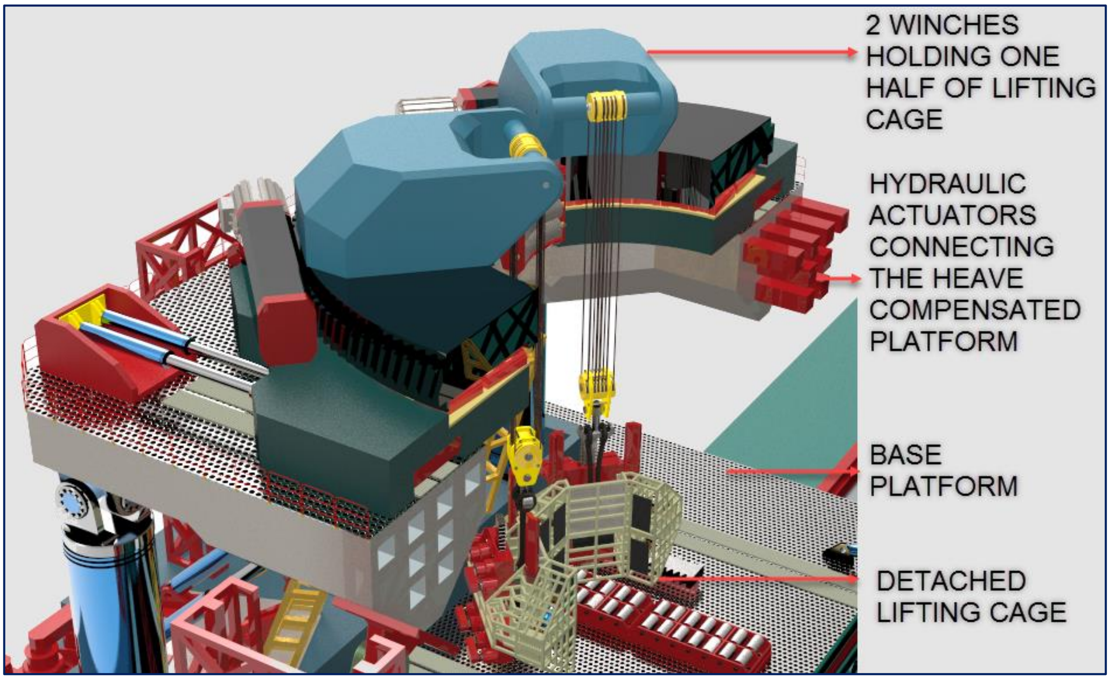


Figure 3.17 Cage Detachment

All the steps mentioned in the design proposal are the various stages of the installation process. The next stage of the design process was to validate the structural stability of the proposed structure. However, all the models involved are not selected for structural validation. Only the **2 critical structures** are evaluated for structural stability which are explained in detail in the next chapter. Various supplier components were to be selected for the entire project. The rationale behind each supplier selection and the component designs and modifications are also explained further. All the above images used in this chapter are modeled in NX and rendered using the software key shot. However, the detailed design part includes the initial concept models before verification and explains how these are reinforced and modified to improve the structural stability of the entire system.

4 Detailed Design

4.1 Design of Lifting Cage

4.1.1 Initial Concept Model

The lifting cage is a concept of an enclosed octagonal structure designed to support the weight of an entire turbine assembly while it is lowered and bolted on top of a transition piece. Usually, wind turbines are lifted and installed using high lift cranes as separate pieces (tower, nacelle & blades) and are lowered on top of the transition piece for bolting. However, in this design the turbine assembly as a whole is lifted and placed on top of the transition piece. The lifting is carried out using winches placed on a heave compensated platform which is explained in another chapter. There are a few factors that differentiate this design from the usual installation procedures that are currently in use.

- A fully assembled wind turbine is lifted instead of separate pieces.
- High lift cranes are not involved in this entire operation
- Lifting point of this installation is at the base of the tower instead of being at the top.

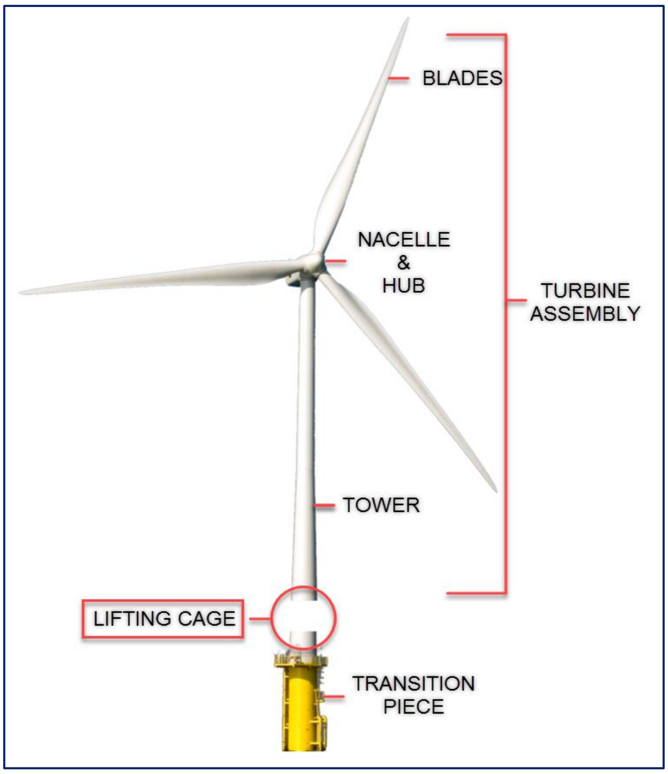


Figure 4.1 Illustration of an Offshore Wind Turbine

Initially, a 3D model as shown in [Figure 4.2] was created using Siemens NX. Since the lifting point is designed to be at the base of the tower, there was a need for an arrangement capable of slowly lowering the entire turbine assembly on to the foundation. The upper and lower half of the cage is connected using a Rack and Pinion system designed for this purpose. This cage comes equipped with hydraulic cylinders and grippers capable of lowering the turbine assembly once the lifting hooks are released. The primary objective was to make sure that the structure designed is capable of withstanding a load of approximately **1000 tons**, which is the weight of a fully assembled wind turbine.

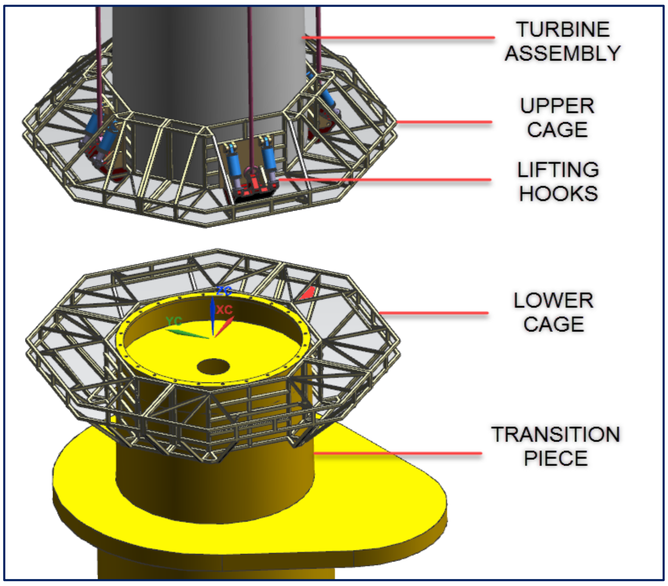
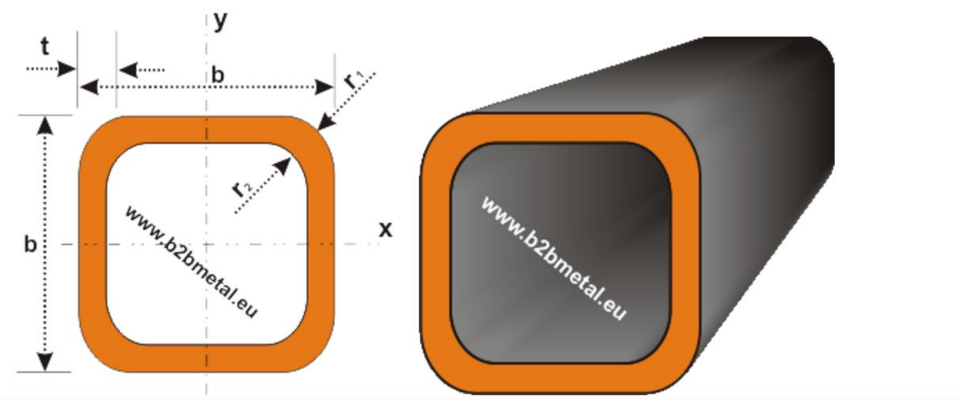


Figure 4.2 Initial Concept Model of Lifting Cage

4.1.2 Material Selection

When it comes to actual structural design, material selection is an important factor. The material chosen for this construction is **HSS of EN 10210**. This material has a yield strength of **355 Mpa** The cross section of the steel section is chosen from the catalogue for steel structures manufactured and sold in Europe. In order to create a light weight structure with the required strength, square tubes are welded in place in an octagonal pattern. The material and the cross section used is as shown in [Figure 4.3]. However, a different thickness of **16mm** was selected.

SQUARE STRUCTURAL HOLLOW SECTIONS - HSS OF EN 10210, PROPERTIES HOT FORMED SQUARE HOLLOW SECTIONS



Specified side dimension	Specified thickness	Mass per unit length	Cross-section	Second moment of area	Radius of gyration	Elastic section modulus	Plastic section modulus	Torsional inertia constant	Torsional modulus constant	Superficial area per metre length	Nominal length per tonne
b	t	M	A	I	i	W el	Wpl	It	C t	As	
mm	mm	kg/m	cm2	cm4	cm	cm3	cm3	cm4	cm3	m2/m	m
100	14,2	36,60	46,60	553,0	3,44	111,0	?	943,0	158,0	?	?

Figure 4.3 Steel Cross section and Material [18]

The initial concept model was later refined multiple times in order to increase the structural stability. The final model of the lifting cage is as shown in [Figure 4.4]. The location for the placements of the equipment's are highlighted.

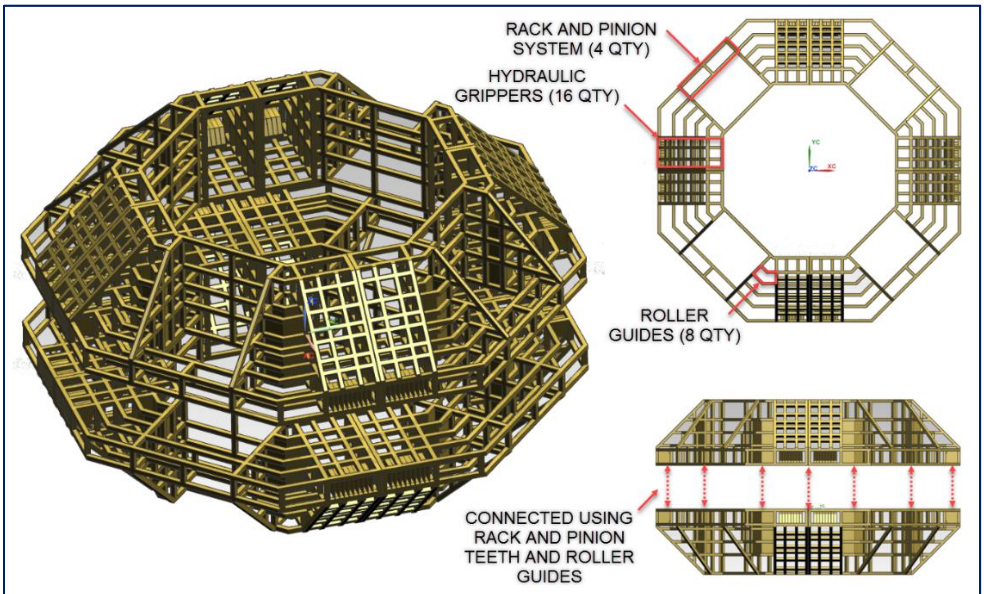


Figure 4.4 Lifting Cage modeled in NX

4.1.3 Equipment selection

The once the lifting hooks are released, the wind turbine has to be lowered using a rack and pinion system. The primary objective was to find a system that has a holding capacity of a 1000 tons and more. The system designed for this is a custom modeled rack and pinion system that can be ordered from the supplier Gusto MSC as shown in [Figure 4.5].

The reason behind this selection is that, these systems are proven designs which are capable of doing heavy lifts. These are used in a combination to lift massive loads. 36 of these variable speed drive systems can be used to jack up an entire construction vessel of around 40,000 tons as shown in [Figure 4.5]. Each of these drives has a holding capacity of 620 tons.

Figure 4.5 GustoMSC catalogue [19]

In this concept design, **8** of these drives can be used to lower the wind turbine on to the foundation. However, the primary objective was to identify the location where this could be placed. In order to do that, a 3D custom model of the rack and pinion system was created using Siemens NX as shown in [Figure 4.6]. With a 620 ton holding capacity each, 8 of these with a total of 5000 tons holding capacity can be used to lower the wind turbine safely and precisely.

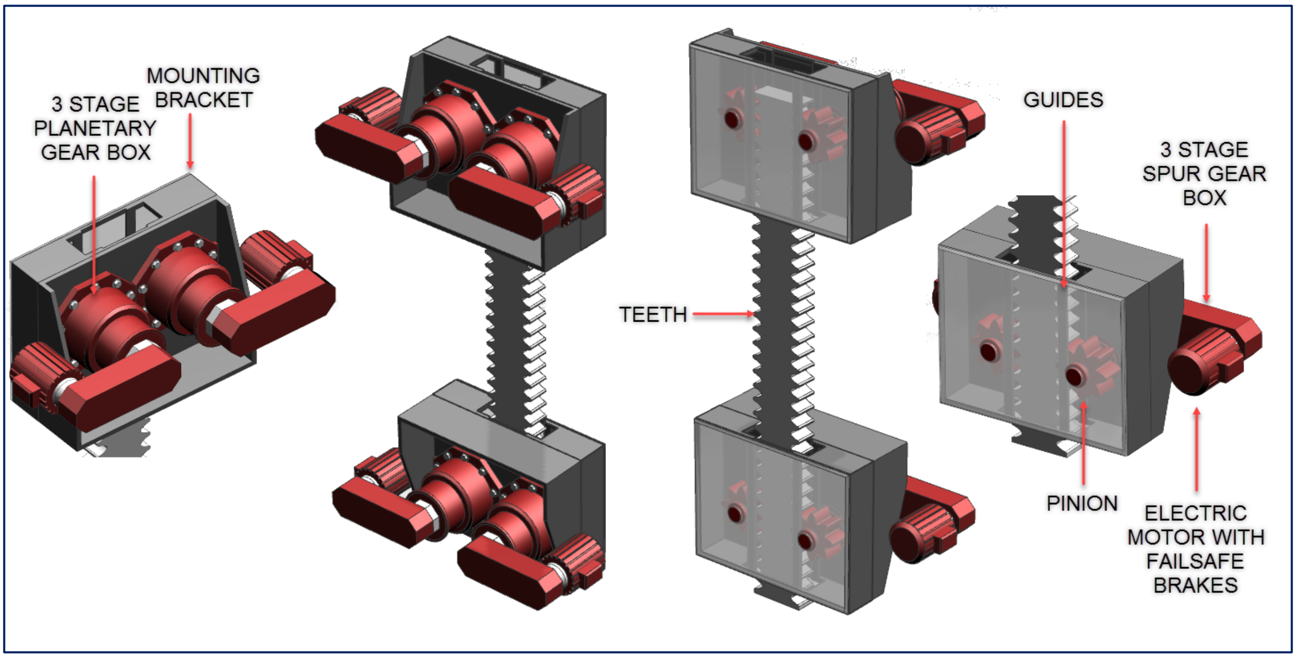


Figure 4.6 VSD Rack and pinion modeled in Siemens NX

4.1.4 Hydraulic Grippers and Roller Guides

Once the lifting hooks are released, the wind turbine has to be supported using hydraulic grippers. These hydraulic grippers are placed at an angle inside the lifting cage. This is done to take advantage of the tapered structure of the wind turbine. The shape of the wind turbine will provide a positive taper lock for the grippers which will in turn provide a mechanical advantage while holding the structure. A cross section of the lifting cage with the grippers is as shown in [Figure 4.7].

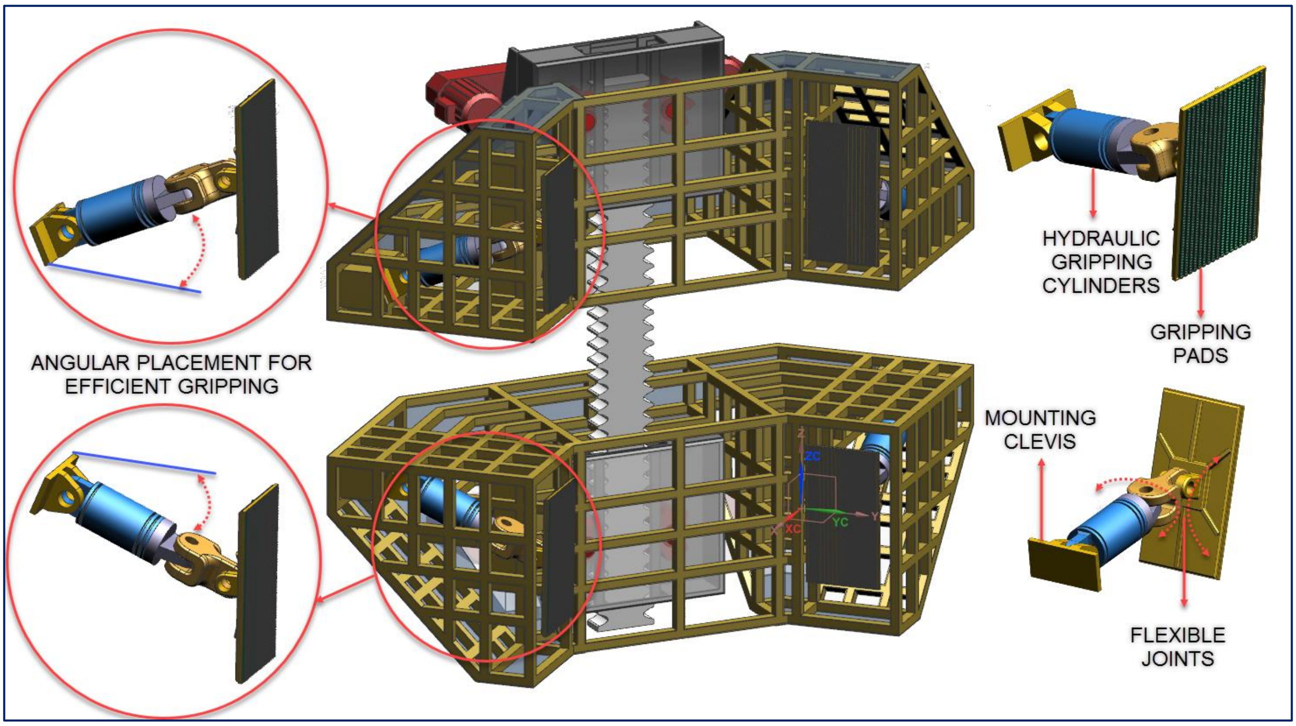


Figure 4.7 Hydraulic Grippers modeled in NX

The weight of the wind turbine will create a massive outward force equivalent to around 1000 tons on the structure. In this scenario, the teeth of the rack and pinion alone won't be sufficient to hold the structure in place. This was verified using finite element analysis. In order to provide additional support for the structure, roller guides are introduced in between the upper and lower cage to reinforce them. Guides will pass through the cage as it is lowered. The placement of the roller guide on a cross section of the cage is as shown in [Figure 4.8].

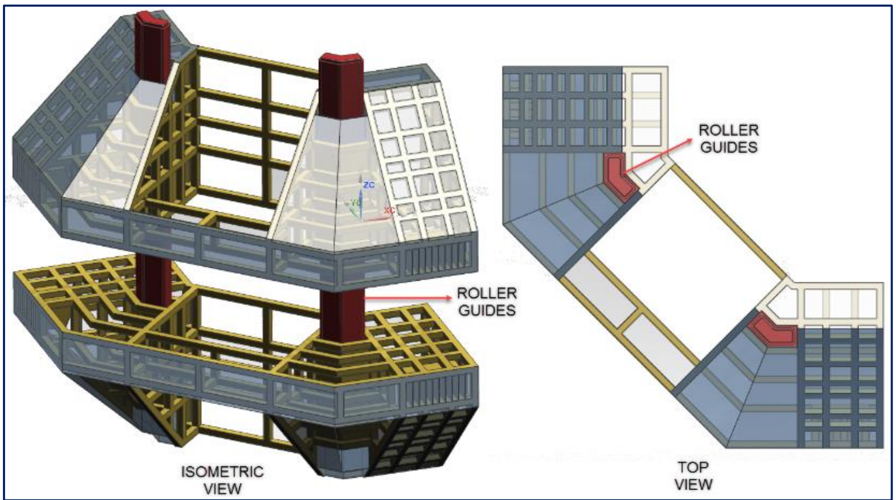


Figure 4.8 Roller Guides modeled in NX

4.1.5 Results of FEA

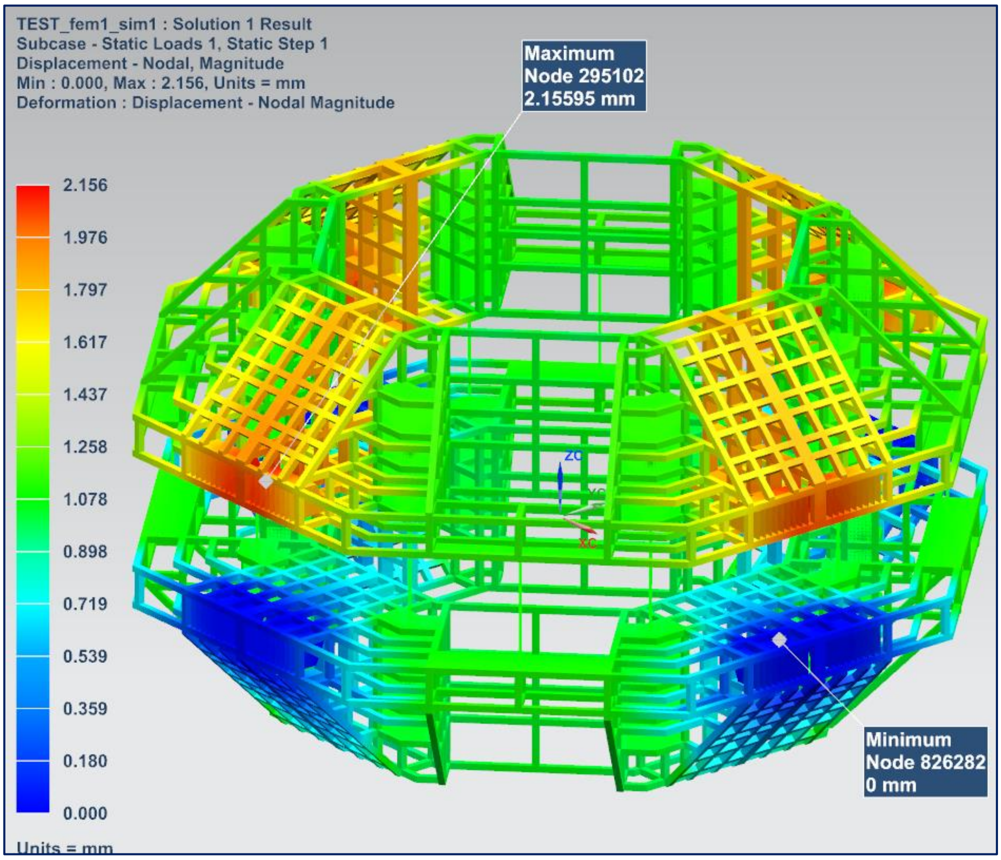


Figure 4.9 FEA Result showing the maximum deflection as 2 mm

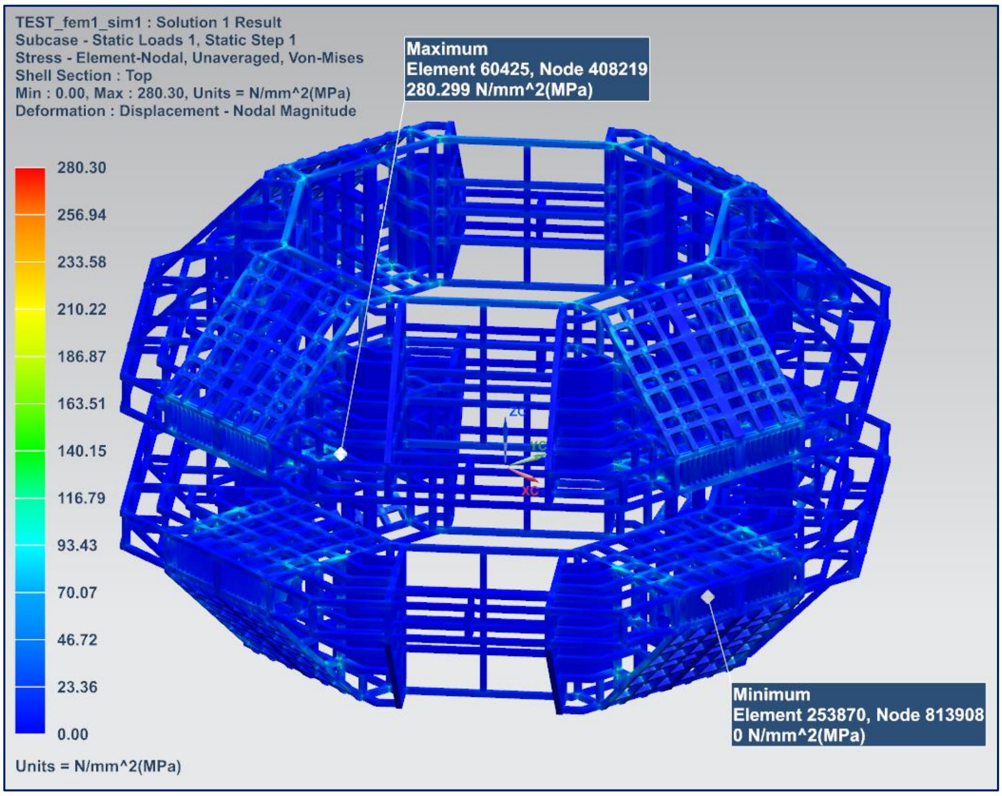


Figure 4.10 FEA Result showing the maximum stress as 280 Mpa

A detailed explanation of the analysis is explained in **[Appendix 2]**

4.1.6 Discussion of results

The material chosen for the lifting cage construction was **HSS of EN 10210**. This high strength steel has a yield strength of **355 Mpa** and the analysis results show that the stresses are well within the proposed limit, **280 Mpa**. The maximum displacement of the entire structure of more than **8 meters** in diameter is only **2 mm** which is acceptable under the norms and standards. The simplifications made are carefully implemented so that the criticality of the analysis is not effected. Refer **[Appendix 2]** for details of analysis.

Only a global analysis on the concept model is carried out in this project. A more critical local analysis can be considered as part of the future work. The open space next to the rack and pinion system is used as a hooking point for lifting the entire structure. This space is also used for lowering the lifting hook in between the lower and upper half of the lifting cage. This is explained further in the next chapter.

The lifting cage is finally covered with a 1-5mm thick plate so that the components are covered from the environmental effects. A partial covering of the model is as shown in [Figure 4.11]. The 3d model depicts the final assembly of the lifting cage with the **8 rack and pinion systems** that power the lift and the **16 hydraulic grippers** that work together in keeping a 1000 ton fully assembled wind turbine in place. The 1000 tons used for all the calculation is an assumed value and there hasn't been a wind turbine that heavy build yet. The concept when modified for future work can consider reinforcing the cage to support a heavier structure. For example, the structure can be easily modified to support a wind turbine of more than 6 meters in diameter and weighs more than 1200 tons.

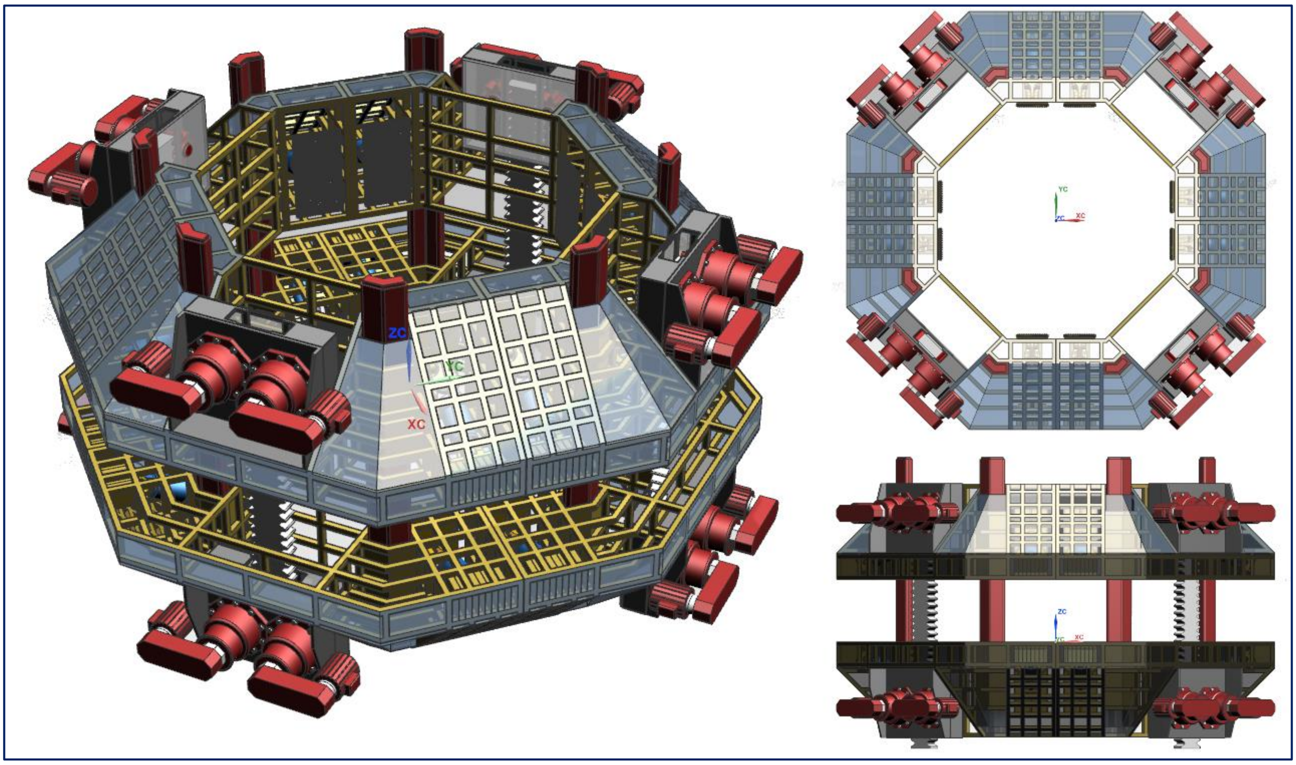


Figure 4.11 Fully Assembled lifting cage modeled in NX

4.2 Design of Lifting Hook

4.2.1 Initial Concept Model

In the previous chapter, the lifting cage and the rack and pinion system used for lowering it on to the transition piece was explained. However, the chapter did not cover the method used to lower the entire lifting cage assembly from the vessel. The lifting cage (upper half and lower half) and the turbine together is lowered down from a platform on top of the vessel. Using a winch system. The concept is explained as shown in [Figure 4.12].

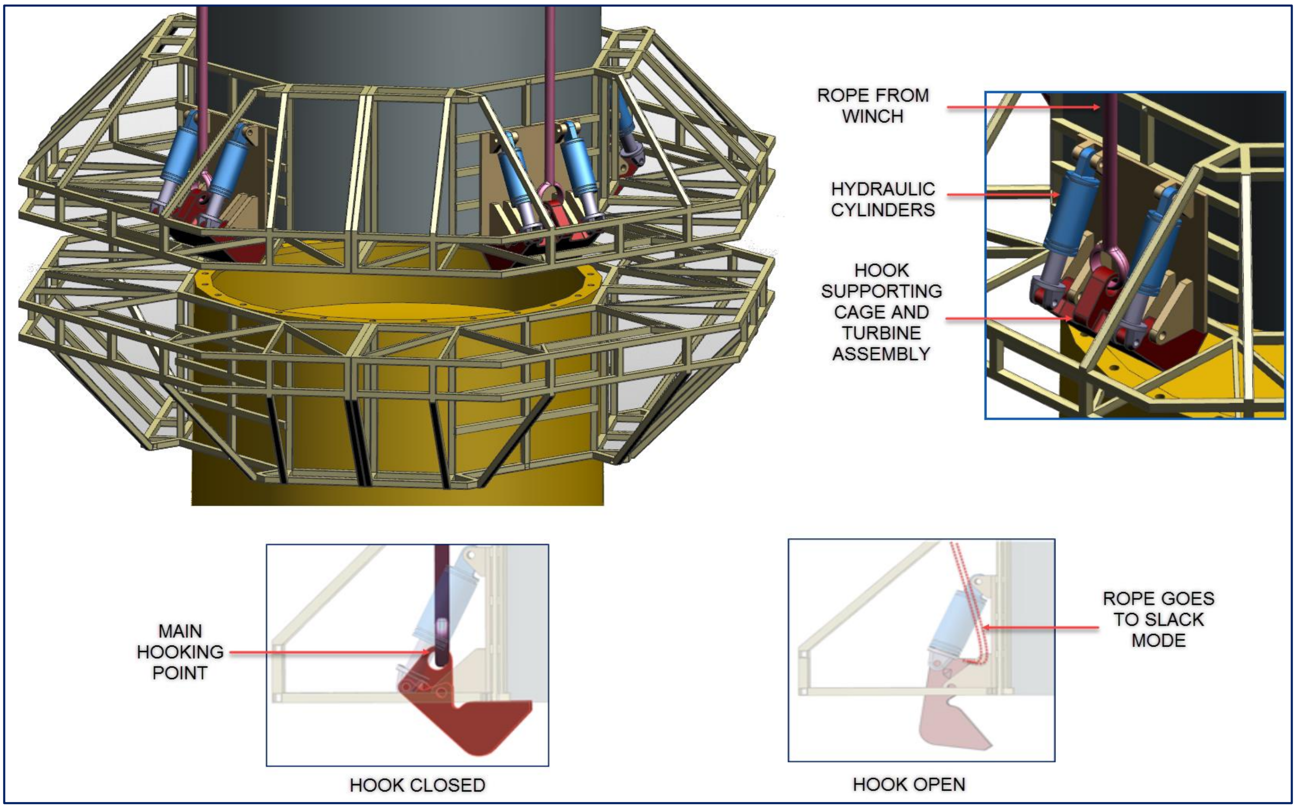


Figure 4.12 Primary design of the lifting hook

Prior to opening the hook, the hydraulic grippers are activated to hold the wind turbine between the tower and the transition piece. The lifting hooks are designed with three important features.

- While lowering the cages, the hook will pass through the space in between them.
- The main hooking point will take up the entire load and the hinge points won't take up the weight of the structure.
- While in open condition, the rope will go into slack mode and rest in the area shown in [Figure 4.12].

It was later realized that the hooking structure primarily made is not strong enough to with stand the weight of the entire structure. The bracket used for mounting the hook alone was analyzed for structural integrity. The hook assemblies alone weigh close to **11 tons**. The material selected for the hook is **SAE 1096, oil quenched steel** which is a high strength steel with a yield strength of **896 Mpa.** The most important feature of the hook is the way it is designed so as to take up the entire weight of the tower and cage while lifting.

4.2.2 Finite Element Analysis and Results

For the FE analysis only the hook assembly was considered since the impact on the cage was minimal. The rear end of the mounting bracket is fixed to lifting cage and the lifting point is fixed to simulate the hooking. RBE (Rigid Body Elements) were used to simulate the pins on the hinge point as shown in [Figure 4.13]. The material used is high strength steel with a yield strength of **355 Mpa**. The results are as shown in [Figure 4.14].

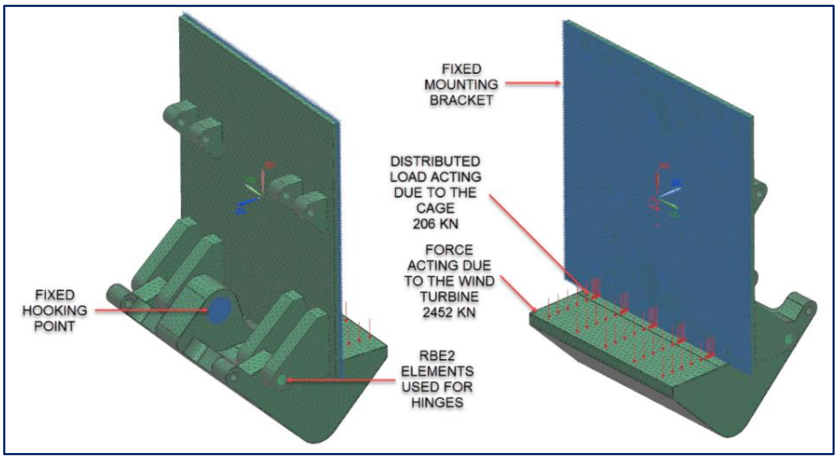


Figure 4.13 Load conditions for the Lifting hook

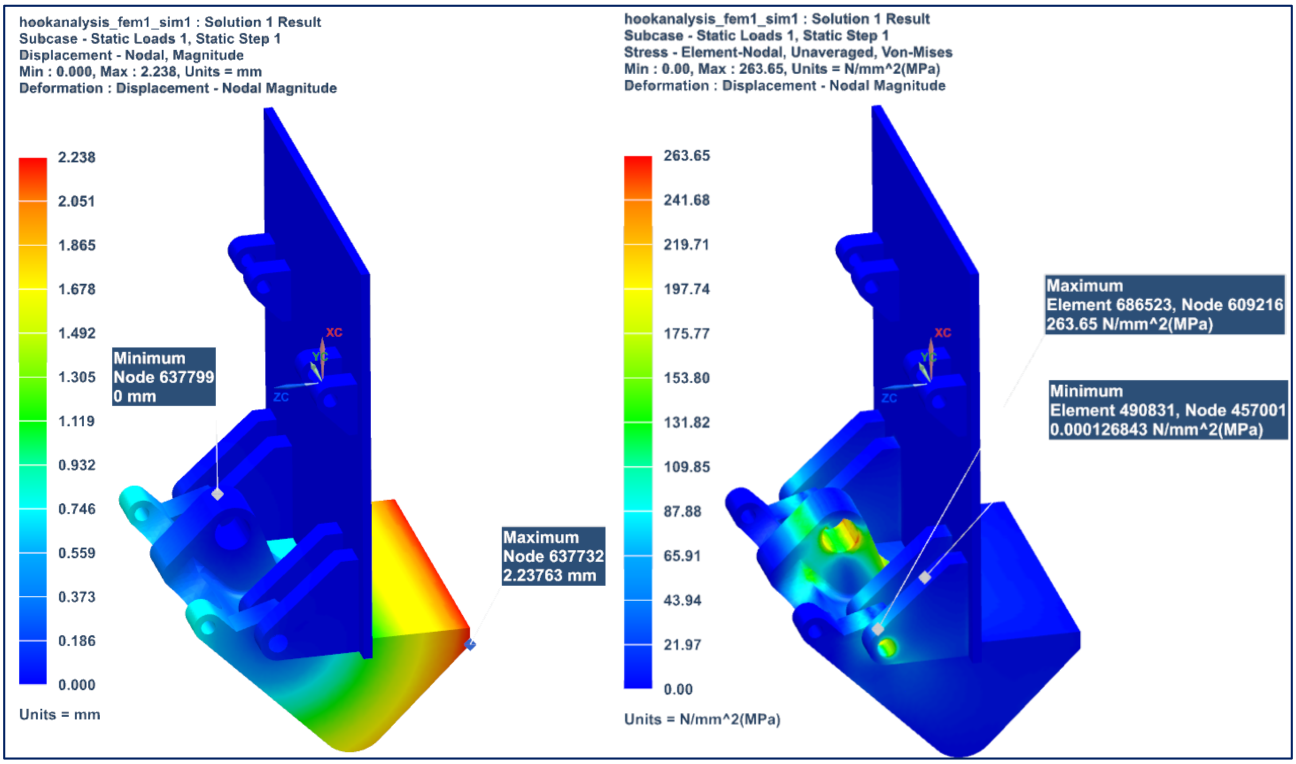
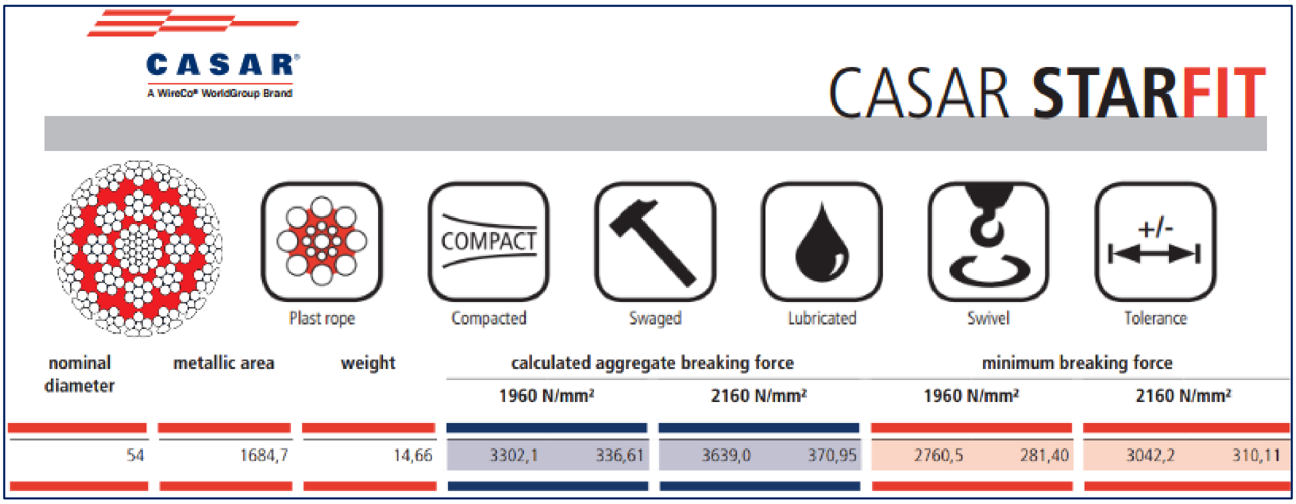


Figure 4.14 FEA Result showing the maximum deflection as 2 mm and maximum stress as 241 Mpa

The result of the analysis shows that the hook is strong enough to support the loads generated. Since the hook is a forged element, the weight of the hook is extremely high. There are several factors which were considered during the local analysis of the hook. A detailed explanation on the boundary conditions, forces applied and material selection are attached along with the [**Appendix 3**]

4.2.3 Lifting Rope Selection

The ropes required for the lifting needs to be selected based on the load that needs to be lifted. Each of the four lifting hooks will have to lift a load of around **250 tons.** Hence a rope was selected from a German manufacturer CASAR. The model of the rope selected and the properties are as shown in [Figure 4.15]. The rope selected is of diameter **54 mm** and the minimum breaking force required is **310 tons**. This rope might not be an ideal selection, but could serve the purpose.



nominal diameter	metallic area	weight	calculated aggregate breaking force				minimum breaking force			
			1960 N/mm²		2160 N/mm²		1960 N/mm²		2160 N/mm²	
54	1684,7	14,66	3302,1	336,61	3639,0	370,95	2760,5	281,40	3042,2	310,11

Figure 4.15 Rope selection from supplier CASAR [20]

The lifting hook the ropes and the crane hook was later modeled in NX to illustrate the exact location and size of the component required. The crane hook modeled in NX is for illustration purpose and the model is not included for FE analysis. The final assembly of the ropes and the hooks are as shown in [Figure 4.16].

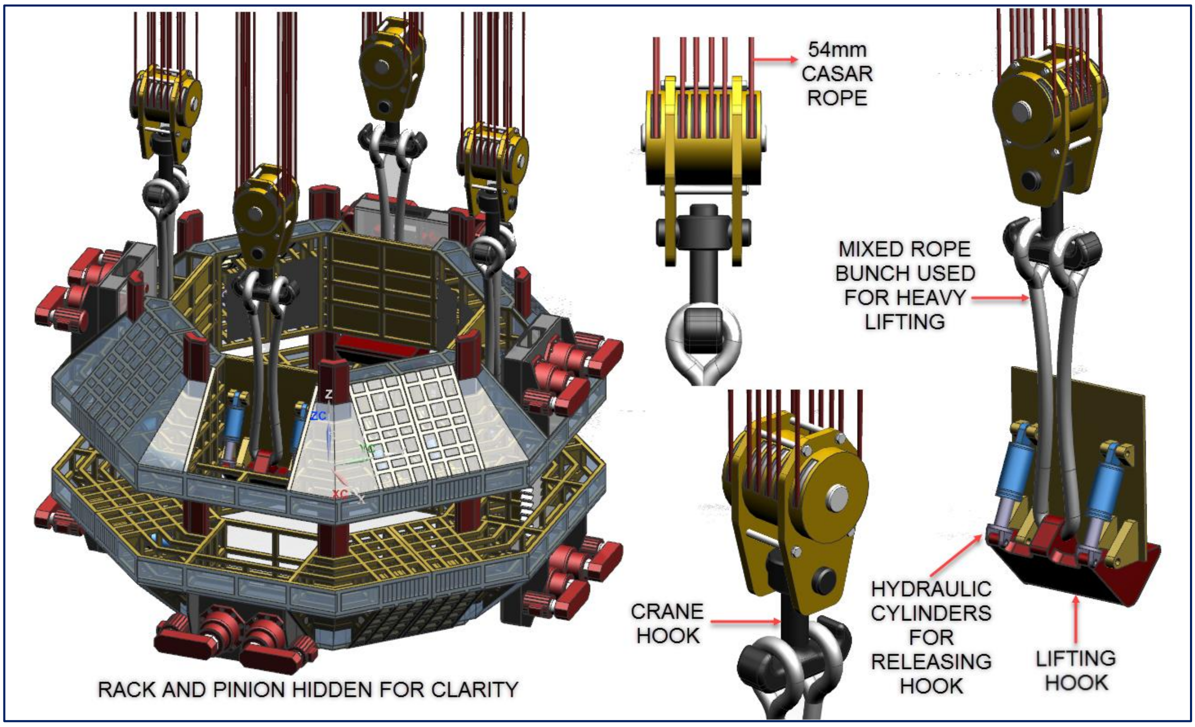


Figure 4.16 Final model with the lifting hook and crane hook with 54mm rope

4.3 Design of Sway and Yaw compensated platform

4.3.1 Initial Concept Model

The primary objective was to design a system capable of compensating the sway and yaw motions since the heave compensated platform will only be able to compensate for the Pitch, Roll and Heave motions as shown in [Figure 4.17]. However, two moving platforms on top of one another needs to be carefully set up in order to prevent the entire structure from tipping off. The sway platform was designed to move by **hydraulic actuators** along a guided path and the yaw platform was designed to move along a circular path with the help of a **helical gear system**. The helical gear system will be powered with help of **4 electric motors**. The ropes from the lifting hook mentioned in the previous chapter is then connected to the **electric winches** on top of the yaw platform.

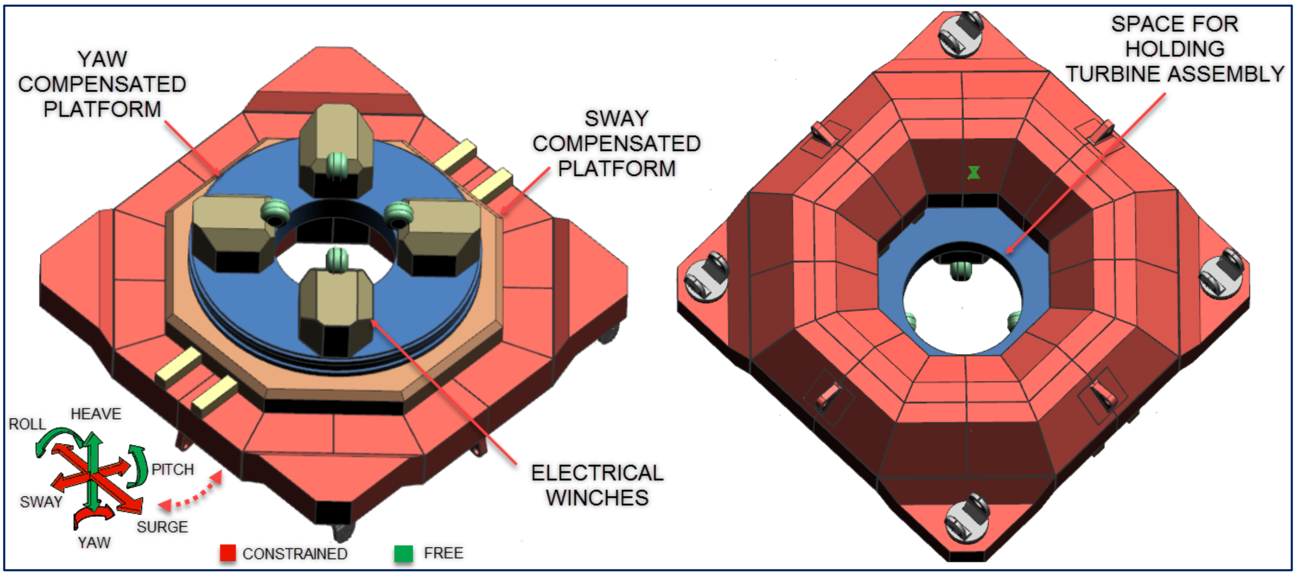


Figure 4.17 Initial concept of sway and yaw platform

4.3.2 Selection of steel rollers

The sway platform should be able to withstand a load of around **2500 tons**. This value is the combined weight of the yaw platform and the turbine assembly together. In order to move a structure with this load, friction is a major factor that needs to be considered. Special load bearing structures with steel rollers were custom designed for this application. The main design of the steel roller was taken from the manufacturer **Hevihaul** shown in [Figure 4.18].

Figure 4.18 Straight and circular rollers selected from Hevihaul [21]

However, these custom rollers had to be modified to match the requirements of the project. The straight rollers were made **7.5 times** larger than the actual one and the circular rollers were made **5 times** larger than the actual model. This helped to increase the load capacity of the individual rollers form **55 tons to 400 tons** and **10 tons to 50tons** respectively as shown in [Figure 4.19]. Since there is a similar product available in the market, structural analysis was not done separately for these rollers. The dimensions by itself justify the fact that the product is capable of bearing a total load of **3200 tones and 3800 tons** respectively.

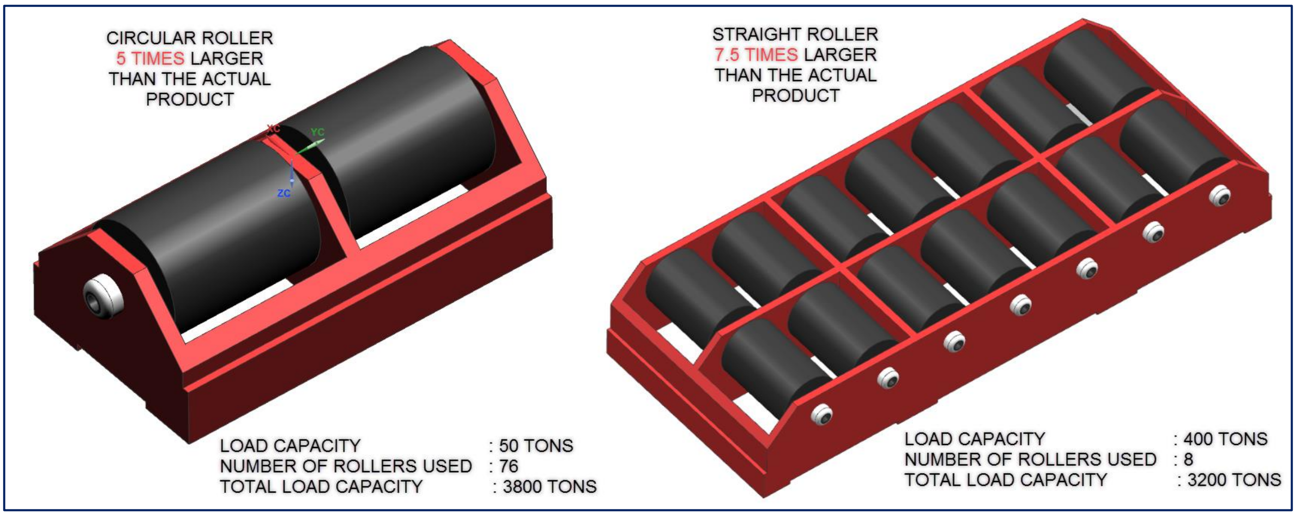


Figure 4.19 Custom designed Straight and circular rollers modeled in NX

4.3.3 Final Model of the platform

Out of the **8 straight rollers**, **4** are assembled on the heave platform and **other 4** on the sway platform. Whereas **all the circular rollers** are assembled on the sway platform only. An exploded view of the complete assembly is as shown in [Figure 4.20].

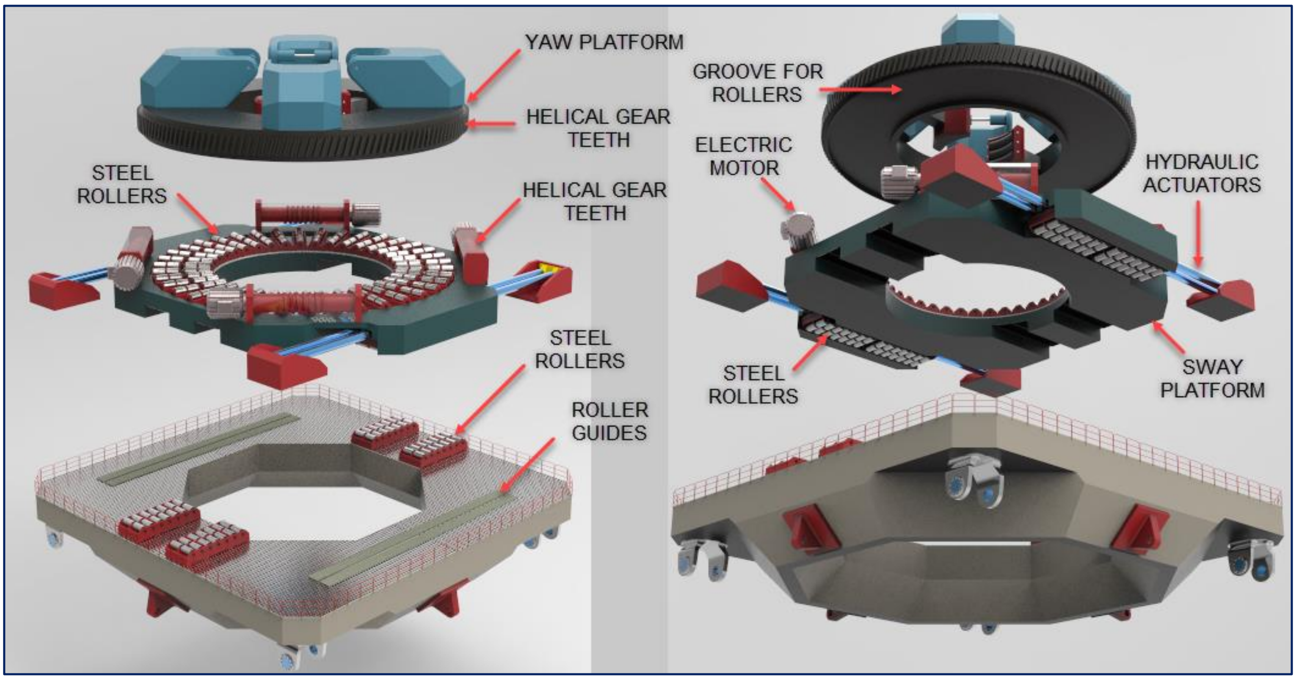


Figure 4.20 Sway and Yaw platform modeled in NX and Rendered using key shots

Special grooves are setup up below the yaw platform for it to smoothly roll over the circular steel rollers. There are 4 helical gear system driven by **4 electric motors** to compensate the yaw motion as shown in [Figure 4.21]. These gear systems are equipped with fail safe breaking system which will assist in holding the platform in place when it is detached. There are **8 hydraulic cylinders** which are used to move the sway platform back and forth by sliding over steel rollers. The friction due to the weight of the turbine is taken care of with the help of these rollers. The steel rollers are designed to roll over a specified path or guide system which also contributes towards reducing the friction between the surfaces. There are **4 Electric winches,** arranged on top of the yaw platform which houses all the pulleys and motors which drives the lifting and lowering of the turbine assembly. A detailed design of the winches is not done for this project, since it is assumed that the component can be directly ordered from the supplier as per the load requirements.

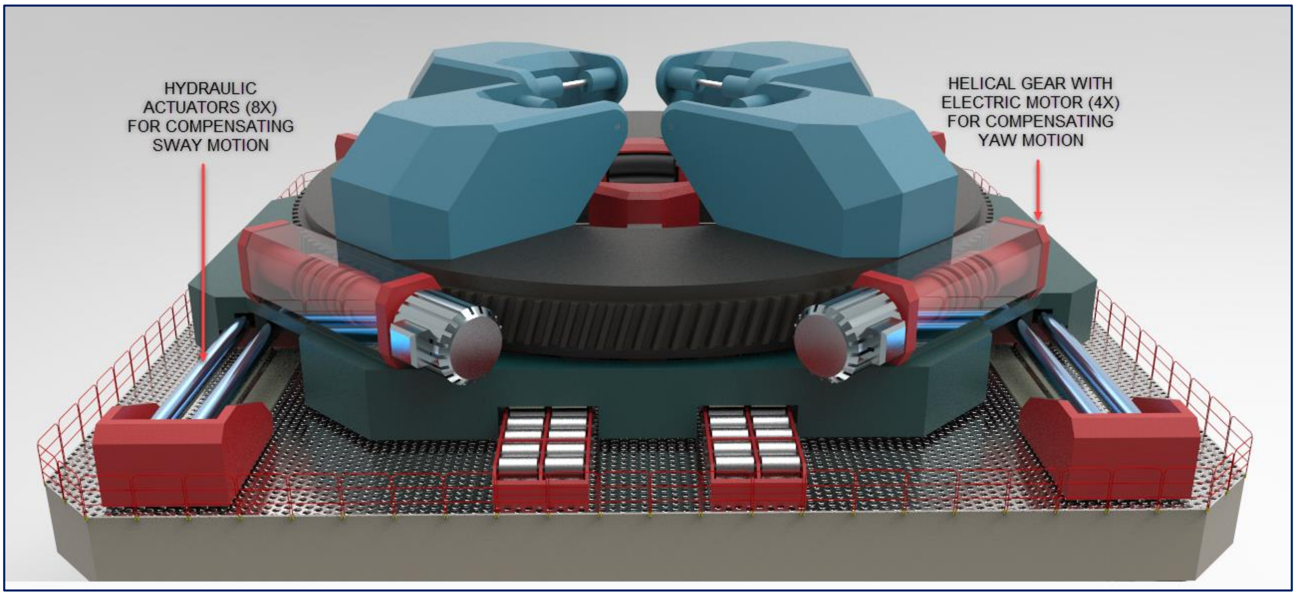


Figure 4.21 Helical gear system and Hydraulic Actuators

The Yaw platform is also equipped with a roller gripper for supporting the wind turbine as it is lowered down to the transition piece while assembling as shown in [Figure 4.22]. These grippers are important to avoid the wind turbine from tipping off. These are actuated by hydraulic cylinders which can sense any deviation and helps to keep the turbine upright. The rollers are arranged horizontally to initiate rolling when the turbine is lowered. Since it is attached to the yaw platform, motion of the rollers won't happen sideways. The rollers are arranged in a predefined angle so that the ropes lowered from the winches won't interfere with the grippers.

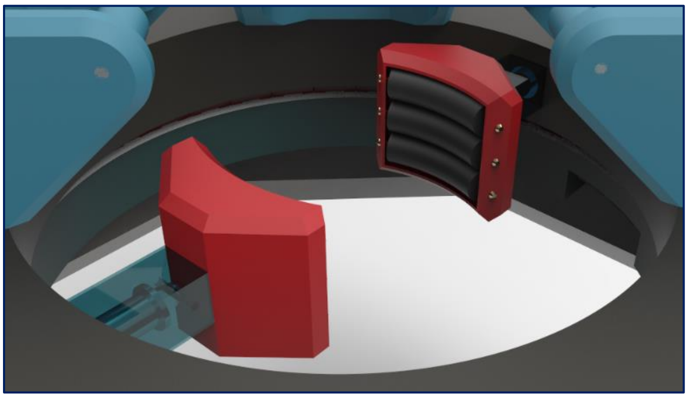


Figure 4.22 Roller Grippers used to align the turbine upright

4.4 Design of Heave compensated Platform

4.4.1 Initial Concept Model

The initial concept of the heave compensated platform was designed by keeping only a few factors in mind. The space in the middle should be able to hold a wind turbine of **6 meters** in diameter. The platform must be in a symmetric shape so that when the platform is split into two, the weight distribution is equalized on both ends. An octagonal structure was selected to improve the stability by keeping a symmetric structure. The platform designed is only made to compensate the heave, roll and pitch motion of the cylinders. There should also be provisions for reinforcing the structure once connected.

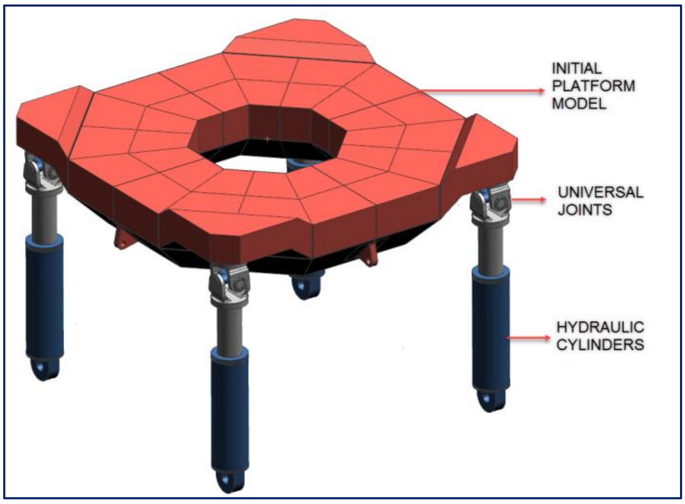


Figure 4.23 Initial concept model of Heave compensated platform

4.4.2 Material Selection

The material selected for the actual construction of the platform was an offshore quality steel plate from the manufacturer Tata steel international as shown in [Figure 4.24]. The material chosen for the plate is **EN10225 S355**, which has a yield strength of **355 Mpa.** Steel plates are welded in place with stiffeners inside so as to reduce the weight and to increase the structural stability. Since the platform is split into two, there are provisions for a locking mechanism which is actuated by hydraulic cylinders which locks the platform in place once closed.

3.3 Offshore stock

TATA

Offshore Plate Stock

Our standard stock range of offshore quality plate includes:

- EN 10225 S355 G1 G2 G3 G6 G7 G8 G9 G10
- EN 10225 S420/460 G1 G2
- EN 10025 S355K2
- EN 10225 S355J2
- API 2H/2W Grade 50
- BS 7191 355EM, 355EMZ
- BS 7191 450EM, 450EMZ
- BS 7191 355D
- Shipbuilding Grade EH36
- BS 4360 50D, 50DD

Thickness (mm)	Length x width (mm)	Plate weight
45	12000 x 2500	10.800

Available with 3.2 accreditation from major bodies such as LRS, BV, ABS and DNV

Figure 4.24 Steel Plate selection from Tata Steel [22]

4.4.3 Final model of HC Platform

The final model of the heave compensated platform is reinforced with stiffeners as shown in [Figure 4.25].

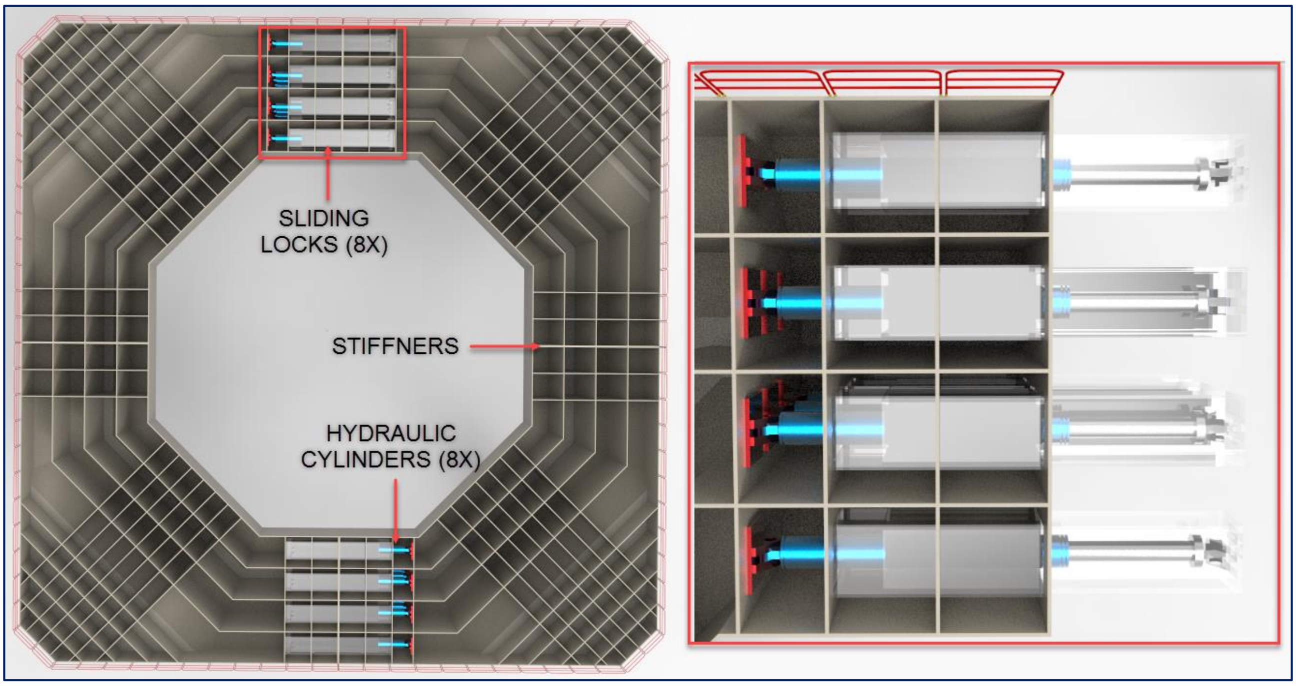


Figure 4.25 The platform reinforced with stiffeners

There **8 hydraulic cylinders** on each side to connect the platform. The sliding locks are supposed to lock both the halves of the platform and keep it from moving apart. Handrails are made all around the platform. This is to ensure safety of the service personnel's while carrying out the repair works. The handrails also give a perspective on the exact size of the platform and a person standing on top of the platform. The space for lowering the turbine is around **18 meters across flats** to ensure proper clearance for the operation. The universal joints allow the platform to move so as to compensate for the heave, pitch and roll motions. A clearly defined locking mechanism is not designed to lock both the halves of the platform. The existing design mainly highlights a provision to support the weight of the turbine assembly. This can be considered for future work on the project.

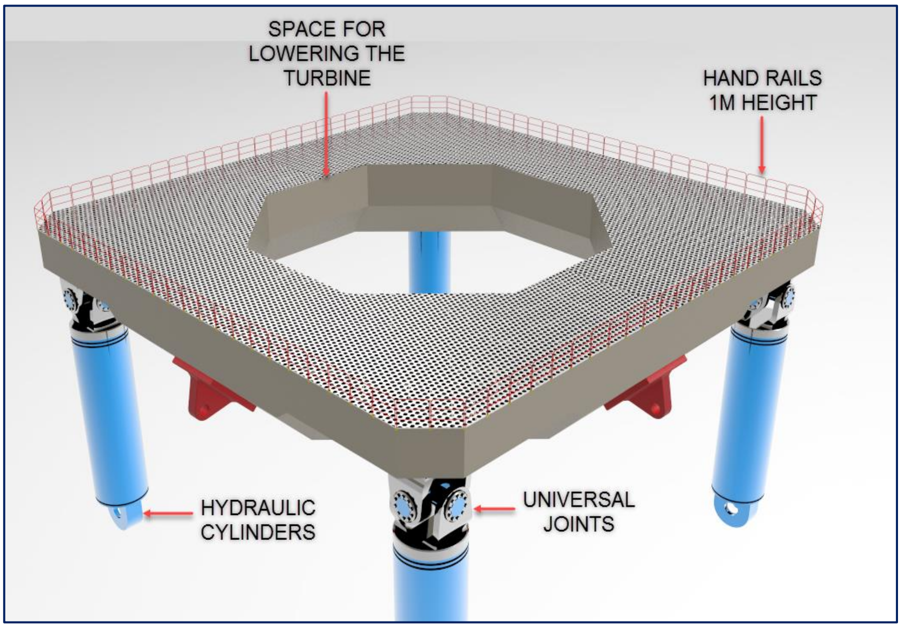


Figure 4.26 The platform rendered in key shots

4.5 Design of Surge and Cylinder Support Platform

4.5.1 Initial Concept Model

Initial design of the surge platform was made by considering the **4 separate bases** for the main hydraulic cylinders. This was later found to be of a problem while extending and retracting the base after installation. The guide systems are introduced for the movement of the slider and rotary component up and down as explained in [Chapter 3.4]. Keeping this guide system separate from the base was also found to be a big disadvantage in the load distribution during the operation. The size of the surge platform shown in [Figure 4.27] was also increased significantly to enable a safe and secure retraction of the cylinder support platform.

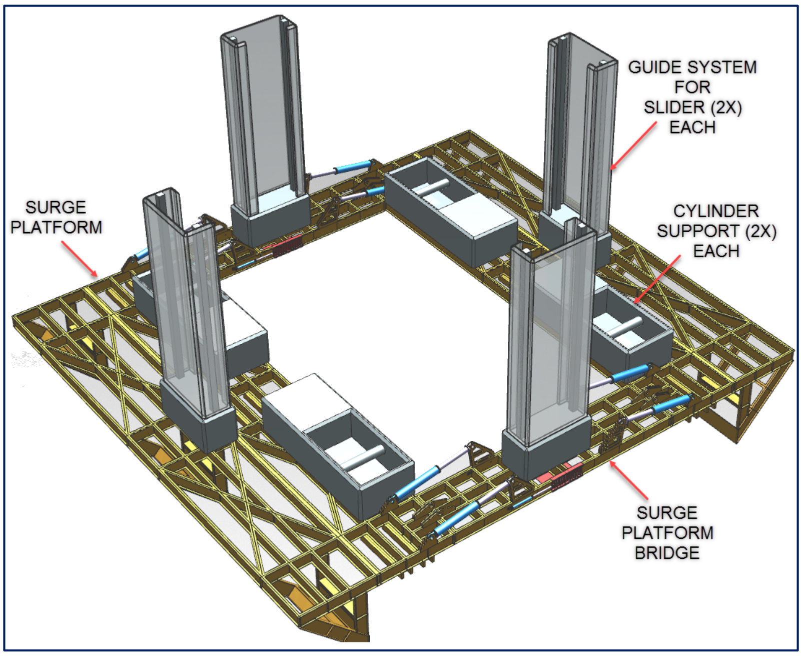
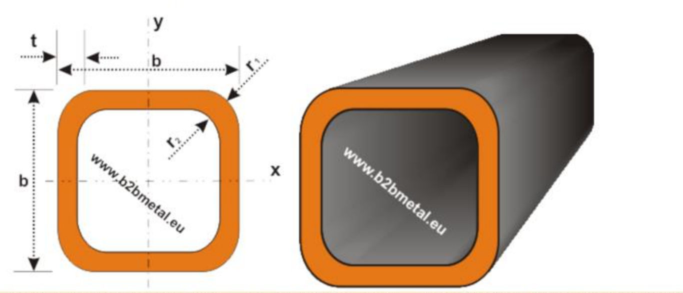


Figure 4.27 Initial design of surge platform

4.5.2 Material Selection

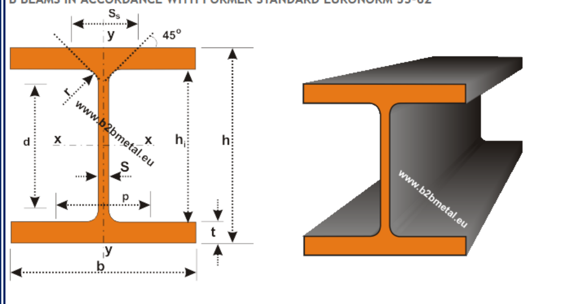
There are two major standard cross sections of the steel used for the construction of the platform. One is a hot formed **square tube of 250 mm X 16 mm** cross section and the second one is a **wide flange HEB1000 beam** which were used to create the final model of the surge and cylinder support platform. Rest of the components are steel plates of different thickness welded together. A very few of these components like the pin joint for the main cylinder housing has to be forged in order to increase the strength and durability. The standards cross sections of the steel were selected from the European market and are as shown in [Figure 4.28].

SQUARE STRUCTURAL HOLLOW SECTIONS - HSS OF EN 10210, PROPERTIES HOT FORMED SQUARE HOLLOW SECTIONS



Specified side dimension	Specified thickness	Mass per unit length	Cross-section	Second moment of area	Radius of gyration	Elastic section modulus	Plastic section modulus	Torsional inertia constant	Torsional modulus constant	Superficial area per metre length	Nominal length per tonne
b	t	M	A	I	i	W el	Wpl	It	C t	As	
mm	mm	kg/m	cm2	cm4	cm	cm3	cm3	cm4	cm3	m2/m	m
250	16,0	115,00	147,00	13270,0	9,50	1061,0	1280,0	21140,0	1.546,0	0,959	8,7

HEB BEAMS, EUROPEAN STANDARD WIDE FLANGE H BEAMS, DIMENSIONS, SPECIFICATIONS. HE B BEAMS IN ACCORDANCE WITH FORMER STANDARD EURONORM 53-62



Identification	Nominal weight 1m	Nominal dimensions					Cross-section	Dimensions for detailing					Surface	
		b	h	s	t	r	A	h1	d	Ø	pmin	pmax	AL	AG
	kg/m	mm					cm2	mm	mm		mm		m2/m	m2/m
HEB 1000	314	300	1000	19	36	30	400,0	928	868	M27	134	198	3,110	9,905

Figure 4.28 Standard cross section of the square tube and H beam selected for construction [18]

4.5.3 Final Model of the platform

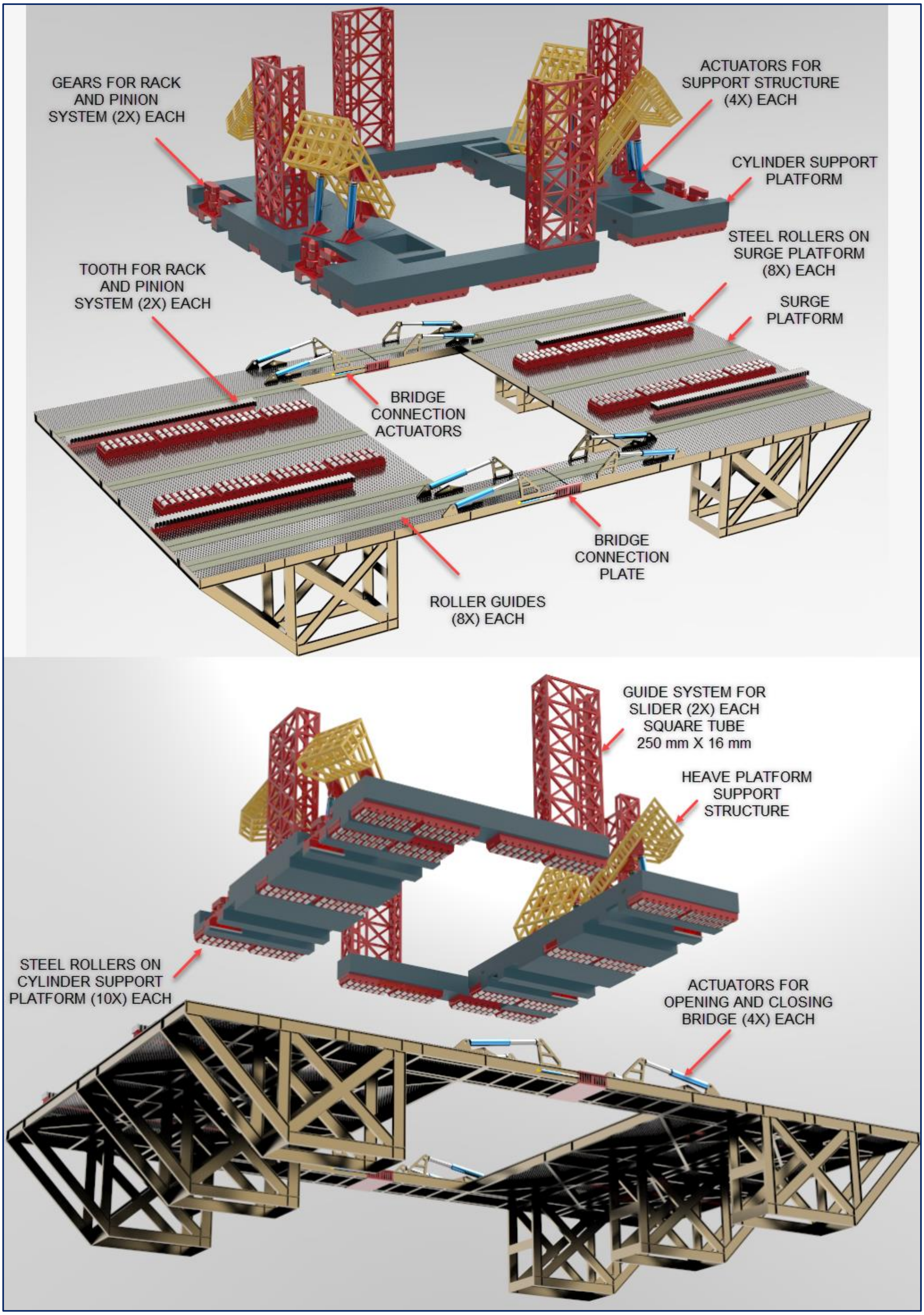


Figure 4.29 Final model of the platform designed in NX and rendered using key shots

The **cylinder support platform** shown in [Figure 4.29] is in fact a modification of the initial separated design. The reason is that the weight of the **guide system for slider** while it is in the middle of the **bridge connection plate** will induce more force on the connection plate. Making it a single weldment will allow the loads to be distributed all over the structure, mostly to the more secure parts of the **surge platform**. Moreover, the rack and pinion system used can be connected to the whole **cylinder support platform** instead of all the separate pieces as shown in [Figure 4.29]. A total of **36 straight steel rollers** as shown in [Figure 4.19] is used in order to make the movement of the platform easier. Out of the 36 rollers, **16 rollers** are welded to the **surge platform** and **20 rollers** are welded to the **cylinder support platform**. The rollers on the surge platform acts as a guiding path for the movement of the platform. By splitting the rollers in between both the platforms ensure a controlled translation movement. There are roller guides on both the platforms which acts as a path for the steel rollers to move on. These are made of special material to ensure a smooth motion with reduced friction. This also protects the platform structure from wear and tear due to the constant sliding motion. The **guide system for slider** was modified into a tubular square cross section of **250 mm X 16 mm** with guide paths for the movement of the **slide link** shown in [Figure 3.10]. This greatly improves the strength of the guide system and also reduces the weight of the structure significantly. It is evident from [Figure 4.29] that the **surge platform** has additional support structures at the outer end. This is to ensure proper balance of the entire structure as the **cylinder support platform** retracts.

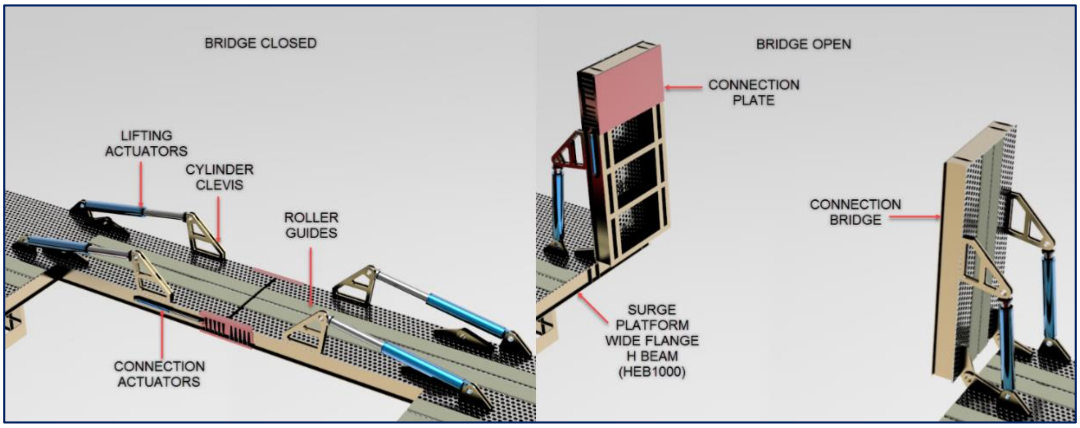


Figure 4.30 Opening and closing of the connection bridge

[Figure 4.30] shows the connection bridge that connects both sides of the surge platform. The connection bridge has **2 hydraulic cylinders** on each side connected to a specially designed **clevis** that allows the lifting and lowering of the platform without any interference. This also ensures that the bridge is perfectly aligned with the surge platform once fully lowered. There is also a **bridge connection pate** that reinforces the connection once lowered. This plate is moved with the help of two hydraulic cylinders (**connection actuators**). The roller guides for the movement of the steel rollers are extended on to the connection bridge to support the sliding motion of the platform.

The surge platform has to move along two tall support structures. The point of contact between the surge platform and the support structure is not designed in this project. Only the rails on which the platform moves are designed. This is explained further in the next chapter.

It was later realized that the **heave compensation platform** shown in [Figure 4.26] needs additional supports while splitting the platform into two. Hence a **platform support** structure dedicated to support the weight of the heave compensated platform while it is retracted was designed as shown in [Figure 4.31]. This support platform is made of welded tubular square cross section of **250mm X 16 mm** to ensure less weight and improved strength. The pin joint at the bottom of the structure is carefully designed so that the bottom face of the structure flushes with that of the base when fully open. This will ensure proper load distribution of the **heave compensated platform** on to the **cylinder support platform**. 2 Hydraulic cylinders are used for the extension and retraction of these support platforms. A total of **4 platform supports** driven by **8 hydraulic cylinders** are used in supporting the entire heave compensation platform while it is lowered and retraced back.

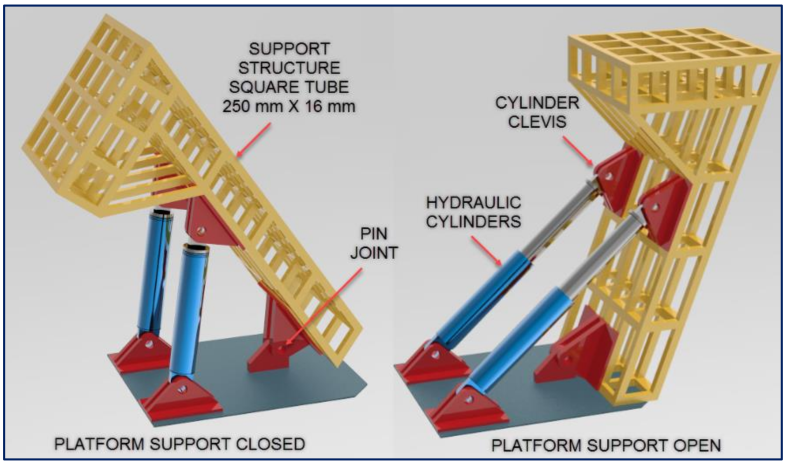


Figure 4.31 Platform Support

The movement of the cylinder support platform is carried out with the help **of 4 rack and pinion system**. It is very much similar to the one shown in [Figure 4.6]. However, it has to be modified to match the dimensions of the platform. Since this is a custom made product, the planetary gear system, motors and teeth can be made as per the required dimensions. The rack and pinion system is assembled horizontally with a provision for the teeth to pass underneath the cylinder support platform. This system is also equipped with braking system which allows the platform to be in a locked in position once extended or retracted. A completely assembled rack and pinion system on one end of the cylinder support platform is as shown in [Figure 4.32].

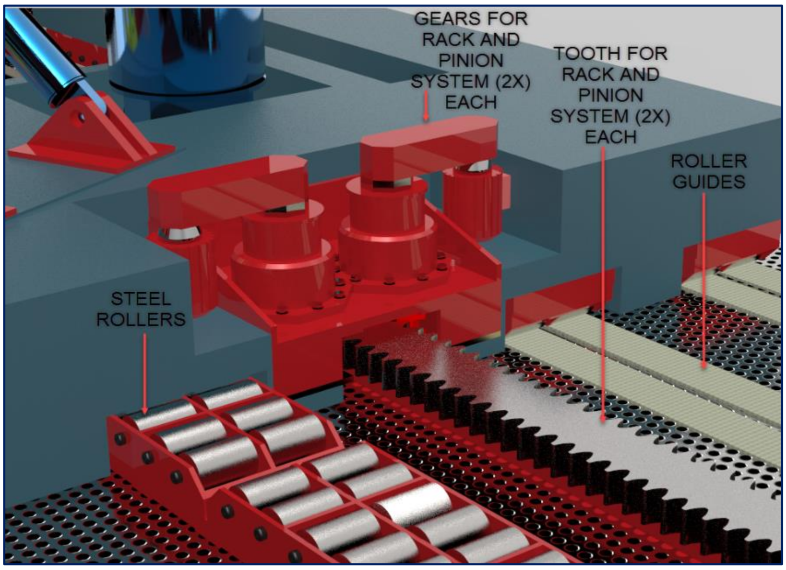


Figure 4.32 Rack and Pinion System

4.6 Design of Support Structures

4.6.1 Material Selection

There are two major standard cross sections of the steel used for the construction of the support structure. One is a hot formed **square tube of 300 mm X 20 mm** cross section and the second one is a **wide flange HEB1000 beam** which are welded as 3 separate layers. The cross welding of the HEB 1000 increases the structural stability to a great extent. The standards cross sections are selected from the same supplier as shown in [Figure 4.28].

4.6.2 Final Model of the Support Structures

The support structures are welded on top of the vessel throughout the whole length of the vessel. The surge platform is then made to slide on top of these support structures. The height of the support structure is raised so as to lift the wind turbine at least **40 meters** from the base of the vessel. This is to prevent the wind turbine from tipping off when lifted by hooking it from the bottom. The support structures align on both sides of the space in between the **catamaran vessel** so as to ensure a smooth installation by moving the turbine assembly on top of the transition piece from the vessel. The top and the side rails highlighted in **red color** was made by welding two HEB 1000 beams together. This will increase the load bearing capacity of the structure. A more detailed design of this part is not done in this project. The rails can be modified as part of future work.

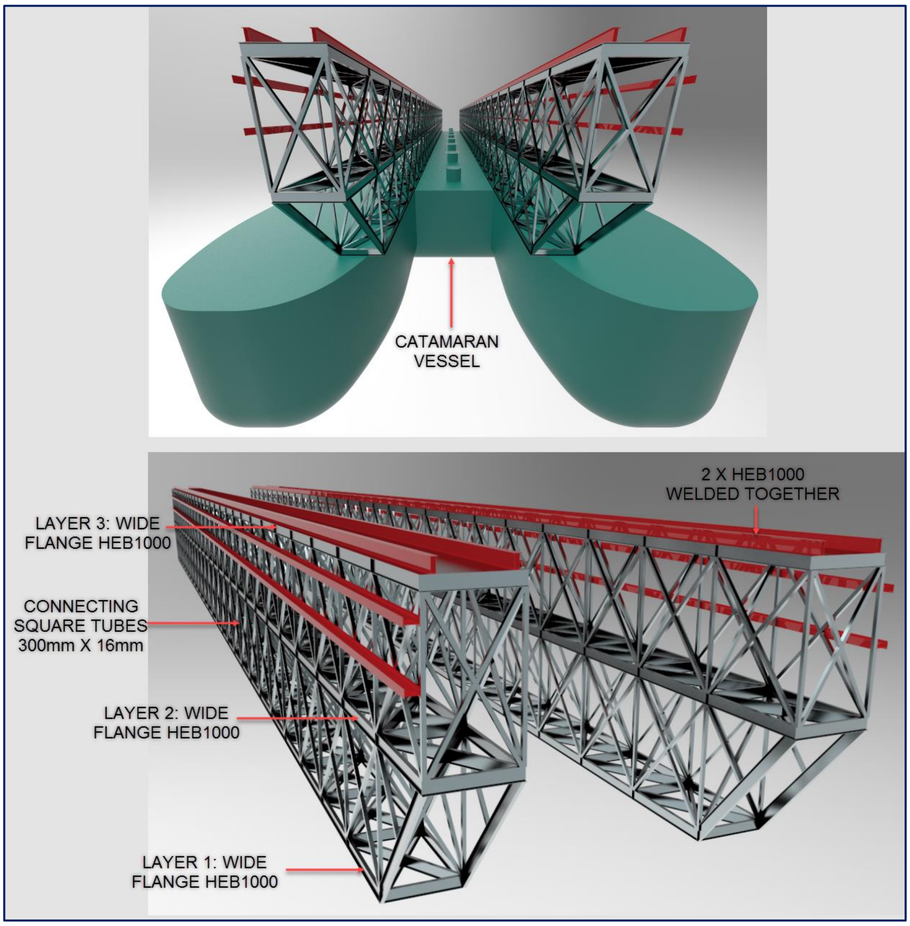


Figure 4.33 Support Structures

5 Motion Simulation

5.1 Setting up the model

After ensuring the structural stability of the concept. The kinematic movements of the links were to be verified. In order to do that, the **motion simulation module in NX** is used. This module has the ability to verify the motion of the various joints in response to the motion of the ship. Due to the immense computing power required for the motion simulation to solve the kinematic linkages of the fully assembled model, a simplified model of the entire assembly is used. The final assembly made in NX is simplified as shown in [Figure 5.1]. This makes it easier for the solver to compute the link movements.

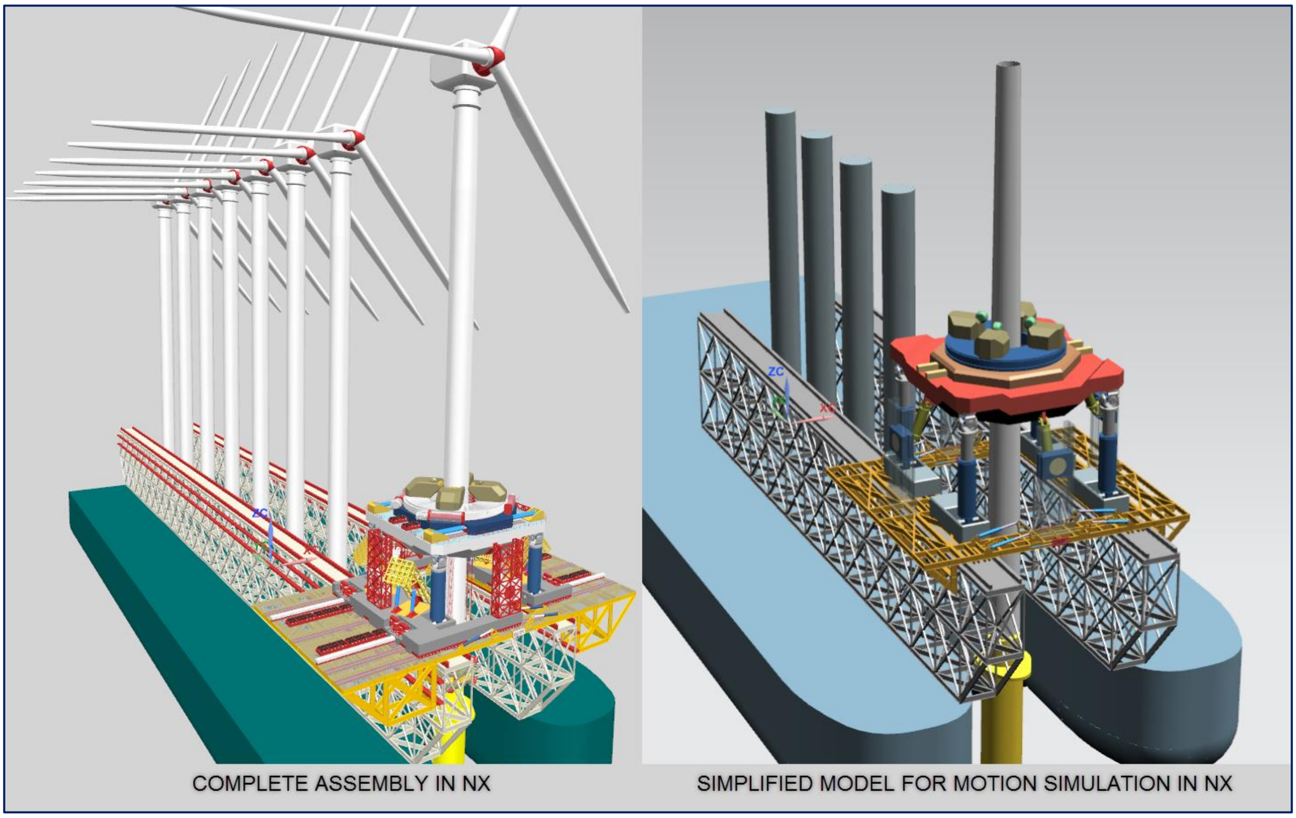


Figure 5.1 Simplified model for motion simulation in NX

In order to set up the model for motion simulation, the whole assembly needs to be converted into links and joints inside the software. The important joints used for the constructions are as shown in [Figure 5.2]. There are a few factors that were included in this motion simulation to replicate the motion of the vessel. These are explained further.

In order to obtain the heave, roll and pitch motion on the same joint, a spherical joint was created for the vessel which rests on another sliding joint. This is a work around done so as to get the simulation to run in the solver. There are **4 spherical joints** at the base of the main cylinder housing which allows the cylinders to tilt sideways. The cylinder rods are connected to the housing using slider joints with limits. The next part is the **universal joint** connected to the top of the cylinder rod using **4 revolute joints**, which allows rotation. The other end of the **universal joint** is connected at **4 locations** to the top platform again as a revolute joint that allows rotation along a specific axis. The fixed link for the platform supports are connected using a revolute joint to another 4 locations on the heave compensated platform. The bottom end of the fixed link is connected to the rotating component as a revolute joint at 4 locations. The rotating component is again connected to the slider as a revolute joint at 4 locations. The slider component is connected to the cylinder support platform using a sliding joint at 4 locations. The sway motion and the surge motions are provided to both the platforms to enable the compensation to happen in the respective directions. The heave motion is applied to the spherical joint to a total **wave height of 2.5 meters.** A roll and pitch motion are applied as drivers to vessel **3 degree each.** The graphs plotting the motion of the vessel is collected by applying markers to a specific location and by attaching a sensor to it. The sensors are then plotted for determining the heave in mm, pitch and roll in degrees. The pitch and roll are applied as a sine wave and cos wave. Sine wave alone was not used in order to achieve realistic vessel motion effects.

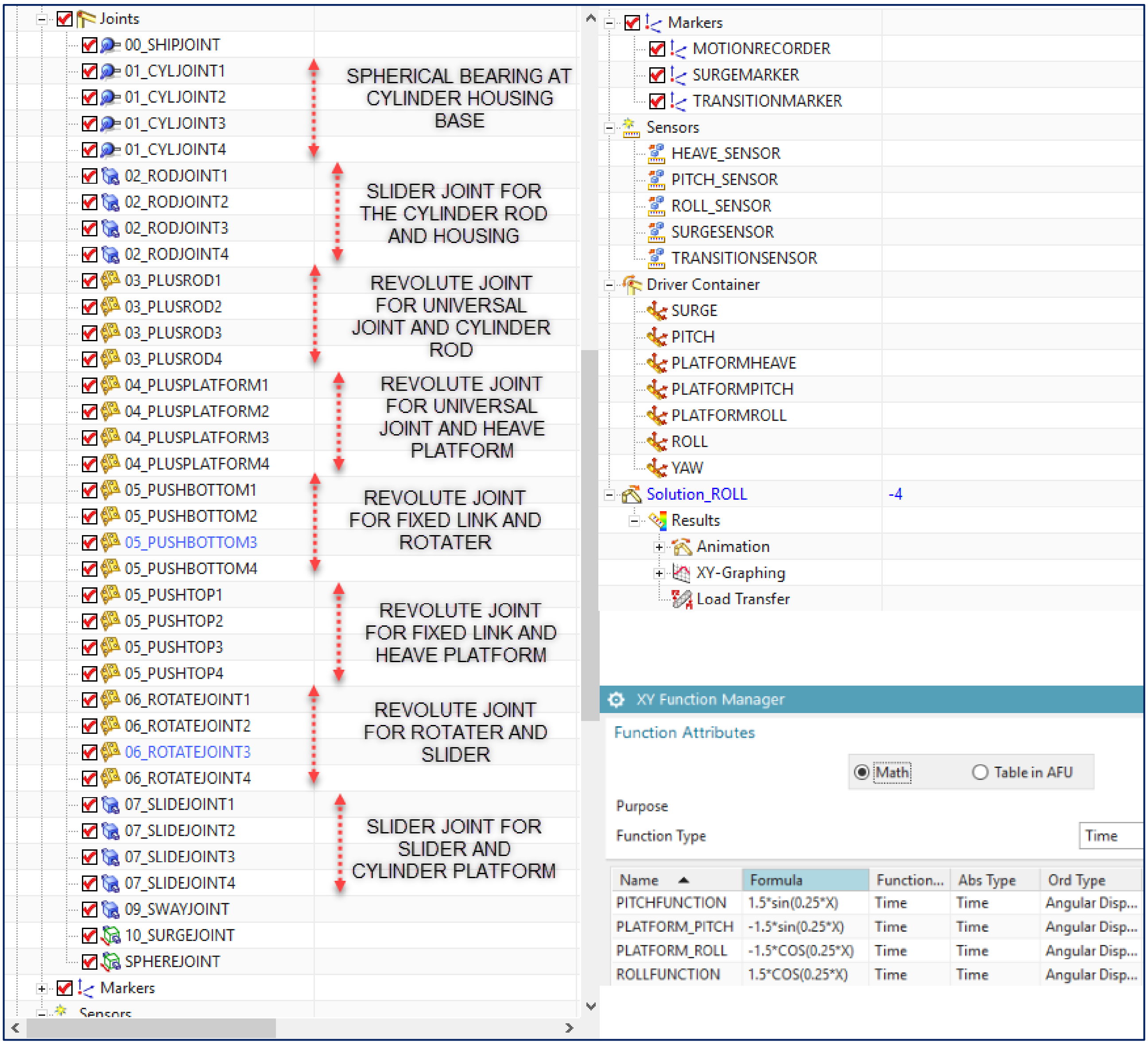


Figure 5.2 Joints and sensors construction for motion simulation in NX

5.2 Applying trigonometric relations

In order to achieve the motion simulation. The primary objective was to apply the connections to the joints. The prescribed motion for the vessel is applied to the **point marked 1** in the [Figure 5.3]. It is an assumed point where the **pitch, roll and heave motion** for the vessel is applied. The figure shows how the pitch motion is compensated by the entire assembly. **D1** is the distance from the center point of the ship to the base of the first cylinder and the one behind it. Similarly, **D2** is the distance to the base of the second cylinder and the one behind it. The **θ** is the pitch applied to the center of the vessel. In this case, **is 3 degrees'** peek to peek. After applying that motion, a sensor is placed at the center point to capture the **θ.** This is then used to find the **X1 and X2.** These are displacement to be applied to the first 2 cylinders and the next 2 cylinders respectively. This will allow the motion of the platform to be compensated for the pitch motion. While controlling the **pitch**, the design of the platform will initiate a **surge** movement along the horizontal axis. This movement is compensated by using the dimension **D3**, which is the distance from the base to the center point of the platform which is a constant. Finding the **X3** will provide the distance that the surge platform should move so as to compensate the surge motion. Thus the pitch and surge motions are compensated by the platform. The compensation of the roll motion is explained further.

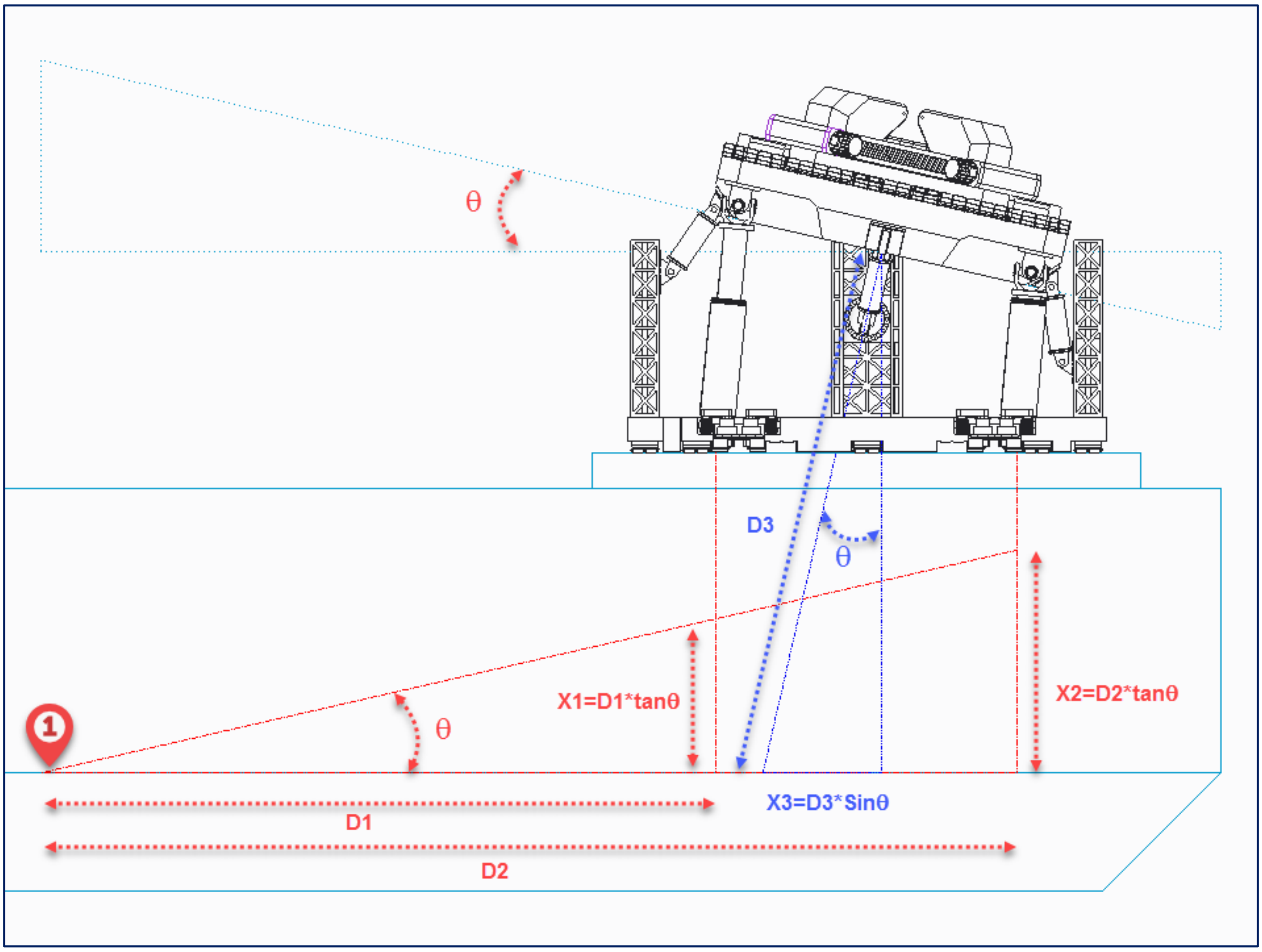


Figure 5.3 Trigonometric relations behind pitch and surge

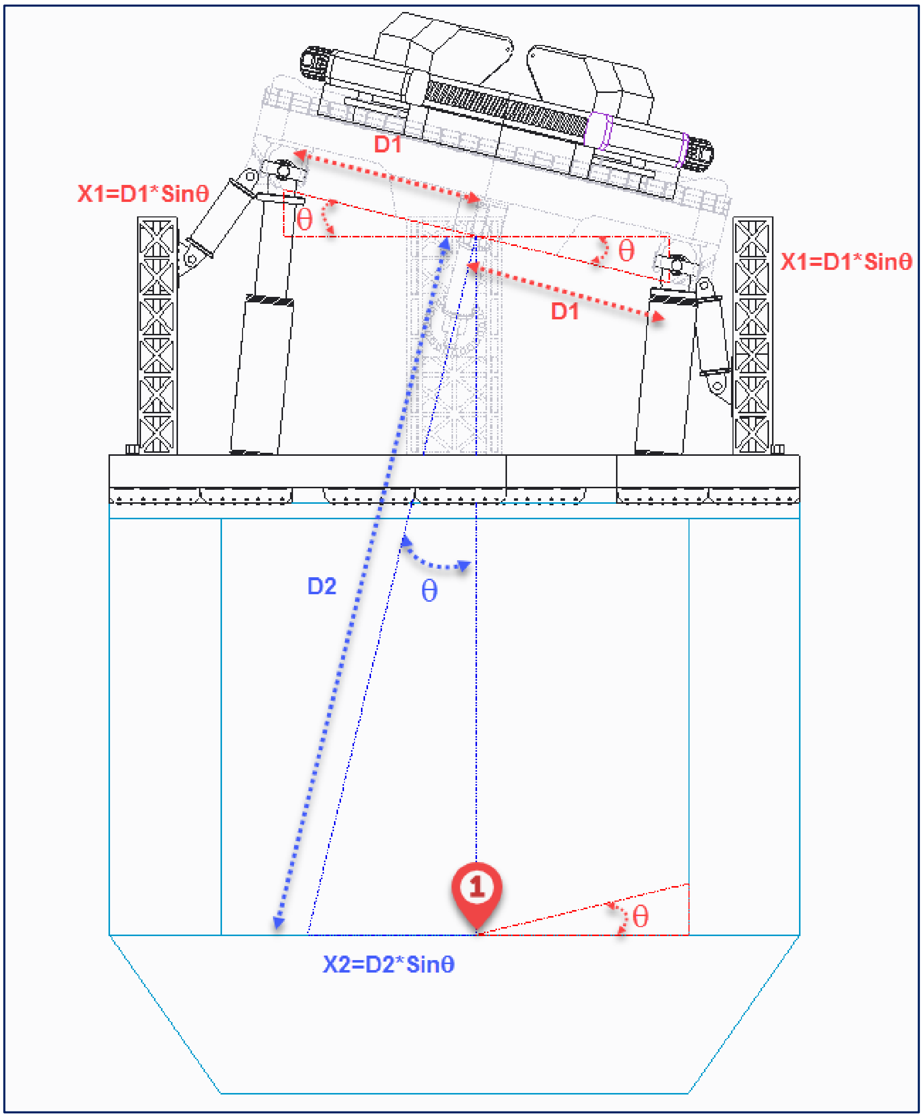


Figure 5.4 Trigonometric relations behind roll and sway

The **prescribed roll motion** of the vessel is applied to an assumed center **point marked as 1** in the [Figure 5.4]. The **θ** is the roll applied to the center of the vessel. In this case, it is **3 degrees'** peek to peek. In this case the known values are **D1** and **D2** which represents the length of the platform which is a constant. The **θ** is captured as usual by placing a sensor at the center point. The distance **X1** is the distance that the first two cylinder needs to displace in order to compensate for the roll motion. Similarly, a negative value is applied to the other two cylinders to compensate for the roll at the other end. The Design of the platform is made in such a way that there will be a slight movement of **sway** once the roll compensation is achieved. This can be corrected by subtracting the value of **X2** from the cylinder displacement for the sway platform. Since the input values are derived from the theta which is a sensor. The values are continuously updated and this gives a real time simulation result by keeping the platform steady in response to the vessel motion. A detailed description of the **heave motion** is not provided since it is a direct vertical movement applied to the point and can be easily compensated by lowering the cylinders to the exact same distance.

A simulation for the **Yaw** motion is not included in this project, there is a yaw platform on top which can directly compensate for the yaw motion of the ship. The trigonometric relations behind compensating all the **5 degrees of freedom** is explained. The resulting real time simulation results are explained further.

There are several ways of implementing pitch, roll and heave compensation for this system. The primary idea would be to give the prescribed motion to the vessel and calculate the force required for each cylinder by gathering inputs from various sensors placed in and along the joints. This in itself requires a more detailed study on the control algorithm which is required for running the simulation. Motion simulation module in NX has immense potential to implement real time inputs from matlab and Simulink or even from an external PLC's from which real time the control signals can be connected. However, this project does not go into the details of implementing the control logic for the motion simulation. The main objective behind this project is to show the kinematic stability of the structure using prescribed motion given as inputs to the joints.

In this project, the sway and surge compensations are activated by applying driver to both the joints and giving inputs to compensate for the motion. The result of the motion simulation shows a blue marker over the graph, which shows the real time positioning of the vessel with the respect to pitch, roll and heave. [Figure 5.5] is a representation of the direct output screen from NX which gives the real time response to the simulation and along with the 3D model. The positioning of the blue marker is constant on all the graphs showing the position of the platform with respect to the vessel motion at a given point of time. The real time simulation video can be accessed by following the link in **[Appendix 1].**

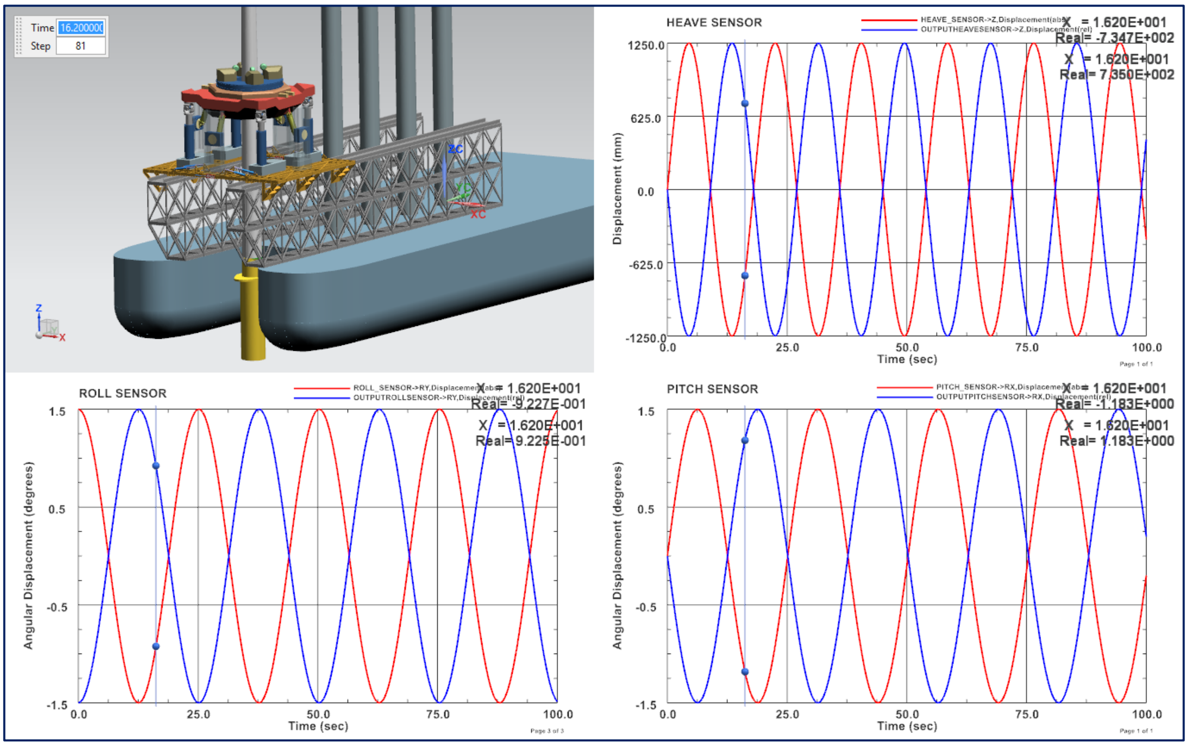


Figure 5.5 Real time simulation results from NX

5.2 Results of Motion Simulation

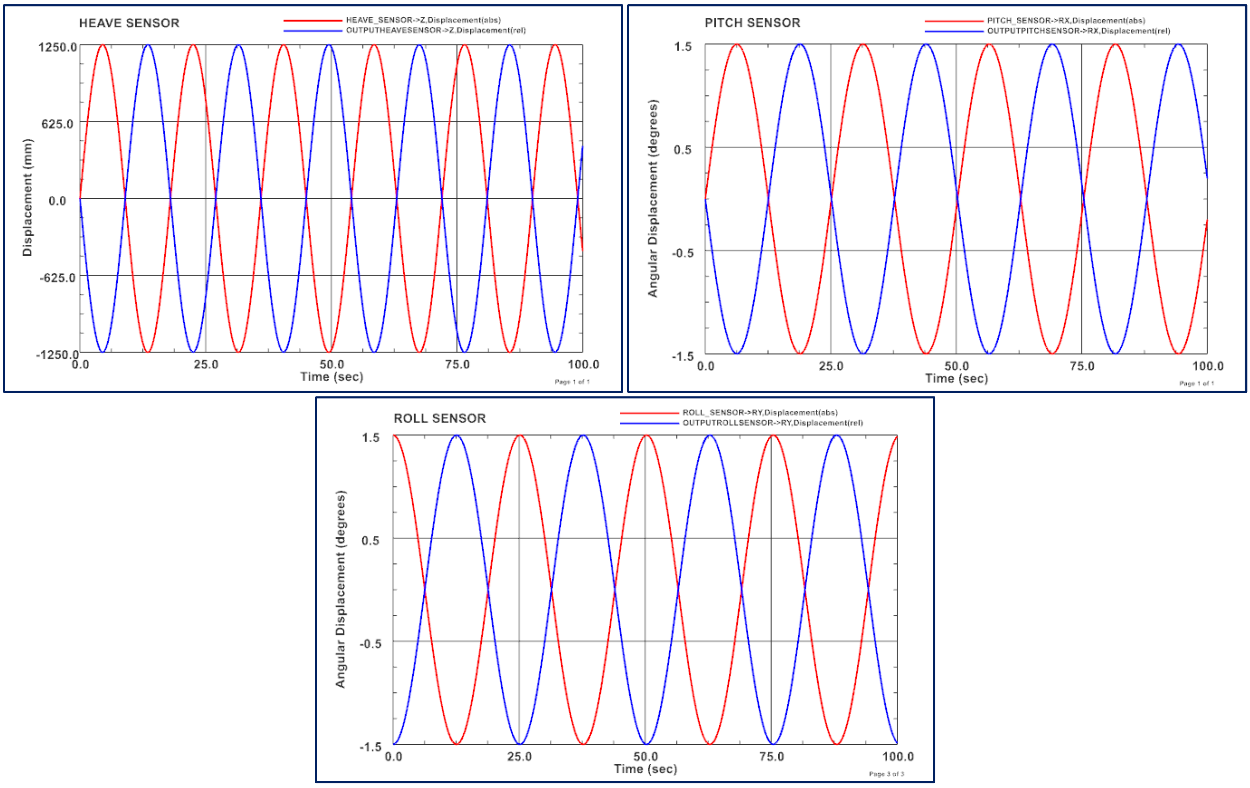


Figure 5.6 Output from the sensor recording the motion of the vessel

The result from motion simulation gives, real time verification of the functioning of the joints and its limits. Figure [5.6] shows the heave motion with a wave height of **2.5 meters** and a pitch and roll of **3 degrees** applied to the vessel as **red curve**. This is done so as to measure the response of the joints for this prescribed motion. The result obtained is the relative motion of the platform with respect to pitch, roll and heave highlighted as **blue curve** on the graph

The most important factor in this simulation is that, the model was simplified and due to that it lost its exact mass properties. Also wave motion is provided to an assumed point instead of the actual center of gravity owing to the loss in mass properties. This was done due to the lack of computing power to simulate the complete 3D model with all the mass properties. This simulation can be repeated with a more powerful system using a complete model, which can analyze the force required for the cylinders to lift the platform and also to analyses the velocities and displacements at each joint.

In short, this motion analysis only shows the stability of the joints in response to the wave motion by compensating only the **displacements happening due to pitch, roll and heave.** However, it is more important to notice the possibilities of NX in developing a more detailed analysis of joint forces and displacements by using a complete 3d model with all the mass properties intact and even by applying control algorithms and control systems or even inputs provided from and external PLC connected using an Ethernet cable. This can be considered for future work on this project.

6 Conclusion

This thesis was able to develop a method that can be implemented for the installation of offshore wind turbines. The major aspects of the thesis were to develop a structurally stable design. This was successfully completed with finite element analysis of some of the critical structures to support the claim. The secondary objective was to test the kinematic stability of the system. This study was carried out using motion simulation module and results are presented which can support the claims. The findings and results are discussed separately in respective chapters. Concept in its entirety was developed using the software Siemens NX and animated using the software PTC Creo. The final animation was rendered using key shot to present a better explanation for the installation. This is uploaded as a video and the link for accessing it is attached in **[Appendix 1].**

The other highlight of the project is the details of the structural design and the material selections. Every component used in this concept design was developed by keeping the manufacturability in mind. Hence it is possible to make this structure from only components available in the European market. The equipment's that are used for the installation can be purchased from different suppliers and those supplier details are also included in this report. The critical components were subjected to structural analysis using NX Nastran and the result are presented in this thesis. However, an entire structural analysis was not conducted due to the limitations of the time available for completing this project. Only the results of FEA are presented in the included chapters. However, different steps involved in setting up the FEA is explained in **[Appendix 2 and Appendix 3]**

The motion compensation was an important part of the report that requires a validation to prove its stability and integrity. This was done using the motion simulation in NX and the results and findings are presented in this report. The assumptions and simplifications made during the analysis are mentioned separately to assist future work in this project. The concept at its entirety requires extensive future research and the possible areas of improvements are listed in the next chapter.

This project further developed could serve as a bright initiative for our journey towards a cleaner and sustainable future.

7 Future Work

- A hydraulic clamping system for the lifting cage needs to be developed in order to assist the splitting of the cage. There is a possibility now to do this manually by clamping both sides of the cage together using specially designed clamps. This is not a safe or easy solution. Hence a hydraulic actuated clamping system has to be further developed.
- The detailed design of the yaw platform is not done. It has to be reinforced with stiffeners to ensure stability. Moreover, the platform needs precise manufacturing of the helical teeth to initiate the yaw motion. In addition to that a locking mechanism is also required for the platform.
- A connection mechanism for locking the sway compensated platform once joined has to be developed further. Currently it is supported by hydraulic cylinders forcing it together from opposite sides.
- The connection links for the Heave compensated platform needs to be developed further. Since a locking mechanism for the same is not discussed in this project. It needs a strong locking mechanism to keep the structure steady during wind turbine installation.
- The surge platform is supposed to move on top of the tall support structures. Only the path for movement is discussed in this project. An actuator for initiating the motion is not discussed. This has to be further developed.
- The storing of the wind turbines, vertically on the vessel needs to fix it using additional fixtures, support structures and tied rods which are not discussed in this project. This can be considered for future work.
- The installation procedure developed is for a fixed foundation in the ocean and not with a moving foundation. If there is a moving foundation, then we need to develop additional clamping mechanisms to fix the vessel to the foundation and copy the motions of the foundations to be replicated for motion compensation. This needs extensive further development.
- A detailed design of the cylinder support platform is also not considered in this project. This has to be done so as to ensure a more reliable support structure for the hydraulic cylinders. In addition to that a control algorithm for the cylinders also has to be developed.
- The hydraulic grippers used inside the lifting cage requires additional support structures in order to maintain the angular placement of the cylinder housing. This can be considered while further developing this concept.
- A detailed local analysis of the critical components can be considered for future work.
- A detailed design of the winch system used for lifting and lowering the wind turbine can be considered for future work.
- The lifting cage can be modified for fit all sizes of wind turbines that are more than 6 meters in diameter and more than 1000 tons in weight.

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Appendix 1 – Animation Video Links

Explaining a concept using an animation could provide more insight into the actual process involved. An animation video was created for explaining the process of installation in a better way. This video can be accessed online using the links provided below. The video is password protected and please use the following password to unlock it.

PASSWORD FOR OPENING ALL LINKS: 1234

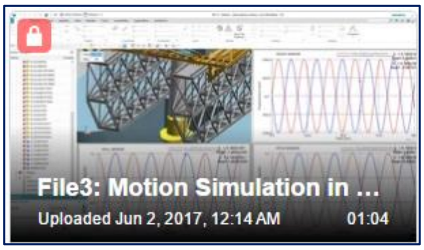
Link 1: Explains the entire installation process in an animated video rendered using key shot.

https://vimeo.com/219957168

Link 2: Explains the motion restrictions of the platform in the directions of heave, pitch, roll, sway and yaw.

https://vimeo.com/219957521

Link 3: Real-time simulation of the motion analysis conducted using Siemens NX showing the heave, pitch, roll, sway and surge being compensated in response to prescribed wave motion.



https://vimeo.com/219956594

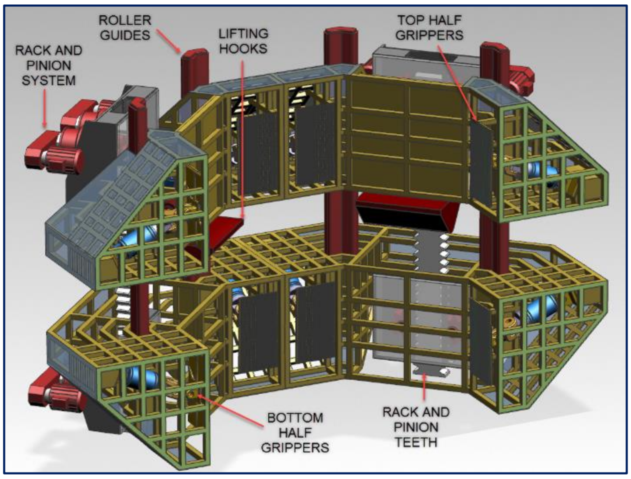
(**Click** on links to access on a webpage, use the same password **"1234"** to open the all the files)

Appendix 2 – Analysis of Lifting Cage

A detailed look into the analysis of the lifting cage from chapter [4.1.6]

1. Defining the scenario

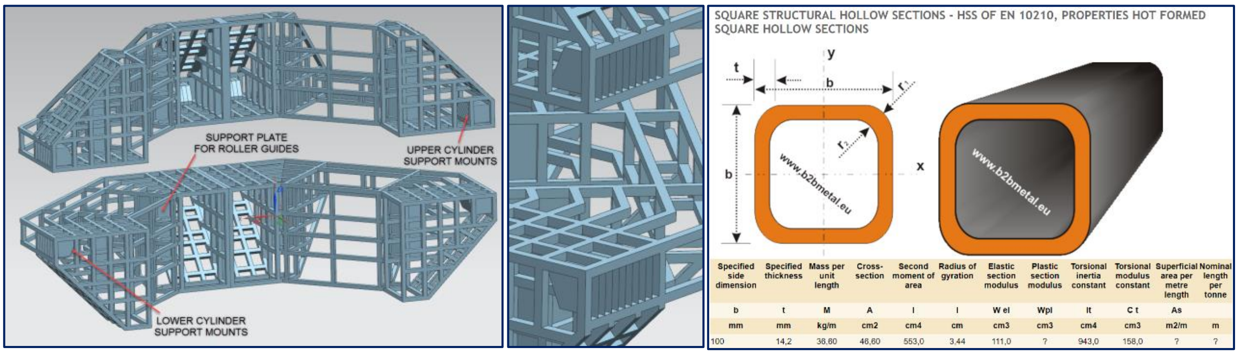
This section is dedicated to a detailed look into the analysis of the lifting cage. The primary objective is to define the scenario considered for the analysis. There is a point in the installation process where the entire weight of the wind turbine is shared by the grippers on the top and bottom half of the lifting cage as shown in the figure. This happens just before the wind turbine is placed on to the transition piece. The lifting hooks will not take part in this operation since the top half grippers will support the weight of the wind turbine assembly and the bottom half is fixed to the walls of the transition piece. This will create an immense outward force on the lifting cage. This scenario is analyzed using finite element analysis.



Lifting hook assembly

2. Model Setup and material selection

The lifting cage is weldment assembly of steel tubes of material **HSS EN10210**, and a dimension of **100X100X16 mm.** The cylinder support mounts are made up of steel plates of **16mm** thickness reinforced with stiffeners as shown in figure. There is also a roller guide support plate of the same thickness **16mm.** First step was to create the entire cage assembly as 2D surface models to make use of shell elements for analysis. By doing this the time required for analysis was vastly reduced. This will allow in giving a specified thickness for the shell elements.

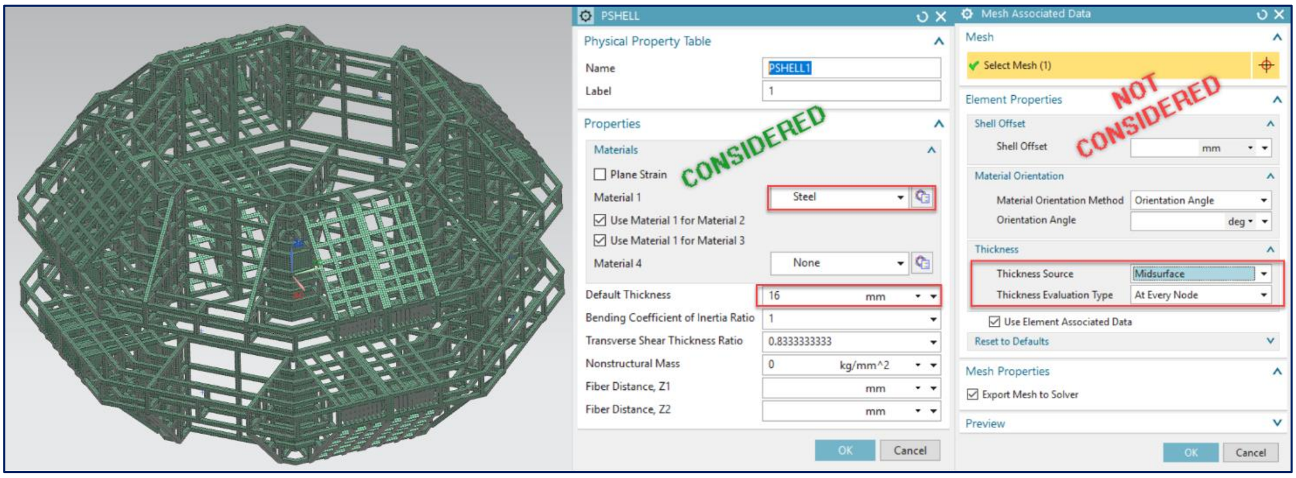


Specified side dimension	Specified thickness	Mass per unit length	Cross-section	Second moment of area	Radius of gyration	Elastic section modulus	Plastic section modulus	Torsional inertia constant	Torsional modulus constant	Superficial area per metre length	Nominal length per tonne
b	t	M	A	I	I	W el	Wpl	It	C t	As	
mm	mm	kg/m	cm2	cm4	cm	cm3	cm3	cm4	cm3	m2/m	m
100	14,2	36,60	46,60	553,0	3,44	111,0	?	943,0	158,0	?	?

Lifting cage 2d surface model for analysis using shell elements

3. Meshing of the model

The meshing of the model has a few major steps, one is the element size selection, type of the element used, assigning the materials and assigning the thickness of the **midsurface planes**. Midsurface planes are an important shell element feature that makes the analysis smoother. It assumes a mid-surface for the 3D model and converts them into shell elements so that varied thickness can be applied during analysis process. The 3D model has to be carefully created for this feature to apply correctly. This is also one of the reason that the cylinder support mounts are also created with plated of **16mm** thickness.

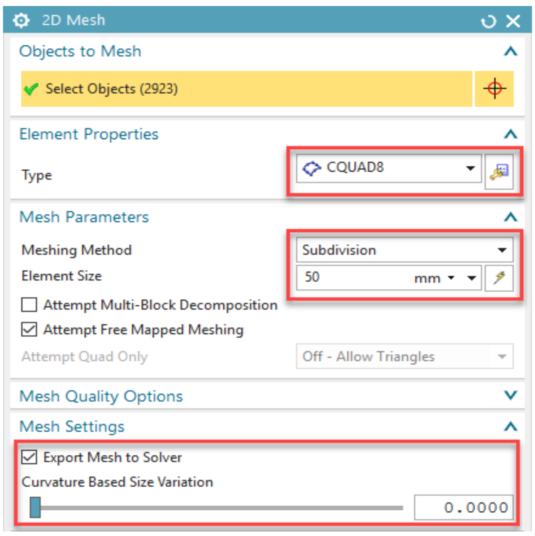


Applying thickness to shell elements

There are two ways of applying thickness to shell elements. One is the by applying a definite thickness or allow it to take the thickness from the source 3d model. This option is activated by setting the source for thickness as midsurface planes. It was found during the analysis that deriving thickness from the 3D model requires huge computational power for a model of this size. Hence a definite thickness of **16 mm** was applied and the material steel was chosen with a yield strength of **355 Mpa** as shown in above figure

4. **Type of element and the element size**

The element type chosen for the analysis is **CQUAD8.** CQAD8 is an isoparametric element with 4 corner and 4 mid-side grid points. These mid-side grid points are what differentiate this from the CQUAD4 elements. Even though CQUAD4 element is enough for linear static analysis, CQUAD 8 was selected to improve the accuracy of meshing. Meshing method of **subdivision** was selected since there are no holes in the model which requires a Paver meshing. The element size selected is **50mm.** An ideal element size for an analysis as a rule of thumb is less than half the thickness of the material. A **convergent study** was not conducted to determine element

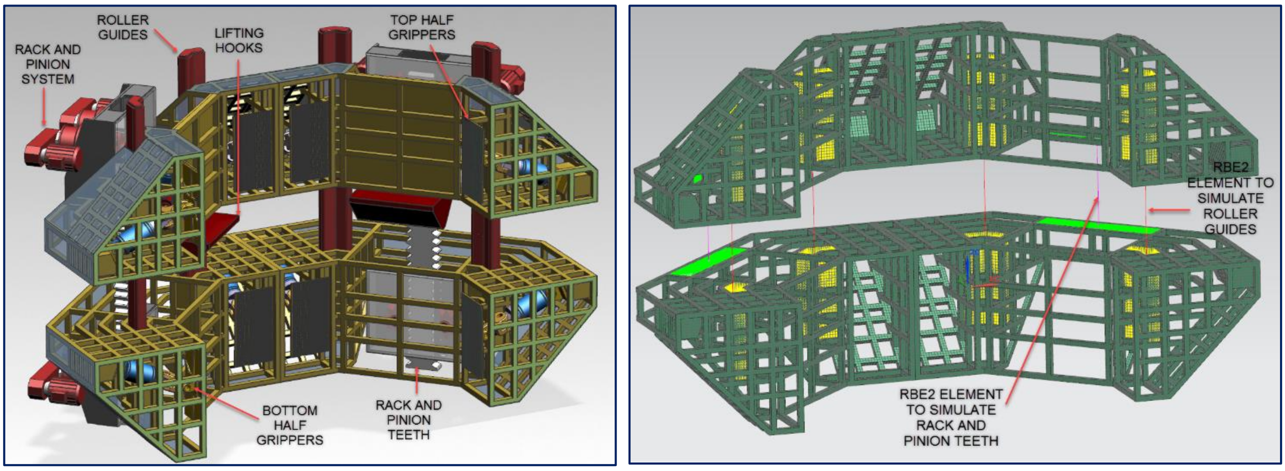


size. If the mesh selected was a **3D tetrahedral mesh**, then as per the ideal selection of the element size, it would have been less than **8 mm** for a thickness of **16mm tube.** This would require immense computation power to solve. This is the reason the analysis was done using shell elements and the least thickness of a side is **100mm.** Hence selection of element size can be 50mm or a little less. In this case**,** **50mm** was selected as **element size.** The curvature based size variation is set to **0** to avoid formation of small elements due to irregularities in the geometry.

5. **1d Connections for simplification**

Creating a 1 dimensional element along a curve or an edge is called a 1D connection. In this case. 1D connection is used to simplify the analysis process. There are rack and pinion systems and roller guides coming inside the lifting cage assembly. However, the point of interest of this analysis is the behavior of the lifting cage and not the strength of the roller guides or the teeth of the rack and pinion system. Moreover, from the supplier information we know that the rack and pinion system has a normal holding capacity of **620 tons each**. Hence we only need to the transfer of force from the top cage to the bottom cage. Hence **RBE2 (Rigid body elements)** are used. This works under the assumption that the connection elements are infinitely rigid and it will only transfer the effect of the load from the top cage to the bottom cage. This will simplify the computation required for the analysis to a great extent.

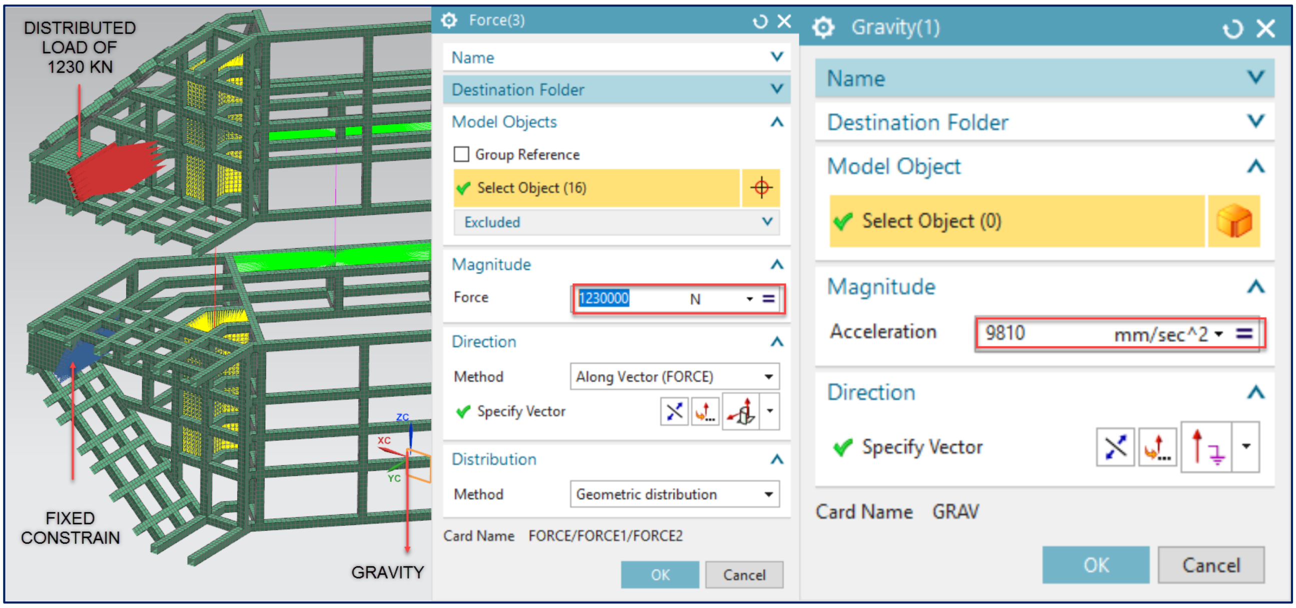
Point to surface and point to point rigid body elements are used as connection elements. The point to surface will distribute the effect of the load along a specific surface and the point to point rigid body elements acts in transferring the load from one point to another.



RBE2 (Rigid body element) selection and purpose

6. **Load Applied and the boundary condition**

The weight of the wind turbine is shared by **8 hydraulic cylinders**. Hence the top 8 hydraulic cylinder mounts will equally distribute the weight of **1000 tons** of that of the turbine. This will leave each mount with a weight of around **125tons** which is equivalent to **1230 KN**. This is not a perfect assumption. It is ignoring the resultant force calculation based on the angle of placement of the cylinders which are acting towards the mount and there are also several other uncertainties based on the cylinder and gripper position. However, this is a simplification assumed to calculate the strength of the lifting cage. Hence, the cylinders and grippers are not considered and the weight of the turbine is converted into a **distributed force of 1230 KN** and applied it on the cylinder mounts as shown in the figure. The self-weight of the structure is also considered for the analysis. The boundary condition is that the **cylinder mounts on the bottom cage is fixed** so as to simulate the hydraulic cylinders attached to the transition piece. Self-weight is applied as a gravity by applying it on –Z direction. This is shown in image below.



Applied load and boundary conditions

Assumed weight of the turbine : 1000 tons

Shared weight by 8 hydraulic cylinders on top : 125 tons

Force applied on each mount : 1230 KN

7. Identifying the safety factor and deflection criteria

As per the **DNVGL standard** for the **design of offshore wind turbine structures**, **DNV-OS-J101.** The safety factor for ultimate limit state for permanent load condition is **1.25.** Hence the safety factor considered for this project is **1.25**.

For the selected steel with Yield Strength = 355 Mpa

Permissible stress = 355/1.25 = 284 Mpa

Similarly, the maximum allowable deflection as per **DNV-OS-J101.**

Table 7-13 Limiting values for vertical deflections

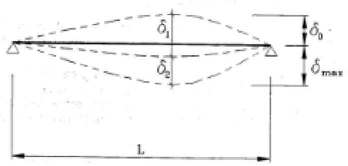
Condition	*Limit for δ_{max}*	*Limit for δ_2*
Deck beams	$\frac{L}{200}$	$\frac{L}{300}$
Deck beams supporting plaster or other brittle finish or non- flexible partitions	$\frac{L}{250}$	$\frac{L}{350}$
L is the span of the beam. For cantilever beams L is twice the projecting length of the cantilever.		

δ_{max} = the sagging in the final state relative to the straight line joining the supports

δ_0 = the pre-camber

δ_1 = the variation of the deflection of the beam due to the permanent loads immediately after loading

δ_2 = the variation of the deflection of the beam due to the variable loading plus any time dependent deformations due to the permanent load.



7.9.2.3 The maximum vertical deflection is:

$$\delta_{max} = \delta_1 + \delta_2 - \delta_0$$

We can take the maximum allowable deflection as L/200 for the steel structures.

In the analysis result the maximum length of the steel tube used is 2 meters.

Maximum allowable deflection is thus calculated: 2000/200 = **10 mm**

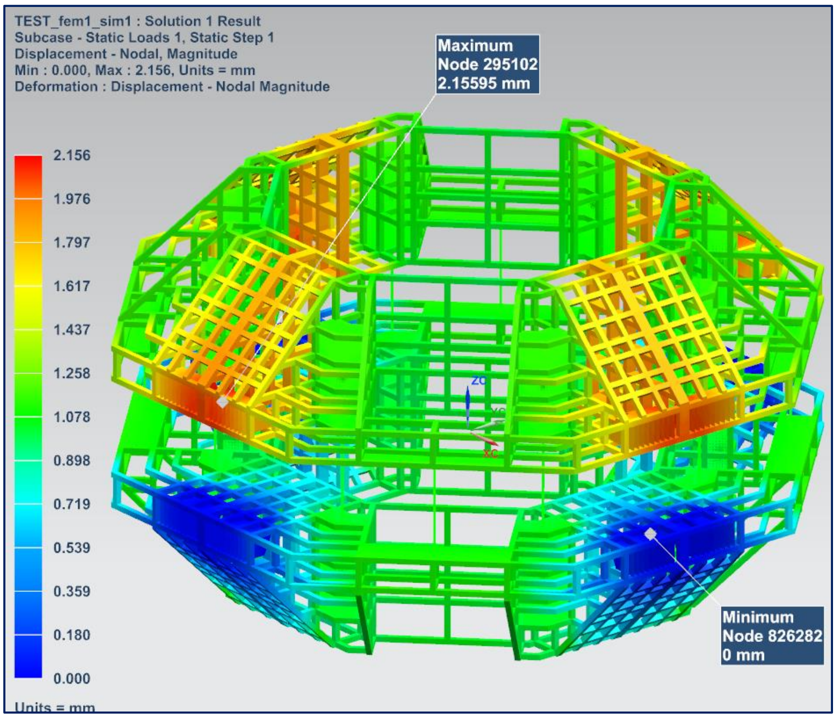
This method was used to determine safety factor and deflection criteria.

Permissible Stress: 284 Mpa

Allowable Deflection: 10 mm

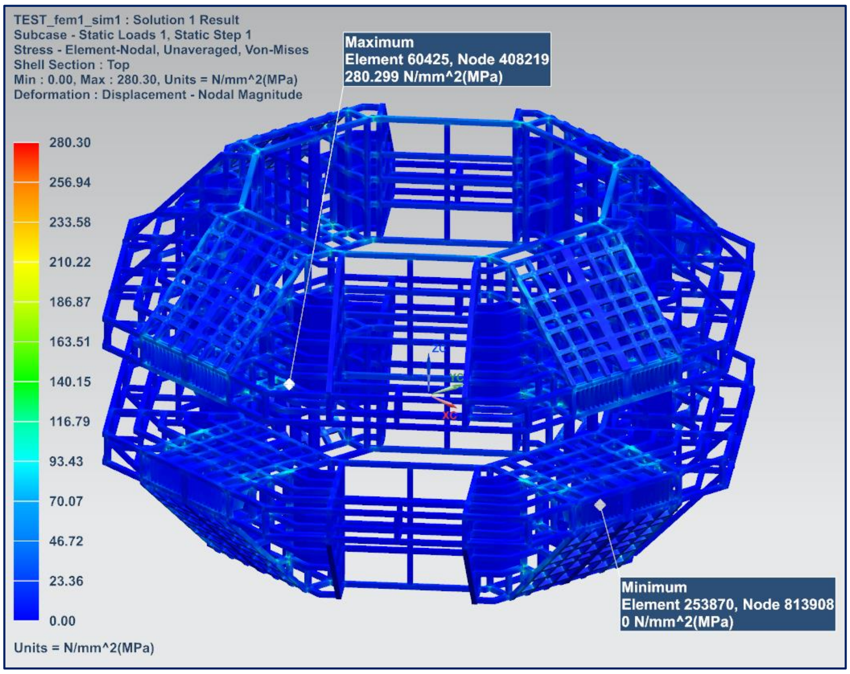
8. Result of FEA

In order to obtain a more realistic result the deformation of the result is set to absolute value with a scale factor of 1. This will avoid all the exaggerated deflections in the model.



Result of Magnitude of Nodal Displacement

The Allowable deflection as per calculation is **10mm** and the actual deflection is **2 mm** which is acceptable as per **DNV-OS-J101.**



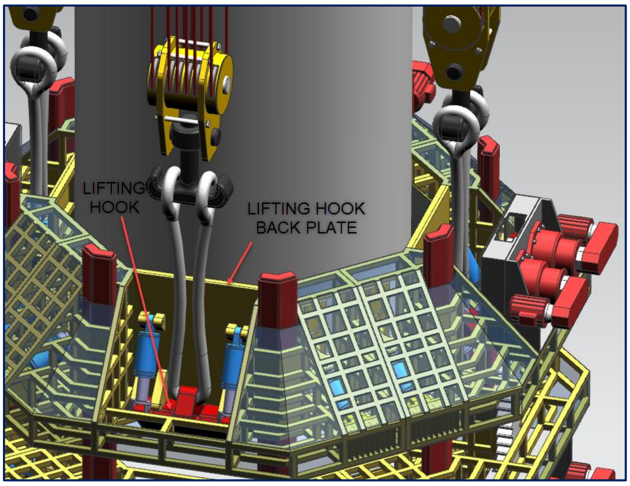
The permissible stress calculated as per the **DNV-OS-J101** for a permanent load with **safety factor 1.25** is **284 MPa** and the actual nodal von-mises stress is **280 Mpa** which is acceptable.

Appendix 3 – Analysis of Lifting Hook

A detailed look into the analysis of the lifting hook from chapter [4.2.2]

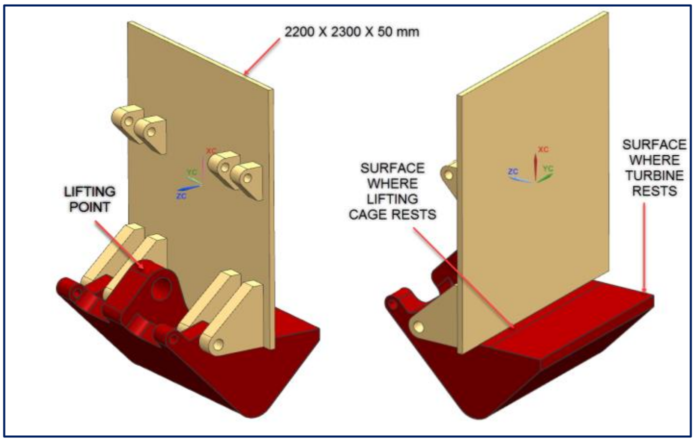
1. Defining the scenario

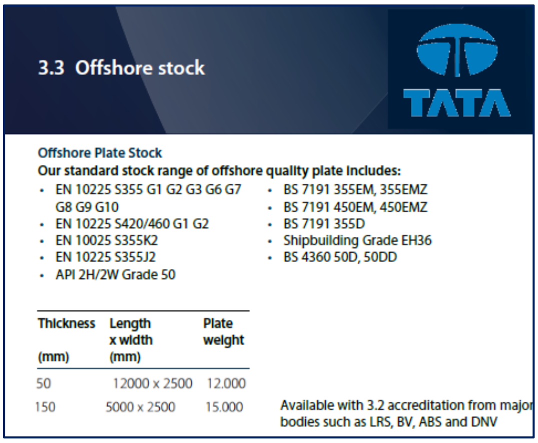
This section is dedicated to a detailed look into the analysis of the lifting hook. The primary objective is to define the scenario considered for the analysis. Lifting hooks are used for lifting and lowering the wind turbine on to the foundation. Hence there is point in the installation process when the entire weight of the wind turbine and the lifting cage is carried by the lifting hook. Hence the criticality of the analysis for this part is of extreme importance. The lifting hook is assembled on the side of the cage by welding it on to the steel tubes. The assumptions and the simplifications made for the analysis is explained further.



Lifting hook assembly

2. Model Setup and material selection





3.3 Offshore stock

TATA

Offshore Plate Stock

Our standard stock range of offshore quality plate includes:

- EN 10225 S355 G1 G2 G3 G6 G7 G8 G9 G10
- EN 10225 S420/460 G1 G2
- EN 10025 S355K2
- EN 10225 S355J2
- API 2H/2W Grade 50
- BS 7191 355EM, 355EMZ
- BS 7191 450EM, 450EMZ
- BS 7191 355D
- Shipbuilding Grade EH36
- BS 4360 50D, 50DD

Thickness (mm)	Length x width (mm)	Plate weight
50	12000 x 2500	12.000
150	5000 x 2500	15.000

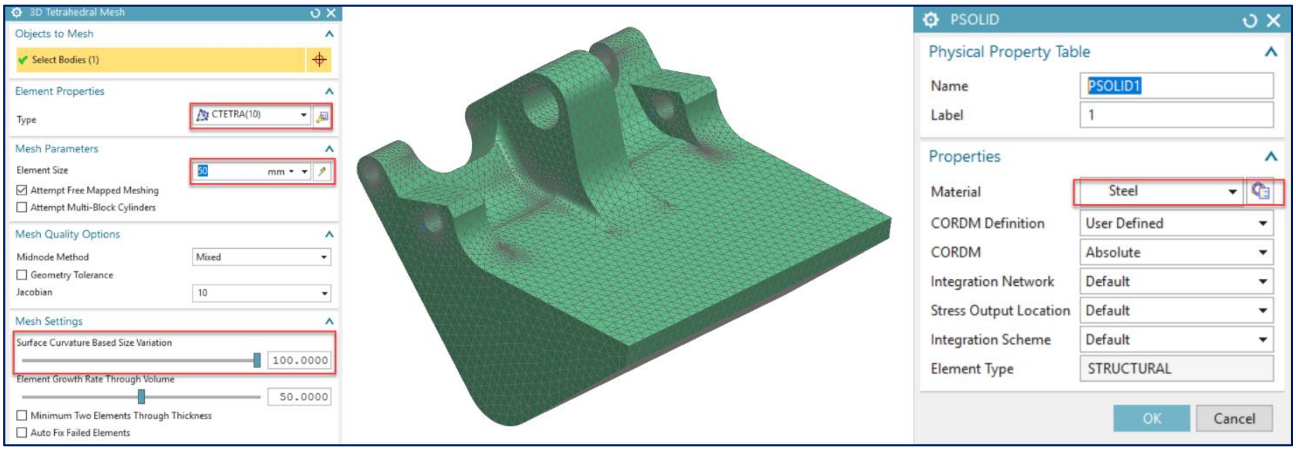
Available with 3.2 accreditation from major bodies such as LRS, BV, ABS and DNV

Lifting hook 3D model for analysis and material selection

The mounting bracket and the clevis for mounting the cylinders are made from offshore stock plate of thickness **50 mm** and **150 mm** thickness respectively. The material used for construction is **EN10225** with a yield strength of **355 MPa.** The hook is a forged part and is extremely stronger than the steel plate. Hence the stress concentration is more important when it comes to the mounting bracket.

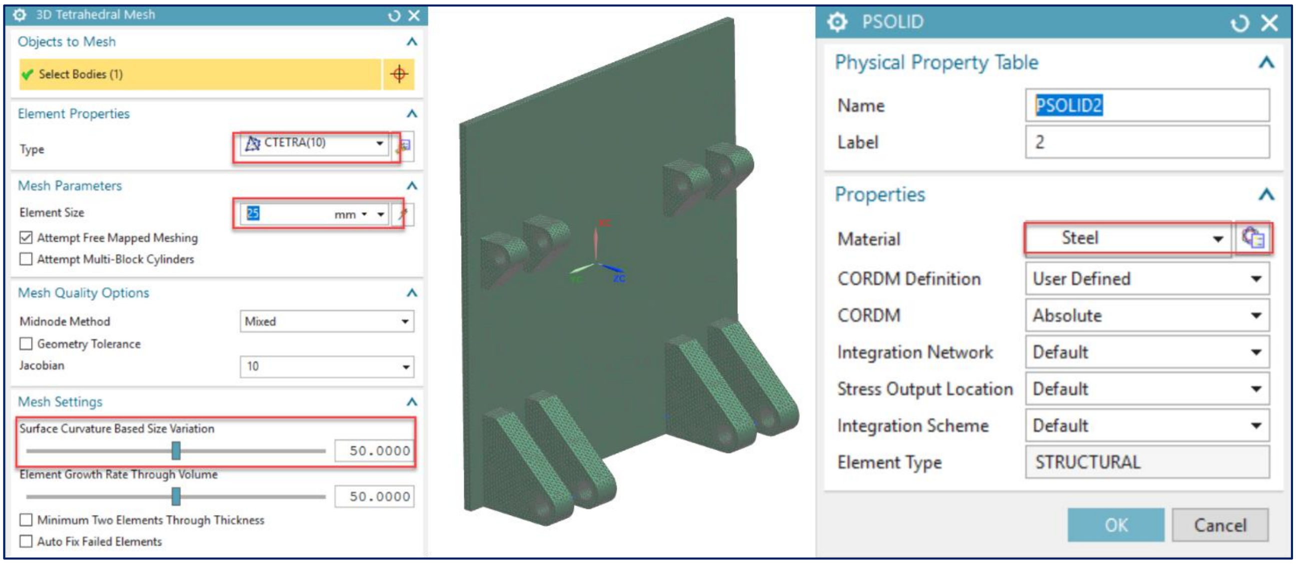
3. Meshing of the model

While meshing the hook, it is done separately since the mesh model is different for both the objects. For the hook **CTETRA10** a parabolic 10 node mesh was selected to improve improves the quality of the analysis. The element size is set to **50mm** chosen after a **convergent analysis.** Convergent analysis is a repetitive way of lowering the element size and evaluating the model response there by arriving at a suitable and accurate element size. This method was considered since the model computation required is very less. It was found that the difference in the result was very less and more accurate when narrowed down to **50mm** from a default value of **200mm** set by the software. The material selected is steel, **SAE 1096, oil quenched** with a yield strength of **896 Mpa**. Curvature based size variation is set to **100** to get a more refined mesh over the parts where there is a fillet. It is highlighted in the image below. The fillet along the hooking point plays a vital role in distributing the stress concentration.



Meshing of crane hook

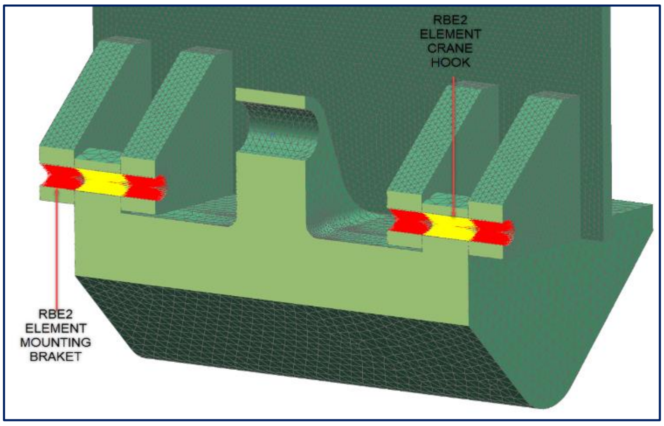
The mounting bracket for the hook is meshed separately using the same element type **CTETRA 10** parabolic 10 node mesh. The bracket was meshed with a more refined element size due to the thickness of the plate. The thickness of the plate is **50mm,** hence half or less than half is the ideal element size. The element size selected was **25 mm.** A convergent analysis is not made in order to identify the right element size. The curvature based variation is not modified since it won't make a difference in the output due to the simplicity of the model.



Meshing of mounting bracket

4. 1d Connections for simplification

The 1d connections are made in order to simplify the analysis. The pin joint connecting the mounting bracket and the crane hook is connected using **RBE2(Rigid body elements)** which can simulate the pin. We are assuming that the pin is infinitely rigid and stability of the mounting bracket and the crane hook is of more importance. **RBE3** is not used instead of **RBE2** since the pin is very small and distribution of load based on the length need not be considered in this case. Both the RBE2 elements are connected together using another point to point RBE2 connection. In order to obtain a more detailed analysis, the RBE2 elements has to be applied only on a specific surface inside the hook. This could assist in clearly depicting the point of contact of the pin inside the hole. However, it is assumed as a whole surface in this analysis. The point to surface command of the RBE2 element covers the entire hole surface. The hook and bracket is connected using these elements. Replacing it will a solid pin could measure the strength of the pin.

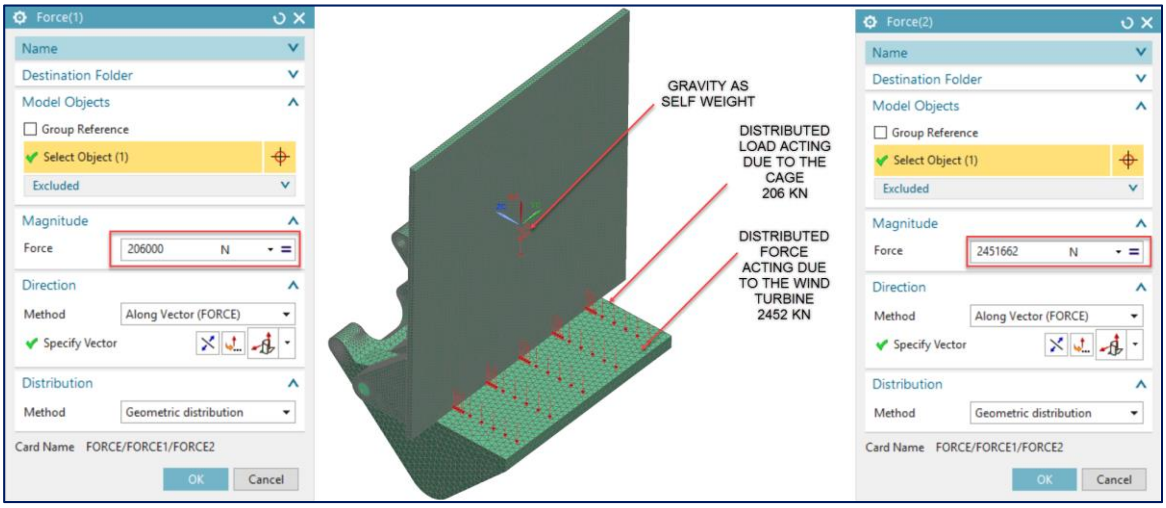


RBE2 element connections

5. Load Conditions

The three loads acting on the hook are the **weight of the wind turbine**, **the weight of the lifting cage and the self-weight of the lifting hook**. The surface of the crane hook is being split into two in order to separately apply both the loads. The reason behind selecting the forces and the split up of the total load shared by all the four hooks are listed below

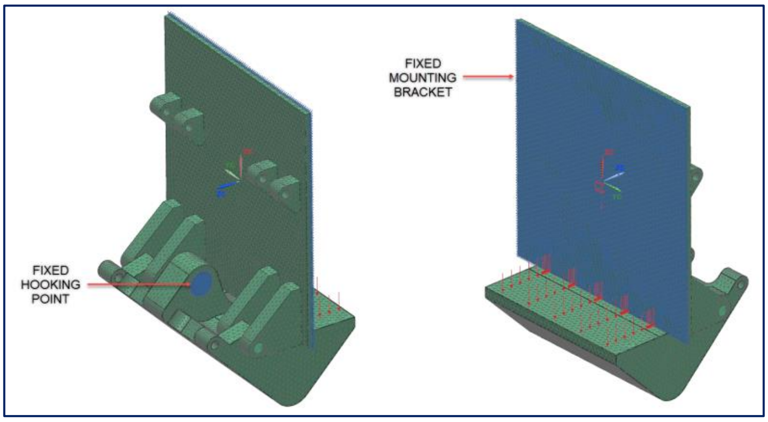
Assumed weight of the turbine	: 1000 tons
Shared weight by each hook	: 250 tons
Total weight of the lifting cage	: 82 tons
Shared weight of the lifting cage	: 21 tons
Distributed loads applied vertically on the hook surface	
Force acting on the surface of the hook due to turbine	: **2452 KN**
Force acting on the surface of the hook due to cage weight	: **206 KN**
Self-weight of the hook	: 11 Tons (applied as gravity)



Load Conditions

6. Boundary Conditions

It is evident from the assembly that the rope is passing through the loop inside the lifting hook. It is assumed that this rope is strong enough to withstand the load acting on it. Hence a fixed constraint is applied on the hooking point to simulate the rope passing through it. For an exact simulation it is more advisable to divide the surface of the hole in order to fix only the top surface. However, in this project the whole surface of the hole is fixed. The final fixed constraint is added to the back side of the plate. It is assumed that the weldment between the mounting bracket and the lifting cage assembly are strong enough to withstand the forces acting on it. These are simplifications made so as to carry out the analysis on the lifting hook assembly.



Boundary Conditions

7. Identifying the safety factor and deflection criteria

As per the **DNVGL standard** for the **design of offshore wind turbine structures**, **DNV-OS-J101.** The safety factor for ultimate limit state for permanent load condition is **1.25.** Hence the safety factor considered for this project is **1.25**.

Steel plate with Yield Strength = **355 Mpa**

Permissible stress = 355/1.25 = 284 Mpa

Steel hook with Yield Strength = **896 Mpa**

Permissible stress = 896/1.25 = 717Mpa

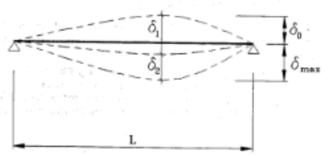
Table 7-13 Limiting values for vertical deflections

Condition	*Limit for δ_{max}*	*Limit for δ_2*
Deck beams	$\frac{L}{200}$	$\frac{L}{300}$
Deck beams supporting plaster or other brittle finish or non- flexible partitions	$\frac{L}{250}$	$\frac{L}{350}$
L is the span of the beam. For cantilever beams L is twice the projecting length of the cantilever.		

7.9.2.3 The maximum vertical deflection is:

$$\delta_{max} = \delta_1 + \delta_2 - \delta_0$$

δ_{max} = the sagging in the final state relative to the straight line joining the supports
δ_0 = the pre-camber
δ_1 = the variation of the deflection of the beam due to the permanent loads immediately after loading
δ_2 = the variation of the deflection of the beam due to the variable loading plus any time dependent deformations due to the permanent load.



Similarly, the maximum allowable deflection as per **DNV-OS-J101.** We can take the maximum allowable deflection as L/200 for the steel structures.

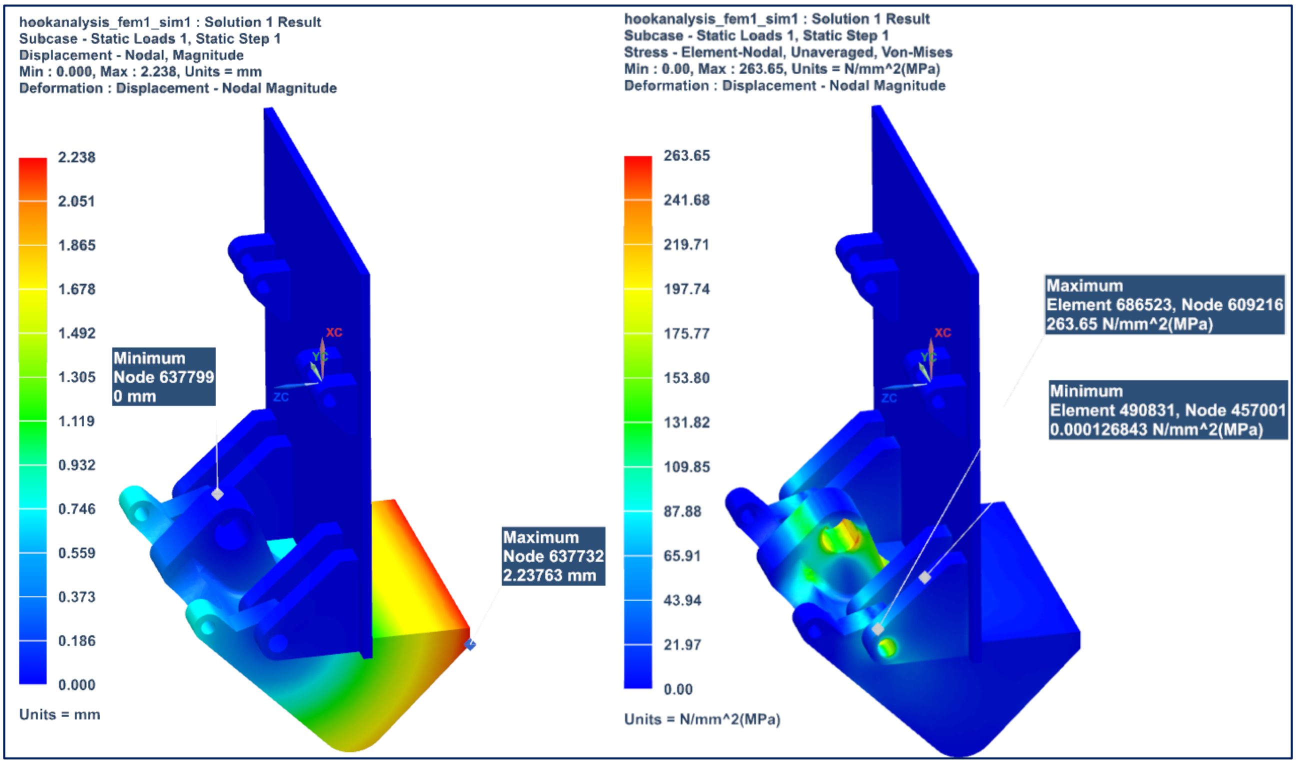
In the analysis result the maximum length of the steel tube used in 2 meters.

Maximum allowable deflection is thus calculated: 2300/200 = **11.5 mm**

Thus the two values are obtained.

Permissible Stress: 284 Mpa
Allowable Deflection: 11.5 mm

8. Results of FEA



Result of Lifting hook FEA

The result of the FEA shows that the deflection of the hook happens at the end where the turbine assembly is kept. Which is obvious due to the fact that more load is acting at that point. The total deflection shown as per the result of the analysis is a deflection of **2mm** which is acceptable for a component of this size and structure and the allowable deflection for this structure is found to be **11.5mm** as per **DNV-OS-J101.** The material selected for the analysis is high strength steel with a permissible stress deformation of **284Mpa** with a factor of safety **1.25** as per **DNV-OS-J101.** The result of the analysis shows that the maximum stress concentration is **264 Mpa** which is inside the acceptable limits for this component. The second material is the hook with a permissible stress of **717 MPa.** This is not taken into consideration since the maximum stress concentration is 264Mpa. However, if the result was showing more than **284 Mpa** on the hook. The result is still valid due to the increased yield strength of the oil quenched hook.

An innovative method for the installation of Offshore Wind Turbines

Prabhu Bernard
Department of Ocean Operations and Civil Engineering
NTNU i Ålesund, Postboks 1517
6025 Ålesund, Norway
prabhubernard@outlook.com

***Abstract*—The objective of this paper is to develop an innovative method for the installation of offshore wind turbines in water depths above 200 meters. The concept developed is a piece of machinery that relies heavily on the existing technological advances in the field of motion compensation and heavy equipment installation. The paper is structured into three phases. A design phase in which a new offshore wind turbine deployment mechanism is developed by considering manufacturability and material selection. An analysis phase that ensures the structural stability of the concept using NX Nastran and a simulation phase that verifies the kinematic stability of the design using NX motion simulation.**

Keywords—concept design; innovation; motion simulation; offshore wind turbine; seimens NX

I. Introduction

Among several sources of renewable energy resources available today, Offshore Wind Turbines (OWT) have proved to be extremely promising for the future of mankind. Currently there are several OWT installations around the world along with many upcoming projects which are in the initiation phase. Installation of these wind turbines are extremely expensive and time consuming owing to the complexities involved in erecting a huge structure out in the ocean. The statistics of the European offshore wind energy shows that only 182 turbines were erected during the first half of 2016 in 13 wind farms operated by four countries as shown in "Fig. 1,".

Meteorological studies have proved that the average wind speed in the offshore area is less turbulent and more intense when compared to the onshore sites due to low surface shear. Installing a wind turbine out in offshore location has always been a challenge and it still remains to be one. A smart and efficient way of installing a 1000-ton wind turbine safely and efficiently in the middle of the ocean is still a prominent research question. This project aims in developing an innovative concept design for the installation of offshore wind turbines which could surpass the current limitations in the installation time and contribute towards a better future. Reducing the installation time could have a significant impact on the capital investments required for the project. The dynamic stability and structural integrity of the concept developed in this project is later verified using motion simulation and structural analysis with the help of a CAD (Computer Aided Design) software, Siemens NX.

	BELGIUM	GERMANY	NETHER-LANDS	UNITED KINGDOM	TOTAL
Number of farms	1	6	2	4	13
Number of foundations installed	14	77	0	86	177
Number of turbines erected	0	56	126	0	182
Number of turbines grid connected	0	43	71	0	114
MW fully connected to the grid	0 MW	258 MW	253 MW	0 MW	511 MW

Fig. 1. OWT installation between 1 January and 30 June 2016 in Europe [1]

A. Problem Definition

Fig. 2. Existing OWT installations using jack up vessel [2]

Most of the wind turbines in operation today are installed on monopiles which are driven deep in to the sea bed closer to the shore for a stable and reliable operation. The installation of these heavy wind turbine is often carried out in an effective manner using jack up vessels which are rooted to the sea bed for increased stability during assembly as shown in "Fig. 2,". However, researchers have found that a more reliable wind speeds are recorded far into the ocean than near to the shore. Installing a wind turbine on a monopile far from shore has its limitations due to the depth of the sea bed and the unpredictability of the sea conditions.

The concept developed in this project is inclined towards the installation of an OWT far in the deep oceans where the monopiles are either floating or moored to the sea bed. In this scenario, the jack up vessels shown in "Fig. 2," cannot be used for the installation owing to the depth of the sea bed. Due to this reason, these heavy installation needs to take place in a constantly floating environment which questions the reliability of the existing technology in achieving a safe and quick installation. This project aims in developing a new concept which can install an entire OWT on top of a monopile.

This is a unique approach which has never been tested before on a structure of this magnitude. This also includes the possibility of carrying up to six or more wind turbines in one travel based on the size of the vessel. Huge catamaran installation vessels could provide more stability while carrying out the operation presented in the report. The main objective behind installing a pre-assembled wind turbine on top of a monopile rather than carrying out a part by part installation out in the sea is to reduce the installation time. A quick and safe installation out in the sea require calm waves and wind conditions which are available only on rare intervals during a 24-hour period. The mechanism developed in this project is also equipped with a motion compensation system which could actively compensate for all the wave motions which would in turn make the installation at offshore condition possible without having to wait for calm sea conditions. In the absence of a technologically advanced motion compensation system, it has been proved in the past that the time required for installing an OWT is considerably high due to the short window of calm waves. This project proposal could significantly reduce the time required for the installation of an offshore wind turbine.

B. *Scope of work*

After evaluating the current investments and projections in the field of offshore energy, it is evident that the total installation of wind turbines needs to increase in order to reduce the consumption of fossil fuels that induces global warming. To achieve the clean energy target projected by the European countries, a paradigm shift is required. The current industrial focus is towards increasing the production of fully assembled on shore wind turbine structures that can later be transferred to offshore sites, providing safety and stability while transporting and installing a fully assembled OWT, developing new technologies that could reduce the wind turbine installation time and increasing the operability at higher sea states by improving the wave and wind motion compensation systems currently available. These factors are to be addressed to meet the current requirements of the industry. Scope of this project is aligned towards tackling these existing challenges and to ensure a safe and reliable installation by implementing this concept.

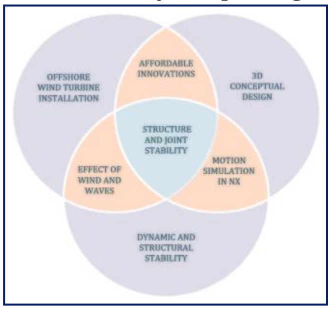


Fig. 3. Scope of Work

C. *Motivation*

The motivation behind choosing the project has two major aspects, an environmental aspect and a technical aspect. The use of fossil fuels has a huge negative impact on the humanity and any effort to reduce it is a step closer to saving our planet. A shift from fossil fuels to renewable energy like wind power could save our future generations from the ill effects of global warming. This transition from nonrenewable energy to renewable energy is made smoother by introducing this concept design which could in turn boost the generation of electricity using wind power and encourage the decommissioning of existing coal power plants which poses a constant threat to mankind.

The technical aspect of choosing the project is to reduce the huge amount of capital investment required for chartering the OWT installation vessels. As per the statistics presented in the report published on offshore wind cost reduction [3]. It is shown that a significant 26% of the whole installation time is consumed by weather downtime as shown in “Fig. 4,”. The weather down time is expensive due to the cost involved in hiring the wind turbine installation vessels. In order to carry out a successful wind turbine installation out in the sea, significant wave height (Hs) is an important factor. For example, installation of a monopile required for mounting a wind turbine requires a significant wave height of 1.5m. However, the North Sea sites are typically dominated by sea states larger than 1.5m almost 40% time of the year

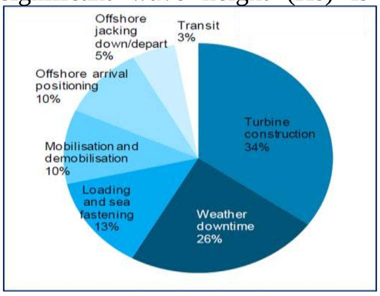


Fig. 4. Turbine installation time in percentage [3]

Increasing the installation capabilities from a significant wave height of 1.4 m to 2.5 meter could reduce the weather downtime to less than one third of the existing time. The floating vessels with highly efficient dynamic positioning system could increase the maximum operating wave height to 2.5 as per the reports published by The Crown Estate [4]. However, these vessels have expensive charter rates per day. A comparison of the charter cost is shown in “Fig. 5,”. As per the report, the operating cost for a large installation vessel with highly advanced dynamic positioning system is around 2.3 Million Norwegian Kroners a day. With this huge investment at stake, reducing weather downtimes could have a significant impact on the trade and strengthen our drive towards clean energy.

Vessel type	Length (m)	Deck area (m2)	Jacket carrying capacity (# jackets)	Maximum operating significant wave height	Operating day rate (£k)
Large floating DP	250	6500	6	2.5	220
Large jack-up	160	4300	3	1.4	150

Fig. 5. Operating day rate for floating and jack-up vessels [4]

In addition to using a floating vessel for installation of Offshore wind turbine, the project focuses on developing a fully functional wave compensation system to assist the installation. This could further increase the possibilities of installing the wind turbines at a much higher significant wave height, thereby reducing the downtime due to weather conditions further more. The most important challenge while designing a heave compensation system for this heavy lifting is to provide a safe and stable operation for the installation at these high sea states.

II. CONCEPT DESIGN OVERVIEW

This part of the paper provides an overview of the concept developed, which involves the end to end methodology followed by a step by step detailing of the entire installation process.

A. *Methodology*

The project has mainly three phases which structure the whole process followed. The phases are summarized as shown below. A design flow chart is created to connect these phases as shown in “Fig. 6,”.

1. Design Phase
2. Analysis Phase
3. Simulation Phase

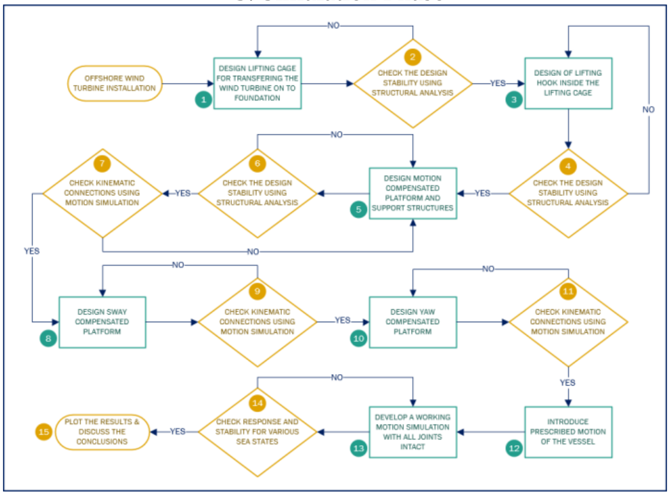


Fig. 6. Design flow chart for OWT installation

The flow chart explains the steps followed during the completion of the project. It also summaries every step which needs to be validated with the respective analysis to be able to proceed to the next level.

Design of Lifting cage for transferring wind turbine on to foundation: Usually the wind turbines are carried to the installation location as separate pieces. In this project the wind turbine is planned to be carried in the vessel vertically after assembling all the components together. However, for transferring the turbine assembly from the vessel the foundation requires utmost precision. In order to meet that, a special lifting and deploying cage is designed for this purpose.

Design of lifting hook inside the lifting cage: The lifting hooks designed in this project is an attachment coming along with the lifting cage. These hooks are hydraulically actuated so that they can be folded in and out after the lifting process. This hook is a critical part which takes up the entire weight of the turbine. Hence a separate structural analysis is required to ensure the stability of the hook as well as the stability of the lifting cage along with the hook.

Design of the motion compensated platform and support structures: The motion compensated platform is designed to compensate for the pitch, roll and heave motion alone. However, this platform has to be at a height almost half of that of the turbine so as to maintain the balance of the system. In order to achieve that, the entire structure is designed on a tall support structure which also compensate for the sway motion. This part is also analyzed for structural stability using FEA.

Design of sway compensated platform: In this concept, in order to compensate the movement in the sway direction, a platform is designed which is actuated by hydraulic cylinders and supported on steel rollers. This will assist in achieving a safe and secure installation by compensating the sway motion.

Design of Yaw compensated platform: Even though the yaw motion is compensated by the thrusters in the vessel, a compensation system is made so as to achieve precision while installation. These are actuated with the help of helical gears driven by electric motors.

Introduce prescribed motion to the vessel: After completing the design face, the kinematic stability of the system needs to be analyzed using the motion simulation module. A prescribed motion is applied for the vessel to move in the direction of heave, pitch and roll. This is done so as to study the response of the joints to these motions.

Develop a motion simulation model with all joints intact: The motion response from the joints are compared in relative to the motion of the turbine to ensure a perfectly synchronized motion simulation.

B. *Concept Development*

The proposal for the project started off with two sketches that combines the initial design idea. This was later tweaked into a working model after checking the feasibility of the kinematics behind the movements.

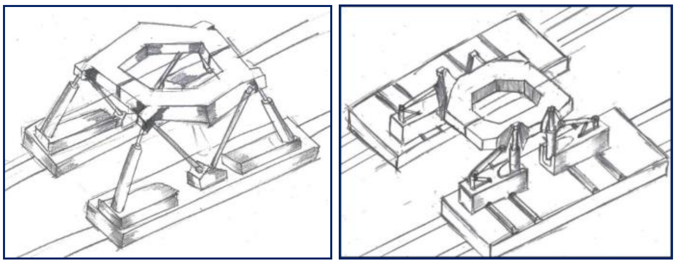


Fig. 7. Concept Sketch

The sketches shown in “Fig. 7,” is made after studying the existing designs available in the market. It shows a lifting mechanism for a vertically mounted wind turbine on a vessel. This arrangement can then be moved back and forth between wind turbines for assembling each one of them. This is the reason why the center of the structure is split into two. This can be opened and closed by pulling the structure back through the tracks. However, the structure like this needs a lot of reinforcements to handle a wind turbine of 1000 tons or more.

After verifying the kinematics of several arrangements holding the hydraulic cylinder and the platforms at different angles using NX motion analysis as shown in “Fig. 8,”, it was evident that the platform has to be connected at the center in order to prevent the entire structure from collapsing due to the motion of the waves.

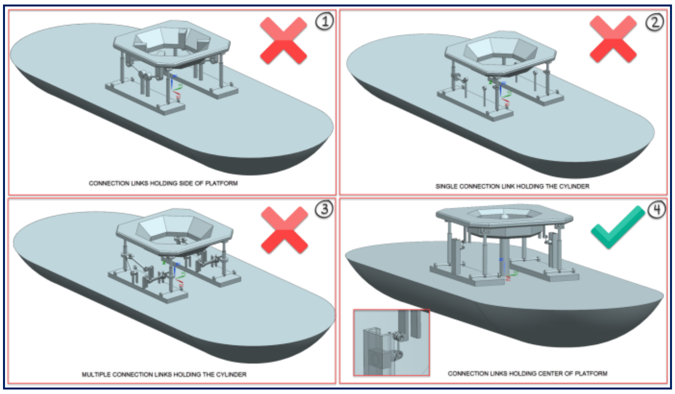


Fig. 8. Kinematics verified using motion simulation in NX

The heave compensation system is only designed to actively compensate the roll, pitch and heave movements of the ship. The sway, surge and yaw movements are constrained by the dynamic positioning system of the ship. However, the design has also considered movements along the sway, surge and yaw direction using actuators to assist a safe and secure installation. This is explained further in the coming chapters.

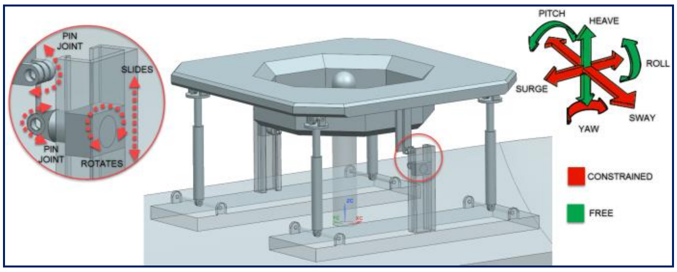


Fig. 9. Motion compensation platform with 3 DOF

The degrees of freedom of the heave compensation system achieved by the hydraulic cylinders and the universal joint are as shown in "Fig. 9,". The figure also shows a sliding l that keeps the platform from tipping off as the cylinders try to compensate for the ship motions. There are similar links used on all four sides of the platform to improve stability while lifting the wind turbine assembly. A detailed explanation of which is provided in the next chapter. The universal joints are used on top of the cylinder rod to achieve the roll and pitch motion of the platform. Spherical joints are used at the bottom end of the cylinder housing which allows the hydraulic cylinders to have a slight angular movement while compensating roll motion.

C. *Design Proposal*

The detailed design of the concept is developed as a 3d model in NX and rendered using key shots. The most important factor considered in the entire design process is that, each and every single component used in the whole assembly can be made from standard cross sections of steel that is available in the European market. The components that needs to be forged and welded are separately explained along with structural analysis to claim the stability of the structure. The whole installation process is explained further in various steps to illustrate the complex mechanisms involved in the concept design. This is a summarized version of the entire process.

Step 1: Arrangement of Wind turbines in the vessel

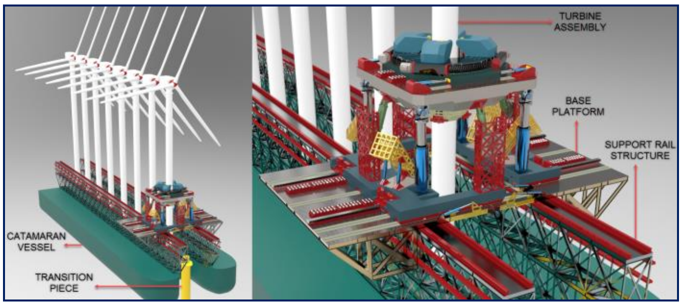


Fig. 10. Complete concept designed in NX and rendered using keyshot

The turbine assembly considered in the concept is around 135 meters tall and weighs close to a 1000 tons. The turbine assemblies are stacked vertically on the vessel as shown in "Fig. 10," using specially designed mounts and tie rods. The assumed vessel dimension used for the installation is of a length of 270 meters and a width of 100 meters. The increased width and multi hull will contribute towards lowering the meta center of the whole vessel and thus improve the stability. This is almost similar in dimension to the catamaran vessel pioneering spirit. The main intention behind this approach is to utilize the same vessel to implement this installation process which will minimize the capital investment required for the entire project. Building a construction vessel alone of this size would cost around 25 Billion Norwegian Kroners (NOK). The transition piece where the turbine is placed will be aligned in a slot in between the hulls. To have a more precise execution of the installation, there should be connection between the vessel and the transition piece that could record the motion of the transition piece with respect to that of the vessel. However, in this project it is assumed that the transition piece is fixed and the connection to the vessel is not taken into consideration.

A support rail structure which runs along the entire length of the vessel is used for sliding a base platform which moves between wind turbines. This platform houses the components required for the heave compensation system and the equipment's required for lowering the turbine assembly on top of the transition piece.

Step 2: Opening and closing of the Base Platform

The base platform is designed so as switch between wind turbines during installation. The hydraulic cylinders which are used for the heave compensation are assembled on a rolling platform (Cylinder Platform) that can move in and out as the base platform open and closes. The open and close conditions of the base platform is as shown in "Fig. 11,". This step is required so as to ensure an easy switch between turbines after installation.

The entire cylinder platform is moved with the help of steel rollers on a defined path. The actuators used for initiating the motion is a rack and pinion system which drives along a tooth on both the sides. A detailed description on each module is separately mentioned in the coming chapters.

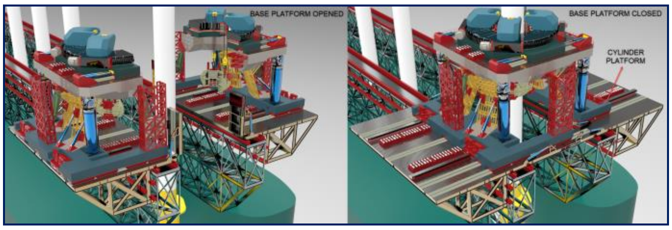


Fig. 11. Open and close condition of base platform

Step 3: Opening and closing of the support structures

The heave compensated platform is moved up and down using 4 hydraulic cylinders. The main heave compensated platform has a weight of around 2000 tons. When the cylinder platform is retracted back after installation, weight of the structure needs to be supported on both sides using additional support structures. However, these supports structures needs to be retracted back once the heave compensation is in operation for safety purposes. Hence a hydraulic actuated support structure is carefully designed to extend and retract whenever required. Once closed, the weight of the heave compensated platform is distributed along the 4 support structures and the 4 main hydraulic cylinders. This will allow safe retraction of the platform by ensuring equal weight distribution along 8 points. There are also 4 additional guide mechanism which can take the weight of the structure. However, this is used as a redundant system to ensure more safety and stability during this operation. The platform is supported by support structures as shown in “Fig. 12,”.

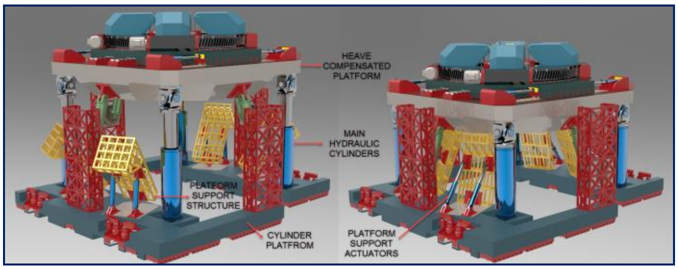


Fig. 12. Open and close condition of platform support structure

Step 4: Pitch and roll movements of the platform

The pitch and roll motion of the platform is achieved by 4 main joints as shown in “Fig. 13,”. A universal joint that connects the hydraulic cylinder to the heave compensated platform, a fixed link with multiple pin joints along with a slide link and a rotating link that constraints the motion of the platform within the prescribed limits.

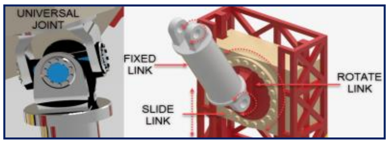


Fig. 13. Main connection links

There are 8 points on the heave compensated platform where these links are connected. In fact, only two of the fixed link connections are enough to constraint the motion. However, 4 connections are installed since there is a combined load of around 3000 tons. As the motion compensation happens the sliding link will move up and down along the vertical guides and will restrict the motion beyond a certain point. This will allow the main hydraulic cylinders to stay upright. Swivel bearings are used at the base of cylinder housings to enable roll motion. The pitch and roll motion of the platform is as shown in “Fig. 14,”.

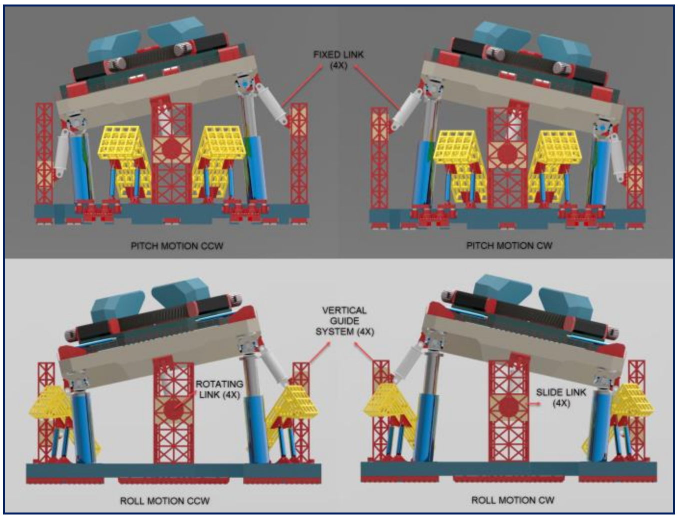


Fig. 14. Pitch and roll motion of the platform

Step 5: Sway and Yaw movements of the platform

The sway and yaw movements of the ship are controlled by the dynamic positioning system. However, while installing the wind turbine on top of the transition piece, some fine adjustments in the direction of yaw and sway in inevitable.

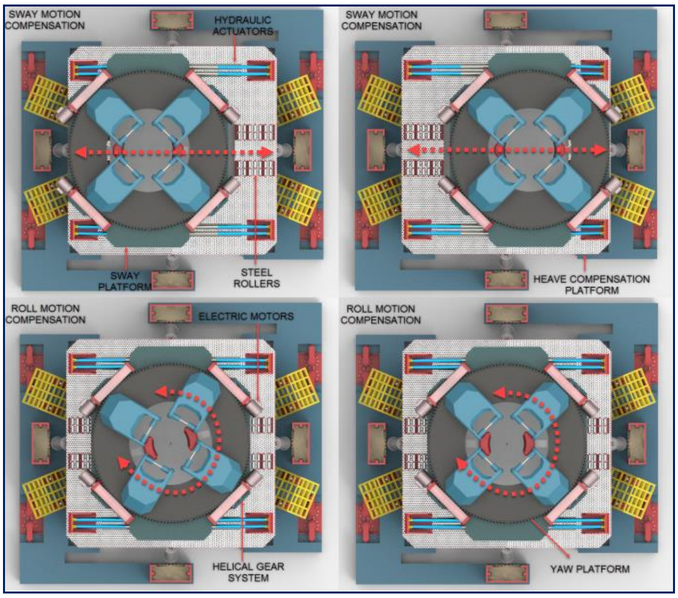


Fig. 15. Sway and yaw motion of the platform

Hence a system is developed to bring in the compensation for the sway and yaw on top of the heave compensation platform. The movement of the sway platform is achieved by using 8 Hydraulic Cylinders. These cylinders propel the platform to move 3.5 meters in both directions. The entire platform is supported on top of steel rollers to assist the motion. The movement of the yaw platform is achieved by a helical gear system driven by 4 Electrical Motors. The yaw platform houses the winch system required to lift and lower the wind turbine. It also houses hydraulically actuated rolling grippers which are used to support the wind turbine as it is lowered down to the platform. These grippers are extended and retracted from within the yaw platform. The sway and yaw movements are as shown in “Fig. 15,”.

Step 6: Lowering of the Lifting cage and hook

A lifting cage is designed to lift a fully assembled wind turbine from the vessel and lower it down to a transition piece pre-installed in the ocean. There are 4 electric winches that assist in lifting and lowering which makes the installation a little flexible. There are 2 hydraulic actuated roller grippers installed inside the yaw platform which can extend and retract while gripping the turbine assembly. These grippers contribute towards constraining and supporting the turbine walls as it is lowered down. Without the grippers, there is a high chance of turbine colliding with the yaw platform due to the wind conditions offshore. Rollers are horizontally arranged as the roller action is supposed to work only when the wind turbine is lowered. The crane hook is designed as a typical hook which are commonly used in heavy lifting operations. 4 heavy ropes are connected to lifting hooks inside the lifting cage which are extended and retracted using hydraulic cylinders. Lifting cage is designed to split into two parts as the installation is completed. The whole lifting assembly is as shown in “Fig. 16,” and “Fig. 17,”. This yaw platform is mainly there to assist in the precise turning of the turbine assembly during installation.

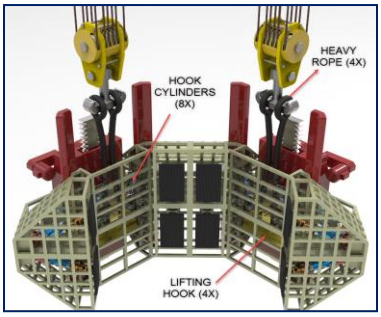


Fig. 16. Lifting hook

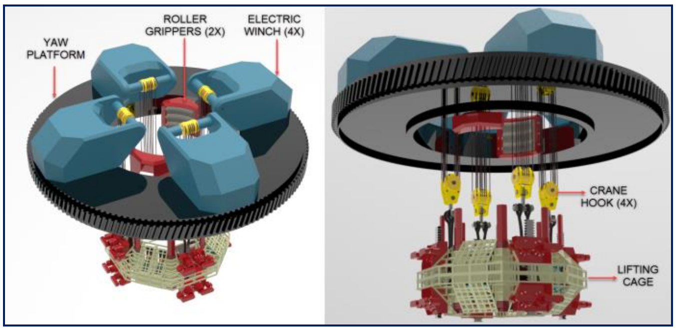


Fig. 17. Lifting cage, crane hook and winches

Step 6: Lifting and lowering the turbine assembly

In order to lift the turbine assembly, the lifting cage has to be opened with the help of the rack and pinion system attached to it. The important part of lifting comes when the upper half of the cage is aligned to the base of the wind turbine as shown in “Fig. 18,”. Once the alignment is corrected, the lifting hooks are closed. This will then allow the ropes and the crane hook to take the entire load of the wind turbine as well as the lifting cage. The lifting points are designed in such a way that the load is distributed equally on all the four hooks.

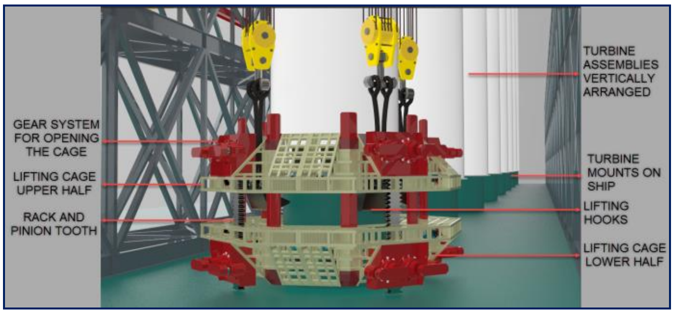


Fig. 18. Lifting of turbine assembly from vessel

The lower half of the lifting cage is then aligned with the transition piece. The hydraulic grippers inside the cage is then activated and takes up the weight of the wind turbine on 16 Hydraulic Cylinders. The hooks are opened and are allowed to pass through the space in between the lower and upper cage as the turbine is lowered on to the transition piece. The ropes are then changed to slacking mode and are relieved of the weight of the turbine.

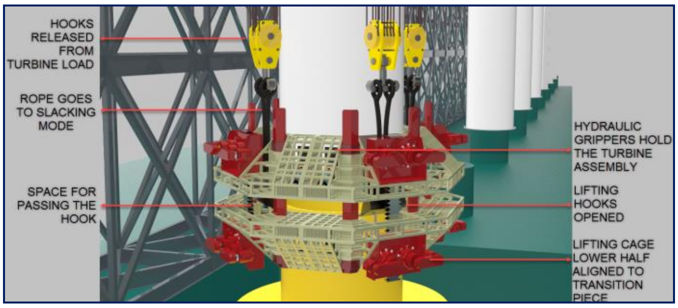


Fig. 19. Lowering of the turbine assembly on to the transition piece

Step 8: Detaching the cage after installation

Once the installation is carried out, the lifting cage is pulled back to the top by keeping it in the closed condition. This will not cause interference with the turbine assembly owing to the tapered structure of the turbine tower. Once it is raised to a height almost up to 3 meters below the heave compensated platform. The Cage is to be detached into two and pulled back to either sides of the installed turbine. The detachment methods are not taken into consideration for this project. This can be a hydraulic cylinder arrangement which locks that detaches the cage once it reaches the required height. Weight of the once half of the lifting cage is then distributed to the two electrical winches pulling it.

There are also hydraulic actuators that moves inside the one half of the platform to improve the stability of the structure once in closed condition. These are as shown in “Fig. 20,”. The lifting cage once detached can be lowered down to the base platform floor and can rest there for inspection before starting the installation of the next turbine.

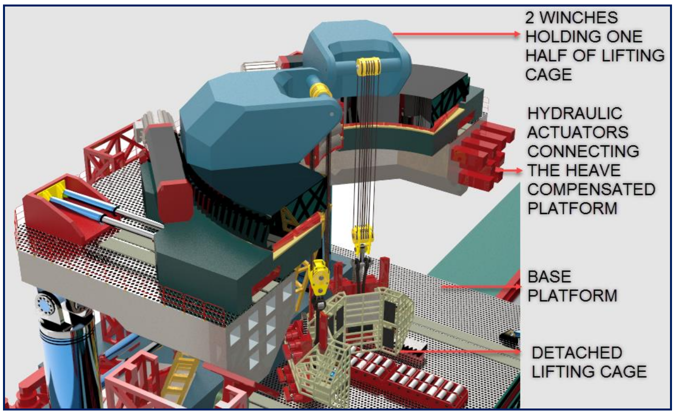


Fig. 20. Cage detachment

All the steps mentioned in the design proposal are the various stages of the installation process. The next stage of the design process was to validate the motion stability of the proposed structure.

III. MOTION SIMULATION

After ensuring the structural stability of the concept. The kinematic movements of the links were to be verified. In order to do that, the motion simulation module in NX is used.

A. Setting up the model

This module has the ability to verify the motion of the various joints in response to the motion of the ship. Due to the immense computing power required for the motion simulation to solve the kinematic linkages, a simplified model of the entire assembly is used. The final assembly made in NX is simplified as shown in “Fig. 21,”. This makes it easier for the solver to compute the link movements.

In order to set up the model for motion simulation, the whole assembly needs to be converted into links and joints inside the software. There are a few factors that were included in this motion simulation to replicate the motion of the vessel. Sine waves and cos waves are applied to a specific point on the vessel to simulate pitch and roll in addition to that a harmonic function was applied to simulate the heave.

In order to obtain the heave, roll and pitch motion on the same joint, a spherical joint was created for the vessel which rests on another sliding joint. This is a work around done so as to get the simulation to run in the solver. There are 4 spherical joints, on the base of the main cylinder housing which allows the cylinder tilt sideways. The cylinder rods are connected to the housing using slider joints with limits. The next part is the universal joint connected to the top of the cylinder rod using 4 revolute joints, which allows the rotation. The other end of the universal joint is connected at 4 locations to the top platform again as a revolute joint that allows rotation along a specific axis. The fixed link for the platform supports are connected using a revolute joint to another 4 locations on the heave compensated platform. The bottom end of the fixed link is connected to the rotating component as a revolute joint at 4 locations. The rotating component is again connected to the slider as a revolute joint at 4 locations. The slider component is connected to the cylinder support platform using a sliding joint at 4 locations. The sway motion and the surge motions are provided for the both the platforms to enable the compensation to happen in the respective directions. The heave motion is applied to the sphere joint to a total wave height of 2.5 meters. A roll and pitch motion are applied as drivers to vessel which gives a 3 degree each. The graphs plotting the motion of the vessel is collected by applying markers to a specific location and by attaching a sensor to it. The sensors are then plotted for determining the heave in mm, pitch and roll in degrees. The pitch and roll are applied as a sine wave and cos wave. Sine wave alone was not used in order to achieve realistic vessel motion effects.

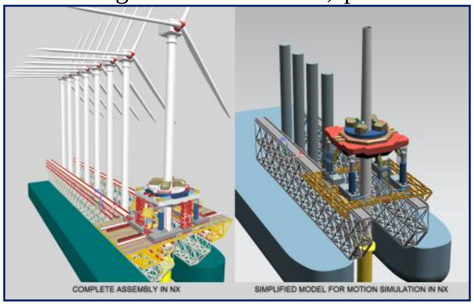


Fig. 21. Simplified model for motion simulation

B. Discussion of Results

The prescribed motion for the vessel is applied to the point marked 1 in the “Fig. 22,”. It is an assumed point where the pitch, roll and heave motion for the vessel is applied. The figure shows how the pitch motion is compensated by the entire assembly. D1 is the distance from the center point of the ship to the base of the first cylinder and the one behind it. Similarly, D2 is the distance to the base of the second cylinder and the one behind it. The θ is the pitch applied to the center of the vessel. In this case, is 3 degrees’ peek to peek. After applying that motion, a sensor is placed at the center point to capture the θ. This is then used to find the X1 and X2. These are displacement to be applied to the first 2 cylinders and the next 2 cylinders respectively. This will allow the motion of the platform to be compensated for the pitch motion. While controlling the pitch, the design of the platform will initiate a surge movement along the horizontal axis. This movement is compensated by using the dimension D3, which is the distance from the base to the center point of the platform which is a constant. Finding the X3 will provide the distance that the surge platform should move so as to compensate the surge motion. Thus the pitch and surge motions are compensated by the platform. The compensation of the roll motion is explained further.

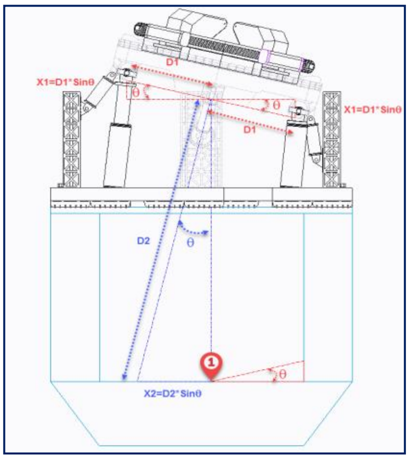


Fig. 22. Trignometric relations behind pitch and surge

The prescribed roll motion of the vessel is applied to an assumed center point marked as 1 in the “Fig. 23,”. The θ is the roll applied to the center of the vessel. In this case, it is 3 degrees’ peek to peek. In this case the known values are D1 and D2 which represents the length of the platform which is a constant. The θ is captured as usual by placing a sensor at the center point. The distance X1 is the distance that the first two cylinder needs to displace in order to compensate for the roll motion. Similarly, a negative value is applied to the other two cylinders to compensate for the roll at the other end. The Design of the platform is made in such a way that there will be a slight movement of sway once the roll compensation is achieved. This can be corrected by subtracting the value of X2 from the cylinder displacement. Since the input values are derived from the theta which is a sensor. The values are continuously updated and this gives a simulation result by keeping the platform steady in response to the vessel motion.

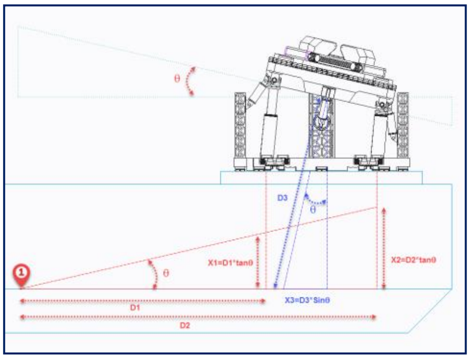


Fig. 23. Trignometric relations behind roll and sway

A detailed description of the heave motion is not provided since it is a direct vertical movement applied to the point and can be easily compensated by lowering the cylinders to the exact same distance. A simulation for the Yaw motion is not included in this project, there is a yaw platform on top which can directly compensate for the yaw motion of the ship. The trigonometric relations behind compensating all the 5 degrees of freedom is explained. The resulting real time simulation results are explained further.

There are several ways of implementing pitch, roll and heave compensation for this system. The primary idea would be to give the prescribed motion to the vessel and calculate the force required for each cylinder by gathering inputs from various sensors placed in and along the joints. This in itself requires a more detailed study on the control algorithm which is required for running the simulation. Motion simulation module in NX has immense potential to implement real time inputs from matlab and Simulink or even from an external PLC’s from which real time the control signals can be connected. However, this project does not go into the details of implementing the control logic for the motion simulation. The main objective behind this project is to show the kinematic stability of the structure using prescribed motion given as inputs to the joints.

In this project, the sway and surge compensations are activated by applying driver to both the joints and giving inputs to compensate for the motion. The result of the motion simulation shows a blue marker over the graph, which shows the real time positioning of the vessel with the respect to pitch, roll and heave. “Fig. 24,”. is a representation of the direct output screen from NX which gives the real time response to the simulation and along with the 3D model. The simulations results are obtained by placing sensors on the motion compensated platfrom and by plotting the relative motion of the platfrom with respect to that of the point at which the prescribed motion of the vessel is applied. The plotted result has heave, pitch and roll compensated. The yaw motion of the platfrom is not considered for motion simulation.

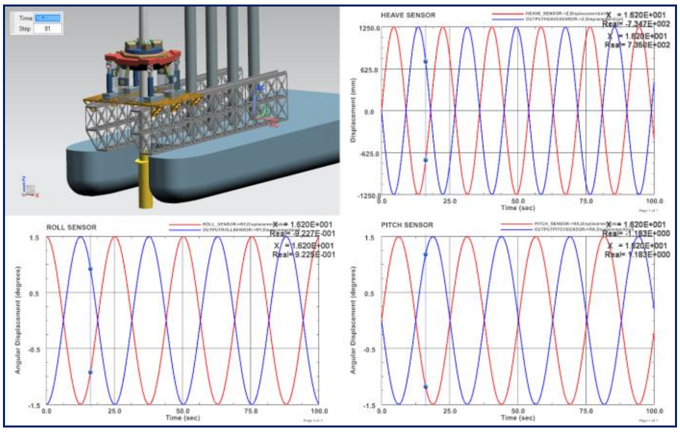


Fig. 24. Realtime simulation results from NX

IV. CONCLUSION

The paper thus discusses the implementation of an innovative concept for the installation of offshore wind turbines. The concept designed in NX was further analyzed for structural stability to ensure that the platform and all the included structures are strong enough to carry out the installation of an offshore wind turbine weighing around 1000 tons. Once this was proved, the motion simulation of the concept was carried out using NX which gives the results proving that the system is stable with all the kinematic linkages responding correctly to the prescribed wave motion. It covers the main three steps, design, analysis and validation. This project can be used for further developing the concept into a working model which could save a huge capital investment in the field of offshore wind turbine installations.

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