Katarina Staalesen

Exploring the Digital Twin Concept for a Rigid Aquaculture Cage

– insight through structural analysis and sensor application

Master's thesis in Marine Technology
Supervisor: Prof. Bjørn Egil Asbjørnslett
June 2019

Master's thesis

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Kunnskap for en bedre verden

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Supervisor 2: Prof. Jørgen Amdahl

Preface

This master thesis is written during the spring semester of 2019 as a part of the five year Master of Science study programme Marine Technology at the Norwegian University of Science and Technology (NTNU). The thesis is a part of the specialisation programme marine resources and aquaculture, with the focus area of study being marine aquaculture structures. The main topic of this thesis is digital twins and use cases for digital twins in the growing aquaculture industry. The choice of topic is a result of a combination of great interest in the development of the Norwegian aquaculture industry and a continuation of work from a student project during the summer of 2018.

The thesis is carried out to give insight into and exemplify the use of digital twins in offshore aquaculture industry. It consists of a structural analysis of a model of Ocean Farm 1 in the software USFOS, sensor evaluation and assessment of placement of the sensors for development of a digital twin.

Trondheim, 06/06-2019

Katarina Staalesen

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I would like to thank my supervisor Professor Bjørn Egil Asbjørnslett at the Department of Marine Technology, NTNU, for help in the forming of this master thesis, and for guiding and helping me through the work. I would also like to thank Professor Jørgen Amdahl at the Center of Autonomous Marine Operations and Systems (AMOS) and Department of Marine Technology, NTNU, for helpful discussion and guidance regarding choice of structural analysis and support during the conduction of the analysis. A huge thank you also goes to Pål Takle Bore for allowing me to use his and Pål Alexander Fossan's model of Ocean Farm 1 for my own purposes, and for helping me with the setup of the analysis.

I also want to thank my fellow students at Marine Technology, and especially the girls at my office for great cooperation and discussions through the past year. A special thank you goes to my family for always being very supportive and encouraging.

K.S.

Abstract

This master thesis aims to give insight to potentials for use of digital twins in offshore aquaculture industry. This is done through structural analysis and sensor application. A global response analysis is carried out for three selected sea states in the non-linear analysis program USFOS, on Ocean Farming's offshore fish farming facility Ocean Farm 1. The simulated sea state has an estimated 100 year return period, and includes sea states close to what Ocean Farm 1 is designed for. From the analysis it is found that the largest stresses occurring in the structure is 55% of the yield stress.

Based on the analysis results, two elements and one parameter are selected for application of sensors for monitoring of the structural integrity of the structure. The chosen elements are element 524 of the main structure which are experiencing high stresses during the extreme weather, and the mooring line with the highest utilisation, number 8. The movements of the structure is the parameter chosen for monitoring, as it experiences large offsets from the neutral position during the extreme weather. These selections are based on a combination of the analysis results, redundancy of the element, and for the purpose of variation to give insight to a few different sensors.

For monitoring of element 524 three strain gauges are proposed installed in a rosette configuration. The information on the strain development can be used for monitoring of the stresses experienced by the element, and also create a time series of the stresses to save the stress history experienced by the element. For monitoring of the forces in the mooring line, an inclinometer is chosen. It calculates the tension in the mooring line based on measurement of angles, and the force in the mooring line can be derived from these measurements. It can be used to monitor the forces, and as for the structural element, create a history of the forces to be able to monitor and evaluate the condition of the mooring line throughout the lifetime. For monitoring of the movements of the structure, a differential global positioning system is proposed used. This is an enhancement method for GPS which increases the accuracy of the position calculation. The analysis shows that the structure can move in an area at the size of a small football field, dependent on the incoming waves and current. It is important to know the exact position of the structure for communication with working boats that are working at or close to the structure.

This thesis also presents different use cases for a digital twin of Ocean Farm 1. One of the main advantages of having a digital twin with input from sensors all over the structure, is the possibility of monitoring it real-time. 85% of the structure is situated beneath the sea surface, and regular manual inspection of these areas are challenging. A digital twin can monitor the wanted parameters and manual inspections can be scheduled when they are needed.

Through the work in this thesis, large potentials for use of digital twins in offshore aquaculture industry has been identified. The investment costs of establishing a digital twin are large compared to only building the structure, but the enhanced optimisation of operations and processes, and the increased safety, evens out the increased costs. Further research and exploration of the topic, and work on establishing a digital twin of Ocean Farm 1 is recommended. It gives larges possibilities for creating insight to the farming processes in new ways and sees almost endless possibilities.

Sammendrag (Norwegian)

Denne masteroppgaven har som formål å gi innsikt i potensialene for bruk av digitale tvillinger i offshore havbruksindustri. Dette er gjort gjennom strukturanalyse og sensoranvendelse. En global responsanalyse er utført for tre utvalgte sjøtilstander i det ikke-lineære analyseprogrammet USFOS, på Ocean Farmings offshore oppdrettsanlegg Ocean Farm 1. Den simulerte sjøtilstaten har en estimert returperiode på 100 år, og inkluderer sjøtilstander nært opp mot det Ocean Farm 1 er designet for å tåle. Fra analysene ble det funnet at de største spenningene som oppstår i strukturen er på 55% av flytespenningen.

Basert på analyseresultatene velges to strukturelementer og en parameter for påføring av sensorer for overvåkning av den strukturelle integriteten til anlegget. De valgte elementene er element 524 av hovedstrukturen, som opplever høye belastninger under de ekstreme værforholdene, og forankringsline nummer 8 som er den linen med høyest utnyttelse. Parameteren for overvåkning er bevegelsenen til strukturen, basert på at den beveger seg et stykke bort fra nøytralposisjonen under de ekstreme værforholdene. Disse valgene er gjort basert på en kombinasjon av analyseresultatene, redundansen til elementet, og med det formål å gi et innblikk i noen forskjellige sensorer.

For overvåkning av element 524 er tre strekklapper installert i en rosettkonfigurasjon foreslått som overvåkingsmetode. Informasjonen om tøyningsutviklingen kan brukes til å overvåke spenningene som elementet opplever, og også lage en tidsserie av spenningene for å lagre spenningshistorikken som elementet opplever. For overvåkning av kreftene i forankringslinen er det valgt et inklinometer. Det beregner spenningen i forankringslinen basert på måling av vinkler, og kraften i forankringslinen kan avledes fra disse målingene. Det kan brukes til å overvåke kreftene, og som for det strukturelle elementet, skape en historikk over kreftene for å kunne overvåke og evaluere tilstanden til forankringslinen gjennom hele levetiden. For å overvåke bevegelsene til strukturen er det foreslått å bruke differensiell GPS. Dette er en forbedringsmetode for GPS som øker nøyaktigheten av posisjonsberegningen. Analysene viser at strukturen kan bevege seg i et område på størrelse med en liten fotballbane, avhengig av de innkommende bølgene og strømmen. Det er viktig å vite den nøyaktige posisjonen til strukturen for kommunikasjon med arbeidsbåter som jobber på eller nær strukturen.

Oppgaven presenterer også forskjellige bruksområder for en digital tvilling av Ocean Farm 1. En av hovedfordelene med en digital tvilling som får input fra sensorer over hele strukturen, er muligheten for overvåkning i sanntid. 85% av strukturen ligger under vannoverflaten, og regelmessig manuell inspeksjon er utfordrende. En digital tvilling kan overvåke alle ønskede parametere, og manuell inspeksjon kan utføres de gangene det er nødvendig.

Gjennom arbeidet med denne oppgaven har det blitt identifisert store muligheter for bruk av digitale tvillinger i offshore oppdrettsindustri. Investeringskostnadene ved å etablere en digital tvilling er store sammenliknet med å kun bygge strukturen, men med bedre optimalisering av operasjoner og prosesser, og økt sikkerhet, utlignes disse kostnadene i løpet av levetiden. Videre forskning på og undersøkelse av dette emnet, og arbeid med å etablere en digital tvilling av Ocean Farm 1 anbefales. Det gir store muligheter for å skape innsikt i oppdrettsprosessene på nye måter, og digitale tvillinger ser ut til å ha nesten uendelige muligheter.

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List of Abbreviations

Abbrevations

ADCP	Acoustic Doppler current profiler
CAD	Computer-aided design
CBM	Condition-based maintenance
DGPS	Differential global positioning system
DNV GL	Det Norske Veritas Germanischer Lloyd
GPS	Global positioning system
HDPE	High-density polyethylene
INS	Inertial navigation system
InSAR	Interferometric Synthetic Aperture Radar
JONSWAP	Joint North Sea Wave Project
MBL	Minimum breaking load
NTNU	Norwegian University of Science and Technology
PET	Polyethylene terephtalate
ppm	Parts per million
RAMS	Reliability, availability, maintainability and safety
ROV	Remotely operated vehicle
RTK	Real-time kinematic system
SAR	Synthetic Aperture Radar
SHM	Structure health monitoring

Symbols

A_{ii}	Added mass coefficient
A_w	Waterplane area
C_{ii}	Restoring coefficient
E	Elastic modulus
g	Acceleration of gravity
H_S	Significant wave height
M_{ii}	Mass
T	Wave period
T_{ni}	Natural period
T_P	Spectral peak period
U_C	Current velocity
γ	JONSWAP spectrum peak parameter
ϵ	Strain
ρ	Sea water density
σ	Stress
σ_j	Von Mises stress
σ_x	Axial stress
σ_y	Yield stress
τ	Shear stress

Chapter 1

Introduction

1.1 Background

From the beginning of the 1970s, Norway has been one of the world leading countries in the aquaculture industry. The cold Norwegian waters are especially well suited for farming of Atlantic salmon. The rapid evolvement of the farming facility technology and methods has established Norway as a leading producer of equipment to the aquaculture industry, making use of expertise from the Norwegian oil and gas industry. The last 30 years the production of Norwegian salmon has escalated, from a produced biomass of 170 thousand tonnes in 1990 to 1.1 million tonnes in 2018 [29, 39]. This is more than 50% of the total worldwide production [18, 39]. The value of the exported salmon has more than doubled in the last 6 years, from 29.6 billion NOK in 2012, to 67.8 billion NOK in 2018 [29]. The reason for this great income growth is a combination of increased production volumes and increased prices. The Norwegian government estimates a potential 5 time multiplication of the produced biomass by year 2050, and see the value created from salmon farming as a very important source of income for Norway in the future [35]. For this to be possible, establishment of new farms and issuance of new licences are needed, but there are several challenges related to this.

The biomass production in Norway is regulated through government issued production licences, which gives the salmon farmer the right to have a certain biomass of salmon in the sea. During the last decade, mostly as a result of the rapidly increased production, several challenges related to the production of salmon in open sea cages has emerged. This has led the Norwegian government to stop issuing new production licences, with the result that the produced biomass is stagnating. Until these problems are solved, or as a minimum are under control, the growth of the salmon production in Norway will be limited. The challenges of the production are linked to both environmental impact and space limitations, and the Norwegian government will not allow further growth without it being sustainable. The Norwegian aquaculture law states that establishment, operation and discontinuing of aquaculture production shall be done in an environmentally responsible way [3, §10].

Today, most of the aquaculture facilities in Norway are located in sheltered areas in the coastal zones, which has been one of the most important competitive advantages for Norwegian aquaculture production [35]. The fjords are especially popular and well suited areas, but these are also areas where the risk of the salmon getting infected by sea lice is high. Some facilities are located at more exposed areas, but these are still classified as inshore. Also the salmon in these farms has a risk of getting infected by sea lice, as the lice usually float with the stream and can spread between farm. Today, the availability of new locations in sheltered areas are scarce, which make sustainable growth challenging [35]. Another challenge is the impacts waste from facilities may have on the wild biological life in their nearby areas. Faeces and spilled feed may lead to rapid growth of algae, which sink to the seabed when they die, usually after only a few days. The decomposition process that follows needs large amounts of oxygen. This can cause lack of oxygen at the seabed under the farms, especially if the water currents do not manage to wash away the algae or supply new oxygen [36]. Emissions from handling and delousing of the fish may also affect the surrounding wildlife. In 2006 a regulation called NYTEK was introduced to reduce escapes from farms by clearer stating the rules that apply for building a safe fish farm [40]. This reduced the number of escapes dramatically, but escapes of salmon still occur and may have severe impacts on the wild stocks of salmon living in the area of the escape. The last years, only a few new licences have been issued from the government, but there has been some growth as it has been possible to apply for a 2-6% increase in licenced biomass. There are no new rounds for sale of licences coming up in the foreseeable future [55].

Figure 1.1: Picture of Ocean Farm 1 before ballasting and installation. Picture by SalMar.

In November 2015, the Norwegian Directorate of Fisheries introduced development licences to the Norwegian aquaculture industry. These licences were introduced to facilitate new technologies that can help solve the challenges in the industry related to environmental impacts and space limitation, and lead to further growth [20]. With the limited space in the fjords, one of the possibilities for further growth involves moving the facilities offshore to more exposed locations, where the environmental forces are larger. This requires development of new technology, or use of technology that has been developed in other industries. The deadline for application for development licences was set to November 17, 2017. The development licences has received a lot of attention in the aquaculture industry. One of the main reasons for this is the possibility of getting the development licences converted to regular licences if the project proves viable and applicable in a large scale. Several of the large salmon production companies have developed designs for new production facilities together with companies that possesses the knowledge and technology needed. As of June 2 2019 there are 11 companies that have been granted a total of 68 development licences. In total there has been 104 applications for a total of 900 licences [19]. The Norwegian Directorate of Fisheries did not specify a number of licences they wanted to issue, but is granting them to the projects they believe will succeed and contribute to the development of the Norwegian aquaculture industry.

The first company to be granted some of these licences, 8 in total, was Ocean Farming AS [19]. This is a SalMar ASA company, which is one of the largest companies operating in the aquaculture industry in Norway. They got licences to realise their exposed aquaculture farm called Ocean Farm 1, and it was installed in Frohavet (Figure 1.2) off the coast of Trøndelag early in September 2017. It is a rigid steel structure with a twelve-sided, cylindrical shape, and pontoons at the lowest part to provide buoyancy [10]. The height of the farm is 68 meters and the diameter is 110 meters, which gives a total volume of 250000 cubic meters inside the net. It can hold up to 1.6 million salmon, eight times more than a conventional cage. It is designed for a significant wave height of 5 meters, as this is the waves that can be expected in the area [10]. A picture of the farm before it was ballasted and moored is shown in Figure 1.1. The technology used in this project is based on world leading Norwegian aquaculture and offshore structure expertise [10, 46]. Several other companies has also been granted development licences for facilities that are supposed to be located more exposed than the conventional farms today. This gives both opportunities and challenges that needs to be considered carefully to ensure a safe environment for everyone involved in the production.

1.1.1 New technologies

In today's marine industry, digitisation and digitalisation are hot topics. Digitisation concerns the change from storing information physically in books and binders, to storing information digitally in a clear and easy way [41]. Digitalisation concerns the use of digital technologies to change business models, and thus is the process of moving to a digital business [23]. At the same time, storing of too much unnecessary information should be avoided, because it will complicate analysis and use of the interesting and necessary data. When analysing, the interesting data must be extracted from the full data set, and the data cleaning process will be complicated and slowed down by all information that is irrelevant [54]. One way of storing and making use of this information is through digital twins, which is a highly relevant and discussed topic today. Shortly explained, a digital twin is a virtual representation of a real process or product [32].

Figure 1.2: The location of Ocean Farm 1 in Frohavet, named Håbranden, indicated by a circle and an arrow. Trondheim can be spotted in the lower right corner. Aquaculture map from Fiskeridirektoratet, ©Kartverket [21].

The idea of a digital twin is by Grieves and Vickers described as "being able to design, test, manufacture, and use the virtual version of the systems" [24, p. 86]. The digital twin links the physical system with its virtual equivalent, meaning that by use of the data obtained from the real structure the digital twin is able to portray the condition of the real structure. The use of a digital twin from an early design phase gives the possibility of testing and understanding the design prior to actually manufacturing the system. This results in a more thorough understanding of the system, and the possibility of doing changes at a much lower cost than during manufacturing or after installation. This is likely to reduce failures when the system is put into service. Fewer failures gives reduced expenses, and the time used to maintain the system will also be reduced. The sum of this will increase the safety for the users [24].

During the last decade, research on, and use of, digital twins has increased rapidly, especially in industries like product design, production, and health management. Tao et al. presents a digital twin's possibility of suggesting services based on information as one of the main reasons, and states that integration between digital twins and services is a promising research direction [54]. The interest for digital twins has also spread to the maritime industries, with increased focus on research on autonomous ships and use of digital twins in the oil and gas industry. Rosen et al. emphasises digital twins as a prerequisite for autonomy, as a realistic model of the current state of the system is very important for an autonomous system to be able to make decisions [45, p. 567]. There also seems to be potentials for use of digital twins in the aquaculture industry. With the new designs of salmon farming facilities emerging from the development licences, it is interesting to investigate how a digital twin can benefit the industry when moving to more exposed locations. It is a relatively new topic, and is therefore poorly explored. The most important project to mention in relation to research on offshore aquaculture structures is SFI Exposed, which is a Centre for Research-based Innovation (SFI) founded by the Research council of Norway and lead by SINTEF Ocean. As fish health is the number one priority for all fish farmers, most of the SFI Exposed research until now has been related to monitoring of the fish, biological factors and environmental factors that effects the health of the fish, such as feeding, oxygen levels and currents. The project will continue until 2022, and focus areas the next years are related to real-time condition monitoring and operational support, and structural analysis of fish farms [9].

With an increasing amount of structures situated at more exposed locations follows an increased need for monitoring of the farms to ensure safe conditions for everyone involved. The conventional cages today are usually not instrumented to monitor the structural integrity, only the fish welfare, if any. As the common type of location for aquaculture farms today is sheltered in a fjord, the cage located at these locations experiences low forces compared to what will be the case when moving to offshore locations. This implies that the offshore structures must be able to withstand a harsher environment, which results in stronger and larger structures. More remote locations and larger structures increases the relevance and importance of monitoring of the structure, which is where the idea of a digital twins comes into play.

1.2 Problem Definition

The work in this thesis is based on a problem definition developed in collaboration with Professor Bjørn Egil Asbjørnslett. The description is attached in Appendix A. This thesis explores the use of digital twins in the aquaculture industry. As the Norwegian aquaculture industry is developing and growing, new areas located further offshore are being used. This requires larger structures than before, that are able to withstand larger forces and at the same time ensure good conditions for the fish. This opens for the use of new technology as the new structures are more advanced than the conventional cages that has been used for the past decades. Digital twins shows large potentials in other industries, several of which are transferable to the aquaculture industry. Through structural analysis and assessment of sensor application, this thesis aims to give insight to possibilities and challenges related to the use of digital twin technology in offshore aquaculture industry. The findings and results will be the start of knowledge basis for the establishment of a digital twin of Ocean Farm 1.

1.3 Objectives

The thesis consists of two main parts, the first one being an analysis of Ocean Farm 1, and the second one exploring the use of digital twins in the aquaculture industry. Eight specific tasks are specified in the problem definition, and are summarised in the following. A structural analysis of Ocean Farm 1 is to be carried out to identify weak points of the structure and areas that are subjected to large forces and stresses. The analysis will be carried out using the program USFOS, and run for some selected sea states and extreme waves. Relevant sensor technology for monitoring of the structural integrity will be chosen for some selected areas based on the results from the analysis, and for the purpose of showing a diversity of potential sensors. There will be chosen at least 3-5 sensors in prioritised order, starting with the sensor that is considered most important. The reason for the specific prioritised order, and the purpose of choosing the specific sensor for the specific location shall be clearly stated and reasoned.

A digital twin can be a powerful tool. The second part of the work in the thesis is to give an example and a description of how the combination of structural analysis, CAD and sensor monitoring can be used to form a digital twin. It shall be presented how monitored parameters and the sensor data provided by the sensors can be implemented with the digital twin to monitor the structural health and serve as decision support. Specific use cases for the digital twin in this context, for example for alerting if a threshold value is exceeded, or for constant monitoring of the condition of the real structure, will be presented. How, why and if the use of digital twins will be beneficial for the aquaculture industry in the future, related to human and fish safety, profitability and structural integrity is something that will be the focus of and will be emphasised throughout the thesis.

1.4 Approach

1.4.1 Conduction of a literature review

First, a literature review was conducted on topics relevant for the thesis. The literature review is based on work from the project thesis written as a pre-project for this master thesis during the autumn semester of 2018. The researched topics includes design principles of marine structures, principles for monitoring and analysis of monitoring data of marine structures, and maintenance policies relevant for use in connection with digital twins. Relevant sensors for use with digital twins has also been reviewed.

1.4.2 Analysis method

The type of structural analysis for this thesis was chosen through consultation and discussion with Professor Jørgen Amdahl at Department of Marine Technology. Several approaches was considered, including creating a new model, and reusing analysis results from analyses conducted by other students. Creation of a model is a very extensive and time consuming task, and reuse of results obtained by others would weaken the learning outcomes. It was therefore decided that most fitting for this thesis was to reuse a model that already exists at the Centre for Marine Technology at NTNU. This way it would be possible to carry out the analysis and obtain results specific for this thesis within a period of time that also allowed enough time to conduct the remaining tasks that were required. The selected analysis is a global response analysis used for identification of highly utilised element members. The results was found through inspection of graphs and plots, and comparison between them. The specific procedure of the analysis will be presented in Chapter 3 together with the input values and results of the analysis, which makes the procedure easier to both explain and understand. Verification of the results are challenging as there are no relevant monitoring data from Ocean Farm 1. However, results will be compared to results previously obtained from analysis of the model, to evaluate the validity of the obtained results.

1.4.3 Exploratory study method

A large part of this thesis concerns use cases for digital twins in offshore aquaculture industry. As this is a poorly explored topic, research on articles related to use of digital twins in other industries has been in focus. The most relevant and comparable industry is offshore oil and gas industry, and the focus has been mainly on finding literature about digital twins in this industry. The common areas of application that have been identified from the literature are extracted, and their potential for application in the offshore aquaculture industry has been discussed. Some aquaculture specific areas of application has also been discussed.

For the part of the thesis concerning sensor selection for the chosen structural elements, a list of three criteria was created, to have specific criteria to evaluate the results against. The thesis also contains parts exploring new ideas that has emerged through the work with the different topics, and the background and assessments of these ideas have been presented where the ideas are introduced.

1.5 Outline of the thesis

The following presents an overview of how this thesis is structured. First, a literature review of the different aspects of the design procedure of marine structures and the state of the art of digital twins are presented in Chapter 2. This chapter also presents some of the work previously conducted in another master thesis in relation to analysis of Ocean Farm 1. In Chapter 3 the analysis is described, presenting the model, the analysis procedure and results of the analysis. The elements of the structure selected for further assessment is also presented in this chapter. Chapter 4 explores the topic of digital twins in relation to exposed and offshore aquaculture structures. A proposal for monitoring of the chosen elements of Ocean Farm 1 by use of sensors is presented, along with use cases for the proposed digital twin of the structure. Chapter 5 contains an overall discussion of the use of digital twins in the aquaculture industry. Lastly, chapter 6 gives a conclusion to the thesis along with suggestions for further work.

Chapter 2

Literature review

Offshore fish farming structures like Ocean Farm 1 are relatively new, and minimal information exists on the topic of digital twins of such structures. Ocean Farm 1 is a unique structure, and there are no standard ways of doing measurements on such a structure. This literature review focuses on the separate topics that builds a digital twin of an offshore aquaculture facility. The searches has focused on comparable offshore structures used in the oil and gas industry, the use of digital twins in various industries, and monitoring policies for offshore structures. First some theory on design and monitoring of marine structures are presented, before sensors relevant for monitoring and use with digital twins are presented. To be able to use a digital twin as a tool for monitoring and portraying of the status of a structure, it needs input from sensors that measure and monitor movements in the structure. Over time, movements can cause damage and failure, and continuous monitoring of the structure can be a valuable tool for prediction of failures, and thereby reduce the probability of it.

2.1 Design of marine structures

2.1.1 Common areas of failure of marine structures

In general, marine structures are subjected to dynamic loads which are caused by wind, waves and current [16]. A typical load history for a member of a given sea-based structure have rapid fluctuations. The cumulative effect of these stresses may initiate fatigue cracks at locations of high stress, typically at weld toes, due to higher probability of micro-defects in these areas [7]. The weld toe is the region of the weld where the welded material meets the weld on the surface of the structure, seen marked as "Saddle or crown" in the picture to the right in Figure 2.1. Cracks caused by fatigue tend to grow with an accelerating speed, which may be hazardous to the structural integrity of the structure [7]. To avoid this there are criteria that needs to be fulfilled and followed in the design and manufacturing process to ensure safe designs. Normally the fatigue design of welded structures are based on SN-curves which are found empirically. The SN-curves give the relationship between the magnitude of cyclic stress and the number of cycles to failure at this stress level for a given material. As it is estimated that 80% to 90% of all mechanical failures are caused by fatigue, it is very important to pay close attention to this from an early design phase throughout the lifetime of the structure. Fatigue processes are difficult to observe and measure, and small cracks often goes undetected by normal inspection methods because they are hardly visible to the naked eye [7]. Over time, fatigue may weaken the members of the structure, and large forces can then cause more damage at a late stage of the lifetime, than when the structure was new.

Tubular joints are a category of welded joints that are used a lot in offshore structures, and typically, they are the most critical parts of a structure. These joints connects the different tube elements of the structure and transfers forces between the main member of the structure, denoted *chord*, and the secondary member, denoted *brace*. In many cases the thickness of the tubes are increased close to the tubular joint, and this thicker part of the tube is for the chord called *can*, and for the brace called *stub*. The location of the maximum stress for a tubular joint tends to be at the *saddle* or the *crown* of the intersection. Which of them experiencing the highest stresses depends on the mode of loading and the geometry of the joint [7]. Figure 2.1 is taken from Berge and Ås [7, p. 201], and is a visual explanation of the terms introduced.

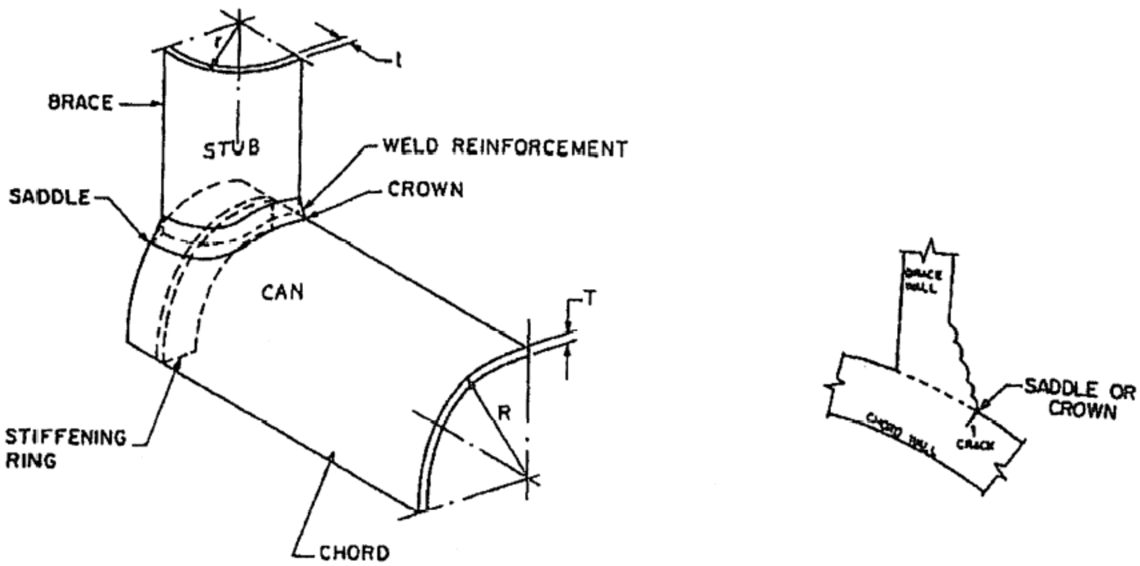


Figure 2.1: Definitions related to tubular joints. Figure by Berge and Ås [7, p. 201]

Tubular members are often used in offshore structures. Berge and Ås [7] gives three main reasons why tubes are preferred for offshore steel platforms. The first is that the due to the circular form of the cross section, small forces are generated from waves and current compared to other types of cross sections. The second is the preferable strength properties, as the uniform cross section gives small stress concentrations and excellent buckling and torsional strength. Offshore structures may experience loads from any direction, and the circular cross section is well suited as the strength properties are insensitive to loading direction. The third is that compared to other cross sectional shapes, the costs for maintenance and surface treatment is lower, due to a smaller area of exposed steel.

2.1.2 Fatigue design of marine structures

There are several approaches to fatigue design, two of the main being "safe-life" design and "fail-safe" design [7]. The safe-life methodology requires that fatigue failure never shall occur. This is applied where fatigue failure of only one component may be catastrophic, an where there is no redundancy in the structure. Redundancy means that even if an individual member of a large structure fails, the remaining parts will have enough structural integrity for the failure to be discovered and repaired, without any threat to the safety of the operation or structure [7]. This means that the structure has the capability of redistributing the load to adjacent members. When the component has reached the end of the expected safe operation life, the component is retired or changed, regardless of the actual state of the component. This is done to ensure a safe operating life, but it is considered conservative and may not be desirable from an economic viewpoint. The fail-safe methodology is used when the structure is required to be redundant, having sufficient reserve strength to tolerate failure of one component. This type of fatigue design requires regular inspections, and repair if needed. Components with multiple load paths are in general fail-safe because they will have structural redundancy. Typical cases where fail-safe design is used are for fatigue in stiffened structures with internal redundancy, such as ship hulls, and for tubular joints in jacket structures [7].

2.1.3 Consequences of failure of aquaculture structures

For aquaculture installations, it is not only the safety of the people working at the location that needs to be taken into consideration. Also the safety and security of the fish is of great importance, in the meaning that it is kept safely in place, and do not escape. For the first production period from September 2018 to January 2019, Ocean Farm 1 contained 1 million salmon, a number that is expected to increase in the next production period [8]. As stated in the introduction, one of the main goals with the development licence program is for companies to develop designs that prevent escape of salmon, as an escape may largely impact the wild stocks of salmon.

For Ocean Farm 1 there is a risk of what would, in the industry, be characterised as catastrophic consequences if the structure fails. A failure of the structure may cause parts of or the whole edge of the net to be immersed under the waterline, or create holes in it, which makes it possible for salmon to escape. An escape has several consequences for the fish farmers, often resulting in fines from the Department for Fisheries and Aquaculture at the Norwegian Ministry of Trade, Industry and Fisheries [3, § 30], expenses related to recapture of the escaped fish, and lost revenues from not being able to sell the fish. If the incident of the fish escape is of severe character, the fish farming company risks losing their licences, and by that lose the opportunity of continued farming after the remaining fish is harvested [3, §§ 27 - 31 a]. In addition to this there will be expenses related to fixing the farm.

2.2 Maintenance policies

Maintenance is in the European and Norwegian Standard for maintenance terminology defined as: "the combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function" [52, p. 8]. Maintenance can be divided into two main categories: corrective and preventive maintenance [58].

2.2.1 Corrective and preventive maintenance

Corrective maintenance is performed to restore a unit back to functional status, after the unit has failed. This type of maintenance is hard to put into a plan, as the exact time of failure is never given. Therefore, corrective maintenance often has an impact on the economy, and safety of both personnel and the environment [58]. It can occur at any time and often without a clear warning prior to the failure.

Preventive maintenance is performed to prevent a unit from failure. There are several regimes for the intervals of this maintenance, one of them being controlled by time. If time controlled, the maintenance is usually based on a fixed time interval between the maintenance actions. The time for the maintenance can be subjected to some adjustment, to ensure the downtime has the least possible effect on safety and economy. A good example, taken from the compendium in RAMS [58], is that the best time to perform preventive maintenance on a ship's engine is during a port stay, when it is not in use.

2.2.2 Condition-based maintenance

Another method used for deciding the maintenance schedule for preventive maintenance is condition-based maintenance (CBM). With a CBM policy, the time of the maintenance action is based on measurements of one or more condition variables that are correlated to a degradation of a component or a system [43]. Maintenance is initiated when the value of the condition variable approaches or exceeds a set threshold value. The condition variables can be either physical variables, system performance variables or variables related to the residual life, which is the remaining life of the system or component. The condition variables can be monitored continuously or on regular intervals [43].

A requirement for CBM is a monitoring system which can provide measurements of the selected condition variables, along with a mathematical model that can predict the behaviour of the deterioration process of the component [43]. Analysis of the measured values forms the basis for development of strategies for monitoring and maintenance of the system. Utilising these values correctly reduces the downtime and costs of maintenance and repair. CBM is facilitated by the rapid development of computer based monitoring technologies, such as advanced sensors [4]. The objective of CBM is typically to determine a maintenance policy that optimises system performance according to certain criteria. A maintenance policy that is relevant for systems with increasing failure rate, is the control limit policy. With this policy the state of the system is divided into different decision areas with different threshold values, where each area represents a specific maintenance decision.

Continuous monitoring is often used for offshore installations and other structures that are working under stressful conditions, because of the safety implications [33]. The offshore industry highly values the safety evaluation and early warning that are made possible with the continuous development of structural condition identification, damage analysis and safety assessment. Continuous monitoring gives the possibility of detecting structural failures before the situation gets severe, and enables safety assessments and performance predictions based on real life data. This data will also give the possibility of calculating the remaining life of a structure more precisely, as it is based on measured values, not general deterioration models. Moreover, field monitoring can verify design parameters and provide a database for post project analysis [61].

2.2.3 Structural health monitoring

For structures, the concept of CBM will compliment what is called structural health monitoring (SHM). Farrar and Worden describe SHM as "the process of implementing a damage identification strategy for aerospace, civil and mechanical engineering infrastructure" [17, p. 303]. SHM involves "the observation of a structure or mechanical system over time using periodically spaced measurements, the extraction of damage-sensitive features from these measurements and the statistical analysis of these features to determine the current state of system health" [17, p. 304]. It can be seen more as the "idea" of implementing a monitoring system that combines a variety of technologies, than a particular technology. By using the information about the health of the structure, a CBM policy can be used to lower the costs and increase the safety, by reducing the downtime for inspections and maintenance [22]. Yan et al. stresses the importance of selecting the right sensors, to ensure sufficient accuracy and reliability of the data [64]. The SHM is dependent on repetitive observations of damage-sensitive features [44], and correct measurements are vital for creating a qualified basis for choices related to CBM.

2.3 Digital twins

2.3.1 Digital twin technology

Grieved and Vickers defines a digital twin as "a set of virtual information constructs that fully describes a potential or actual physical manufactured product from the micro atomic level to the macro geometrical level" [24, p. 95]. Furthermore, Grieved and Vickers states that "at its optimum, any information that could be obtained from inspecting a physical manufactured product can be obtained from its Digital Twin" [24, p. 95]. For this to be possible, the virtual representation must receive information from the physical object. Such information includes environmental conditions and load information for specific areas, that can be analysed to determine the condition of the system and calculate the structural integrity [49].

Cameron et al. [11] defines three types of data that must be coordinated in order to have a well-functioning digital twin. The first is measurements of the system and it's surroundings, to collect useful data for analysis purposes. The second is a description of the configuration and construction of the system, often visualised as a 3D geometric model of the given system. The third data type is simulations and analyses of the system based on the obtained information. The combination of these types of data produces useful information for the users of the system. Figure 2.2 shows the conceptual framework and the interaction between the building blocks of a digital twin.

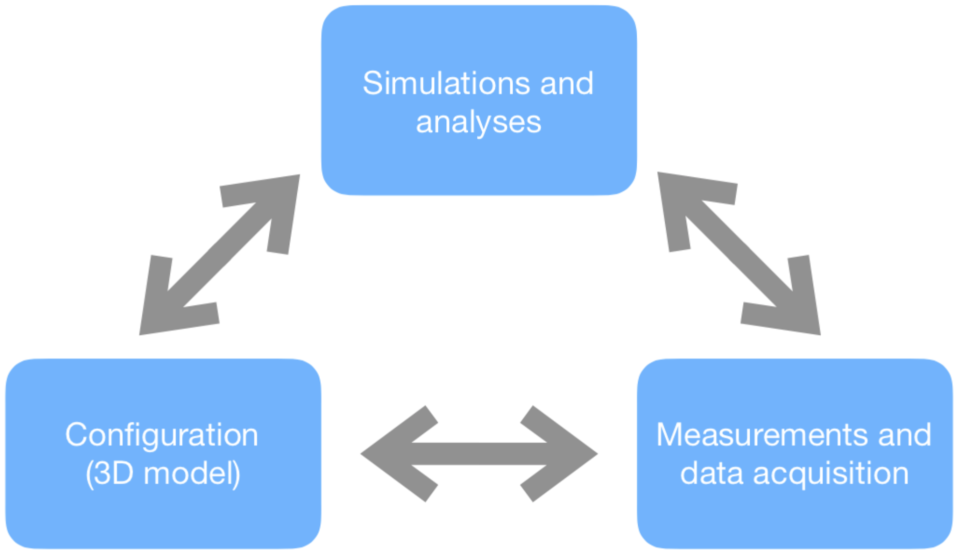


Figure 2.2: Conceptual framework of a digital twin. Adapted from Cameron et al. [11].

Development and implementation of the digital twin technology in the industry is going fast [54]. Digital twins can enhance all the stages of a system's life [49], from the early stages of the concept and design, through the engineering, production and construction processes, during the operational life, the retirement and decommissioning [11, 24]. This gives a great variety of use cases for digital twins. They can be used for monitoring of ongoing processes by visualising and updating the real-time status of the object [54]. A digital twin can in the conceptual design phase give a quick overview of relevant data, and enable communication between customers and designers, and thereby be beneficial from the very start of the process [11]. It can facilitate adjustments of operating processes, test ideas or changes ahead of the action actually taking place, and also during the design phase. Human operators can use digital twins for decision support when monitoring complex production processes, or use them for production optimisation [54]. The use cases are almost never ending, and a lot of research is currently done related to digital twins, both for offshore oil and gas production, ships, and some research also explores the aquaculture industry. Rosten et al. presents the importance of autonomy and digital twins for the future of manufacturing [45]. Schleich et el. addresses model conceptualisation, representation, and implementation of digital twins, as well as applications along the product lifecycle [49]. As mentioned in the introduction, the Norwegian project SFI Exposed is planning on doing research related to real-time condition monitoring and operation support, and structural analysis of offshore fish farms, which both are important building blocks of a digital twin [9].

At the same time as having large potentials, a successful digital twin is a very complex system, and requires correlation between the structured data from design, measurements and simulations, and unstructured data from logs and documentation. In the variety of simulations and analyses possible, it is important to decide what is the wanted outcome and focus of the simulation, to minimize unnecessary information handling and processing. As an example, in the case of monitoring the structural integrity of a system, it is important that a structural simulation is carried out [11]. Or, when monitoring the state of rotating equipment, analysis tools that detects unwanted events in vibration and temperature data should be in focus.

2.3.2 Use of a digital twin for CBM

As introduced, a digital twin requires input data from measurements to be able to monitor and do simulations on the real structure [43]. These input data usually originate from sensors installed on or in connection with the structure [4]. The recent evolvements in sensor technology enables live communication of data concerning the operating condition of the real structure. Data is sent immediately from the sensors to advanced analysis tools integrated with the digital twin [49]. The same data, when processed, can be used for condition-based maintenance and structural health analysis. These policies and the technology of digital twins have the possibility of complementing each other throughout the lifetime of the structure.

2.4 Review of sensors for monitoring of structural movements

The remaining part of this literature study will mostly concern different types of sensors relevant for monitoring the structural integrity of offshore structures, which are also compatible with digital twins. By being compatible it is meant that the sensor is able to transmit the measurements and signals immediately. The types of sensors and the data measured and sent from the specific sensor will be addressed. In addition, relevant rules and regulations for Ocean Farm 1 will be presented.

2.4.1 Field monitoring of offshore structures

Field monitoring of offshore structures enables direct obtaining of raw data in real time, which again enables timely detection of structural failures, safety assessments, and predictions of performance change and remaining structural life. The use of specialised monitoring systems to reduce failure risk has been enabled through field monitoring which collects real-time data and feedback information from the structure [61].

A field monitoring system for offshore structures should provide a comprehensive understanding of structural dynamic behaviour to enable calculation of the accumulated damage and to assess the overall safety status of the structure. To do this, tracking and feedback information on metocean, structural motions, and operational status needs to be obtained. This requires sensors with satisfactory performance to ensure reliability of monitoring systems [61].

2.4.2 Use of sensors for collection of data/information

To be able to utilise the possibilities a digital twin provides in relation to monitoring and maintenance, data from the structure needs to be provided for the digital twin. This is done by installing sensors that monitor the relevant parameters, and share the information they acquire. The network of sensors constitutes a monitoring system, which primary function is to provide real-time information about the system [61]. When this information is implemented in a digital twin that contains programs and analysis tools that can structure the data, it can be presented in a clear and easy way.

Over the last 10 years, wireless communication and sensing technology has developed in a way that allows for monitoring of various types of structures using wireless sensor networks. A wireless sensor network consists of heterogeneous sensors which can communicate with its neighbours and thereby provide a set of physical data from its environment. The sensors are usually battery powered, and thus, have no cables or wires attached to them. This simplifies the installation of the sensor system, and thereby reduces the costs, compared to installing sensors that depends on wired connection to transfer data [12]. Chatzi and Papadimitriou discusses the advantages of using wireless sensor networks for monitoring of structural response [12]. Wireless sensor networks are particularly well suited when the sensors are only required to provide output data, as is mostly the case when monitoring structural response to environmental conditions.

2.4.3 Sensors for monitoring of structural motions

This subsection presents some of the most common sensors used for monitoring of global structural motions of structures located in the sea. The monitored parameters includes position, orientation and inclination of the structure.

A *real-time kinematic* (RTK) system is used to measure the position of a structure, and is an enhancement method for GPS accuracy. It is a satellite navigation system used to increase the precision of position data, and the system is based on having a fixed base station at a location away from the structure that is monitored. It consists of the base station, a satellite, and one mobile unit, which calculates the position from comparison of its own measurements and measurements from the base station. It executes high precision in monitoring of the six degrees of freedom of a structure. This results in a very high precision, with an accuracy of 1 cm ± 2 ppm horizontally and 2 cm ± 2 ppm vertically [31].

Common on board systems for monitoring of inclination and orientation are *differential GPS* (DGPS), *gyroscope*, *accelerometer* and *internal navigation system* (INS) [61]. The DGPS is, like the RTK system, an enhancement of GPS, which improves the accuracy of the position measurement. It is based on having stationary reference stations with known position that calculates a correction value for each GPS satellite, and communicates this value to all GPS devices with DGPS receivers within reach [38].

The gyroscope and accelerometer are sensors measuring movements of the structure it is located at. The gyroscope is a physical sensor that detects and measures the angular motion of an object, and the accelerometer measures the acceleration. The INS uses all of these inputs to continuously calculate roll, pitch, heading, position, and velocity [47], but the measurement data can also be used individually. Relevant characteristics of the sensors are summed up in Table 2.1.

Table 2.1: Common sensors used for monitoring of structural motions. The table is adapted from Wang et al. [61].

Measured parameter	**Specific Sensors**	**Characteristics**
Position, motions of 6 degrees of freedom	INS, DGPS and RTK	Accurate at the centimetre level, but susceptible to interference
Linear displacement	Accelerometer	Based on Newton's second law
Orientation, angular velocity	Gyroscope	Orientation of this axis is unaffected by tilting or rotation of the mounting
Static inclination	Angular rate sensor	Also known as mechanical gyroscope

2.4.4 Sensors for monitoring of structural integrity

The majority of structural monitoring is conducted to ensure safe conditions for the workers, and continued operation. Especially important is the structural integrity of the structure, as it affects both of the previous mentioned factors. Offshore structures will be exposed to many loads during the lifetime, especially oscillatory movements, which over time causes deterioration. Fatigue and corrosion of structures are some of the most important causes of deterioration [1]. Monitoring and early detection of damage is crucial for safe operation. This subsection presents some of the most common sensors for monitoring of structural integrity. There exists a variety of sensors, with some operating offline and some online. For use with digital twins, online sensors that are able to transmit signals immediately are the type that will be most useful, and are therefore in focus.

A *strain gauge* is the most common instrument for measurement of strain in an element. It is based on the principle that the electrical resistance in a conductive wire changes when the wire experiences strain, which happens when it deforms [6]. The conductive wire is laid in a pattern on an insulated flexible foil, and attached to the element with an adhesive. It measures both tension and compression of the element it is attached to, dependent on the form of the deformation. The size of the strain gauge is usually between 4 and 12 millimetres, and it measures the strain with an accuracy of $1 \cdot 10^{-6}$. A strain gauge measures the strain in only one direction, and are usually installed in a set of three, called a rosette, to be able to capture the full strain condition. The change in resistance is measured when the element deforms, and is converted to a mean strain through calculations. The most common instrument for measuring the change in resistance is called a Wheatstone bridge, which is an electrical connector designed for measuring the resistance of an unknown resistance [25]. The resistance of the wire increases when the strain gauge is stretched, as the wire then becomes thinner and longer. The resistance decreases when the strain gauge is compressed, because the wire then is thickened and shortened.

Fiber-optic sensors has a wide range in the areas of application. They are ideally suited for subsea applications and have many positive sides. Fiber-optic sensors have high multiplexing capability, immunisation to electromagnetic interference, little signal loss, are small in size, have high resistance to dynamic fatigue, and corrosion resistance. Examples of use cases for fiber-optic sensors are measurement of strain, temperature, vibration and pressure [53]. Wang et al. [61] emphasises the large possibilities of the fiber-optic sensors for multi-parameter measurements, and states that this should be in focus for future research as use of this type of sensor for such measurements are relatively new. The company Scaime, a specialist on structural monitoring, have used fibre-optic weight sensors for monitoring of the net of fish farms by continuously controlling the tension exerted on the net attachments [48]. This specific sensor must be connected to an external monitoring unit to be able to send the signals.

A direct method of monitoring the tension in the mooring lines is by placing *load cells* underneath the base of fixed chain stoppers. This is a good method, but it is highly inaccurate for monitoring of the friction in the fairleads [61]. The load cells measures the change in load which are used to calculate the tension in the mooring line. The tension in the mooring lines can also be found by the use of *inclinometer-based* tension calculation. This method derives an approximation for the tension in the mooring line by measuring the angle of the mooring line at or near the top point where the line is connected to the structure [61]. An inclinometer should be installed as close to the mooring line's attachment point to the structure as possible, and measures the angle with respect to gravity [28].

Tiltmeters, which is a type of inclinometers, are used for monitoring of surface deformation of the structure. Tiltmeters are designed to measure very small changes from the vertical level, and does this by measuring the deformation gradient. The real deformation is obtained by integration of this gradient [61]. The tiltmeters are large compared to other types of sensors, and it is therefore a limited number of places it can be located.

DGPS have several other areas of application in addition to monitoring position of a structure. The use of an accurate position monitoring system based on DGPS for monitoring the tension in the mooring lines, can be very cost-effective. With appropriate software and data analysis, this system can give information on both the mooring performance and potential mooring line failure. DGPS can also be used for monitoring surface deformation. It is not as precise as tiltmeters, but gives very good results [61].

InSAR is a third way of measuring the deformation of the structure surface, and specifically the vertical deformation. InSAR stands for Interferometric Synthetic Aperture Radar and it is a radar imaging system that transmits microwave signals through a SAR antenna on board of a satellite which illuminate targets on the surface. The deformation is found by measuring the distance from the satellite to a specified point on the structure, and comparing the values over time. Matori et al. tested an enhancement method for InSAR called Persistent Scatterer Interferometry (PSI), which gave good results and millimetre accuracy of estimations of structural deformations [34]. This technique improves InSAR by using a large number of SAR images over the same area. A comparing of the different methods for monitoring of deformation was done by Wang et al. [61], and the information is adapted and extended in table 2.2.

Table 2.2: Characteristics of different deformation monitoring techniques. The table in adapted from Wang et al. [61].

Deformation of monitoring techniques	**Advantages**	**Weakness**
Tiltmeters	• Excellent monitoring precision • Near real-time data feedback • Relatively low cost	• Array design of the tiltmeters needs to be considered carefully • Some types of tilt sensors suffer from drift-tilt, which causes accumulated error
DGPS	• Monitors deformation in three dimensions • Good robustness • Continuous data are available	• Provide monitoring only at a single point • Requires cloudless weather
InSAR with PSI	• Can cover large areas • High precision	• Relatively high cost

2.4.5 Sensors for monitoring of metocean parameters

Metocean parameters include wind, waves, currents, and sometimes also internal waves and ice, and the combination of them [16, 61]. A structure situated in the ocean can experience large structural responses when subjected to extreme environmental loads, and therefore it is essential to monitor the metocean parameters that may influence the operations. This subsection presents some of the most common sensors and methods for monitoring of metocean parameters.

Anemometers are used for measurements of both wind direction and wind speed. There are several types of anemometers, and Wang et al. presents four different types [61]. The anemometers work in slightly different ways, but common for most of them is that the measurements are obtained from a moving part of the sensor, for example rotating vanes or blades, or deflecting cantilevers. Some of them, as the hot wire anemometer, utilises changes in material resistance due to heat transfer for measurement of the flow rate [63]. The anemometer should be placed so that the wind passing it is not disturbed by the structure it is positioned at [31]. Table 2.3 is adapted from Wang et al., and is extended for additional types of sensors to give a better understanding of the different anemometers.

The first four anemometers presented in Table 2.3 are well known and has been used for many years, while the *Atmospheric Laser Cantilever Anemometer* (2dALCA) anemometer is relatively new on the market, and was used for the first time in an onshore test in 2012 [27]. It is based on measurements of the deformation of a small cantilever located on the tip of the anemometer. Jeromin et al. [27] compares the 2d-ALCA to the hot wire anemometer, and among others point out the advantage of the 2d-ALCA being insensitive to temperature as a major advantage of the 2d-ALCA over the hot wire. The 2d-ALCA was designed specifically to withstand the rough offshore environment, and can therefore operate autonomously. Based on the test from 2012, Jeromin et al. concludes that the 2d-ALCA gives more detailed results than any other available anemometer used for wind energy applications.

Table 2.3: Properties of the parameters of different types of anemometers. Adapted from Wang et al. [61] and extended.

Anemometer type	**Working principle**	**Wind speed (m/s)**	**Accuracy (%)**	**Remarks**
Vane	Based on rotational speed of a vane	≥ 3	1.5	Low cost and little maintenance
Hot wire	Based on measured current and resistance	1-9	5	Low accuracy and need to adjust the temperature
Ultrasonic	Based on frequency of a vortex	1-25	1.5	High reliability and stability
Hall effect	Based on change in voltage	0-20	1.1	High precision and wide application range
2d-ALCA [27]	Based on measurement of deformation of a cantilever	1-100 [42]	-	Highly resolved measurements [42]

Acoustic Doppler current profilers (ADCP) measures deepwater current profiles. This includes speed, direction, spatial distribution of sediments or plankton carried in the water, and range to boundary for the many levels through the water column. It uses sound to explore the environment by emitting a sound signal, which returns due to scattering of particles in the water. Analysis of the returned signal gives a description of the currents [50]. Wang et al. presents three different types of ADCPs, classified by the frequency at which the ADCP operates. The three types are summarised in Table 2.4. By combining several ADCPs with different ranges, and placing them in different depths in the water column, they can give details of the currents at depths up to 3000 meters [61]. The ADCP should be placed under the sea surface, and the signals can be transmitted both via a data cable or wireless [31].

Table 2.4: Properties of different ADCPs.

ADCP type	Signal frequency [kHz]	Range [m]
Ocean Surveyor (OS)	38	1100
Long Ranger (LR)	75	750
Horizontal (H)	300	200

A *wave buoy* measures significant wave height, wave peak period and wave direction by the use of several sensors such as motion reference units and DGPS. It also contains units for storage and processing of data, and a transmitting antenna for transfer of the sensor data [31, 61]. A wave buoy can be placed far from the structure it is installed in connection with, to avoid the measurements being contaminated by the waves reflected and generated by the structure. It has high accuracy, but is also expensive and requires maintenance throughout the lifetime, which makes it less suitable for a long lived installation [15].

An *X-band radar* measures several wave parameters, such as height, period and direction. The X-band radar scans the surface and can estimate the directional wave spectra for several kilometres based on the data obtained in the area it is installed [61]. It measures the sea state based on digitised sea clutter images, by analysing the temporal and spatial changes of the backscatter from the sea surface. It can also analyse the data to obtain surface current information. The X-band radar can be large in size, and might therefore be difficult to install on an aquaculture farm. Table 2.5 gives a summation of the two different wave measurement methods presented.

Table 2.5: Comparisons between the different wave measurement sensors. Adapted from Wang et al. [61].

Type	Working principle	Measurement	Measuring range	Resolution	Remarks
Wave buoy	MRU based or GPS based	Wave height Wave period Wave direction	-20 - 20 m 1.5 - 33 s 0 - 360 °	0.01 m 0.1 s 1°	High accuracy, high cost and maintenance
X-band radar	Operated in short pulse mode, measures the sea state from digitised sea clutter images	Wave height Wave period Wave direction	0.5 - 20 m 0 - 360° 3.5 - 40 s	0.1 m 1° 0.1 s	High reliability and stability

2.5 Optimisation of sensor placement for monitoring

Wang et al. [61] also gives an introduction to design of monitoring systems for offshore structures. They state that the most important factors for an efficient and reliable monitoring system is good stability, durability, compatibility and credibility performances. It is also of great interest to reduce interference on the structure. The following list summarises the most important factors to take into account when deciding the location and number of sensors for a monitoring system. It is based on the findings in the paper by Wang et al. [61], and is here classified into four types.

- Damage: the location where damage is most likely to occur should be evaluated, and the monitoring should focus on these locations.
- Optimisation: the optimal location of the sensors should be calculated with an optimisation method to ensure sufficient extent of the sensors to capture the entire mode of response.
- Connection: the connection between the different apparatuses of the monitoring system should be within an easy reach to ensure fast and easy data transmission and power supply, if needed.
- Installation: the location at which the different apparatuses is installed, should exhibit the most appropriate conditions for the given parameter to monitor.

2.6 Rules and standards applying to Ocean Farm 1

The internationally accredited registrar and classification society DNV GL has been involved in verification and certification of Ocean Farm 1 [46]. DNV GL released the first edition of "Rules for classification of Offshore fish farming units and installations" in July 2017, and an updated version was released in July 2018 [14]. As these rules were created and written parallel with the development of Ocean Farm 1, and DNV GL was the company responsible for the classification of Ocean Farm 1, this set of rules should be used when addressing the rules that apply for the structure. The most important standards and regulations that applies is the Norwegian standard for aquaculture facilities "NS9415.E:2009 Marine fish farms - Requirements for site survey, risk analyses, design, dimensioning, production, installation and operation" [51], and the Norwegian regulation "Forskrift om krav til teknisk standard for flytende akvakulturanlegg", on short term called NYTEK [40].

The DNV GL rules is specified intended for "... classification of offshore fish farming units or installations of conventional designs fabricated in steel or other metallic material" [14, p. 23]. The rules are made to ensure safe conditions for all involved personnel from the design phase and start of fabrication, throughout the lifetime of the structure. It is also stated in the rules that: "The interpretations are not aiming at introducing additional requirements, but at achieving uniform application of the principal requirements. The interpretations can be regarded as norms for fulfilling the principle requirements." [14, p. 24]. The rules are intended for use where classification is part of the certification process for meeting national requirements. When a structure is classified by these rules, it is assured that internationally accepted principal requirements are met, but it can not be assured that it meets all statutory requirements [14].

The following list is taken from the DNV GL rules [14, Ch. 3 Sec. 2 1.1.2, p.38], and lists the discipline areas covered within the class *OI Offshore fish farming installation*. This class is specified for non self-propelled fish farming unit intended for long time service and permanent positioning, which is the class applying to Ocean Farm 1.

- safety principles and arrangement
- materials
- hull design and construction
- mooring
- stability, watertight and weathertight integrity
- utility systems and equipment related to marine and safety functions
- electrical systems and equipment related to marine and safety functions
- instrumentation and telecommunication systems related to marine and safety functions
- fire protection

The classification is done based on four main activities, being approval of the design, certification of materials and components, surveys during construction and installation, and survey during commissioning. In addition the structure is surveyed regularly during the whole operational life [14].

2.7 Relevant previous work on analysis of Ocean Farm 1

Several previous students at the Department of Marine Technology at NTNU has done work related to Ocean Farm 1. The most recent study, and the study of most importance for this thesis, was by Bore and Fossan in their master thesis "Ultimate- and Fatigue Limit State Analysis of a Rigid Offshore Aquaculture Structure" from 2015 [10]. Their thesis has been of great help in the execution of the structural analysis in this thesis, and was of great help in the preparation phase for the analysis.

Their fatigue limit state analysis was conducted for 7 joint members, each of the joints located above the 7 pontoons. They discussed how a member that was not included in the analysis might be more critical with respect to fatigue, but regardless, they stated they were confident that at least *some* of the most critical elements are included. The results from their analysis shows that in general, the most critical members with respect to fatigue are the intersection points between the bottom radial beams and the vertical columns. The most utilised members found in the ultimate limit state analysis where spread over the whole structure, but common for the location of these elements is that they are located close to a joint. The visual representation of their results are included in Appendix B, where Figure B.1 shows the 14 most utilised members of the structure and Figure B.2 shows the 10 most damaged elements of the structure. They were found from the ultimate- and the fatigue limit state analysis respectively.

Chapter 3

Analysis of Ocean Farm 1

This chapter explains the steps of the analysis carried out to analyse the USFOS model of Ocean Farm 1. It presents the structure and the analysed model, description of the analysis, and the results. Lastly, it contains a discussion of the results and presents the choice of elements for further use.

3.1 Design and modelling of Ocean Farm 1

3.1.1 Introduction to the design and model of Ocean Farm 1

Ocean Farm 1 is an offshore production unit for Atlantic salmon. The idea behind it was to create a concept that is robust enough to be installed and operated in exposed waters. It was initiated by SalMar, one of the largest salmon producers in Norway, who teamed up with several experienced Norwegian companies. Global Maritime, a marine offshore and engineering consultancy company, have been responsible for design and system integration of the structure [46]. The structure has a lifetime of 25 years, and is designed to withstand the forces that are assumed to occur during this time period. The model of Ocean Farm 1 used for analysis in this thesis is based on drawings and information from Global Maritime. The model was created by Bore and Fossan for their master thesis in 2015 [10], and has undergone some modifications and improvements by Bore in his doctoral thesis in the recent years.

The program used for analysis of the structure is called USFOS. USFOS is a finite element program for non-linear static and dynamic analysis, and is mostly used for analysis of space frame structures, like jackets [57]. When running an analysis, USFOS reads a text file containing the information about the configuration of the structure, along with a control text file defining the analysis. The file containing the model information is generated through a MATLAB script, and this script was created by Bore and Fossan [10].

The model as displayed in USFOS is presented in Figure 3.1. It is not a completely correct replica of the real structure, but it is close enough to give reliable and valid results. Small adjustments and changes has been made to some parts of the model compared to the drawings, to be able to model the elements with the correct strength properties. This has resulted in some altered thicknesses of some elements, most importantly of the mooring lines. Bore and Fossan concluded that the changes did not affect the results significantly [10].

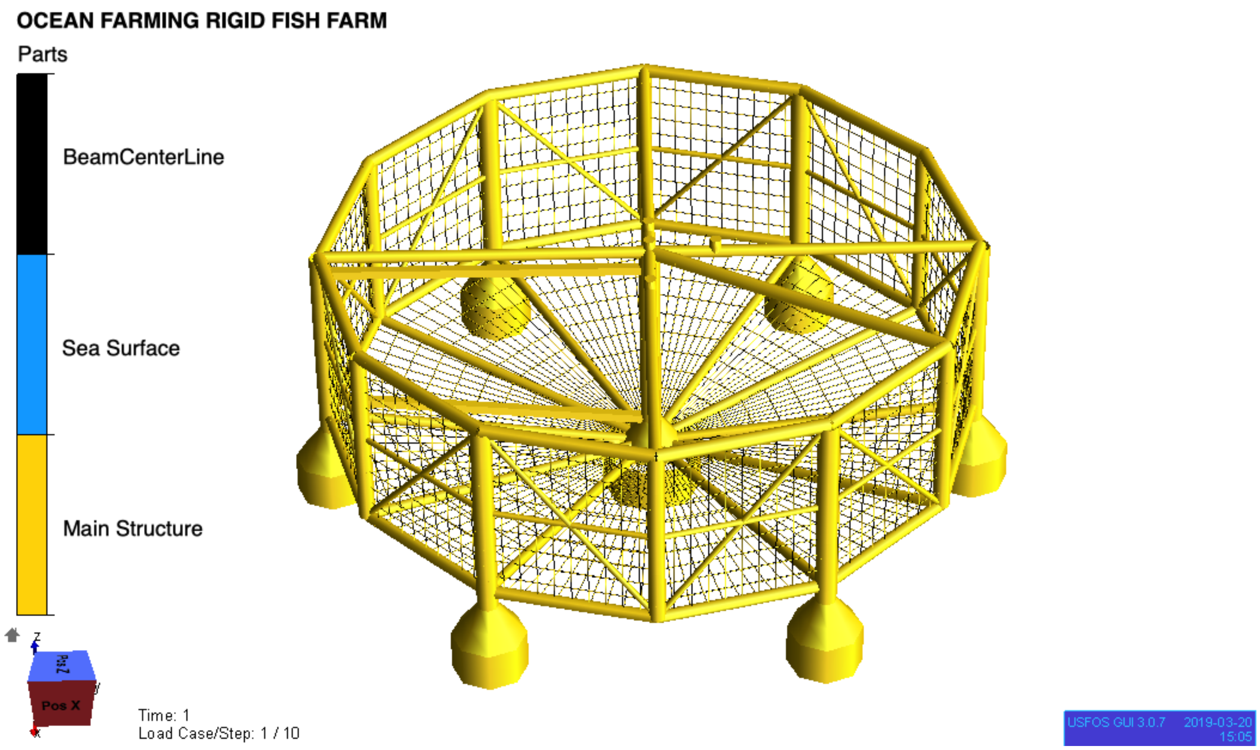


Figure 3.1: The model of Ocean Farm 1 as displayed in USFOS. The sea surface is not displayed.

Ocean Farm 1 is cylindrically shaped, has a frame with twelve sides, and a net that is attached to the sides and the bottom. This makes up the hull, which is designed to withstand environmental forces, support the superstructure and the net, and ensure stability and minimal motions. The hull is made up of several circular beams, and the circular cross section is, as described in section 2.1.1, preferred due to its favourable strength properties. The structure is ensured adequate buoyancy through seven pontoons that are located at the lowest part of the structure, six under the outer columns and one under the center column. The hull includes all columns, braces, beams and the pontoons. Ocean Farm 1 also has a superstructure, which is the wheelhouse, that contains rig controls and living quarters. It is not included in the model as it does not contribute to the structural strength of the structure. The most important main dimensions of the structure, as specified in the structural drawings from Global Maritime, are listed in Table 3.1.

Table 3.1: The main dimensions of Ocean Farm 1, as presented by Bore and Fossan [10].

Dimension	**Value**	**Unit**
Diameter	110.0	[m]
Circumference	341.6	[m]
Overall height (excl. superstructure)	50.8	[m]
Height vertical outer columns	33.0	[m]
Height outer pontoons	13.0	[m]
Height center pontoon	7.0	[m]
Diameter outer pontoons	12.0	[m]
Diameter center pontoon	17.0	[m]
Operational draft	43.0	[m]
Volume net (approx.)	245000	[m^3]

As presented in the literature survey, joints are known to be weak parts of an offshore structure. The joints are likely to be subjected to fatigue and cracks at an earlier stage than the other members of the structure [7]. For Ocean Farm 1, the joints are designed and produced with a larger thickness than the tubular beams they are connecting. This is most likely done to avoid, or at least reduce, fatigue and increase the strength of the joints. The transitions from joint elements to tubular beam elements are not captured fully correct in the model, as it is not modelled detailed enough to so, but it is sufficient for the analyses carried out. To capture this fully, a separate model of only the joint must be modelled and analysed.

Bore and Fossan had to change some of the beam thicknesses when modelling, and specified their focus when modelling in 5 points [10]. Summed up, their focus was on modelling the diameter, thickness, and weight of the members as correctly as possible, with critical parts as the joints in 100 percent accordance with the structural drawings. For beams with sections of different thicknesses, an equivalent thickness was introduced to the whole beam to give the correct weight, and this was also applied to the pontoons as they consist of internal bulkheads and stiffeners. Figure 3.2 displays the thicknesses of the different elements of the structure as modelled in USFOS.

The structure is built in NV-36 steel. This steel type is common for offshore structures, and is by DNV GL classified in the strength group "High strength steel (HS)" [13]. The material data for this steel type is presented in Table 3.2.

Table 3.2: Material data used for the hull structure elements [10].

Property	**Symbol**	**Value**	**Unit**
Modulus of elasticity	E	210	[GPa]
Yield stress	σ_y	355	[MPa]
Poisson's ratio	ν	0.3	[-]
Density	ρ	7850	[kg/m^3]

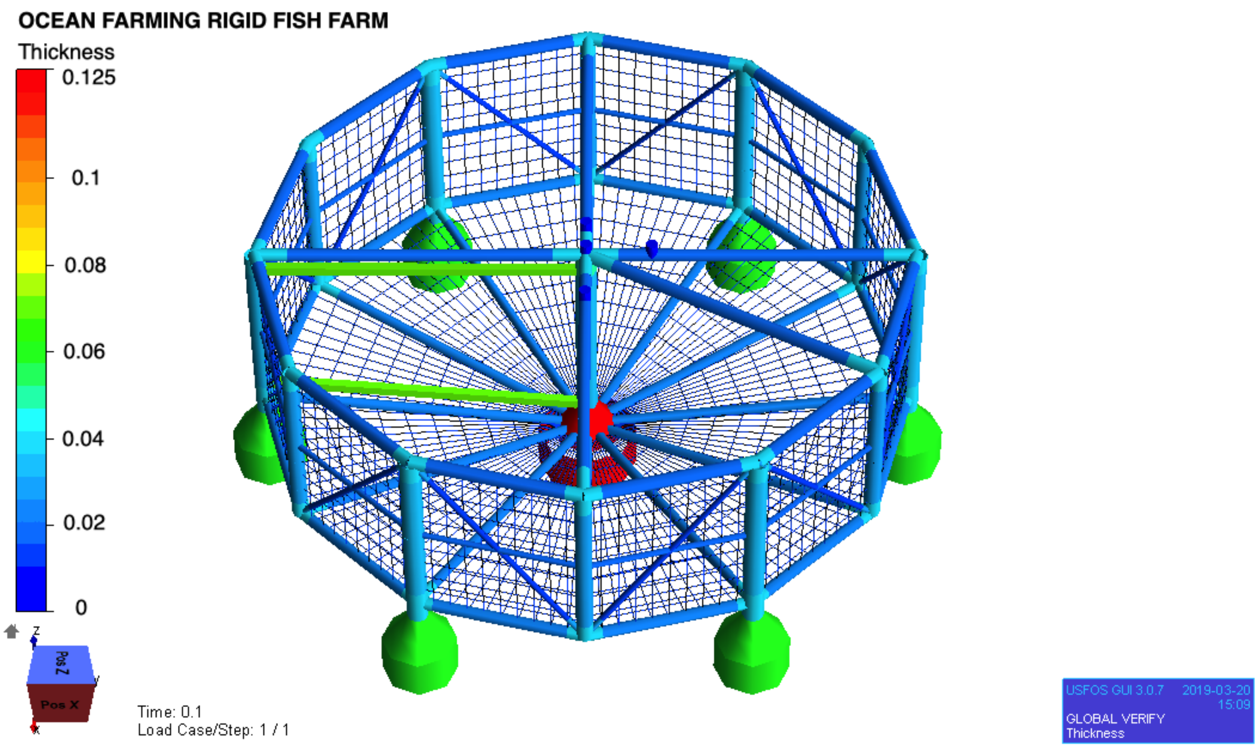


Figure 3.2: The thickness of the different elements of Ocean Farm 1, displayed in different colours.

3.1.2 Design and modelling of the mooring lines

Eight mooring lines, symmetrically attached to the hull with 45° angle between each line, ensures that the structure does not drift off. The mooring system is a catenary system, comparable to the mooring layout typically used for semi-submersible platforms [10]. The layout is seen from a top view in Figure 3.3, with numbers indicating the number of each mooring line. The mooring lines are attached in pairs to the hull, at the top of four of the six outer pontoons. In a catenary system the mooring lines arrive at the seabed horizontally, and the anchor points are only subjected to horizontal forces [60]. The mooring lines of a catenary mooring system are usually made of chain or steel wire, and for Ocean Farm 1 the main part of the mooring line is made of chain, with a shorter section of fibre rope at the end closest to the structure [10]. The total length of the mooring lines are 1100 meters. The profile of the catenary mooring system is shown in Figure 3.4. The most important properties of the mooring lines are given in Table 3.3.

Table 3.3: Properties of the mooring lines [10].

Property	**Chain**	**Fibre**	**Unit**
Length	1000	100	[m]
Diameter	88	160	[mm]
Axial stiffness, EA	681	235	[MN]
Submerged weight	147	4	[kg/m]
Minimum braking load, MBL	7051	8123	[kN]

The modelling of the mooring lines has been done in a simplified manner, as USFOS has no built-in option that allows easy modelling of mooring lines. They have been modelled with tubular beam elements. Bore and Fossan explains how this was done: "The geometry and mechanical properties of these beam elements were chosen to best match the properties of the real mooring lines. For the chain part of the mooring line, an equivalent diameter was used, giving the same cross-sectional area as the typical chain cross-section. Since the mooring lines are modelled as tubular beams, a thickness must also be given. The density is calculated so that the lines will have the same submerged weight as specified, and the yield strength is taken as the axial stress over the cross-section area giving the specified minimum breaking load (MBL)." [10, p. 58].

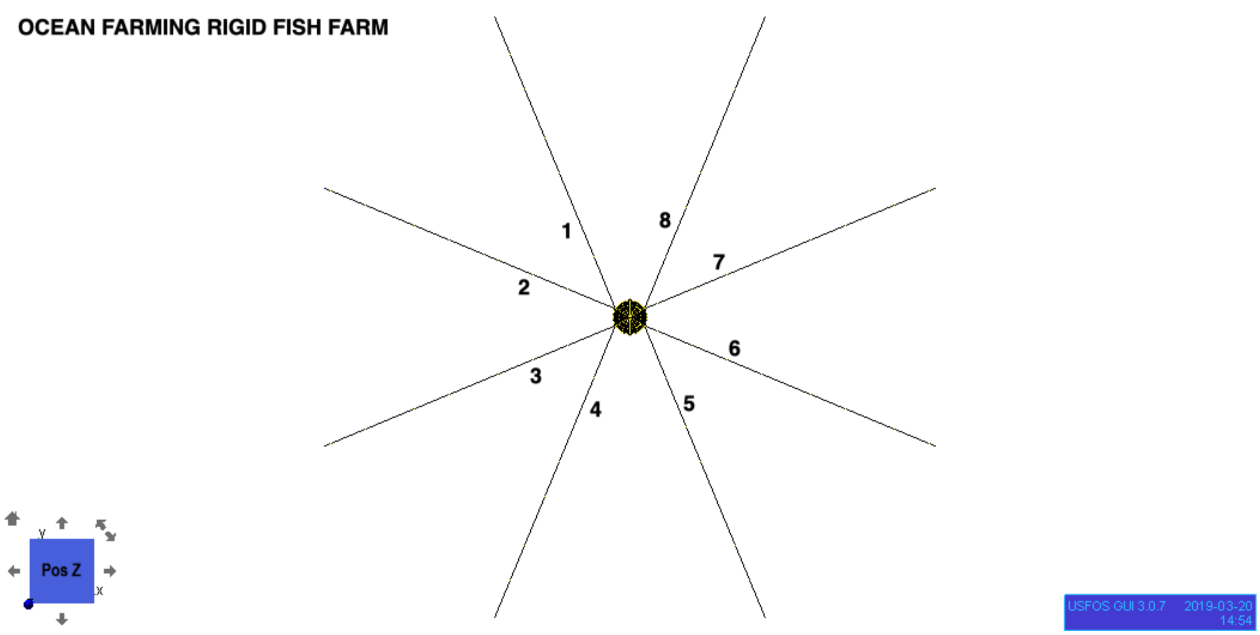


Figure 3.3: Top view of the Ocean Farm 1 model showing the symmetrical mooring layout. The mooring lines are marked with numbers.

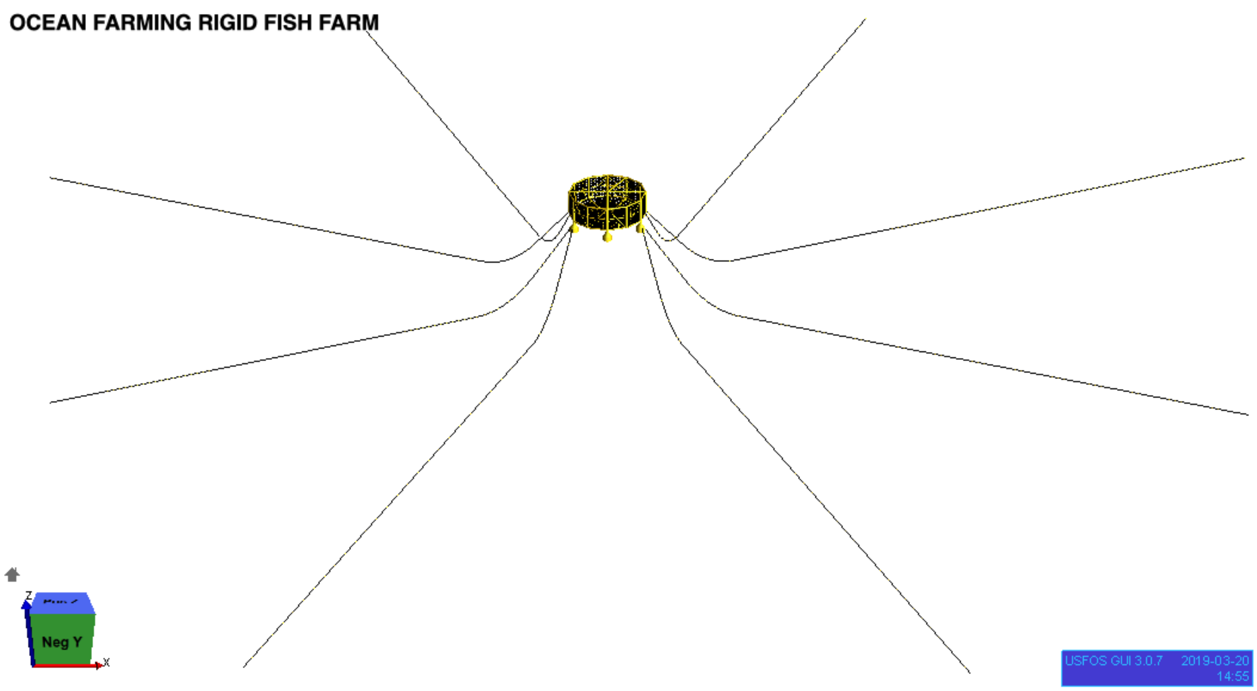
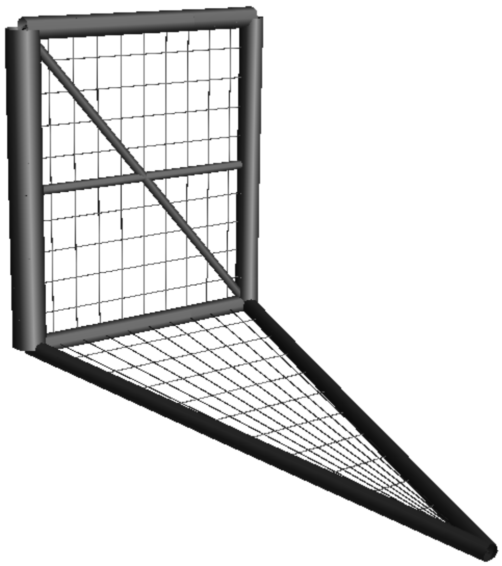


Figure 3.4: Overview of the model showing the catenary mooring system.

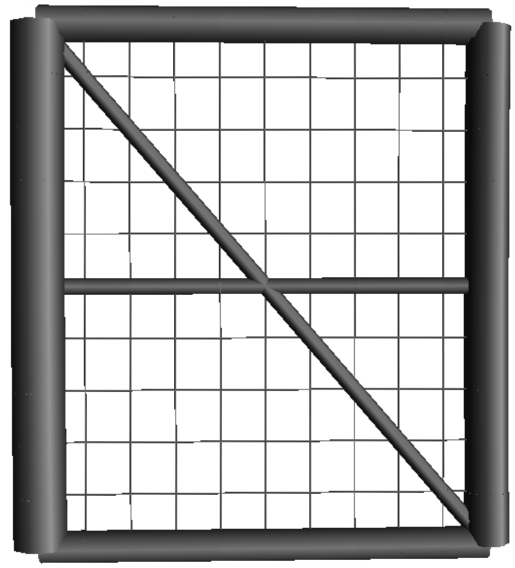
3.1.3 Design and modelling of the net

The net is a critical and very important part of the structure, as it is the part that keeps the fish in place and predators out. For Ocean Farm 1, *EcoNet* from AkvaGroup is used for the netting [10]. The EcoNet is a semi-rigid structure made from the strong and lightweight material polyethylene terephthalate (PET). This material is stiffer than the conventional fibre nets used for nearshore farming, which significantly reduces the deformation of the net due to environmental loads. Some of the advantages this net has over conventional nylon fibre net is that it can stretch about 1.5 – 1.7 longer than nylon before it breaks, and it is designed to remain intact if a wire is cut [2]. It is certified by the Norwegian Standard 9415 (NS9415) to stay in the water for up to 14 years. On their web site, Akvagroup states the lifetime to be at least 20 years [2]. Nevertheless, this means that the net is likely to have to be changed one time during the assumed 25 years lifetime of the structure. The mesh size of the EcoNet installed at Ocean Farm 1 is 35-by-43 millimetres with hexagon shaped meshes.

In an analysis, this fine mesh size increases the computational time drastically, and the net is therefore modelled with a larger mesh size than in reality, as can be seen in Figure 3.5. In the model the mesh is square with the size 3.3-by-2.8 meters at the vertical sides of the structure, seen in Figure 3.5b. This corresponds to 10-by-10 elements. In the bottom part of the structure the net mesh also consists of 10-by-10 elements, with decreasing mesh size towards the center column. This part of the net can be seen in Figure 3.5a. The force in the net in the model is equivalent to the forces in the fine meshed real net. It is equivalent in the meaning that force divided by area gives the same result.



(a) The net at 1/12 of the structure.



(b) The net wall of 1/12 of the vertical part of the structure.

Figure 3.5: The net as modelled in the USFOS model.

3.1.4 Behaviour of the structure

The characteristic behaviour, or motions, of a marine structure is described by six degrees of freedom, three translations and three rotations. Ocean Farm 1 has several similarities to a semi-submersible platform, and just like it, is based on having a large mass relative to the water plane area. The resonance periods can be calculated by Equation 3.1, and for the heave motion of a semi-submersible it can be specified as in Equation 3.2 [16, p. 69]. In Equation 3.2, A_w is the waterplane area, and the common design procedure is to require natural periods in heave, pitch and roll to be larger than $T = 20$ seconds [16]. Relative to most wave periods at open sea, this is a high natural period, which reduces the chance of experiencing large excitations of the structure due to resonance. From Equation 3.2 it is seen that a high natural period can be achieved by a small waterplane area, which is the case for Ocean Farm 1.

$$T_{ni} = 2\pi\sqrt{\frac{M_{ii} + A_{ii}}{C_{ii}}} \tag{3.1}$$

$$T_{n3} = 2\pi\sqrt{\frac{M + A_{33}}{\rho g A_w}} \tag{3.2}$$

Bore and Fossan investigated the natural periods of the model of Ocean Farm 1, and found that the lowest natural period was the period in heave. This is the only natural period that is close to 20 seconds. All natural periods are displayed in Table 3.4, and they are all above 20 seconds. Therefore, it is not likely that the structure will experience excitation due to the first order wave forces [16]. However, non-liner second order wave forces from wave drift loads and wind gusts can cause resonance, but that is not investigated further either in this thesis, nor in the master thesis of Bore and Fossan.

Table 3.4: The natural periods of the model of Ocean Farm 1. Table adapted from Bore and Fossan [10].

Motion	**Period [s]**
Surge	209.2
Sway	204.0
Heave	26.8
Roll	37.8
Pitch	36.3
Yaw	180.2

3.2 Description of the analysis

The analysis that has been carried out is a selective global response analysis in time domain. A full global response analysis is investigating the ultimate limit state of the structure, and is a very time consuming analysis. This selective analysis has been chosen as analysis method due to both time limitations and requirements for the accuracy of the result. It is a selective analysis as it investigates the response of the structure with waves coming from three different directions, while a full analysis would analyse the response with waves coming from all 360° directions. As the goal of the analysis is to identify some of the most critical and exposed element members to make up a basis for the sensor selection for the digital twin, the accuracy in terms of the magnitude of the result values are not the most important part. With this type of analysis the results are likely to be within 80 – 90 % of the results that can be expected from the full global response analysis. In cooperation with Professor Jørgen Amdahl this was decided as accurate enough for the purpose of the analysis.

For the conduction of the analysis the USFOS record identifier *SpoolWave* was used. In USFOS, the input data is organised and recognised from record identifiers, which reads a special set of input values [56]. When using SpoolWave, USFOS simulates an irregular wave field of specified duration based on a given wave spectrum. It searches for the 1^{st}, 2^{nd} and 3^{rd}, and so on, highest wave crest, depending on what is specified by the user. A full analysis would be a 3 hour time domain simulation, which is very time consuming. With the SpoolWave option the duration of the analysis is significantly shortened. This option searches for the highest wave in the 3-hour storm and simulates only a short time period close to the occurring of this wave. Assuming the largest structural response will occur in connection with the highest wave, this form of analysis is able to give reasonable answers in shorter time. The results from Bore and Fossan's thesis indicates that in most cases this is true, and thereby is a valid assumption [10].

Specifically, the SpoolWave option moves the start of the analysis to a specified "time before peak", and runs the analysis from this point. The time before peak is set to 250 seconds, as significant transient effects will be present after the start-up of the analysis. The transient effects are linked to the large drift off the structure experiences after the start-up of the analysis, and they last for almost 150 seconds. The total analysis time is set to 300 seconds. This means that when started, USFOS searches through the 3 hour simulated sea state, finds the highest wave occurring during this time period, starts the analysis 250 seconds before this wave occurs, and runs the analysis for 300 seconds from this point. The highest wave is described as "peak elevation" in Figure 3.6, which illustrates how the SpoolWave option in USFOS is carried out.

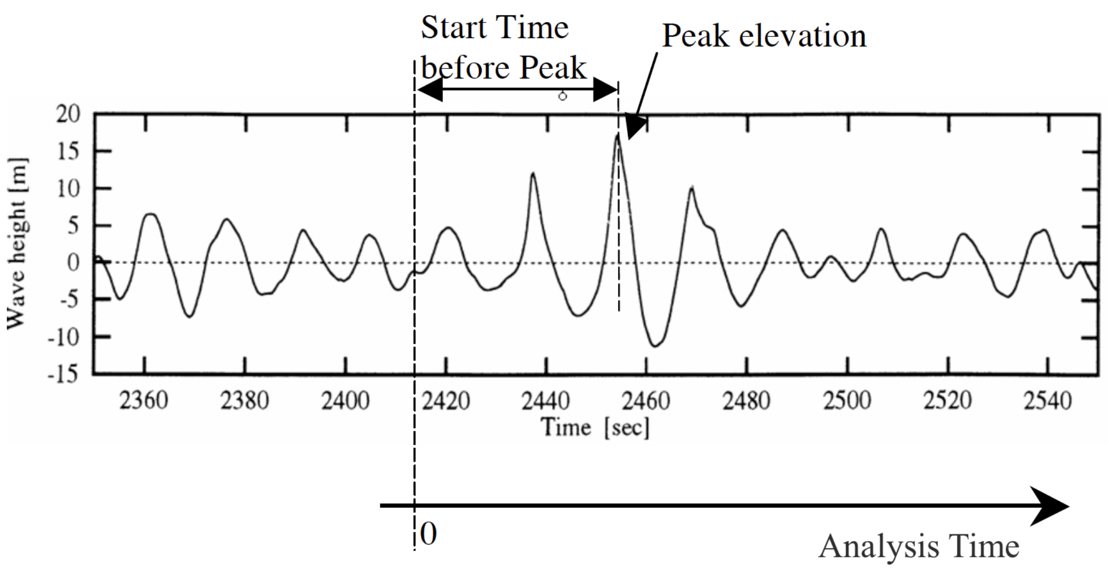


Figure 3.6: Illustration of how an analysis using the SpoolWave option is carried out in USFOS. Illustration from USFOS User's Manual [56].

3.3 Environmental conditions and input values

The input parameters to the analysis are based on parameters from Bore and Fossan's master thesis from 2015 [10]. Their parameters are based on information from Ocean Farming that where collected in a period before Ocean Farm 1 was installed.

It has been carried out a total of three analyses, with the difference between the analyses being the direction of the incoming waves and current. The waves and current are set to come from the directions 315°, 180° and 135°. These directions are specified in Figure 3.8. Bore and Fossan found in their analysis that 315° was the wave and current direction that gave the highest utilisation of the members [10]. This is also the wave direction with the highest probability of occurrence, based on environmental analyses by Fugro Oceanor. Figure 3.7 shows the wave directional probability in the area where Ocean Farm 1 is located. Waves coming from 180° and 135° has the second and third highest probability of occurrence, respectively.

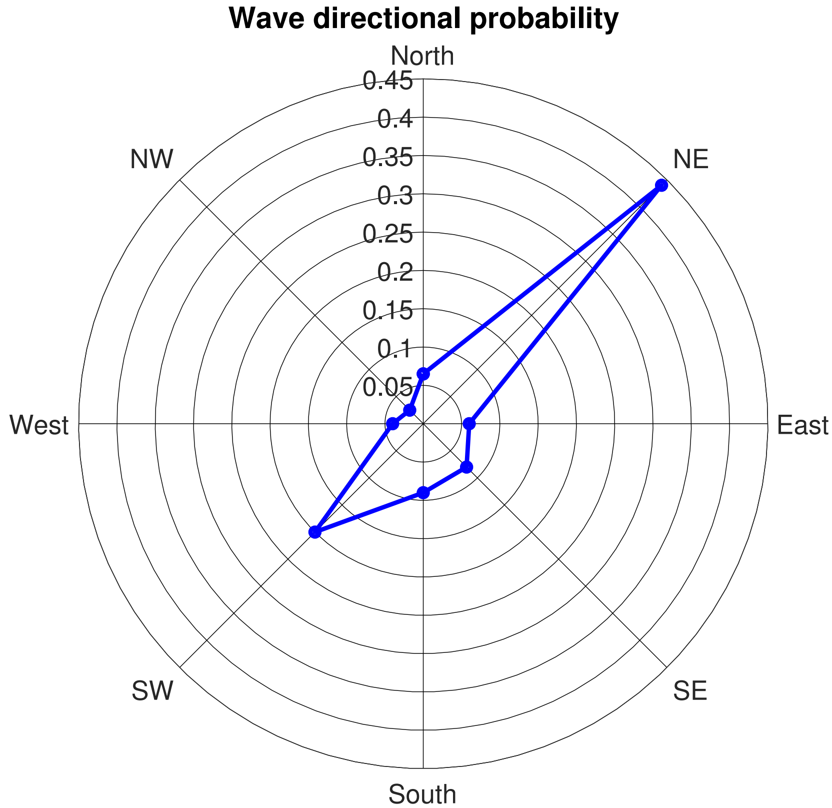


Figure 3.7: The wave directional probability at the location of Ocean Farm 1. The Figure is based on analyses by Fugro Oceanor, and is adapted from the master thesis of Bore and Fossan [10, p. 93].

Figure 3.7 shows that 44% of the time the waves are coming from northeast (315°), and waves and current from this direction should be considered carefully in the analysis. Waves coming from southwest (135°) accounts for 20%, and waves coming from south (180°) accounts for 9%. The northeast and southwest directions are direclty opposite directions, indicating the current is going somewhat back and forth. These are the three directions chosen for the analysis, and they are emphasised according to their probability of occurrence.

The high joint probability of waves coming from northeast and southwest are expected, considering the bathymetry and topography at and in proximity of the location in Frohavet. The north, northwest and west directions are protected by parts of the archipelago Froan, and the south, southeast and east directions are protected by the mainland of Trøndelag. Thus, only the northeast and southwest directions have long distances of open sea, giving the opportunity for current and waves to build up. This can be seen on Figure 1.2 in the introduction.

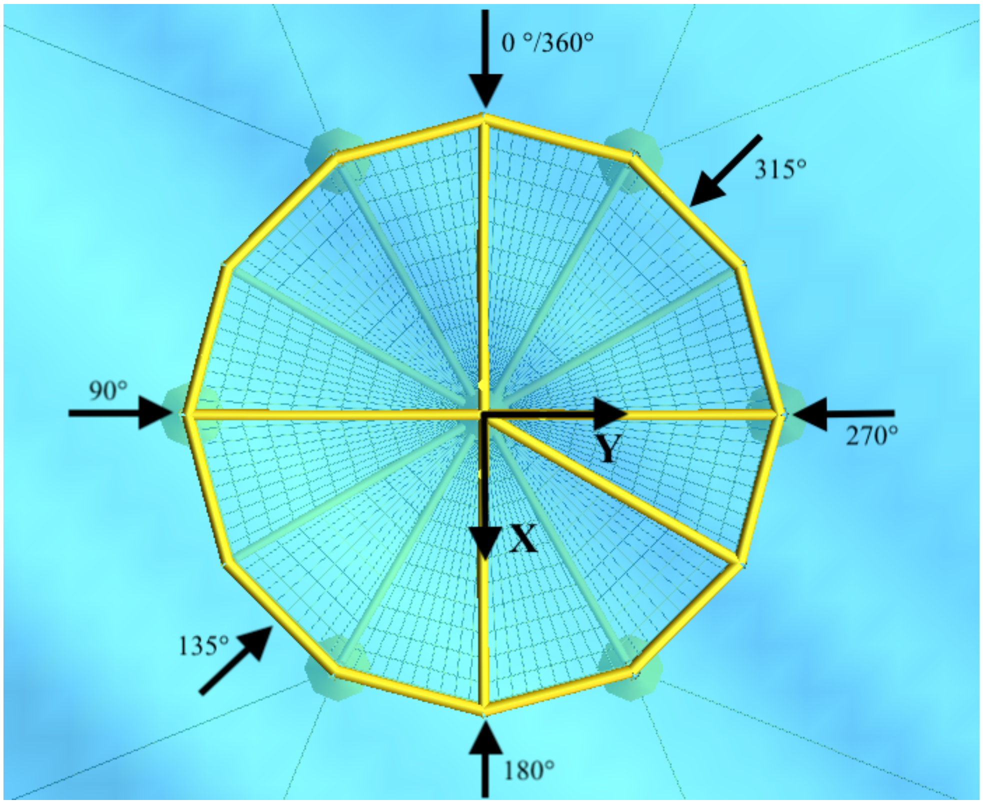


Figure 3.8: Overview of the model showing the wave directions and positive directions for X and Y as defined in USFOS. The positive X-direction is pointing south.

The sea states in the analysis are modelled by a JONSWAP spectrum. This spectrum is widely used in connection with stochastic analyses on structures on the Norwegian continental shelf. The spectrum is based on work carried out during the *Joint North Sea Wave Project*, thereby the name. The wave spectrum is specifically describing the sea states in the North Sea. It is based on significant wave height, H_S, peak period, T_P, and a peak parameter, γ [51]. The significant wave height is set to 5 meters and the peak period set to 11 seconds, based on estimations for a sea state with 100 year return period. The peak parameter was by Bore and Fossan calculated to 1.1 [10, p. 80]. The current velocity used in the analyses is the 100 year current velocity in the area, 0.75 m/s [10]. For each analysis, the current is applied in the same direction as the waves. The values characterising the sea state used in the analysis are listed in Table 3.5, and in addition the current velocity, U_C.

Table 3.5: Characteristics of the JONSWAP sea state spectrum and current velocity.

Wave spectrum	H_S [m]	T_P [s]	γ	U_C [m/s]
JONSWAP	5.0	11.0	1.1	0.75

3.4 Walkthrough of the analysis

3.4.1 Generation of the model

The model is, as previously presented, generated by a MATLAB script. The model file is equal for all three analysed directions, except from the line specifying the direction of the current and the waves. This direction has to be specified in the MATLAB script before generating the model file to get the correct current blockage factor for downstream elements. This factor takes into account the shielding effect of the net panels upstream on the net panels downstream, and was calculated by Bore and Fossan to be 0.9 [10]. This effect leads to a reduced incident current velocity on the net panels downstream, which again will affect the loads experienced by the downstream members.

3.4.2 Setup of the control file

The model file is read into USFOS along with a control file. The control file specifies the analysis steps, and is required by USFOS to run an analysis. The head file specifies the drag and inertia coefficients, C_m and C_d, the filling rate of the pontoons, and the beam types. It also specifies the analysis type, which in this case is a dynamic analysis of 300 seconds, with a 0.1 seconds time step. The SpoolWave command is also specified here, with a time before peak of 250 seconds and a time step of 0.1 seconds. The peak wave is searched for in a simulated irregular wave field of 3 hours, and is specified to be the highest wave during the time period. The wave data that is used is the previously presented JONSWAP spectrum. In addition the wave periods are limited to range from 2 to 28 seconds. The wave and current direction is also specified here, as in the model file. The current speed is set to 0.75 m/s, and the current profile is specified from the sea surface to the sea bed at 150 meters depth. A seed is also applied to the wave data. This seed ensures that the modelled and analysed sea state are the same for all runs of the analysis. This makes it easier to compare the results from the analyses to each other. The most important information in addition to the information given in Table 3.5, is summed up in Table 3.6.

Table 3.6: Input values to the USFOS control file. The most important values in the analysis.

Parameter	**Value**	**Unit**
Length of analysis	300	[sec]
Time before peak	250	[sec]
Time step	0.1	[sec]
Storm length	3	[h]
Lowest wave period, T_{min}	2.0	[sec]
Highest wave period, T_{max}	28.0	[sec]
Sea surface level	0.0	[m]
Sea depth	150	[m]

When the model file and the control file are set up and ready, they are read into USFOS by using a menu called *USFOS Analysis Control*. This menu also enables editing of the model and the control file if needed. The analysis is stared and carried out by clicking the *Run* button. The results are automatically displayed in the post processor when the analysis is finished.

3.4.3 Extraction of results from the analysis

The results from the analyses can be extracted in two ways. Both ways make use of USFOS's integrated graphical user interface called *Xact*, which is mainly a post processor for the analysis results. It includes several options for visualisation of the different results. Some of the results from these analyses were found through inspection of plots of the axial stress (σ_x), shear stress (τ), and the von Mises stress (σ_j). The axial stress can arise from two different types of forces, the normal force (N) and the bending moment (M). The normal force acts normal to the cross section area of the material and creates a constant stress over the cross section, while the bending moment gives a stress that varies linearly over the cross section and is zero at the neutral axis [5]. The shear stress is the force parallel to the cross section divided by the cross sectional area. This gives a stress that varies with the distance from the center axis squared, and which is maximum at the center [5]. The von Mises stress is the name of a criteria that is used to determine if the stress is higher than the yield stress, at which the element, dependent on the type of material, will start to deform heavily or buckle. This happens if the von Mises stress reaches the value of the yield stress (σ_y). The von Mises stress is calculated from the axial and shear stresses in x-, y-, and z-direction. The formula for the von Mises stress can also be reduced to a pure shear stress criteria to state that a material yields if the shear stress times $\sqrt{3}$ reaches the yield stress [6]. A load and a material factor should be applied to the calculated von Mises stress to account for design or calculation errors. The material factor is in DNV GL's Offshore standard for steel structures given as 1.15 for tubular structures [13, Ch.2 Sec.4 4.1.4, p. 43], and the load factor is given as 1.3 [13, Ch.2 Sec.1 4.4.1, p. 20]. The differences between these types of stresses in terms of formula and yield criteria are described in Table 3.7.

Table 3.7: Overview of the different stresses inspected in the analysis.

Type of stress	**Formula**	**Yield criteria**	**Explanation**
Axial	$\sigma_x = \sigma_N = \frac{N}{A}$ $\sigma_x = \sigma_M = \frac{M}{I} z$	–	Axial stress is the force in the axial direction divided by the cross sectional area.
Shear	$\tau = \frac{F}{A}$	$\sqrt{3}\tau \geq \sigma_y$	Shear stress is force divided by cross sectional area parallel to the direction of the applied force.
Von Mises	$\sigma_j = \sigma_j(\sigma_x, \sigma_y, \sigma_z, \tau_{xy}, \tau_{xz}, \tau_{yz})$	$\sigma_j \geq \sigma_y$	A stress value used to determine if a given material will yield.

The stress plots are colour coded, with the elements experiencing the least stress, which may also be negative, coloured blue, and the elements experiencing the most stress coloured red. It is possible to plot the stresses for each time step of the analysis, and that way find the most severe conditions. Inspection of these plots then gives a good indication of which elements that should be kept in focus.

The other way of extracting results are through graphs. Xact has a large variety of result values that can be plotted in graphs. A set of parameters predefined in USFOS can be plotted through the *History plot* feature, and can give information about all the elements and nodes of the structure. The values used by Xact for the plots can be extracted, and imported into programs that can read spreadsheet data, for further post processing. It is also possible to customise values for plotting in the control file before the analysis is started. These values are saved during the analysis and can be plotted through the *Dynamic plot* feature when the analysis is finished. For this thesis the values were extracted from the History plot graphs and exported to MATLAB for customised plotting of the results.

3.5 Results of the analysis

In the following, the results of the analysis are presented, along with interpretation of them. This is presented together to give a better understanding of the results. First the analysed sea state is presented. This sea state is equal for all three analyses, except that they are acting from different directions. Then, the results related to the response of the structure are presented for each of the three directions, before the combined results for all analyses are presented.

3.5.1 The sea state

The highest wave crest occurring during the analysis is 4.95 meter, and as can be expected, this occurs at time 250 seconds. With a significant wave height of 5.0 meters, 4.95 meters is a fitting wave height for analysis purposes. The lowest wave trough occurring is –3.55 meters, at 41.7 seconds. At 246.4 seconds a trough of –3.4 meters is occurring. This gives a total change in surface level of 8.35 meters over a period of 3.6 seconds, in connection with the largest wave. The analysed sea state is equal for all three analysed directions, and the developments of the sea state is shown in Figure 3.9. The sea state changes a lot throughout this period, and seams to be a good representation of a storm.

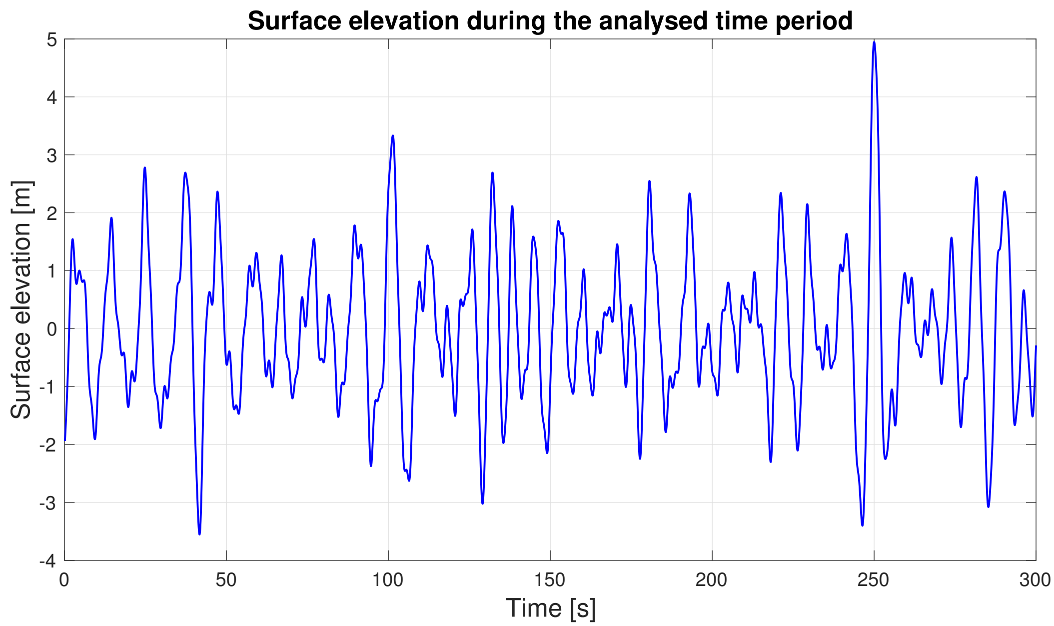


Figure 3.9: The changes of the surface elevation during the analysed time period of 300 seconds.

3.5.2 Results 315 degrees

As could be expected, the structure is moving with the direction of the current and waves in the analysed sea state. Figure 3.10 shows the displacement of the center column of the structure from the neutral position (top right corner) throughout the analysis. The plot shows that the maximum displacement of the structure during the analysis is 24.57 meters south (positive x-direction) and 24.75 meters west (negative y-direction). The current and waves are coming from the northeast direction, and Ocean Farm 1 is moving in the southwest direction. The maximum total displacement from the neutral position is 34.87 meters. All displacement plots have the displacement in y-direction plotted on what is normally the x-axis and the displacement in x-direction plotted on the normal y-axis. This is done to match the definition of directions from Figure 3.7, so that direction north is always pointing upwards against the top of the page.

Figure 3.11 shows that the structure moves more or less directly from the neutral position to about 22 meters south and 22 meters west. After this, the location of the structure is varying inside a rectangular window between 22 meters south, 22 meters west and 25 meters south, 25 meters west, indicating that it is moving back and forth in a smaller area.

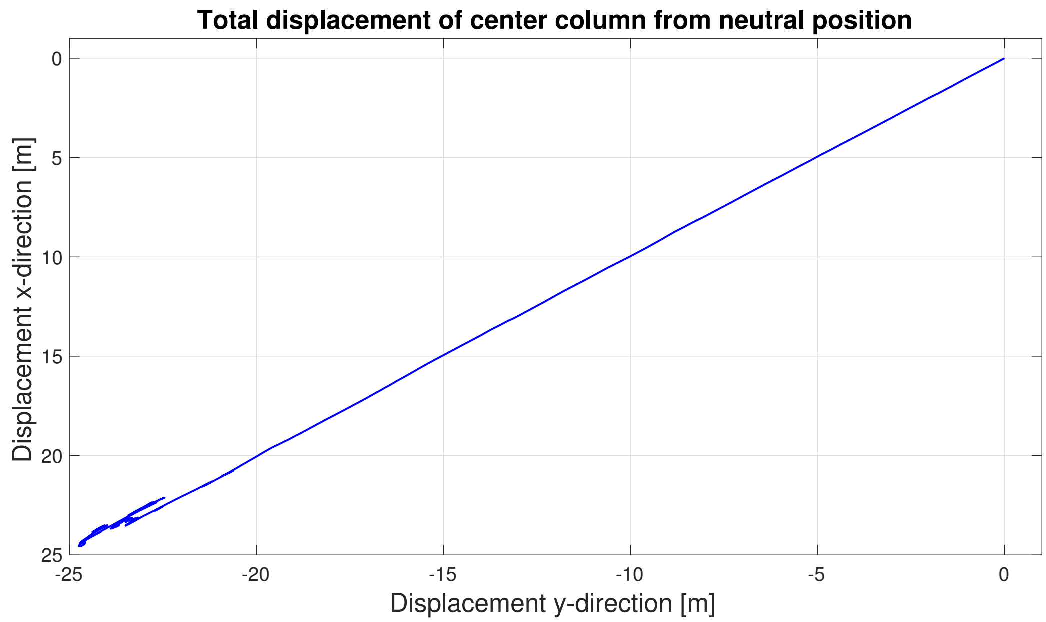


Figure 3.10: Displacement of the center column during the analysed time period of 300 seconds, with waves coming from 315° (See Figure 3.8 for explanation of the directions).

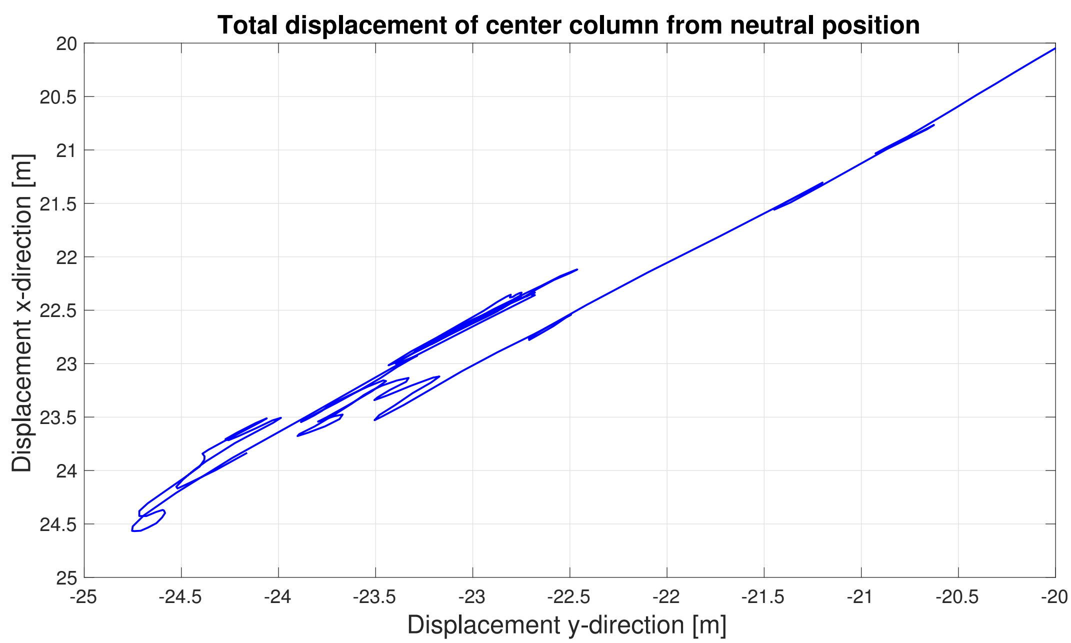


Figure 3.11: Zoom in on the maximum displacement of the center column during the analysed time period of 300 seconds, with waves coming from 315°.

The large displacement of the structure will affect the mooring lines significantly. Figure 3.12 shows how the span of mooring lines 1 to 5 are shortened and hanging almost vertically from their connection point at the structure, while mooring lines 6, 7 and 8 are stretched and having a more horizontal profile than in neutral position. The figure displays the position of the structure at 255 seconds.

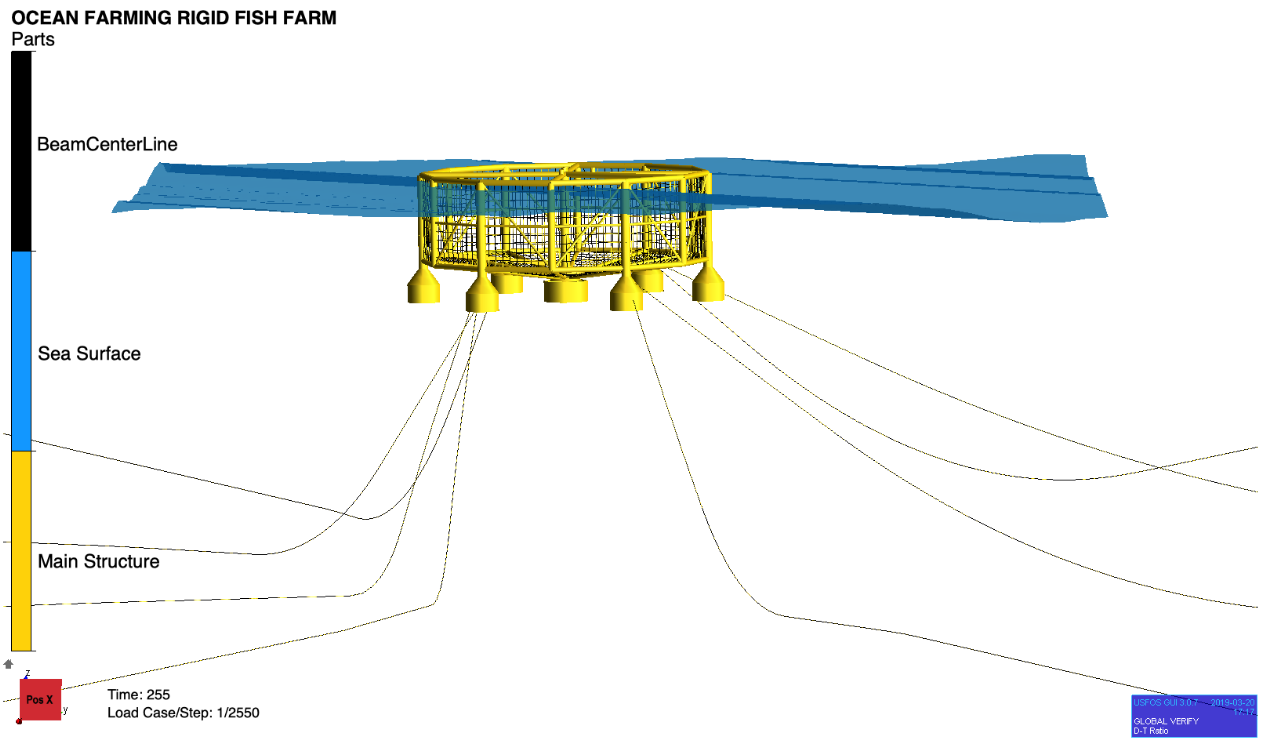


Figure 3.12: Displacement of Ocean Farm 1 after 255 seconds, seen from x-direction. This shows the change of the shape of the mooring lines as Ocean Farm 1 is floating with the current.

Table 3.8 shows the maximum force experienced in each of the 8 mooring lines, and their time of occurrence. The forces in the mooring lines are axial forces, acting in the longitudinal direction of the lines. The maximum force is occurring in the mooring line element closest to the structure, in the connection point between the structure and the mooring line. The largest force is found in line 8, with a force of 1.655 MN. The forces in mooring line 7 are also of significant size. The minimum breaking load of the mooring lines was presented in Figure 3.3, and is for the fibre part of the line 8.123 MN. This means that the maximum force occurring in the mooring line is 20.4% of the minimum breaking load. All the forces of significant value are occurring in connection with the peak wave at 250 seconds.

Table 3.8: Maximum force in the mooring lines at the connection point to structure, at time of occurrence. Current direction 315°. Mooring line numbering is displayed in Figure 3.3.

Mooring line number	Force [MN]	Time of occurrence [sec]
1	0.425	254.0
2	0.196	2.0
3	0.186	2.0
4	0.186	2.0
5	0.194	2.0
6	0.549	273.0
7	1.365	252.0
8	1.655	252.0

Figure 3.13 shows the development of the force in mooring line 8. It increases almost steadily the first 150 seconds before it starts to oscillate and decrease. This matches the movement of the structure, as it steadily moves in the southwest direction for the first 150 seconds of the simulation, and by that tightens the mooring line.

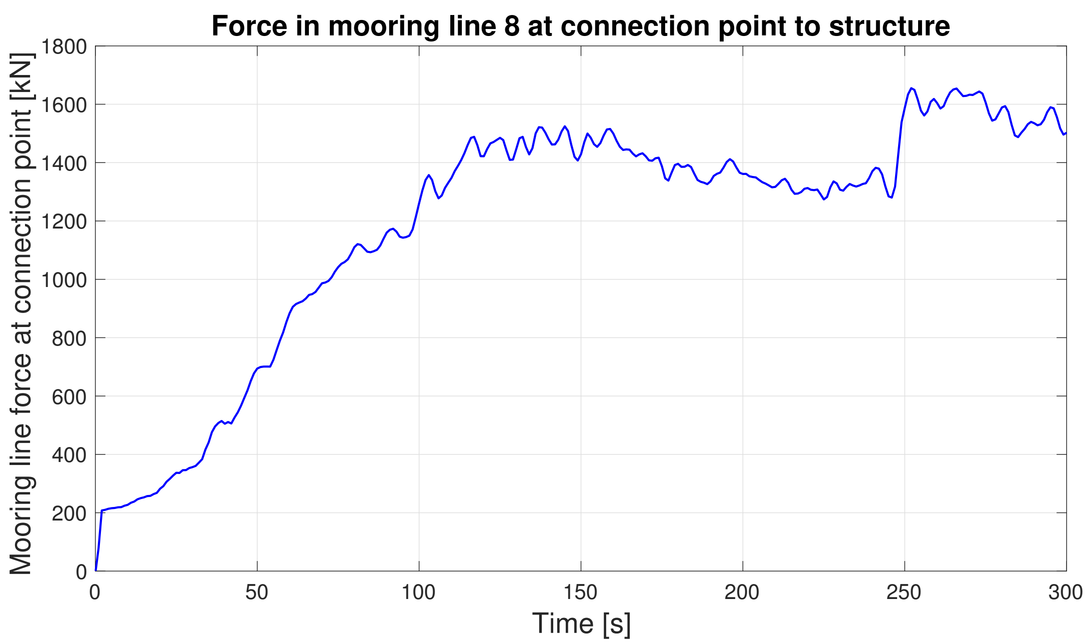


Figure 3.13: Force variation in mooring line number 8 during the analysed time period of 300 seconds.

The axial stress of the elements in the structure at time 248 seconds, is shown in Figure 3.14. This is the time at which the largest stresses occur. The arrows and points 1, 2 and 3 indicates the three members that experiences the largest axial stresses, and these areas of the structure should be kept in focus for further assessments. For this stress plot the red colour indicates positive stresses, tension, and the blue colour indicates negative stresses, compression.

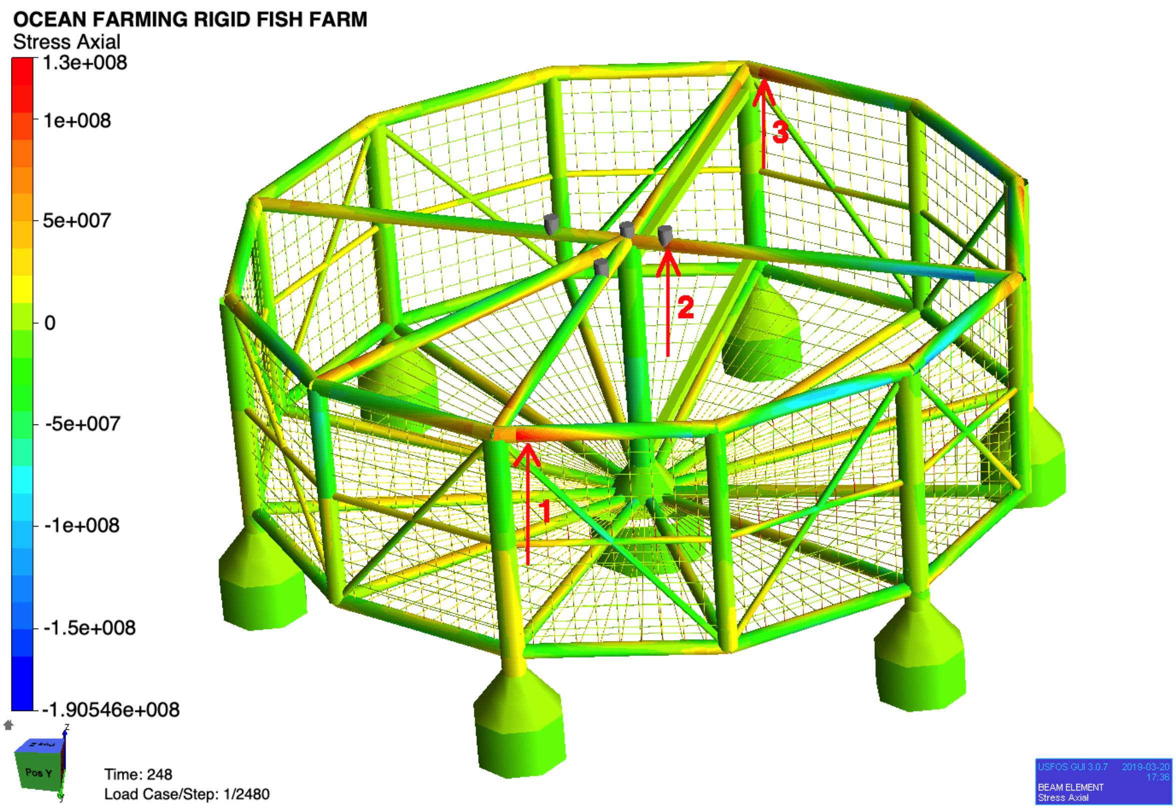


Figure 3.14: Distribution of axial stress in structural members at time 248 seconds, direction 315°. The values are given in Pa.

Figure 3.15 shows the shear stress of the elements in the structure at time 248 seconds, which is the time the largest stresses occur. The arrows and points 1, 2 and 3 indicates the three members that experiences the largest shear stresses. The red coloured elements are experiencing the largest shear stresses. The largest shear stresses are in the range of 32.3 MPa. Multiplied by $\sqrt{3}$, the value for comparison to the yield stress becomes 55.9 MPa. This is 15.7% of the yield stress, indicating that the shear stresses are not likely to cause major damage.

Figure 3.16 shows the von Mises stress of the elements in the structure at time 248 seconds, which is the time the largest stresses occur. The arrows and points 1, 2 and 3 indicates the three members that experiences the largest von Mises stresses, and these areas of the structure should be kept in focus. The red coloured elements are experiencing the largest stresses, and due to the formulation of the von Mises stress, this stress can only be positive. The contour plot must therefore be compared to the axial stress plot to determine if the elements are experiencing tension or compression. The element marked 1 is in tension, while the elements marked 2 and 3 are in compression. The largest stresses are in the range of 130 MPa, which are significantly larger than the shear stresses. Multiplying this value with the load and material factors gives a value of 194.35 MPa. This equals 54.7% of the yield stress.

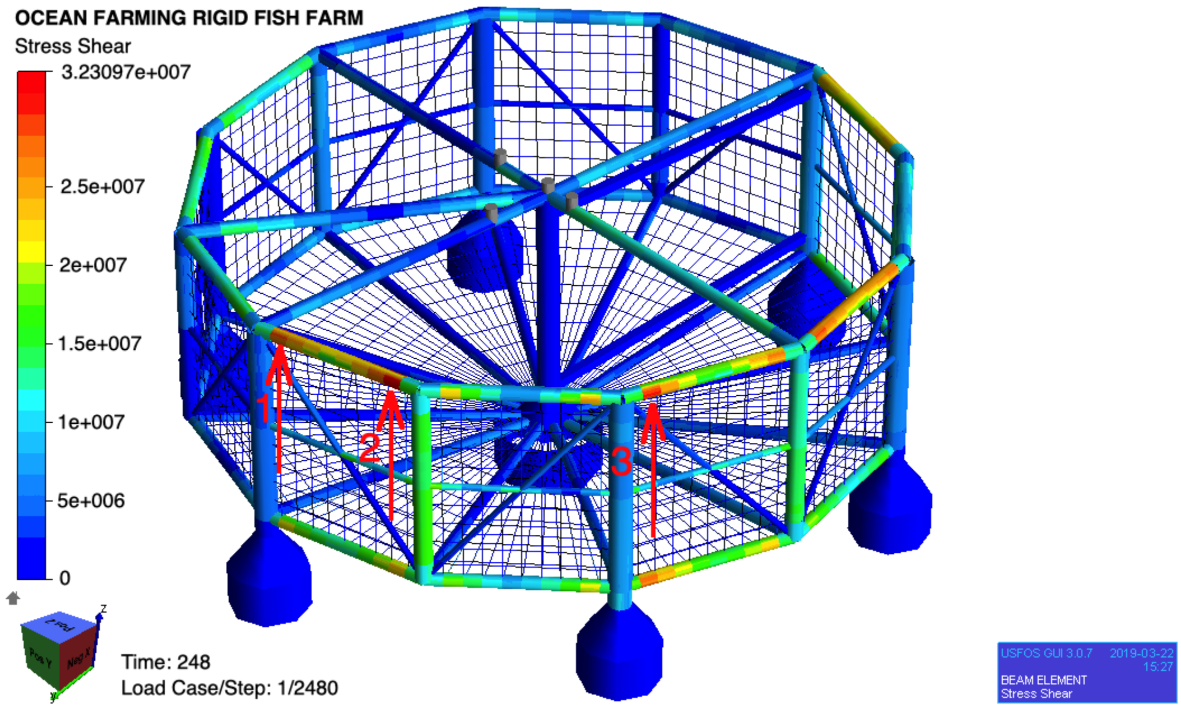


Figure 3.15: Distribution of shear stress in structural members at time 248 seconds, direction 315°. The values are given in Pa.

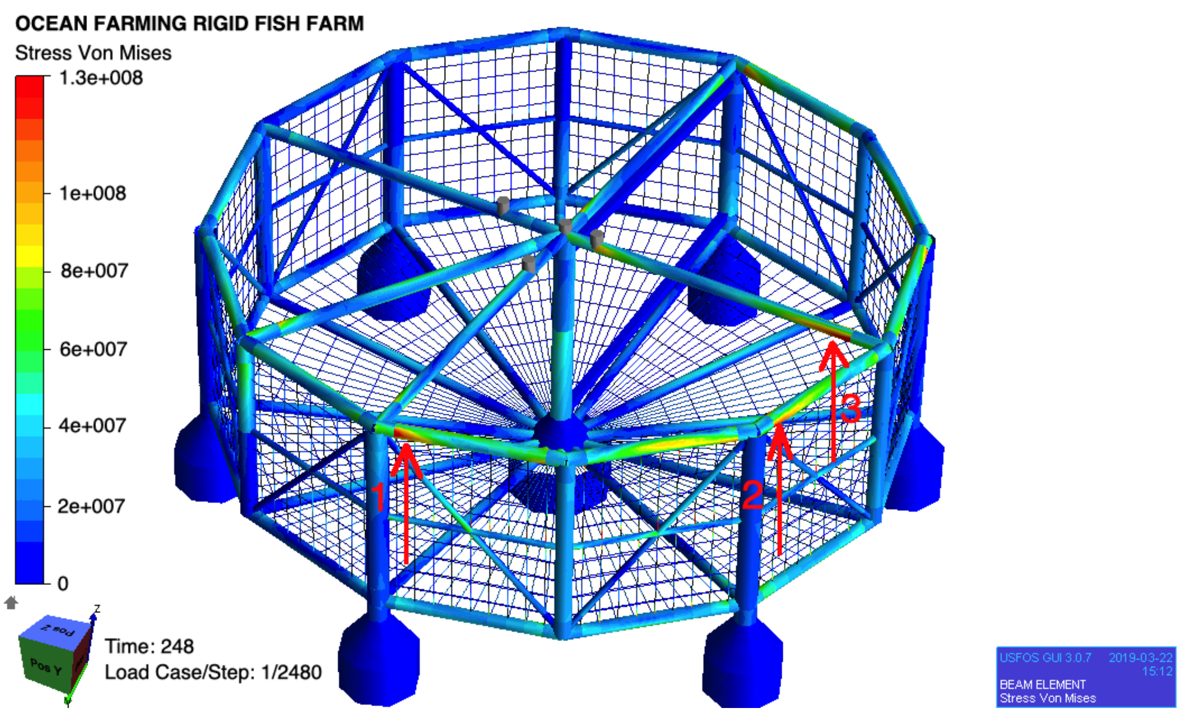


Figure 3.16: Distribution of von Mises stress in structural members at time 248 seconds, direction 315°. The values are given in Pa.

3.5.3 Results 180 degrees

As for current direction 315°, the structure is moving with the current and waves when they are coming from a direction of 180°. This current direction corresponds to the current coming directly from south, and the structure is moving in direction north. The displacement of the middle column of the structure from the neutral position (lower left corner) is shown in Figure 3.17. The largest displacements of the structure from the neutral position is 34.64 meters north and 0.14 meters east, giving a total displacement of 34.64 meters.

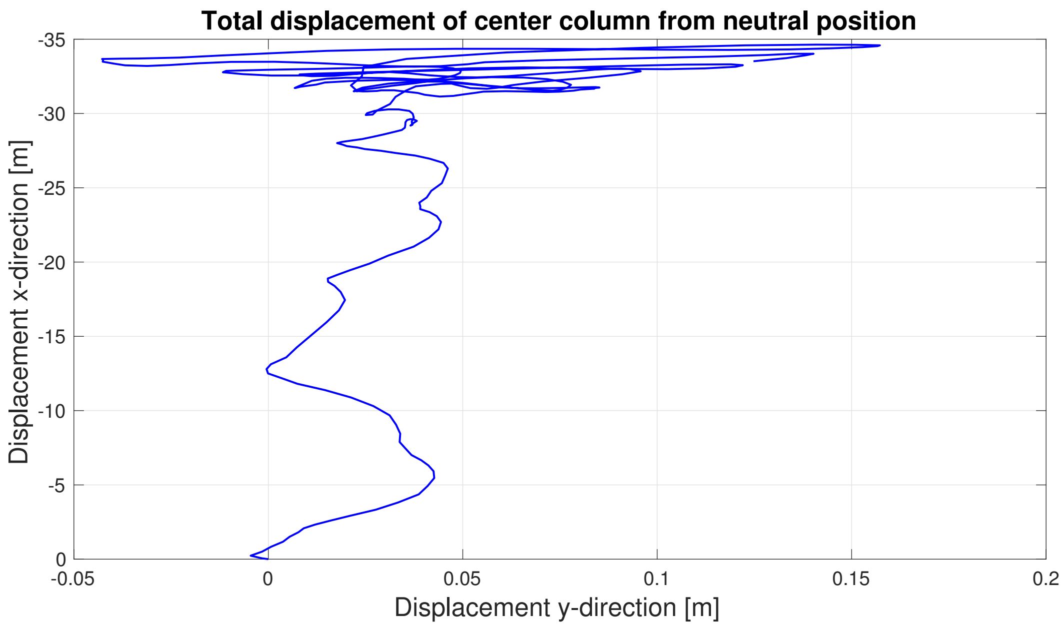


Figure 3.17: Displacement of the center column during the analysed time period of 300 seconds, with waves an current coming from 180°. Note that the seemingly large movements in the y-direction is caused by the width of the plot being only 0.25 meter in the x-direction.

Table 3.9 shows the maximum force in each of the 8 mooring lines, also here occurring in the connection point between the structure and the mooring line. Mooring line 4 is experiencing the largest forces, with mooring line 5 almost experiencing the same level of forces. The maximum force in mooring line 4 is 19.3% of the MBL, and is not likely to cause large damage to the mooring line.

Table 3.9: Maximum force in mooring line at connection point to structure, at time of occurrence. Current direction 180°.

Mooring line number	Force [MN]	Time of occurrence [sec]
1	0.186	2.0
2	0.191	2.0
3	0.463	250.0
4	1.565	264.0
5	1.549	265.0
6	0.469	250.0
7	0.191	2.0
8	0.186	2.0

The stresses that occur in the structure when the waves and current are coming from the direction 180° showed to be of smaller magnitude than for the direction 315°. As less than 10% of the waves and current are expected to come from this direction, the results from this analysis, except the results already presented, will not be considered.

3.5.4 Results 135 degrees

As for the other two analyses, the structures is moving in the direction of the current and waves, which are now coming from the direction of 135°. This direction corresponds to southwest, and the structure is therefore moving in direction northeast. This is directly opposite of the current direction of 315°. The displacement of the middle column from the neutral position (lower left corner) is shown in Figure 3.18. The largest displacements of the structure from neutral position is 25.07 meters north and 24.68 meters east, giving a total displacement of 35.18 meters.

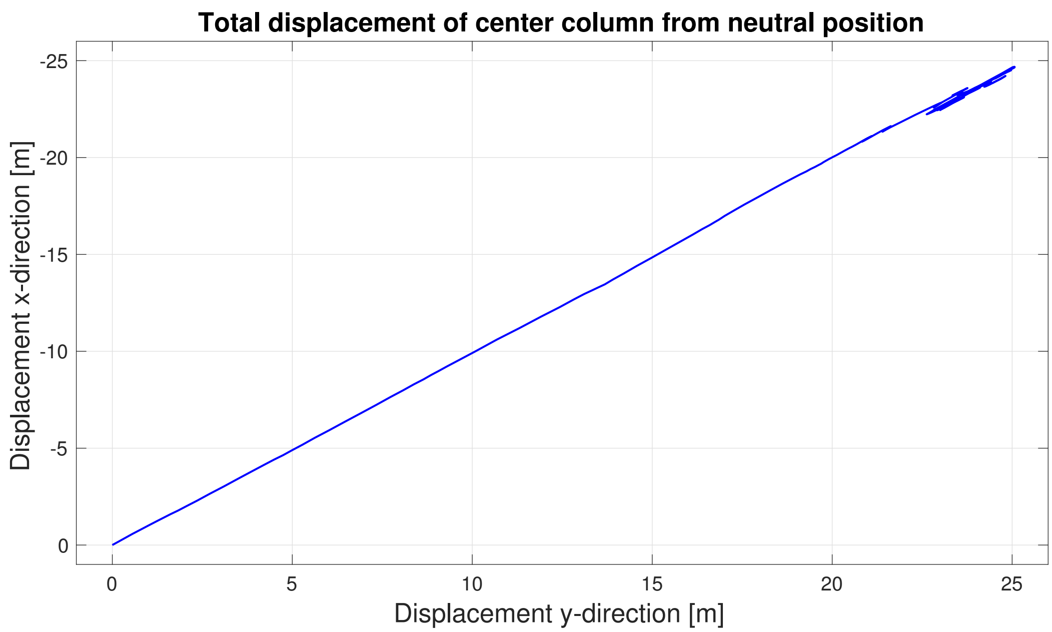


Figure 3.18: Displacement of the center column during the analysed time period of 300 seconds, with waves coming from 135° (See Figure 3.8).

Figure 3.19 shows that the structure moves more or less directly from the neutral position to about 22 meters east and 22 meters north. After this, the location of the structure is varying around 24 meters east and 23 meters north. This is indicating that it is moving back and forth in a smaller area after it has reached its maximum displacement.

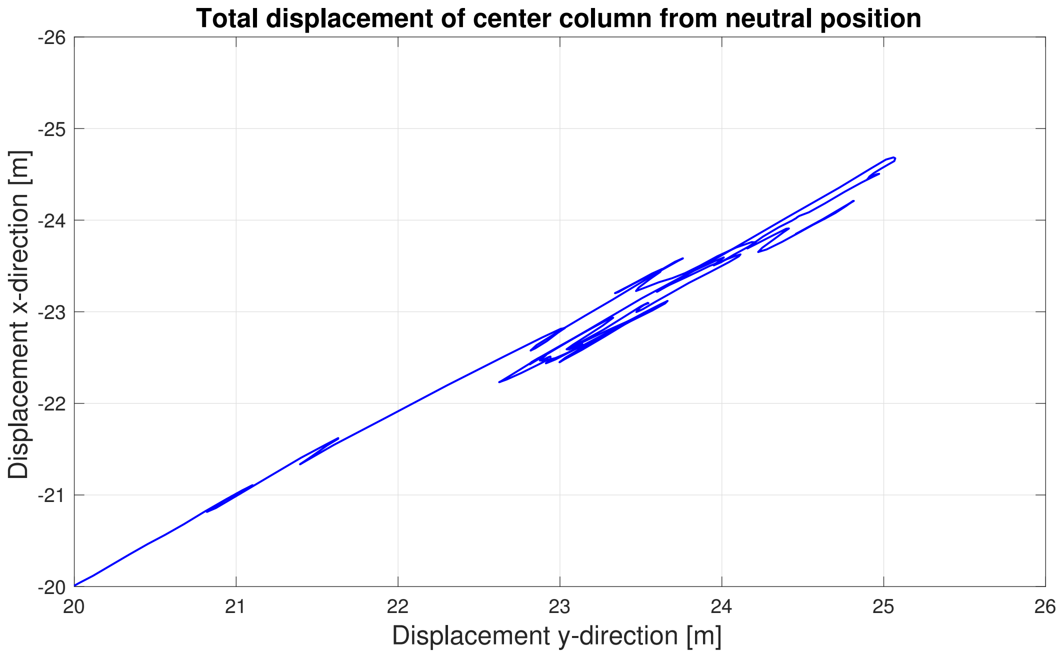


Figure 3.19: Zoom in on the maximum displacement of the center column during the analysed time period of 300 seconds, with waves coming from 135°.

In Table 3.10, the maximum force in each of the 8 mooring lines are presented. It shows that it is mooring line number 4 that experiences the largest forces. Mooring line 3 is also experiencing significant forces. The maximum force in mooring line 4 is 21.0% of the MBL, and as for the other analysed directions, not likely to cause major damage to the mooring line.

Table 3.10: Maximum force in mooring line at connection point to structure, at time of occurrence. Current direction 135°.

Mooring line number	Force [MN]	Time of occurrence [sec]
1	0.194	2.0
2	0.551	273.0
3	1.379	252.0
4	1.702	252.0
5	0.426	252.0
6	0.195	2.0
7	0.186	2.0
8	0.186	2.0

Figure 3.20 shows the plot of the axial stress of the elements in the structure at time 248 seconds. This is the time at which the largest stresses occur. The points 1, 2 and 3 indicates the three members that experiences the largest axial stresses, and these areas of the structure should be kept in focus in further assessments. For the axial stress the red coloured elements are in tension and the blue coloured elements are in compression. Note that the structure in the figures now is seen from the opposite direction of the plots shown for direction 315°.

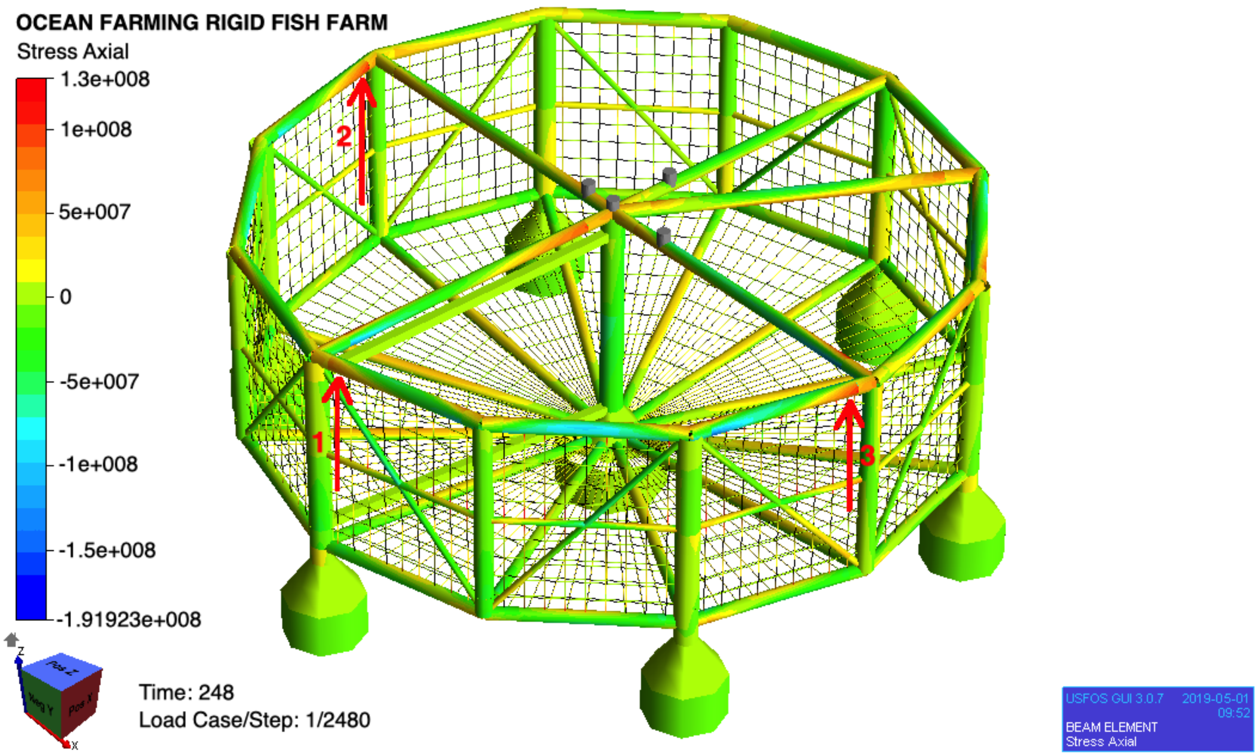


Figure 3.20: Distribution of axial stress in structural members at time 248 seconds, direction 135°. The values are given in Pa.

Figure 3.21 shows the shear stress of the elements in the structure at time 248 seconds. As for the axial stress, this is the time at which the largest stresses occur. The points 1, 2 and 3 indicates the three members that experiences the largest shear stresses, and these areas of the structure should be kept in focus. The red coloured elements are experiencing the largest stresses, which are of the same order of magnitude as the shear stresses for direction 315°. Applying the safety factor gives that the maximum shear stress is 16.2% of the yield stress, and are thereby not likely to cause major damage.

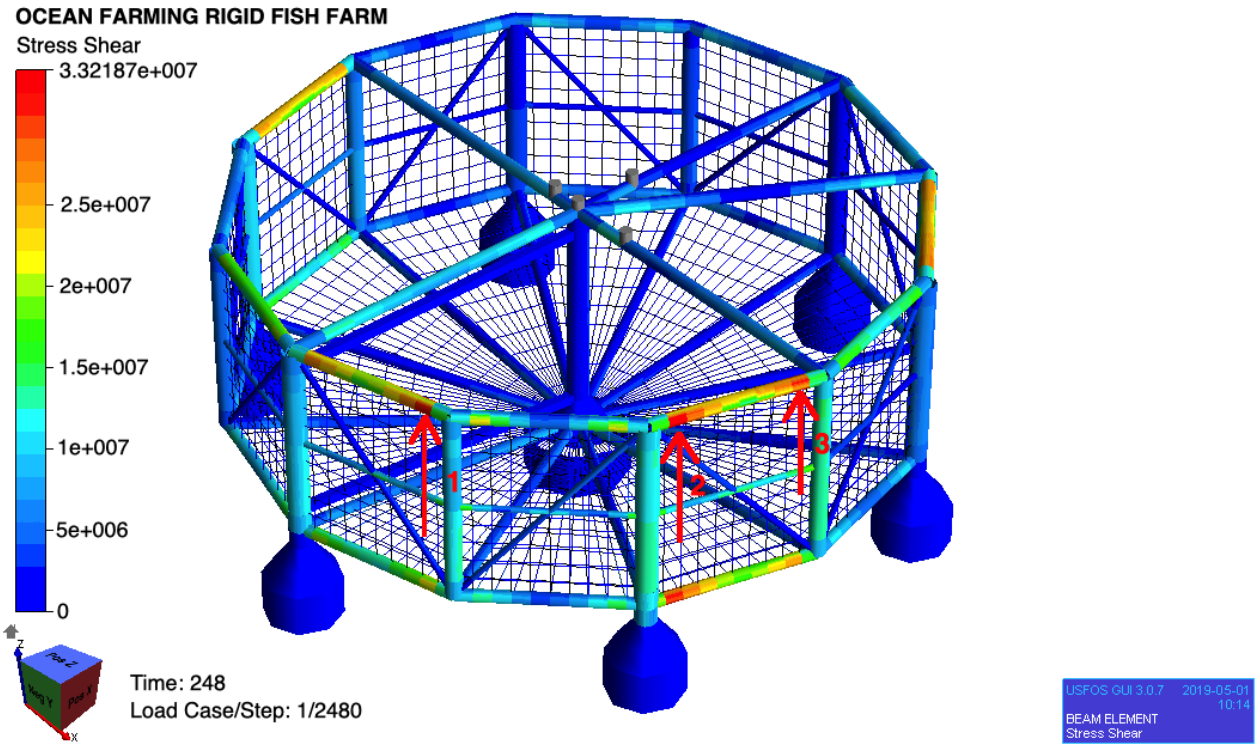


Figure 3.21: Distribution of shear stress in structural members at time 248 seconds, direction 135°. The values are given in Pa.

Figure 3.22 shows the von Mises stress of the elements in the structure at time 248 seconds. As for the axial and shear stress, this is the time at which the largest stresses occur. The points 1, 2 and 3 indicates the three members that experiences the largest von Mises stresses, and these areas of the structure should be kept in focus. The red coloured elements are experiencing the largest stresses, and by comparison with the plot of the axial stress it is determined that the element marked 1 is in compression, while elements marked 2 and 3 are in tension. The maximum stress is in the same range as for the 315° direction, giving a maximum stress of about 55% of the yield stress of the structure. These are stresses of the most notable values, and they should be considered carefully in further assessments.

By comparing the stress plots for direction 315° and direction 135° it can be seen that the results are similar, only mirrored to the other half of the structure. They are not exactly the same, as the extra horizontal member at the top of the structure between the horizontal members at 180° and 270° will absorb more forces when the waves and current are coming from direction 315°, than from 135°. It is reasonable that the results will be like this, as the sea state of the analyses are the same.

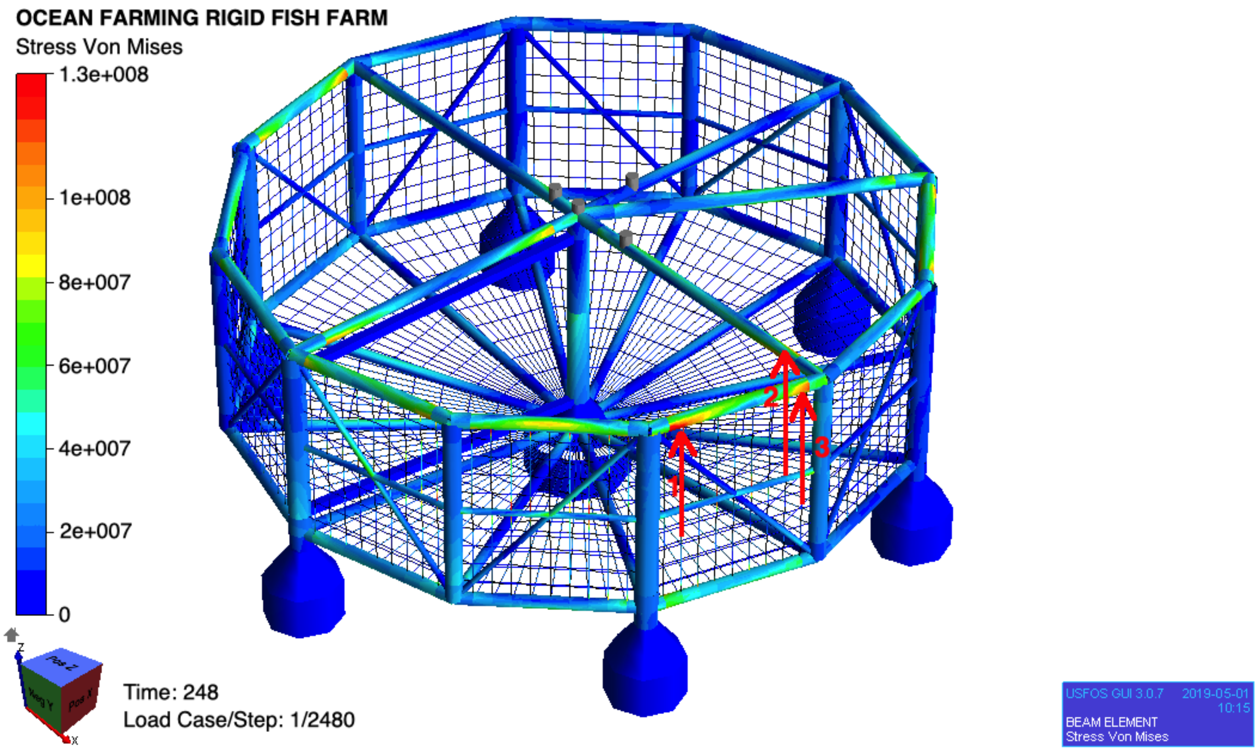


Figure 3.22: Distribution of von Mises stress in structural members at time 248 seconds, direction 135°. The values are given in Pa.

3.6 Choice of elements for sensor application

3.6.1 Criteria for choice of elements

When choosing the elements to apply sensors to, there are three criteria that are followed. The first one is the analyses results. From these it is possible to identify several elements that will experience higher loads than others. The chosen elements will not necessarily be the absolute most critical or damaged points, but the analyses give valuable guidance in choosing elements that are more susceptible to damage. To be able to choose areas or elements for monitoring and placement of sensors, it is also important that the three analyses are seen in connection with each other, to identify some of the overall most exposed areas of the structure. The second criteria is that the chosen element is a critical element in terms of redundancy. Failure of a redundant element is not as critical as failure of a non-redundant element. A non-redundant element should therefore be prioritised if the choice is between to similar elements. The third criteria is diversity. For this thesis it is valuable that the chosen elements gives the opportunity of installing different sensors. There are several ways of monitoring elements and installing sensors, and introducing a variety of sensors is beneficial for giving a comprehensive understanding of a digital twin. As important as identifying weak elements, is knowing how to monitor these elements and why these are the ones that should be monitored.

3.6.2 Relevant elements based on results from the analyses

Table 3.11 sums up the mooring lines experiencing the largest and the second largest forces for each of the analysed wave and current directions. Based on the wave directional probability (Figure 3.7) it can be expected that the waves will come from the northeast direction 44% of the time. This makes the connection point of mooring line number 8 the most exposed of the mooring lines, and a highly relevant point for monitoring. As line number 8 experiences more forces than line number 7 it is likely to take damage first, and is therefore more relevant for monitoring than line 7. The combined probability of waves coming from the south and southwest directions is 29%. With line number 4 experiencing high forces with waves coming from both directions, the connection point of this line to the structure is also a relevant point for monitoring.

The mooring lines on the back side of the structure, relative to the incoming direction of the waves and current, are experiencing forces less than 140 kN. This is less than 10 % compared to the maximum mooring line forces. As the force created by the submerged weight of one mooring line is 147.4 kN, the forces in these lines are less than the force the lines are applying to them selves if free spanned all the way to the anchor point. Forces of this magnitude should therefore not cause any damage to the line when they are in this position. The reason that the force is smaller is that the catenary mooring system makes some parts of the mooring lines rest on the sea bed, and they are thereby not contributing any weight. The lines that often are in a neutral or near neutral position are not likely to be the first to experience damage, and the focus should therefore be on the lines that often experience large movements and high forces.

Table 3.11: The two mooring lines experiencing the highest forces for each of the analysed wave and current directions.

Direction [°]	**Mooring line experiencing the largest forces**	**Mooring line experiencing the second largest forces**
315	8	7
180	4	5
135	4	3

Element 524 is considered one of the most utilised elements of the structure. This is the element marked with an arrow and the number 1 in Figures 3.14, 3.15 and 3.16, and it is also pointed out in Figure 3.23. This element experiences large forces when the waves and current are coming from the 315° direction. The axial and von Mises stresses are in the range of 130 MPa at the largest, which was found to be about 55% of the yield stress. It is the most utilised element member of the structure with respect to all the types of stresses. The side of the element facing the incoming waves is in tension, while the back side of the element is in compression. The location of this element is close to a joint, which, as explained in the literature study, often are the elements experiencing the highest stresses and thereby are most subjected to damage. The element is located close by the direction of 270°, and is close to the incoming angle of the current and waves when they are coming from direction 315°. With the waves coming from this direction 44% of the time, this element is considered a relevant element to monitor.

The analysis shows that the structure experiences large displacements from the neutral position in the analysed sea state. The total displacements are 34.87 meters, 34.67 meters and 35.18 meters for the three analyses. With the simulated sea state being equal for the three directions, this indicates that this is the position where the forces applied to the structure from the waves and current are in equilibrium with the forces in the mooring lines. 35 meters displacement corresponds to 0.32 diameter of the structure, and gives an area of approximately 3850 m^2 that Ocean Farm 1 can be situated in. To put this into perspective, it is about the size of a small football field. Knowing the exact location of the structure is important, especially at times when work boats are doing operations on or in connection with the structure. Knowing the position can also be used for other purposes, such as calculating the forces in the mooring lines based on the displacement and the profile of the lines, and then compare with measurements from the mooring lines. A sensor for monitoring of the motions and movements of the structure should therefore be considered.

Element 604, marked with an arrow and the number 2 in Figure 3.21 and number 1 in Figure 3.22, is another element that is experiencing large stresses. From the plot of the axial stress, it is seen that the side of the element facing the incoming current is in compression, while the back side is in tension. The maximum von Mises stress is also in this case in the range of 130 MPa, which has been found to be about 55% of the yield stress. The axial compression stress appears to be a bit larger, in the range of 150 MPa. If the same safety factors used for the von Mises stress are applied to this stress, this corresponds to 63% of the yield stress. At first, the forces in this element look quite similar to element 524, but another type of sensor or post-processing of the data might be necessary to be able to make qualified decisions based on the information about this element. This makes it an interesting element to investigate closer.

3.6.3 The chosen elements

The elements found relevant for monitoring based on the analyses results have been evaluated with respect to the other two criteria as well. In the following the chosen elements are presented in prioritised order, along with reasoning for choosing the specific element.

The chosen elements are shown in Figure 3.23. Element 524 is the first element that is chosen for application of a sensor. Seen from the analysis criteria it is chosen based on being one of the most utilised members of the structure. If this element is a redundant or non-redundant member is hard to determine fully without doing a more thorough analysis. Based on the configuration of the structure it nevertheless seems likely to have little to no redundancy as it is one of the main members of the structure. If this element breaks, the chances that a large part of the net will break are great, and this is something that has to be avoided. It is therefore an interesting element based on the redundancy criteria as well. As it is the first chosen element, it is also interesting seen from the diversity criteria perspective.

Mooring line number 8 is the second element that is chosen for installation of a sensor. Based on the analysis results it is found to be the mooring line that is likely to experience large forces most often, as the wave directional probability chart shows that the current almost half of the time comes from direction 315°. This mooring line is connected at 330°. As of the redundancy criteria, it is not as critical as element 524. Mooring line 8 is connected to the structure right next to mooring line 7, at the same vertical structural member, and they can be considered as mutually redundant. In calm water and normal operating conditions, braking of one mooring line should not cause any large problems, but if breaking should happen during a storm it can be a larger challenge. The sum of the forces in mooring line 7 and 8 during the analysed sea state is always less than the minimum breaking load of one mooring line, at least in new, undamaged condition. It is an important member of the structure, and is therefore chosen regardless of this, as the line may deteriorate over time. Mooring line number 4 is also experiencing large forces, but as all the mooring lines are equal and therefore can be monitored in the same way, the focus will be on mooring line number 8. From the diversity criteria perspective, it is an interesting element as it is a totally different element than element 524.

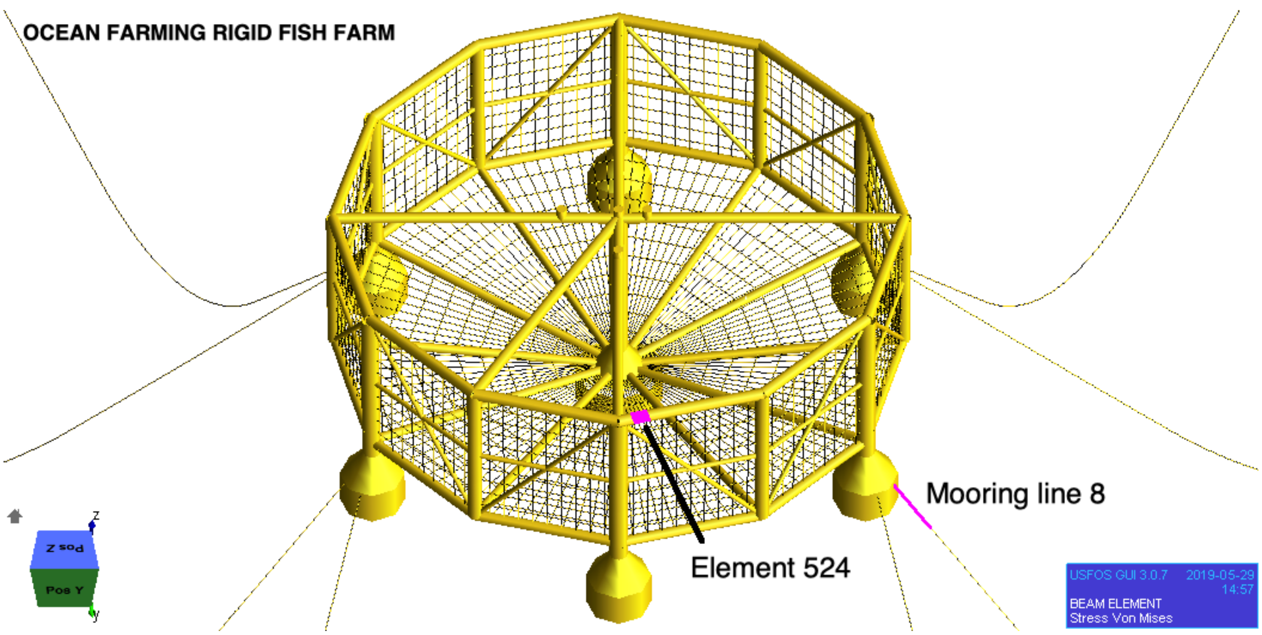


Figure 3.23: Overview of Ocean Farm 1 with the elements chosen for sensor installation highlighted in pink.

The third parameter chosen to monitor is not a specific element, but the motions and the movements of the structure. Ocean Farm 1 experiences large displacements in tough weather conditions, and it also experiences other motions like heave and sway. The measurements of the motions can be used for other purposes in addition to knowing the exact location, and is versatile information. As this is a global structural motion, the specific location of the sensor must be considered carefully, and can not be found from the analysis results. The structural redundancy criteria is not relevant for this type of monitoring, while the diversity criteria is met, as monitoring of global motions requires other sensors than the two previous chosen elements.

3.7 Discussion of analysis results and element selection

To evaluate the results of the analysis and the chosen elements, a comparison to the results found by Bore and Fossan can be made [10]. The elements 524 and 604 was found to be the most interesting elements to monitor based on the analyses carried out in this thesis. The most utilised and most damaged members from Bore and Fossan's analyses is presented in Figure B.1 and Figure B.2 in Appendix B respectively. Element 524 was identified as one of the 14 most utilised members in the ultimate limit state analysis, while element 604 was not one of those 14 elements. Several of the elements pointed out in the stress plots in the results are also among these 14 most utilised elements. The analysis in this thesis is most comparable to the ultimate limit state analysis of Bore and Fossan, and the results could be expected to be similar to what was obtained by them. This helps to substantiate the results of the analysis in this thesis, and approve the chosen analysis method.

The analysis carried out in this thesis is selective and simplified compared to doing a full global response analysis. A complete structural analysis is complex and thereby time consuming, and would also include other analysis methods. When analysing the response from waves and current coming from several directions, there are methods and formulas for calculating the combined overall effects on the structure. As the analyses in this thesis only dealt with forces incoming from three directions, the combined effect were not calculated, but found through comparison and evaluation of the different stress plots and force developments in the various elements of the structure. Therefore, it can not be known for sure that the elements found to be most utilised, is in fact the most utilised members. This is also seen from the comparison to the results of Bore and Fossan. Nevertheless, as the purpose of the analysis was to identify some weak elements of the structure, the results are evaluated as comprehensive enough for the intended use in this thesis.

From the analysis it was found that the force in the mooring lines rarely exceeds 20% of the minimum breaking load of the material. Therefore, the chances of damage to the mooring lines are small, at least in the beginning of the lifetime of the structure. As time goes by, the strength of the mooring lines can be reduced due to fatigue, and damage can then occur at forces and stresses lower than the minimum breaking load indicates. An experimental study by Weller et al. [62], showed reduced strength and axial stiffness of fibre mooring lines when ageing, primarily caused by tension fatigue cycling. This indicates that through the lifetime of the structure, monitoring of the mooring lines will become increasingly important.

As presented, the joints of the structure have a larger thickness than the tubular elements the joints are connecting. The model of Ocean Farm 1 contains a simple representation of the joints, which is not able to fully capture the transfer of loads between a joint and a tubular element. To capture this fully and get a correct representation of the stress distribution in the joints, a separate, more detailed model must be created. In Section 2.1.1 the saddle and crown was introduces as the areas that can be expected to experience the largest stresses, but from the USFOS model it seems as the location of the maximum stress is located at a distance from these areas. For the purpose of the analyses of this thesis the results from the joints are considered accurate enough, but to give better insight into the stress distribution in the joints, a more detailed model must be made.

Chapter 4

The digital twin concept for offshore aquaculture structures

This chapter describes a possible approach to creating a starting point for a digital twin of Ocean Farm 1, and presents some of the most important building blocks that are required. It also discusses and presents sensors for monitoring of the three chosen elements from the last chapter. Several use cases for digital twins are also presented and discussed, specifically related to use in offshore aquaculture industry.

4.1 Choice of sensors

4.1.1 Background for choosing sensors

When choosing a sensor, several factors must be taken into account. In Section 2.5, four main focus areas when selecting sensors and sensor placement for offshore structures was presented. These have been used as a starting point for the sensor selection. It is very important to know what information the sensor needs to provide, and the first step is therefore to know material properties and measurable characteristics of the element that is going to be monitored. Examples are knowing the elastic modulus, the yield stress, or the fatigue life of the element material. Other details of the element may also be relevant, but the most important part is that the information is measurable in some way. The chosen sensor must provide data that can be linked to the known element parameters. The sensor data will not necessarily be applicable right away, but the information can be used for calculations of values that are comparable to the element characteristics. Both point data and time series that shows the development of the measured data are valuable for assessment of the structural integrity.

Another important feature of the sensor, is the ability to transmit data in real time. To have a fully working digital twin it needs to be fed continuous information about the state of the structure. The less delay, the more up to date the digital twin is, and the more useful and valuable the information it provides is. With this in mind it is important to choose an online sensor which is capable of transmitting the information immediately, or install it in combination with a transmitter. In combination with an external transmitter the only requirement for the sensor is that is must be able to send the signals to the transmitter. To ease the installation process and the needed infrastructure, the sensor, or the combination of a sensor and a transmitter, should preferably be transmitting the signals wirelessly to the receiver. This way there is no risk of loss of data signal due to wires being cut or fibres breaking as a result of other operations near the wires. Nevertheless, wireless signals are more prone to periodical disruptions, and the sensors should be able to store information locally for at least a shorter period of time if the signal is cut. The chosen sensors should also be easy to install and operate, and not depend on regular supervision or repair.

The most relevant sensors for use in the creation of a digital twin of Ocean Farm 1 was introduced in Section 2.4. In addition to utilising the properties of a specific sensors, it can also be considered using several sensors in combination. Measurement data almost always contains noises that disturbs the signal and makes it harder to extract the information that is interesting. By using different sensors measuring the same parameters, but in different ways, data can be compared, checked and verified. The cost of installing more than one sensor must be considered carefully against the ease of cleaning data from a single sensor, when sensors are chosen.

4.1.2 Monitoring of element 524

Element 524 is a structural member that is located at the top ring of the structure. The element is highlighted in Figure 4.1. This element is located next to a joint, which from literature is known to be an especially exposed area of a structure. As this element is a part of the main structure, the material properties of the element is known, and was introduced in Table 3.2. The most convenient way of monitoring this element is by measuring parameters that can be used to calculate the stress in the element. From the analysis it is known that this element experiences large stresses, and by installing a sensor on this element, it can be monitored that stresses are kept within given limits. Rules and regulations often contains guidelines for establishment of maximum allowance values of stresses, and by implementing threshold values based on this, an automatic warning can be given from the monitoring system if the value is reached.

Stress can be calculated either from the applied force, as presented in Table 3.7, or from the stress-strain relationship known as Hooke's law, $\sigma = E\varepsilon$ [37]. This law states the relationship between stress, σ, and strain, ε, to be proportional with the material's elastic modulus, E. This law holds for linear-elastic materials, which most engineering steel materials behaves as until they reach yield. The material being elastic means it will go back to its original form if stresses are removed before it reaches yield stress magnitude, and being linear means that the relationship between stress and strain are approximately linear until a certain stress [6]. Hooke's law can be used in 1, 2 and 3 dimensions, and for a applications to a real structure, the 3 dimensional form should be used.

In Section 2.4.4, strain gauges were presented. They are applicable sensors in this case, for monitoring of strain in the element. By applying at least three strain gauges in a rosette configuration, it is possible to calculate the full strain condition. The changes and variations of the strain in element 524 are calculated based on the change of resistance in the conductive wire of the strain gauges. The values from the strain measurements are transmitted to a receiver that can feed this information to the systems of the digital twin. From the strain values, the stress can be calculated, and a time series of the stresses experienced by the element can be created. This time series can be used to both identify large stress values, and calculate the remaining fatigue life of the element to be able to take action before it fails. Early warning of possible damage is very important to ensure safe operating conditions at the structure.

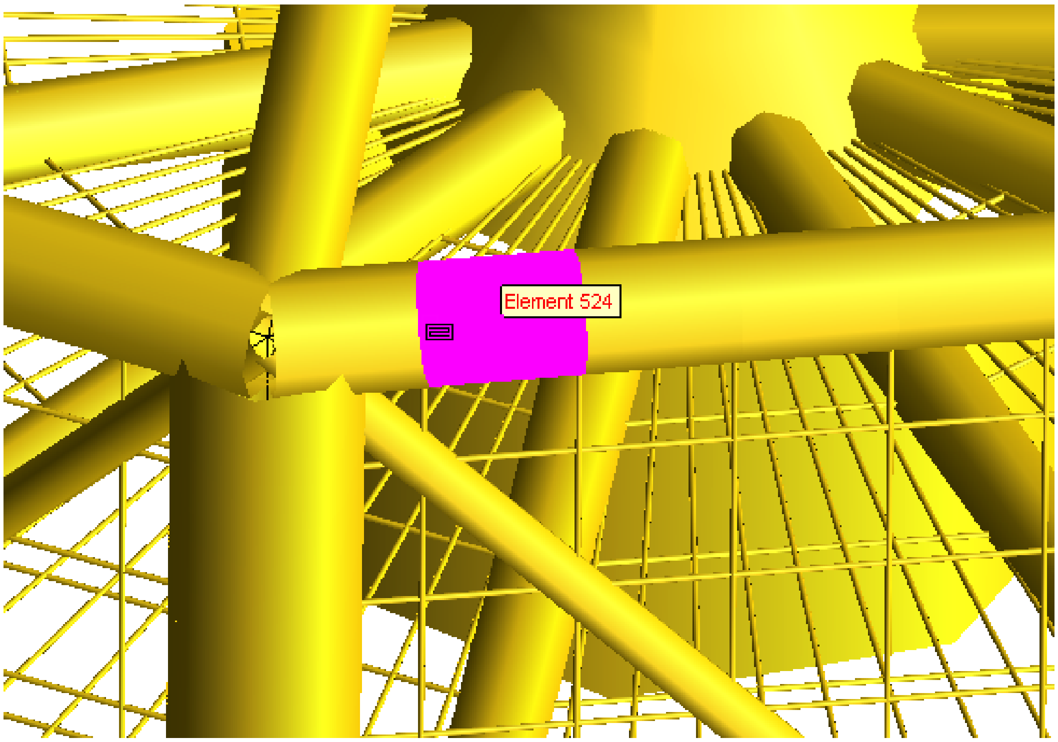


Figure 4.1: Element number 524 visualised with along with the location of the sensor.

The proposed placement of the strain gauge is shown with a small black box in Figure 4.1. This locations is chosen based on the analysis results, that showed this as the location where the highest stresses can be expected. As the size of the strain gauge sensor is small, it is important to install it at a location where the deformations are measurable. The element at which the sensor is applied is expected to experience the largest stresses of all the adjoining elements. Therefore, it can also be expected to take damage first if damage should occur in this area of the structure. By monitoring this element, the stresses in the adjoining elements can be under supervision, even if they are not directly monitored.

4.1.3 Monitoring of mooring line 8

Mooring line number 8 is attached to the structure near the bottom of one of the vertical members of the outer ring, just above the pontoon. The USFOS model does not show the attachment configuration for the mooring lines properly, as they are actually connected to the structure through hinges that are welded to the outside of the vertical columns. The first element of the mooring line as displayed in USFOS is highlighted in pink in Figure 4.2, and labelled element 6245, as this is the number of the element in USFOS. An important material property of the mooring line is the minimum breaking load. This load is given in kN, and measurement of the force in the mooring line is therefore a proper parameter that can be compared to this value.

The tension in the mooring line can be calculated from inclinometer measurements. Inclinometers are presented in Section 2.4.4, and they calculate the tension from the angle of the mooring line. To find the tension, specific formulas describing the catenary profile of the mooring lines can be used. As tension is just a specific term for stress due to elongation, it can be described in the same way as stress in Table 3.7; as force divided by cross sectional area. It is thereby possible to calculate the axial force in the mooring line from the measured tension, by multiplying it by the cross sectional area. This axial force can be compared to the MBL, to monitor how the magnitude of the force in the mooring line develops compared to allowed levels.

This sensor type calculates the tension from the measured angle of the mooring line, so it is important that it is installed at a part of the mooring line that is moving. The best place to install the sensor will be at the link that is connected to the structure, as it is rigid part, and not flexible as the mooring line itself. The link is also the part of the mooring line that is closest to the main structure, which gives the shortest way for transfer of signals. The attachment point of the lines are submerged, which makes transfer of the signals more complicated than above the sea surface. Wireless underwater communication is challenging, and to ensure precise signals and as little loss as possible, this should be avoided for Ocean Farm 1 [30]. Therefore, the signals should be transferred via a cable to a transmitter that is located above the sea surface, where the signals can be transmitted wirelessly to the receiver and sent to the digital twin's system.

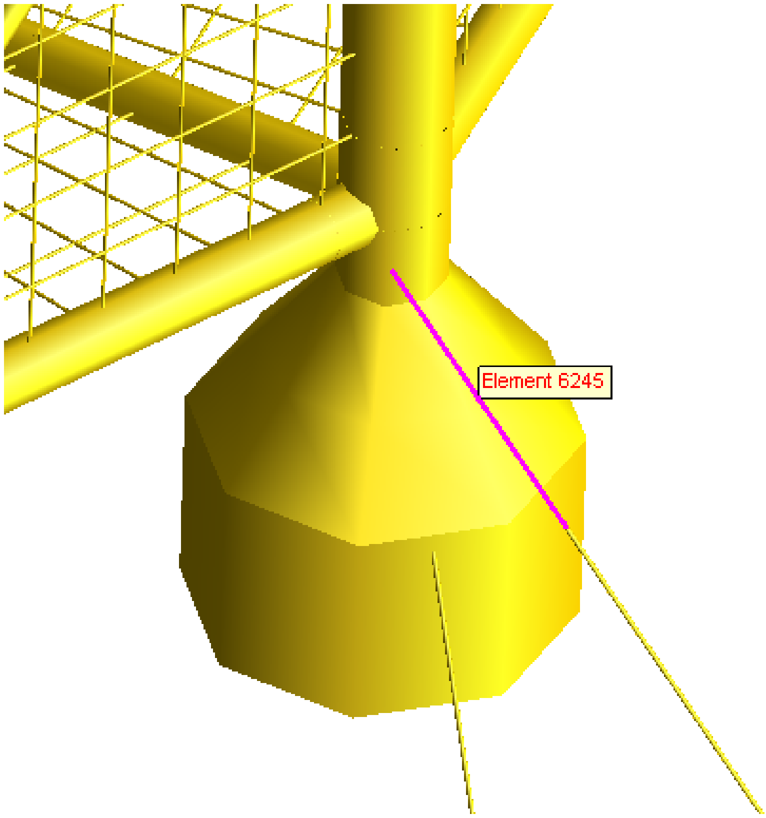


Figure 4.2: The element of mooring line 8 that is connected to the structure.

As this type of sensor provides an estimate of the tension based on measurements of a parameter that is not directly linked to tension, it can not be expected that the measurement is exact. This must then be taken into account when analysing the data from the sensor, which is usually done by applying a safety factor. Because the tension, based on the analysis results, is expected to reach a maximum of 20% of the MBL, some uncertainty in the measurements of the mooring line tension can be accepted. The producers of the sensors provide information about the precision of the sensors, and the level of uncertainty in the measurements can be known and taken into consideration when inspecting the measurement data.

Mooring line 8 is chosen as the line to monitor as it is the mooring line that is expected to experience the largest forces. As mooring line 7 is attached to the structure at the same are, the lines will have some redundancy. Monitoring of both mooring lines can be done, but mooring line 8 is the line that are likely to break first due to natural wear and is therefore more important to monitor than line number 7. If line 7 breaks, it is also likely that the forces in line 8 increases drastically, because most of the forces from line 7 will be redistributed to line 8. This way monitoring of mooring line number 8 to a large extent says something about the integrity of line number 7 as well.

4.1.4 Monitoring of structural movements

The sensors for monitoring of structural motions were presented in Section 2.4.3. For monitoring of the structural motions, a DGPS is chosen. The Norwegian Coastal Administration has developed and installed a DGPS system that covers most of the Norwegian coastal zone, and thereby also the location of Ocean Farm 1 [38]. It is therefore relatively easy to use this system, as the only devices that has to be installed at the structure is a GPS receiver and a DGPS antenna. The signals from the DGPS can be used to track the location of the structure to know when it is located at its intended location, and when it experiences drift off from this location. The DGPS receiver antenna should be installed in connection with the wheelhouse, at a location where there is little interference in the signal reception.

Monitoring of metocean parameters are also relevant when monitoring the structural movements. Knowing the waves, wind and current can give a good overview of the environment around the structure, and are valuable information when doing analyses on the structure through the digital twin. The combination of knowing how far the structure has moved from its neutral position and knowing the specific environmental forces that causes it, can build up a knowledge basis of the movements of the structure, that can be used to predict the behaviour of the structure in an expected environmental condition. For best utilisation of the monitoring data of the movements of the structure, a 2d-ALCA anemometer for measurement of wind, a wave buoy for measurement of waves and an ADCP for measurement of current should also be installed.

4.2 Building blocks for a digital twin of Ocean Farm 1

As presented in the introduction, a digital twin is a virtual representation of a real process or product. A digital twin is often presented as consisting of at least three parts. These parts are a 3D model for visualisation of the digital twin, measurements and data acquisition for monitoring of important parameters of the structure, and simulations and analyses for utilisation of the acquired data. The connection between the three building blocks was presented in Figure 2.2 in the literature survey. There are several methods for obtaining all of these three blocks, and in the following a description of how these blocks can be create for Ocean Farm 1 is presented.

4.2.1 Creating a 3D model

The first building block is having a 3D representation of the structure. Computer-aided design (CAD) is design or modelling carried out through the use data programs. Such programs are especially well suited for creation of 3D models, and have the possibility of modelling every single part very accurate. Vrabič et al. [59] emphasises the value of having an accurate representation of all parts of a complex system, to be able to study the interactions between various parts of the system.

The detail level of a CAD model is beneficial as it can include weight of the components which are important when doing analyses on the digital twin. To get accurate results form the analyses, it is important that configuration, weight and placement of all the elements in the model are correct, to get correct weight distribution, center of gravity and center of buoyancy. For the digital twin to be able to display the actual state of the structure, the model must be very accurate.

Vrabič et al. also highlights the advantages of using a universal file format called .STEP when creating a 3D model, as this format is compatible with all types of CAD software [59]. As USFOS is not a CAD program and does not support this file format, the model of Ocean Farm 1 used for analyses in this thesis is not a good starting point for creation of a digital twin. As a starting point for creation of a digital twin of Ocean Farm 1, a new model has to be made in another program, containing a richer detail level than the USFOS model does.

4.2.2 Collection of data and information

The second building block is collection of data and information about the structure, all its systems, and environmental parameters from the surroundings. This can be collected with sensors and instruments monitoring relevant parameters. In Section 4.1.1, proposition of sensor installation for three elements at the structure was presented. The monitoring of the structural element gives valuable information about the state of the specific element, and this monitoring method can be applied to a lot of other elements of the structure as well. The monitoring proposed for the mooring line can also be applied to all the other mooring lines. The digital twin needs information on all relevant parameters of the structure to correctly display the state of the structure. It is therefore important to create a full sensor system that monitors all the parameters. All the information is sent to the digital twin systems where the information is used as input to calculations, analyses and systems. DNV GL emphasises the importance of having records of the past and current state of, and changes to, the structure or system of the digital twin [26].

4.2.3 Implementation of analysis tools

The third building block is simulations and analyses based on the measurement data. The implemented analysis tools should be able to utilise the sensor data and transform it into useful information that describes the state of the structure. Examples where given in Section 4.1.1, as to which parameters to monitor and how these values can be used for calculation or estimation of values that are comparable to characteristics of the monitored element or parameter. Automatic alerting can be implemented to help discover damage or abnormalities at an early level. For this to be possible, failure modes or thresholds must be defined, so it is clear when alerting shall be made.

4.2.4 The importance of standardisation of sensor data

There are several challenges when it comes to making the sensor data usable, and also using the sensor data. The sensor data must be cleaned for noise, as noise disturbs the relevant data, and can give wrong results if used as information source. What type of noise it is, is also dependent on what is measured, and the sensor used for the measurement. Sensors measuring position can have noise that alters the accuracy of the position measurement, or the actual position. To clean the data in a fast and easy way is crucial for the usability of the digital twin, and good tools are therefore important. To have a standard format on the incoming data will be helpful for the cleaning process, so that the integration of the data in the digital twin is easy. Everything from input values to names should have their own standardised format, preferably a standard that is common for the whole aquaculture industry. The process of standardising all data formats and information can be costly and time consuming, but once it is done, it eases the use of the digital twin and the creation of all similar future digital twins. A common standard for all of the aquaculture industry will be helpful for both creators and users, and also for the development of digital twins in the industry. A common standardisation must be initiated by the producers in the industry, or by the government to be regulated in a standard.

4.3 Use of the digital twin for condition monitoring

In Section 2.2 condition-based maintenance was introduced. Large potentials for use in connection with a digital twin was identified, and Section 2.3 stated that this monitoring policy and the technology of a digital twin is complementing each other well. In this section, the implementation of condition-based monitoring for monitoring and decision support for Ocean Farm 1 is explored.

For a digital twin to work as decision support in relation to maintenance decisions, a predefined set of threshold values must be established. The threshold values makes it possible for the digital twin to alert the personnel or other persons working with monitoring of the structure. This way inspections and repair can be carried put when needed, which will be both cost-saving and time-saving. As a digital twin portrays the current state of the structure, decisions related to maintenance can be based on up-to-date data about the structure, which makes it easier to do maintenance at the best suitable time according to the damage that has emerged. Data programs and analyses can be created to monitor all sorts of parameters, from heeling of the structure to stress levels in a small local area. Monitored parameters should, as earlier discussed, give valuable information that are possible to implement in calculations and analyses, which also can be evaluated against known parameters of the different elements.

It is important to ensure use of well suited and high level sensors, that requires little maintenance of the sensor itself. For the inclinometer installed on the mooring line, maintenance and repair is especially challenging as the sensor is located under water. With a structure like Ocean Farm 1 that has an operational draft of 43 meters, which is 85% of the overall height of the main structure, a large portion of the sensors will be installed and operate beneath the sea surface. This is likely to ease the monitoring and inspection of the structure. Manual inspection of structural parts situated beneath the sea surface is complicated and challenging, and often requires personnel with special training. Short time hiring of personnel is expensive, and the task they carry out is challenging. New technology such as inspection with the use of remotely operated vehicles (ROVs) has made some operations easier and cheaper, but it still requires both personnel and time to carry out the inspection. With sensors continuously monitoring parameters of the structure, and a digital twin to structure the data and monitor the integrity of the structure, manual inspections can be carried out only when needed, which is hopefully at a much lower interval than without having continuous monitoring. Real time knowledge of the condition of the structure will increase the safety both due to safer working conditions and early detection of damage. Condition monitoring is thus considered one of the main advantages of having a digital twin of Ocean Farm 1.

4.4 Use cases for digital twins in offshore aquaculture industry

In this section, different use cases that have been identified for digital twins are evaluated and discussed. Section 2.3 identified many application areas for digital twins in other industries today, which in this section is explored specifically for the offshore aquaculture industry. The use cases mainly builds on existing use of digital twins, but also includes some new ideas for use that are specific to the aquaculture industry.

4.4.1 Designing with correct dimension

The conventional Norwegian aquaculture industry uses cages consisting of a high-density polyethylene (HDPE) floating collar and a flexible net. These are relatively cheap materials, and there has not been very much development of the designs for the last decades. The cheap materials has often resulted in overdimensioning to ensure that the structures withstands the environmental forces, without caring about the cost of doing this. With development licences and new designs emerging, the cages are getting larger and are built in stronger materials. Materials such as steel are more expensive than HDPE, and the combination of more expensive materials and larger structures automatically increases the costs. If these structures were overdimensioned as well, the costs would be too high for the investment to be profitable. A digital twin allows the design to be tested and verified prior to the actual manufacturing and can be a very helpful tool for assigning the right dimensions to the structure. In this way a digital twin can be cost-saving, because it is not spent more money on materials than necessary. For structures that are supposed to be placed in exposed locations, information from offshore oil and gas structures, and rules and regulations for these are highly relevant as information sources on design and dimensioning of offshore structures.

4.4.2 Advantages of having a 3D model

Having a 3D model of a structure has many positive sides. A 3D model is beneficial alone, as well as as an integrated part of a digital twin. As we live in a three dimensional world, a 3D model is, to most people, more intuitive to understand than two dimensional drawings. In the maritime industry it is still most common to use 2D drawings in the design process. To change from 2D drawings to 3D models in the design process has large possibilities for cost reductions and efficiency improvements in the design phase. All the most common and used 3D modelling programs today have integrated functions for creation of 2D drawings from 3D models. It should therefore be no hinder for the manufacturers, as they are still able to get the 2D drawings just like before. To create structures in 3D directly, also gives the possibility of testing the design right away. Today, most of the calculations and tests on design are done on 3D models in analysis programs. By creating the 3D model directly, several steps of the design and test phase can be simplified and done in a shorter time. 3D models can also help create a unique insight into the structure, how its infrastructure is and how the different parts of the structure are linked together and affects each other. A 3D model is interactive in a whole different way than a 2D drawing, and the possibility of investigating and getting to know the structure before it is built or before the personnel has been at the structure is a very valuable feature. It can be used to study different plans, such as evacuation plans, and to drill the personnel in their tasks in case of an emergency. That way they will have a thorough understanding of the structure before being there in person, and live practises at the structure can be done with a lot more consistency and accuracy from the first time. A digital twin creates insight in ways that are not possible if only 2D drawings are used. To explore the structure before it is built, can identify weaknesses and strengths, and gives the possibility of exploring scenarios and responses before the structure is built [26].

4.4.3 Put data into system

One of the largest advantages of a digital twin is the possibility of putting data and information into system. A prerequisite for having a fully working digital twin is implementation of real time data to the 3D model, so that the digital twin at all times portray the real state of the structure. The sensors and apparatus installed on the structure collects and sends larges amounts of data. To be able to utilise this data in an efficient way, systems sorting the received data are needed. Such systems can be implemented in digital twins to include both calculations and analysis of the data. The data is connected to the points at the 3D model at which they are measured, and can be visualised through it. This will give a clear and intuitive presentation of the information, and it should be easy to understand where the data originates from and how it is used in the digital twin.

When the sensor data is cleaned it can be used for calculations in the digital twin environment. The calculations and their results are stored in the digital twin so that it is always up-to-date on the state of the structure. The digital twin also contains product information about all the materials that are used, and can update and have an overview of the state of all the structural members at all times. This is valuable information throughout the entire life of the structure. From the very beginning, the digital twin can give information on the actual performance of the structure. Comparing this information to the calculated and expected performance will give valuable information about the structure from the start. This can go on throughout the entire life, and the digital twin can be used to verify the performance of the structure.

4.4.4 Saving of costs

The use of digital twins have the potential of being highly cost-saving, but to understand the potential for reduction of costs, the bigger picture must be understood. A digital twin is a complex and large system, and is more demanding and costly to develop than drawings or a stand alone 3D model. The initial costs will be larger than for similar designs that does not develop a digital twin, but the potentially saved costs throughout the lifetime of the structure is likely to outweigh these additional initial costs. The additional investment costs include detailed modelling of the structure as a 3D model, installing sensors at the structure, and creating programs and systems for processing of data from the sensors. If producing several facilities that are approximately equal, the model and system design can be reused. This way the initial investment in the production of a digital twin can be seen as an investment for a large number of structures. Several other cost-saving aspects of a digital twin are already discussed. A short recap of these shows that it can help in the design process as the design, and changes to it, can be tested immediately, it can be used for decision support during the lifetime of the structure, and it can increase the efficiency of the processes at the facility. In addition to being very useful throughout the whole lifetime of the structure, the digital twin as an as is version of the facility is very useful at the end of the lifetime. Norwegian rules says that offshore installations shall be removed at the end of the lifetime, but after many years in operation the structure is not likely to be as strong as it was at the time of installation [26]. Today, when offshore oil and gas platforms are removed, great efforts are put into calculating the current condition of the structure. It is necessary to know this to be able to plan the removal so that no materials are lost and no damage is caused on the environment. These calculations could be eased significantly by having a digital twin that contains all the information about the structure, so that the actual state of the structure is known. This also would increase the accuracy of the calculations and results, and increase the possibility of the removal operation being successful. DNV GL also suggest a use for digital twins, after the structure is retired [26]. By retaining all digital twins in a "digital graveyard", information is available to provide learning for future projects. This data can help the development of improved and better calculation and analysis models for new structures.

4.4.5 Decision support

A digital twin can be a very powerful tool for decision support. The current state of the structure is always displayed by the digital twin, and if a specific action affecting the structure is considered taken, it can be tested and assessed prior to the action actually taking place. Examples of such actions are installation of new equipment that will increase the weight and alter the stability of the structure. When adding extra weight to a structure it is important to know that the structure still provides enough buoyancy to keep the structure floating, with a freeboard large enough to still fulfil the rules that apply. An up-to-date model of the actual state of the structure will be helpful in the process of deciding whether or not the structure is capable of carrying the extra equipment. If the newly installed equipment in addition alters the stability of the structure, a new ballasting of the ballast tanks can be found from tests of and calculation from the digital twin. Both of these calculation processes would be a lot more demanding as they would require alterations to the original design prior to doing the needed calculations. With a digital twin that is already up to date on the state of the structure, the alterations can be tested right away.

4.4.6 Increase efficiency

A digital twin can increase the efficiency at a facility in different ways. It is a versatile tool in planning of operations, both for functionality testing and preparing of operations. Being well prepared is a key factor to successful execution of operations, and with a digital twin the operations can be simulated and tested before being carried out. This way challenges can be discovered and solved prior to the action taking place, and thereby facilitate smooth and effective operations. At an aquaculture facility, the fish are the most important asset, and the personnel at the facility are first and foremost employed to look after the fish and ensure it is healthy and that the conditions for growth are as optimal as possible. The personnel also has the responsibility of ensuring that the structure is intact, which can be a demanding and extensive job. With a digital twin portraying the condition of the structure, the tasks regarding monitoring of the integrity of the structure can be outsourced to companies that are specialised in this area. This will allow the personnel on the facility to focus on the fish, and only do task related to monitoring or maintenance when it is necessary.

4.4.7 Eases interaction with classification societies

All maritime structures, such as ships, platforms and aquaculture installations, must be certified according to national rules and regulations. There are several companies doing this, and also national regulatory bodies. This certification is a proof that someone else than the designing company itself is verifying that the design is good, and that it fulfils the requirement for installation in the area it is intended. This is also a requirement to get insurance for the structure. DNV GL are working towards an integration of use of digital twins in their classification processes [26]. With the use of digital twins they are able to get information in advance of inspections, and can, based on the calculated state of the structure, plan the inspection to focus on the most damaged members. This way they both improve the efficiency of their inspections and increase the likelihood of discovering potential damages. Inspections of digital twins are not likely to replace the on-site inspections, at least not in the foreseeable future, but they have a large potential for being a valuable tool for planning and streamlining of the inspection processes.

4.5 Challenge of finding the balance between number of and use of sensors

Purchase and installation of sensors are both costly and time consuming, compared to not having any sensors. The additional costs of installing sensors should therefore be considered carefully against the benefits the specific sensor gives. Not only does a large number of sensors increase the initial costs, but the large amount of data they produce also requires handling. Before implemented in a digital twin, this data must, as previously explained, be sorted and put into system. The larger the amount of data, the more data must be cleaned and sorted, and the more extensive and expensive this process becomes. Therefore, it is important to find a balance between the number of sensors, and the information that is wanted and needed. Each sensor and its contribution to the information pool should be considered carefully. If the sensor gives information that is not possible to get from any other sensor, it is a good candidate for installation at the structure. If the information can be retrieved or derived from another sensor, it might not be necessary to install that particular sensor. Having a suitable number of sensors for the specific structure, ensures efficient use of the data and the digital twin. A digital twin has, as earlier described, many positive features, and the investment in sensors from the design phase are highly likely to pay back during the lifetime of the structure in terms of saved costs.

Chapter 5

Discussion

This chapter discusses some of the overall findings from Chapter 3 and Chapter 4. The different use cases for the digital twin have been discussed while presented in Section 4.4, and the specific use cases will not be addressed further in this chapter.

The sensors chosen for monitoring of the elements, are believed to serve their tasks well, given that they operate as intended. The elements chosen to monitor are based on an analysis that is selective, where waves and current from only three chosen directions were selected. The chosen elements and sensors may therefore be well suited for monitoring of this specific combination of sea states, but not for all combinations of sea states. A full analysis would provide the whole load picture of the structure, and sensor selection based on these results may be different from what is chosen for this thesis. For selection of sensors when creating a real of a digital twin, a full structural analysis is considered a good starting point. However, the analysis carried out in this thesis serves well for the wanted outcome of the analysis, and for the purpose of exploring different sensors.

The selection of sensors was a comprehensive process. Finding information on the monitoring principle of the sensors and what parameters they are monitoring was a relatively straightforward process. It was more challenging to find good information on the size, how to install them, and the potential noise they capture. This made the sensor selection challenging, and it was not possible, based on the information obtained through the literature review, to obtain a good understanding of how the sensors would work in collaboration. Therefore, only one sensor was chosen for each of the structural elements. In principle, this information should be good enough to provide the data that is wanted, but without knowing all the analysis and cleaning processes the data undergoes in the digital twin, it is hard to determine if the data being provided by the selected sensors in this analysis would be of good enough quality.

The net is a very important part of the structure and should have been considered monitored, but it is challenging to give a good interpretation of the stresses in the net based on the analysis. The net is modelled coarser than it is in reality, and only gives an indication of the total stresses in an area of the net. It can not be specified from this how the forces are distributed in the actual net. Because of this, the stress in the net has not been considerably investigated. The twines of the net are small, which makes monitoring of the whole net complicated by use of sensors directly applied to the twines. It would also be challenging to monitor the net for the purpose of preventing damage, as the whole net would need monitoring. As described in Section 3.1.3, the net is designed to remain intact even if a wire is cut, and immediate detection of a cut wire should therefore not be the most critical detection. A proposal for monitoring of the net would be by the use of cameras that detects holes visually through pictures, or by the use of fibre-optic weight sensors which already has been applied for this purpose for flexible nets. Given that the net in fact stays intact if a wire is cut, damage to or breaking of a larger structural member will cause greater damage. If one of the tubular beams that the net is connected to breaks, the probability that a large part of the net is being damaged is high, and the tubular beam is therefore evaluated as more important to monitor.

In Section 3.6.2, element 604 was evaluated as an interesting element to monitor based on the large stresses experienced by the element, and the stresses being "opposite" of what element 526 experienced. After deciding to monitor element 524 with strain gauges, and seeing that the these sensors measure strains in both compression and tension, it can be stated that element 604 can be monitored in the same way. The decision of only bringing element 524 of the two to the sensor application part can be evaluated as a good decision, as it would not have served the purpose of showing a variety of sensors.

The importance of choosing the correct or best analysis method based on the wanted outcome is highlighted in a paper by Cameron et al. [11]. When installing sensors it is important to know which data is interesting, and what results that are wanted from the sensors. By clearly knowing the wanted outcome of simulation, unnecessary information handling and processing can be minimized. Starting out with an analysis that identifies relevant elements for monitoring, and choosing analysis method based on the specific element parameters has through this thesis shown to be a suitable way to attack the problem.

Chapter 6

Conclusion

6.1 Concluding remarks

The ongoing developments of the production units in the Norwegian aquaculture industry opens the possibility and need for use of new technology. Several production companies have made investments in new and large structures for production of salmon in a more exposed environment than what is common today. These structures are large and complex, which makes monitoring of the structural integrity more relevant in this industry than it has been up until now. With large structures and more complex systems, it is harder to keep an overview of all operations manually, and the need for an easier way to keep everything under control arises. Compared to conventional aquaculture cages, the forces acting on these structures are larger, and different than before. Monitoring structures by the use of sensors are common procedure in other industries today, and there are almost unlimited amounts and types of data that are possible to obtain from sensors. To be able to utilise the data in an effective way, it must be sorted and presented in an easy and understandable manner. A digital twin has through this thesis shown the possibility of providing an efficient way of organising the data.

Through this thesis, different use cases for digital twins in the aquaculture industry has been investigated. Overall, there are large potentials for efficiency improvements and cost reductions by implementing a digital twin in the development procedure from the beginning of the design of the structure. The biggest drawback of a digital twin is the increased investment cost in the start of a project. On the other hand, during the lifetime of the structure the digital twin has large potentials for cost saving measures, and over time the investment and the savings will hopefully even out, and also be cost saving in the later years. The investment cost will also be largest the first time a digital twin is created, and if several other structures that are equal or similar is created, the costs of creating a digital twin of the second or third structure is less expensive because systems can be re-used and adapted. These costs include detailed modelling of the structure as a 3D model, installing sensors at the structure and creating programs and systems for processing of data from the sensors. Today, a 3D model is usually made for calculations and analysis of the design of the structure prior to the manufacturing, which can be a good starting point for a digital twin.

The process of choosing sensors for installation, and the elements that need to be monitored, is complicated and requires a good data basis. To ensure the costs of the digital twin does not escalate, it has to be a balance between the cost of the sensors and instalment, and the value of the data the sensor provide. A thorough assessment of which sensors to install is important, to ensure the chosen sensors are advantageous and gives valuable information. From the analysis of the design, prior to the manufacturing, it should be possible to identify exposed and highly utilised members. An evaluation can, based on this, be made to if it is necessary to monitor the adjoining elements of a highly exposed element. If the chance is great that the exposed element will be the first to failure, it might be enough to monitor this element, and base the deterioration of the adjoining elements on the data from this element. To be able to make such a decision, a full structural analysis that tests all possible scenarios occurring at the location must be carried out. A structural analysis has been a good starting point for the sensor selection in this thesis, and if a full structural analysis is carried out, it should be possible to identify and distinguish between the many relevant elements to monitor.

One of the main advantages of a digital twin that has been identified was the possibility of monitoring parts of the structure that are situated under the sea surface, in a clear and easy way. Regular manual inspection of these areas are challenging, but a digital twin can monitor the wanted parameters, and manual inspections can be scheduled when it is needed. This way the safety of the workers are increased, as they do not need to carry out challenging maintenance task often, and the structural integrity of the structure is continuously monitored, which increases the probability of early detection of damage.

A digital twin has the potential of enhancing all life stages of a structure, from the design and manufacturing phases, throughout the operational life, to the decommissioning. It can be used to test the structures reaction to environmental forces both prior to and after an event, to gain knowledge about its response pattern. It can also be used for training of personnel and planning of operations to reduce the risk of unwanted incidents. It can be used for monitoring of the structural integrity of the structure, which can be used by both the production company for planning of inspections, and of classification societies. Classification societies base most of their inspections on fixed time limits, but by having a digital twin of the structure and all important information it is possible to streamline the inspection process by inspecting when necessary, based on the condition of the structure, and not time. Sensors are able to give a lot of information about the state of a structures, and implementation of sensors should be evaluated thoroughly when new aquaculture structures are built. The almost unlimited possibilities a digital twin provides, makes it a valuable resource for the aquaculture industry as it moves to more exposed locations.

6.2 Suggestions for further work

The work in this thesis has identified many potentials for digital twins in the offshore aquaculture industry, and these should be investigated more thoroughly, preferably in combination with a fully developed digital twin of the fish farm. The following list presents suggestions for further work based on some of the findings in this thesis.

- In this thesis it is stated that a digital twin gives large cost saving potentials for the structure it is connected to. This is mostly based on findings in the literature, and no thorough investigation of the value of the potentially saved costs have been carried out. A full economic analysis should be carried out to find the actual cost saving potential.
- In the case of actually creating a digital twin of Ocean Farm 1 a more thorough analysis of the structure should be carried out. For full monitoring of the whole structure, more sensors than what is presented in this thesis must be used, and monitoring of more elements must be implemented.
- Making of a digital twin of Ocean Farm 1 would require installation of sensors at the actual fish farm to be able to collect information that can be sent to the digital twin. Today, the only sensors installed are concerning the fish health, and not the structural health.
- Expand the list of monitored elements and the applied sensor. An even more thorough survey of which sensors that can be used should be carried out, preferably in cooperation with a company that specialises in this area. This way the best information is obtained which might make it easier to choose the sensors.

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Appendix A

Master thesis problem definition text

NTNU Trondheim
Norwegian University of Science and Technology
Department of Marine Technology

MASTER THESIS IN MARINE TECHNOLOGY

SPRING 2019

For stud.techn.

Katarina Staalesen

Topic:
Use cases for digital twins in offshore aquaculture industry

Background

As the Norwegian aquaculture industry is developing and growing, new areas located further offshore are being used. This requires larger structures than before, that are able to withstand larger forces and at the same time ensure good conditions for the fish. This opens for the use of new technology as the new structures are more advanced than the conventional cages that has been used for the past decades. To facilitate new technology that can help solve the challenges related to space limitations and environmental problems, the Norwegian Directorate of Fisheries introduced development licenses to the Norwegian aquaculture industry in 2015. The licenses are granted to the projects they believe will succeed and contribute to the development of the Norwegian aquaculture industry. Several of the projects that have been granted licenses are intended for exposed aquaculture locations, one of them being Salmar and Ocean Farming's Ocean Farm 1.

Following the expected increasing amount of aquaculture structures that will be situated at more exposed locations in the years to come, comes an increased need for monitoring of the farms to ensure safe conditions for everyone involved. The offshore structures must withstand a harsher environment, which results in stronger and larger structures. More remote locations and larger structures increases the relevance and importance of monitoring of the structure, which is where the idea of a digital twin comes into play.

Objective

The objective of the thesis is to give insight to the digital twin concept for offshore aquaculture industry, through the use of structural analysis and assessment of sensor application. An analysis of the offshore aquaculture structure Ocean Farm 1 will be carried out to identify weak points of the structure and the areas that are subjected to large forces and stresses. The findings and results will be the start of a knowledge basis for the establishment of a digital twin of Ocean Farm 1. Relevant sensor technology for monitoring of the structural integrity will be chosen based on the results from the analysis. The thesis will give an example and a description of how the combination of structural analysis, CAD and sensor monitoring can be used to form a digital twin.

NTNU Trondheim
Norwegian University of Science and Technology
Department of Marine Technology

Tasks

The candidate is recommended to cover the following parts in the master thesis:

a. Review state of art within the topics of digital twins and structural monitoring. That means to document what others have done and published previously.
b. Carry out a structural analysis of Ocean Farm 1 to identify weak points of the structure and areas that are subjected to large forces and stress. The analysis shall be carried out using the program USFOS, and shall be run for some selected sea states and extreme waves.
c. Based on the analysis a set of sensors is to be selected to monitor these areas. There will be chosen at least 3-5 sensors in prioritised order, starting with the sensor that is considered most important. The reason for the specific prioritised order, and the purpose of choosing the specific sensor for the specific location, shall be clearly stated and reasoned.
d. Give a description of how the combination of structural analysis, CAD and sensor monitoring can be used to form a digital twin.
e. Present how the monitored parameters and the sensor data provided by the sensors can be implemented with the digital twin to monitor the structural health and serve as decision support.
f. Present examples of specific use cases for a digital twin in the aquaculture industry.
g. How a digital twin will be beneficial for the aquaculture industry in the future, related to human and fish safety, profitability and structural integrity is something that shall be in focus and emphasised throughout the thesis.
h. Conclusions and recommendation for further work.

General

In the thesis the candidate shall present his personal contribution to the resolution of a problem within the scope of the thesis work.

Theories and conclusions should be based on a relevant methodological foundation that through mathematical derivations and/or logical reasoning identify the various steps in the deduction.

The candidate should utilise the existing possibilities for obtaining relevant literature.

The thesis should be organised in a rational manner to give a clear statement of assumptions, data, results, assessments, and conclusions. The text should be brief and to the point, with a clear language. Telegraphic language should be avoided.

The thesis shall contain the following elements: A text defining the scope, preface, list of contents, summary, main body of thesis, conclusions with recommendations for further work, list of symbols and acronyms, reference and (optional) appendices. All figures, tables and equations shall be numerated.

The supervisor may require that the candidate, in an early stage of the work, present a written plan for the completion of the work.

The original contribution of the candidate and material taken from other sources shall be clearly defined. Work from other sources shall be properly referenced using an acknowledged referencing system.

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Deliverable

- The thesis shall be submitted in one (1) copy:
- Signed by the candidate
- The text defining the scope included
- Drawings and/or computer prints that cannot be bound should be organised in a separate folder.
- The bound volume shall be accompanied by a CD or DVD containing the written thesis in Word or PDF format. In case computer programs have been made as part of the thesis work, the source code shall be included. In case of experimental work, the experimental results shall be included in a suitable electronic format.

Supervision:

Main supervisor: Bjørn Egil Asbjørnslett

Sub-supervisor: Jørgen Amdahl

Deadline: 11.06.2019

Appendix B

Results from Bore and Fossan's master thesis

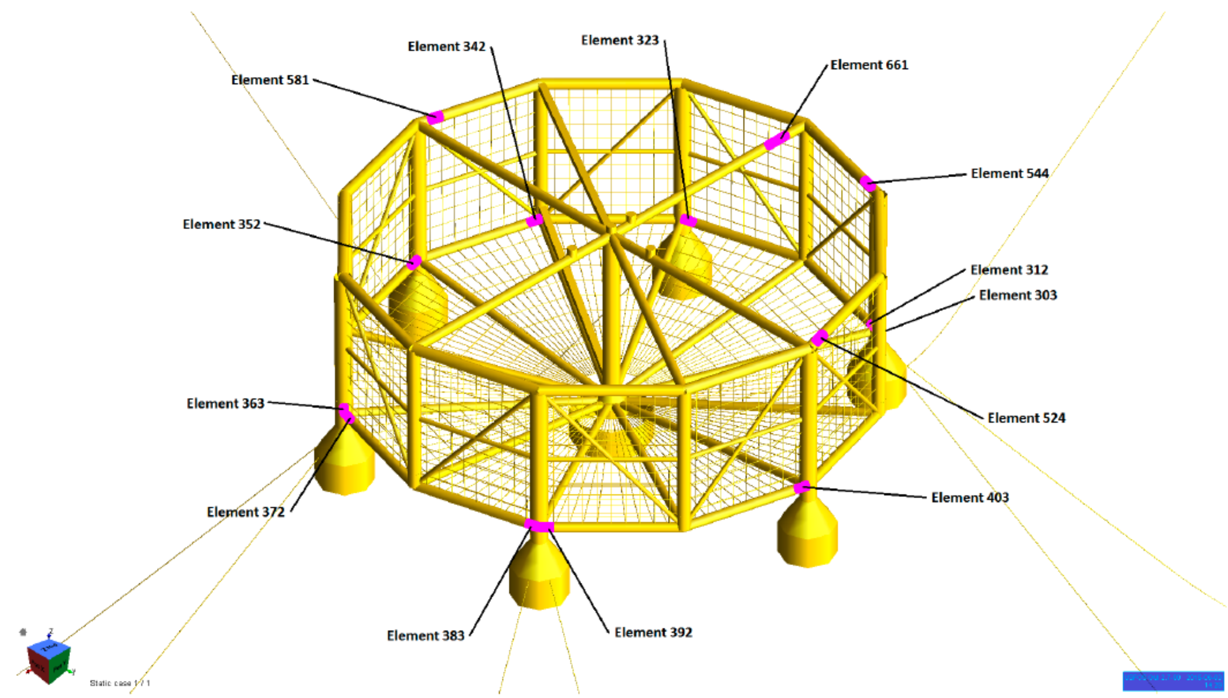

Figure B.1: Visualisation of the most utilised members as found by Bore and Fossan. The most utilised members are highlighted in pink. The Figure is from the master thesis of Bore and Fossan [10, p. 86].

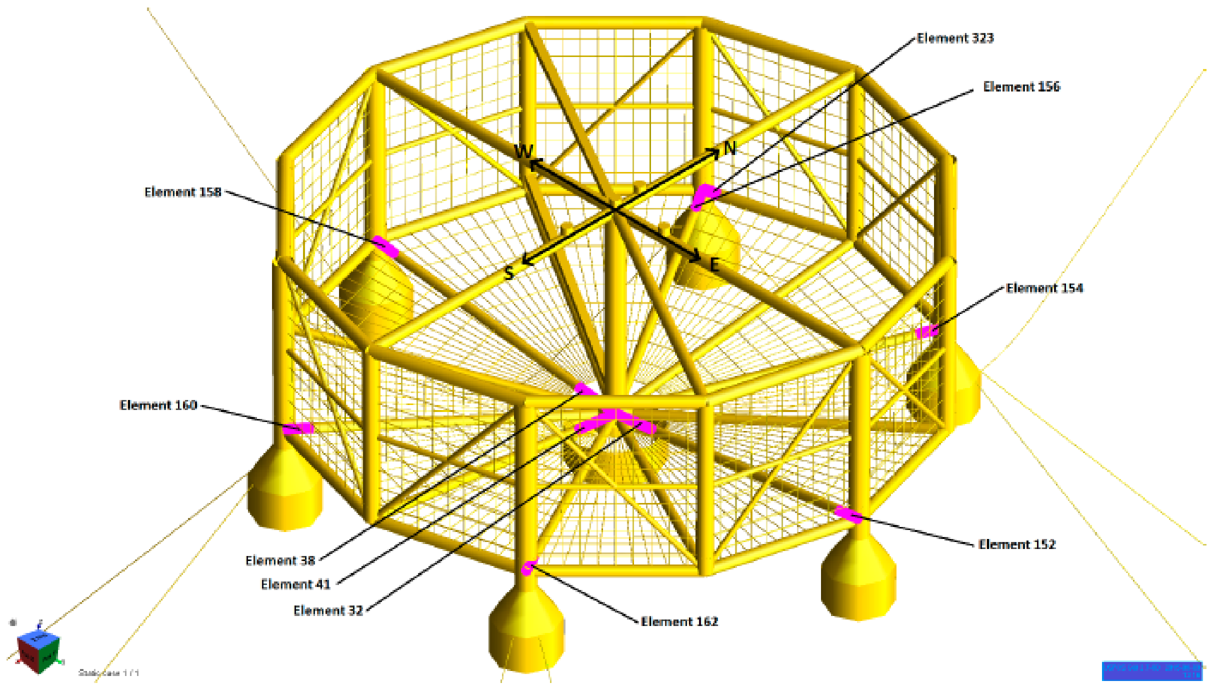

Figure B.2: Visualisation of the top 10 most damaged elements in the complete model as found by Bore and Fossan. The most critical members are highlighted in pink. The Figure is taken from the master thesis of Bore and Fossan [10, p. 99].

Katarina Staalesen

Exploring the Digital Twin Concept for a Rigid Aquaculture Cage

NTNU

Kunnskap for en bedre verden