High Energy Ship Collisions With Bottom Supported Offshore Wind Turbines

Rinke Kroondijk

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Abstract:

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In this thesis the "Federal Maritime and Hydrographic Agency" in Germany, also known as Bundesamt für Schifffarth und Hydrographie requires in the standard "Design of Offshore Wind Turbines" that an offshore wind turbine needs to be risk evaluated against a ship tanker of more than 500 MJ in collision energy in order to be classified as collision energy. This is to prevent environmental pollution in form of oil spill.

Whether the offshore wind turbine models used in this thesis are collision friendly or not relies on different factors. When the given soil properties are used the analyses show in all cases except one that the offshore wind turbine models can be called collision friendly. The case were it could not be called collision friendly was a case with the small jacket at a water depth of 27 m getting hit by a loaded ship at a column of the jacket, but installing a horizontal brace on this jacket would make it also collision friendly.

The effects of soil, water depth and a horizontal x-brace are looked further into in this thesis. If the soil had been stronger it is not certain that the outcome would be the same. When the jackets were fixed to the sea bed, several of the models could collapse in the dangerous direction over the ship. A horizontal brace was seen to have a positive effect when installed on the different jacket models. It seems also that it is more favorable to use jackets at deeper water.

Keywords:	Advisor:
Ship collision Wind turbines Finite element analysis; USFOS	Professor Jørgen Amdahl

Master Thesis 2012

for

Stud. Techn. Rinke Kroondijk

High energy ship collisions with bottom supported offshore wind turbines
Analyse av høyenergi skipsstøt mot bunnfaste offshore vindkraftverk

Offshore wind turbines may be located close to ship traffic lanes and thus exposed to ship collision. According to the Bundesamt Fur Seeschiffahrt und Hydrographie; Standard for Design of Offshore Wind Turbines (2007) the turbine has to checked for collision with a tanker of 160 000 dwt., corresponding to a displacement of 190 000 tons. The impact speed is 2 m/s, which gives a kinetic energy of more than 500 MJ for sideway drifting and added mass of 40%. For comparison, the standard collision energy with offshore vessels on the Norwegian Continental shelf is only 14 MJ.

With such huge amount of energy, it is not possible to design the wind turbine to resist the tanker (if the turbine was designed strong enough, the tanker would have to suffer major damage).

The best option is likely to construct the turbine such that it collapses into the sea in the drift direction of the tanker, actually without stopping the tanker, thus preventing the nacelle from dropping down on the tanker – and hence – opening of cargo tanks and direct hits of sailors – is avoided. The collapse may either be induced by buckling, yielding of the support structure, or foundation failure, e.g. piles being pulled out of the soil on the tension side.

To achieve such a design may be challenging; Because of the large inertia the support structure will be subjected to significant compression on the hit side in the early stages of collision. How to avoid the negative influence of failures on the hit side of the support structure; e.g. local buckling of stiffened/unstiffened columns etc.?

The USFOS software is a versatile tool for the global analysis, possibly in combination with other shell FE codes for local analysis. The purpose of the present work is to investigate the possibility of achieving the design requirements of the BSH standard.

The following tasks should be addressed:

1: Background

Perform a brief review of potential location for bottom supported offshore wind turbines in Europe and present areas with large ship traffic. Present an overview of relevant support structures (monopile, concrete foundations, jacket supports etc). Literature review of studies related to assessment of the consequences of ship impact with respect to structural damage and environmental pollution. Perform a brief review of the risk picture with respect to ship

size and collision energy. Review of the Standard for Design of Offshore Wind Turbines issued by the Bundesamt Fur Seeschiffahrt und Hydrographie (2007). Other relevant standards should be considered.

2: Calculation model

Establish calculation models for the jacket, tower and nacelle for different water depths including any thrust force representing the wind turbine. The ship-jacket force interaction may be modeled as a nonlinear spring with representative properties. The pile/soil interaction shall be modeled with available features in USFOS. Strong and soft soil conditions shall be considered. Modeling of potential local buckling modes shall be considered by using shell finite element modeling of the lower end of the tower shall with appropriate imperfections. Establish failure criteria for fixation of the turbine to the tower.

3: Case Study

Perform static and dynamic analysis of selected support designs subjected of the ship impact. Conduct sensitivity studies where important parameters are varied.
Identify collapse patterns:
Will the tower collapse away or over the ship? The effect of water depth shall especially be studied.
Will the tower suffer local buckling in this process?
Will the turbine fixation fail, so that the turbine drops freely down on the ship deck?
What is the likely consequence of a fall on the ship deck?

4: Monopile

To the extent that time permits, perform analysis with a monopole support.

5: Conclusions and recommendations for further work

Literature studies of specific topics relevant to the thesis work may be included.

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

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

Theories and conclusions should be based on mathematical derivations and/or logic reasoning identifying the various steps in the deduction.

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

Thesis format
The thesis should be organised in a rational manner to give a clear exposition of 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, references and (optional) appendices. All figures, tables and equations shall be numerated.

The supervisors may require that the candidate, in an early stage of the work, presents a written plan for the completion of the work. The plan should include a budget for the use of computer and laboratory resources that will be charged to the department. Overruns shall be reported to the supervisors.

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.

The report shall be submitted in two copies:
- Signed by the candidate
- The text defining the scope included
- In bound volume(s)

Drawings and/or computer prints which cannot be bound should be organised in a separate folder.

The report shall also be submitted in pdf format along with essential input files for computer analysis, spreadsheets, Matlab files etc in digital format.

Deadline: September 14, 2012

Trondheim,   April 20, 2012

Jørgen Amdahl
Professor

Contact person at Virtual Prototyping:
Tore Holmås

Preface

This report is written by Stud. Techn. Rinke Kroondijk. It is the result of the course "TMR4900 Marine Structures – Master thesis" at the Department of Marine Technology at the Norwegian University of Science and Technology (NTNU) in Trondheim. The scope of work corresponds to 30 credits, and is the final piece to the Master of Science degree. The work had a delayed start in the spring semester 2012. It did therefore not need to be submitted until early fall 2012. The work has been carried out under the supervision of Professor Jørgen Amdahl.

During the work of the thesis it became clear that running all the different analyses several times with changing parameters was quite time consuming. As a result of this, the shell analyses and monopile analyses have been reduced in extent. Only one shell analysis is performed in order to see what happened in one case. Theory of local buckling and deeper explanation of local buckling of the tower is therefore not mentioned in this thesis. Regarding the monopile a few analyses have been done, but the results are not verified and therefore not written much about. There was also not enough time to perform hand calculations regarding absorb energy of the different impact analyses.

Several people have contributed to the realization of this report. First I would like to thank NTNU and my supervisor Professor Jørgen Amdahl for the cooperation and contributions during this thesis work. Gratitude is also given to my cohabitant Conny Vigre for support and taking care of our five children throughout the studies.

Bergen, 2012.09.14

Rinke Kroondijk

Abstract

As the worlds demand for energy is increasing mostly due to the increase in population, and coal, oil and gas deposits are limited, it is desirable to gather energy from renewable energy sources. Wind energy is a form of renewable energy. Wind turbines have been common on land and near shores for some time, but now one wants to take advantage of the wind resources further away from the coast. As the length from the coast increases, so does the water depth making it necessary to use other foundations than the well-known monopile.

In this thesis the "Federal Maritime and Hydrographic Agency" in Germany, also known as Bundesamt für Schifffarth und Hydrographie requires in the standard "Design of Offshore Wind Turbines" that an offshore wind turbine needs to be risk evaluated against a ship tanker of more than 500 MJ in collision energy in order to be classified as collision energy. This is to prevent environmental pollution in form of oil spill.

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List of Abbreviations

AIS	Automatic Identification System
ALS	Accidental Limit State
BSH	Bundesamt für Schifffarth und Hydrographie (Federal Maritime and Hydrographic Agency in Germany)
CFFD	Collision Friendly Foundation Design
EWEA	European Wind Energy Association
MWL	Mean Water Level
OWT	Offshore Wind Turbine
TEU	Twenty-Foot Equivalent Units
ULS	Ultimate Limit State
VTS	Vessel Traffic Service

Symbols

Different symbols are explained were they first appear.

1 Introduction

1.1 General

The worlds demand for energy is steadily increasing. The biggest reason for this is that the population on earth is still growing. In 1975 there were 4 billion people on this planet. Today we are over 7 billion people. Estimates for 2050 are 9.5 billion.

Coal, oil and gas deposits are limited. This combined with the respect to the earth's environmental conditions it is desirable to utilize energy from renewable energy sources. Wind energy is a form of renewable energy and has been used by mankind for centuries. First with traditional windmills, but in the second half of the 20th century it also became important for power production. Today, with newer technology one wants to take advantages of the enormous wind power potential offshore. According to the European wind energy association (EWEA) installed wind capacity at end 2011 will, in a normal wind year, meet 6.3% of the EU's electricity needs (EWEA12).

Offshore wind farms offer clear advantages compared to farms near shore or on land. Offshore locations have stronger and more stable wind resources. A wind farm can be located over a large and open area with less noise restrictions and no visibility from shore. Larger wind turbine generators up to 5MW, 6 MW and 10MW can therefore be utilized. These can produce energy at a much higher capacity and also yield compared to onshore (NorWind).

One downside with offshore wind farms on the other hand, is the damage potential associated with collision with large merchant vessels. According to the standard issued by Federal Maritime and Hydrographic Agency in Germany, offshore wind turbines have to be checked for accidental collisions with drifting vessels. For this it is possible to use a 160,000 dwt tanker drifting sideways at 2 m/s (BSH07). This is the size of a Suezmax tanker, which can load approximately 1,000,000 barrels. Fully loaded this gives a kinetic energy of more than 500 MJ. With this enormous amount of kinetic energy it is virtually impossible to design a jacket for this event.

It is therefore desirable to make offshore wind farms with so-called "Collision Friendly Foundation Design (CFFD)". In case of a ship collision with such a foundation type, the ship will not be damaged or more generally spoken emission of harmful substances will be minimal (Biehl05).

1.2 Thesis structure

Chapter 2 contains background information for the thesis. It includes a description of wind area potential, different support structures for wind turbines, and a brief literature review of earlier relevant work concerning ship collisions with wind turbines as well as a review of the different standards used today.

Chapter 3 describes more in detail of how the offshore wind turbine (OWT) foundation models are built up, and what parameters that have been considered in the analyses.

Chapter 4 contains information about the different computer models used in the analyses. Models are shown in the GUI of USFOS.

Chapter 5 displays the results of the static and dynamic analyses done of the ship impact with the OWT. The analyses are executed in USFOS.

Chapter 6 discusses the results given in chapter 5.

Chapter 7 concludes the whole thesis. Recommendations for further work are also given.

2 Background

2.1 Wind farms location in Europe

During 2011, 10,281(excluding Russia) MW of wind power was installed across Europe, of which 9,616 MW in the European Union. 8,750 MW was installed onshore and 866 MW offshore.
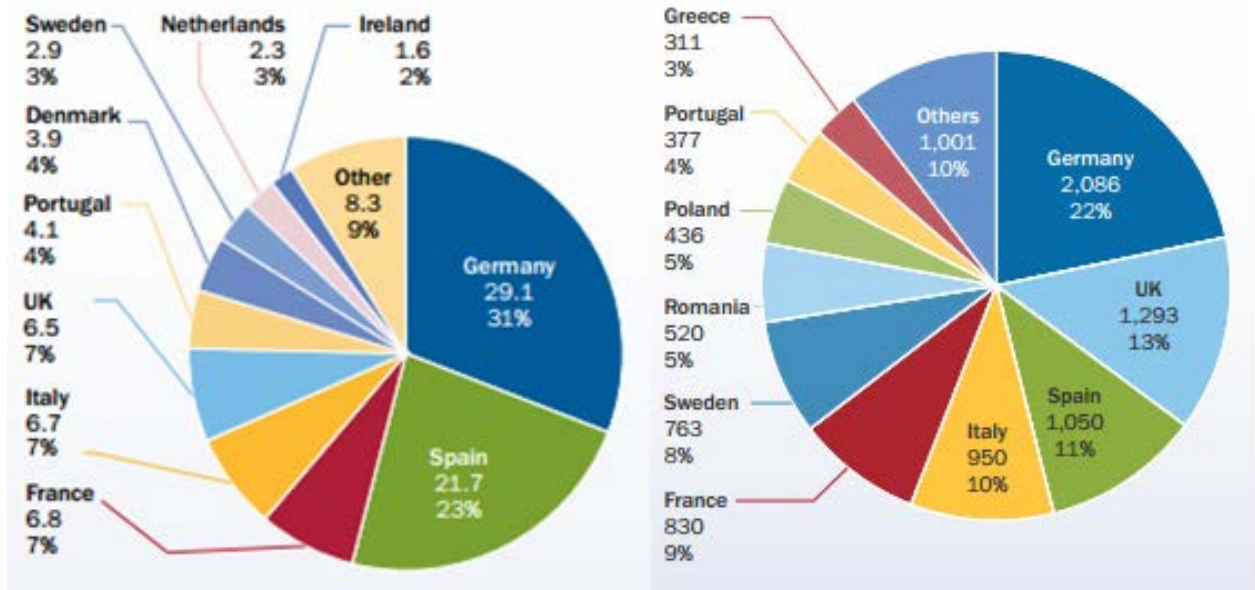
Figure 2-1: EU member state marked shares for total installed capacity at end 2011 in MW (left) and for new capacity installed during 2011 in MW (right) (Source: EWEA12)

Today installations on land are by far the biggest contributions to the total wind energy production. As figure 2-1 shows, Germany and Spain are the countries with the largest capacity, and also among those with largest installed capacity along with UK and France in 2011.

2.1.1 Wind resources
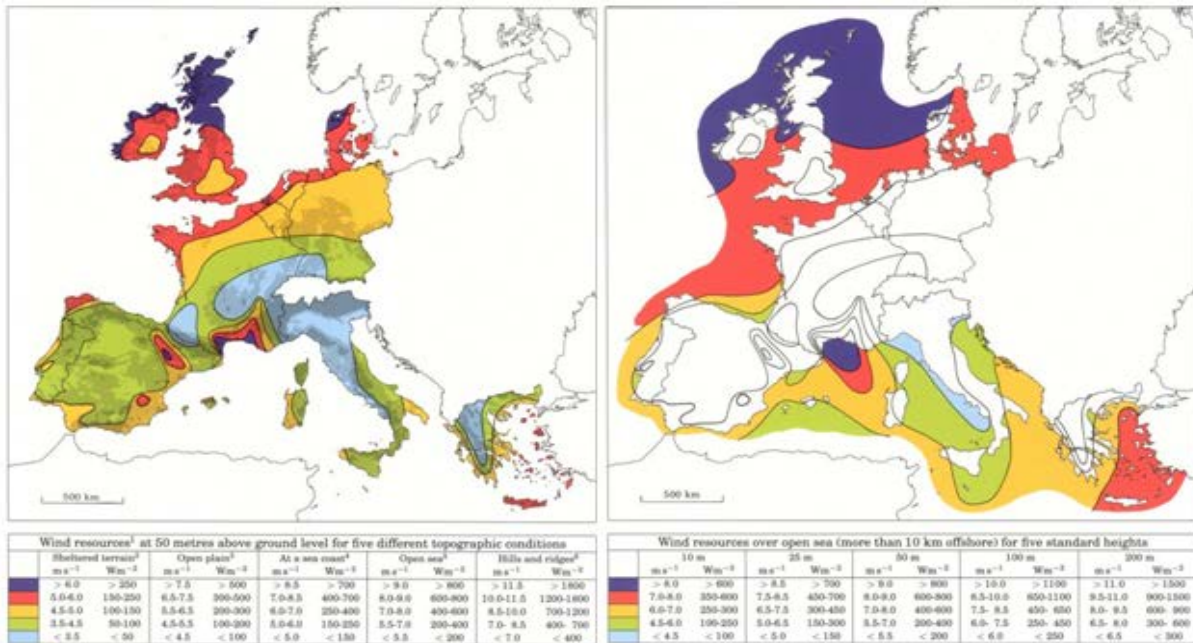
Figure 2-2: Map of wind resources in Europe onshore (left) and offshore (right) (Source: DTU Wind Energy)

The map on figure 2-2 to the left depict the generalized wind climate (wind atlas) for Europe, i.e. the mean annual wind as it would be at 50 m above the ground, if the terrain was flat, uniform and featureless, and with a specific surface roughness length. In order to get the actual wind climate or wind resource at some height above ground level for a specific site, one would have to model the situation in much more detail - using the wind atlas data set as one of the inputs. The graphics with legend provide some information on how the wind would be in some types of simple landscapes. To the right a corresponding map for offshore wind resources in Europe is presented. Areas in red and purple have the highest wind resources offshore, and are of potential locations for offshore wind farms.

2.1.2 Ship traffic lanes
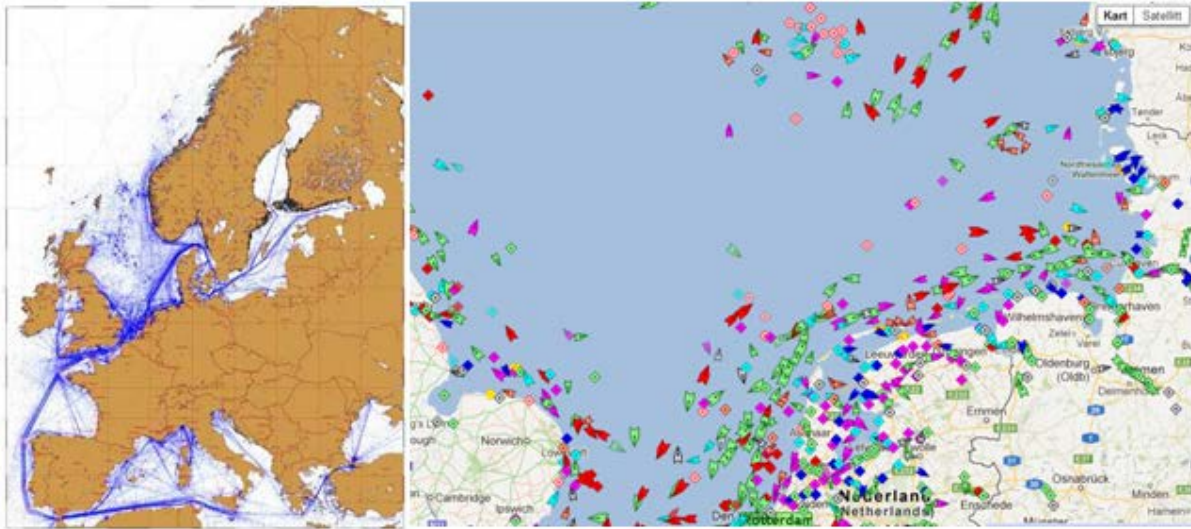
Figure 2-3: Map of ship movements from satellite NO$_2$ traces (Source: sensysmag.com) (left), live map from marinetraffic.com (right)

Figure 2-3 shows the largest ship trafficking lanes in Europe. To the left a satellite photo of Europe with NO$_2$ traces. To the right a print screen image from marinetraffic.com, showing more detailed ship trafficking along the coasts of Denmark, Germany, The Netherlands and somewhat of UK.

2.1.3 Offshore wind farm sites

Figure 2-4: Offshore sites in commission and under installation (Source: LORC)

As seen on figure 2-4 all offshore wind sites are relatively close to shore in shallow and sheltered waters. The water depths vary from 1 m to 50 m. In coastal areas the potential for conflict is considerable, especially in terms of shipping lanes, fisheries, birds and sea mammals. If figure 2-4 is combined with the figures on 2-3 it becomes clear that many of the installed offshore sites today are located near a shipping lane. There is clearly a risk potential for a ship collision with bottom supported offshore wind turbines.

2.2 Support structure

During the last decade or so, wind turbines have gone from being placed only on land, to also be placed offshore. At this time, wind farms are still only consisting of bottom supported structures, but in the recent years, technology is under development for also making floating offshore wind turbines economical reasonable. Meanwhile are the bottom supported structures moved a bit further away from the coast, and into slightly deeper water.

Monopile
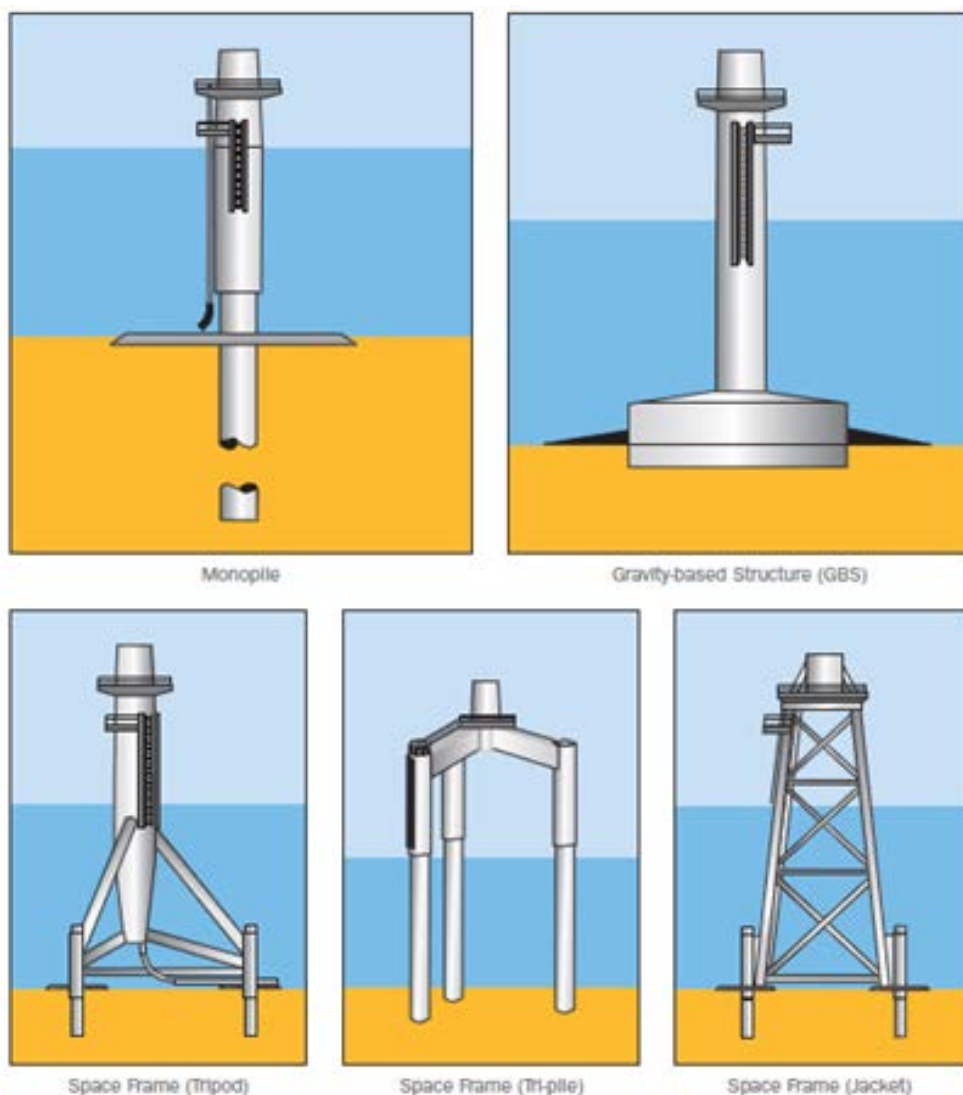
Gravity-based Structure (GBS)

Space Frame (Tripod)

Space Frame (Tri-pile)

Space Frame (Jacket)

Figure 2-5: Examples of different substructure design (Source: EWEA 2011)

The type of substructure needed varies mainly with the wanted first natural period of the structure(Nielsen06). Figure 2-5 shows examples of different bottom supported structures. In the following there will be a short description of the different substructures:

2.2.1 Monopile

A monopile is a single steel pile which is embedded into the sea bed. How far the pile goes into the sea bed, the size of pile diameter / wall thickness is mainly determined by maximum water depth and rated capacity of the wind turbine. Today, suitable for water depths up to 25 meters, although in the Belwind1 wind farm project monopiles are used up to a water depth of 37 m.

2.2.2 Gravity based structure (GBS)

GBS are designed to avoid tensile or uplift forces between the bottom of the supported structure and the sea bed. Dimensions will increase mainly with turbine capacity, the site wave conditions and water depth. Currently most suitable for water depths up to 30 m, although some designs are being considered for deeper sites where meteorological and oceanographic conditions are suitable, as for instance the Baltic Sea.

2.2.3 Tripod

The tripod is a standard three-legged structure made of cylindrical steel tubes. The central steel shaft is attached to the turbine tower. The base width and the pile penetration depth can be adjusted to suit the environmental and ground conditions. The size of the multi-pod foundation will increase with the capacity of the turbine, but it will also be affected by wave conditions and water depth at the site. Structure well suited for sites ranging in water depth from 20 to 50 m.

2.2.4 Tri-pile

Tri-piles consist of three foundation piles connected via a transition piece to the turbine tower with the transition piece located above the water level.

2.2.5 Jacket

Jackets differ from tripods and tri-piles in that they consist of a larger plan area through the majority of the structure, positioning the steel further from the centre of the axis, which results in significant material savings. Knowledge is known from the offshore oil and gas sector for decades. As with the tripod design, the structure is "pinned" to the sea bed using piles. It is argued that the increased manufacturing and assembly costs of such a structure when compared to the tripod are offset by significantly lower mass for the same stiffness characteristics, and that automated production processes have the potential to reduce costs further.

2.2.6 Other demonstrated fixed substructure designs

Aside from the mainstream substructure types detailed in 2.2.1 – 2.2.5, there are other designs including battered piles and suction buckets. Battered piles include a reinforced concrete pile cap sitting on battered (inclined) driven steel piles and are suitable only for shallow, well sheltered waters. Suction buckets consist of an upturned cylinder "sucked" into place thus

removing the need for expensive cumbersome piling. However, suction buckets are limited to use in relatively uniform benign soils and hence are unsuitable for many European sites (EWEA 2011).

2.3 Literature review

2.3.1 Review of the risk picture

Although the probability of occurrence of ship collisions is low, the scale of the consequences could be large. Is must be considered that in a collision incident parts of the ship structure can be damaged. Leakage of operating supply or cargo such as oil or chemicals is possible. In a worst case scenario the ship could break apart and sink.

In general risk R is defined as the product of collision frequency f and consequence c of undesired events:

$$R = f * c \qquad (1)$$

Considering the ship collision risk for an offshore wind farm f is the ship collision frequency and c is loss of harmful substances, e.g. oil spill.

Regarding the frequency f there are mainly two different scenarios with collision with an offshore installation:

- Collision of powered ships
- Collision of disabled/drifting ships

To keep the frequency at minimum AIS transponders installations on the wind turbines helps other ships locate and identify the offshore structure. Additionally help could also be a VTS system, radar control, existing thugs, etc.

	Time (years) between to collisions
Acceptable	> 100
"From case to case", enhanced analysis required	50 – 100
Not acceptable	< 50

Table 2-1: Acceptance criteria for wind farms in the German EEZ.

Table 2-1shows the acceptance criteria for collision frequency for offshore wind farms in the German bight (Biehl, Lehmann06).

The aspect of collision safety is mostly treated in connection with the design of tankers. There is an international binding agreement (MARPOL 73/78 Annex I, Directive 13F), which determines the minimum dimensions of double bottoms and double hulls. Additionally, the

European Union decided to phase out single hull tankers more quickly to reduce the environmental impact of collision with tankers (Dalhoff, Biehl).

Biehl studied the effects of offshore wind farms with respect to the safety of shipping in order to estimate the related risks to people, ship traffic and the environment. He used LS-DYNA as software and did calculations with four different OWT support structures: A monopole, a jacket and two tripod foundations. The locations of these foundations were in the North Sea and the Baltic Sea. Regarding the ship types used in the analysis, he used ships that are commonly to find in those waters: A 31,600 dwt double-hull tanker, a 150,000 dwt single-hull tanker, a 2,300 TEU container ship and a 170,000 dwt bulk carrier were selected (see figure 2-6) (Biehl 2005).
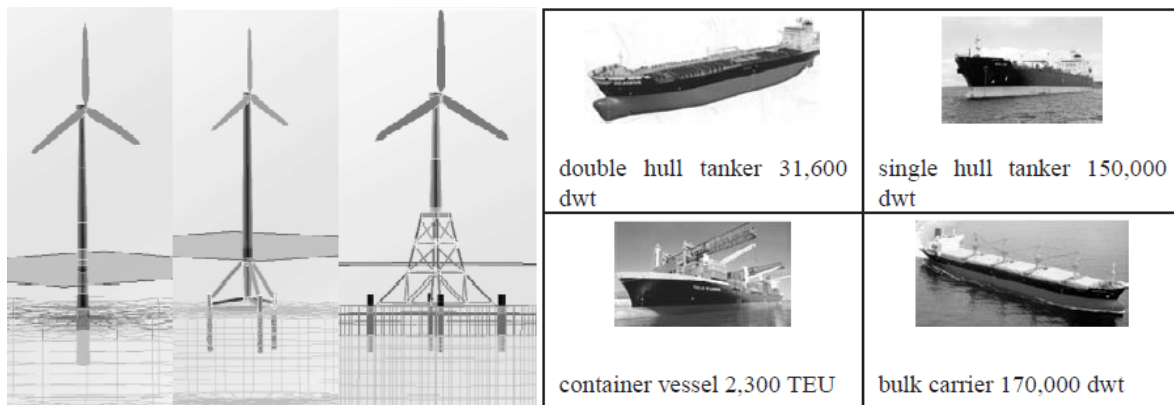
Figure 2-6: Different OWT foundations (left), different ship types (right) (Source: (Biehl 2005))

Together with Dalhoff, Biehl continued his earlier work. They looked at if the OWT foundations would be collision friendly. The results of their analysis were that the mono pile foundations exhibit the lowest risk in case of collisions. Only local buckling occurred without rupture of the ship hull. Much of the impact energy was transformed into deformation at the mono pile. For the tripod severe consequences could occur if the ship hit the diagonal chord and the central joint. To minimize risk the central joint of a tripod should be located lower than the maximum draught of a ship that travels regularly in the area. Regarding the jacket foundation the impact energy can be transformed into large deformations as far as the structure is able to withstand the ship's impact long enough without being torn off the foundation piles. Local damage in the model caused by the jacket's joints should not lead to widely damaged areas of the ship's hull, but it is possible that the wind turbine tilts towards the ship, since the damaged jacket structure acts like a plastic hinge for the OWT (Dalhoff, Biehl).

The concern of the nacelle hitting the ship was further investigated by Biehl and Lehmann. The nacelle could either have a free fall from the tower top bearing when the structure is hit by a ship, or the entire structure could collapse towards the ship. A 450 ton nacelle impact was analyzed in detail by FE calculations. Three different impact locations were selected: bulkhead, center of the tank and hull. For the bulkhead and hull there were only moderate

damages. If it hit the center of the tank, the nacelle could penetrate the deck and both inner and the outer shell, leading to a worst case scenario with maximum oil outflow (Biehl, Lehmann07). This analysis was done without accounting for the viscosity of the cargo. That might not represent the reality and give a pessimistic answer.

Ramberg studied three different impact scenarios on an offshore wind turbine with jacket foundation with nonlinear static and dynamic analysis in USFOS. A loaded ship with 532 MJ (a tanker of the Suezmax size) impact energy hitting the jacket at either 20 m or 12.5 m below the sea surface, and a ballasted ship with energy of 196 MJ impacting at 5 m depth. None of the analysis showed that neither the tower nor the nacelle would hit the ship, meaning that the jacket would be defined as collision friendly (Ramberg11). These analyses were performed with a water depth of 42 m. The effect of different water depths were not accounted for.

Amdahl and Holmås studied basically the same OWT impact scenario with a Suezmax tanker at 42 m water depth. The conclusions were the same. The jacket collapsed in the desired direction (away from the ship), but they executed an extra analysis with the jacket fixed at the seabed. The impact location was set closer to the sea bottom. This showed that the tower then was likely to collapse in the dangerous direction toward the ship (Amdahl, Holmås11).

2.3.2 Review of different standards

2.3.2.1 Standard Design of Offshore Wind Turbines – BSH

The standard is intended to provide legal and planning security for development, design, implementation, operation and decommissioning of offshore wind farms. In short, it tells about certificates and approval requirements. Information regarding risk analysis of a ship impact with an OWT is found in "Annex 1 Hull-retaining configuration of the substructure". It should be demonstrated that there will be no major environmental pollution incidents because either the entire collision energy can be absorbed by the ship and the offshore wind farm structure or the offshore wind farm fails during the collision procedure without ripping open the ship's hull.

Further, in short, the following general conditions are to be met:

1) When using a simulation, the OWT is to be idealized in a suitable way for contact problem.
2) It is to be represented at least up to the deck height of the ship plus 5 m. The masses and the inertias of the parts shall also be considered.
3) Soil conditions applied at least as elastic springs.
4) Grouting may be considered as a rigid connection or a linear-elastic material.
5) For ship size in calculations, a single-hulled tanker with 160,000 dwt is to be used.
6) Calculation shall assume a ship drifting sideways at 2 m/s. At the moment of collision, longitudinal speed is 0 m/s.

If a simplified process (yield hinge method, etc) is used, the energy absorbed from the ship's structure shall be used for calculating the degree of damage to the ship and therefore the (environmental) threat (BSH07).

2.3.2.2 DNV Standards

DNV has many standards and recommended practices. The DNV-OS-J101 "Design of Offshore Wind Turbine Structures" provides principles, technical requirements and guidance for design, construction and in-service inspection of offshore wind turbine structures, here defined as the support structures and foundations for offshore wind turbines. Regarding substations for wind farms, or wind turbine components such as nacelle, rotor, generator, etc other standards apply.

According to the DNV-OS-J101, accidental limit states (ALS) correspond to either maximum load-carrying capacity for (rare) accidental loads, or post-accidental integrity for damaged structures. Risk associated with possible ship collisions shall be addressed as part of the basis for design of support structure. For service vessel collision the limit state shall be considered as a ULS.

For design against accidental ship impacts, the characteristic impact load shall be taken as the impact load caused by unintended collision by the maximum authorized service vessel in daily operation. The service vessel is assumed to be drifting laterally and speed shall not be assumed less than 2.0 m/s. Effect of added mass shall be included. Also effect of fendering shall be considered. Note that supply vessel may grow in size over the years and the accidental load may become substantial (DNV11).

The DNV recommended practice DNV-RP-C204 "Design against accidental loads" also covers a section of ship collisions developed for jackets. Historically this was used for larger jackets used by the oil industry. It says that the structural effects from ship collision may either be determined by non-linear dynamic finite element analyses or by energy considerations combined with simple elastic-plastic methods. It describes more in detail about collision mechanics, design principles and dissipation of energy.

2.3.2.3 NORSOK standard

Regarding accidental loads, the NORSOK N-004 "Design of steel structures" standard says that the structure shall be checked for all ALSs for the design accidental actions defined in the risk analysis. It is to be checked in two steps:

a) Resistance of the structure against design accidental actions
b) Post accident resistance of the structure against environmental actions. Should only be checked if the resistance is reduced by structural damage caused by the design actions.

It further says that design recommendations for the most common types of accidental actions are given in Annex A "Design against accidental loads", which basically is retelling parts of what stands in the DNV-RP-C204 regarding accidental loads (NORSOK04).

2.3.2.4 Comparison of the different standards

The different standards conformity that the vessel hitting the OWT should have an impact drifting speed of 2 m/s (or higher). The biggest difference is in the size of the vessels. While the BSH standard quite specific takes into consideration that a large tanker of 160,000 dwt can hit an offshore wind turbine, the standards from DNV do not. The J101 only considers ships of the size of a service vessel, and the C204 operates with a supply vessel in the range of 2 - 5000 tons that can be used for impact against jacket legs with diameter 1.5 m – 2.5 m. Therefore the standards from DNV may not be applicable for offshore wind turbines when considering that they most likely will collapse if hit by a 160,000 dwt tanker. Also, the jacket legs of an OWT that are in the danger zone of being hit by a ship are usually smaller than 1.5 m in diameter, meaning that the DNV standard would be even less suitable for this kind of event.

On the other hand, the DNV standard is much more specific regarding the energy dissipation between ship and structure. It considers bow, stern and broad side impact of how a vessel will affect denting on a jacket leg or brace. Probably due to lieu of calculations and experience the BSH standard has not mentioned anything about a similar dissipation description for a large tanker in their standard.

A standard or an international guideline that would combine information about dissipation description for vessels of different types and sizes against offshore structures would therefore be preferable.

3 Analysis specifications

3.1 General

There are made in total three different offshore wind turbine models in this thesis. Two models with a jacket foundation, and one model with a monopile foundation. Regarding the jackets, they only differ in size. In order to distinguish them, they are called the "the large jacket" and "the small jacket".

3.2 Software

The following software is used in the nonlinear analyses:

- USFOS. Version 8-5, 2010-01-01
- USFOS Graphical User Interface (xact). GUI version 2.5-00

Although newer versions are available the versions above are used. USFOS is a computer program for nonlinear static and dynamic analysis of space frame structures. USFOS is for integrity assessment, collapse analyses and accidental load analyses for offshore jacket structures, topsides, jack-ups and other frame structures, intact or damaged. The program accurately simulates the collapse process, from the initial yielding, through to the formation of a complete collapse mechanism and the finale toppling of the structure (usfos.com).

3.3 Material properties, constants and units

3.3.1 Material property for structural steel for OWT
Steel properties:

- Young's modulus: *2.1 x 10^{11} N / m^2*
- Poisson's ratio: *0.3*
- Density: *7580 kg / m^3*
- Yield stress: *350 MPa – 420 MPa*

3.3.2 Constants
The following constants are used in the analyses:

- Density of sea water: *1025 kg / m^3*
- Gravity: *9.81 m / s^2*

3.3.3 Units
Units used in the nonlinear analysis are:

- Length [m]
- Time [s]
- Mass [kg]
- Force [N]
- Stress [Pa]

3.4 Environmental conditions

Regarding the environmental conditions such as marine growth, drag and mass coefficients values are found in the NORSOK N-003 standard, see table 3-1.

Water Depth	Marine Growth	Drag Coefficient	Mass Coefficient
m	mm	[-]	[-]
Above + 2m	0	0.65	1.6
2m to - 40 m	100	1.05	1.2
Under - 40 m	50	1.05	1.2

Table 3-1: Hydrodynamic forces for given water depths

The drag and mass coefficient values are based on the fact of that the members are smooth or rough. Due to marine growth, one could say that it in practice smooth members are above, and rough members are below two meters above sea level.

3.5 Coordinate system

All the models follow the same coordinate system. The origin of the coordinate system is located at MWL in the centre of the substructure. The Z-axis is pointing upwards, meaning the mudline is defined as a negative Z-value.

3.6 Soil coordinates and conditions

All analyses use the same soil properties. The localization of the different soil layers is specified with top/bottom coordinates of each layer. The Z-coordinate of the mud line is specified in the global coordinate system. All soil layer Z-coordinates are given relative to Z_{mud}, meaning that the upper layer starts with $Z = 0$ in soil coordinates. Also here the soil Z coordinate points upwards.

The soil conditions are subdivided into 12 layers with different properties consisting of stiff and soft clay and sand. The layers between 1.8 m - 10.1 m is of soft clay and layers between 10.1 m – 14.6 m and 27.7m – 44.5 m of sand. The rest is stiff clay. Graphically disks with diameter proportional to the layer strength represent the soil layers.

3.7 General wind turbine specifications

The wind turbine has a power of 5 MW. It is mounted on a 62 m high cylindrical tower. The tower diameter varies between 4 m at the top to 6 m at the bottom. The wall thickness is 30 mm. The nacelle weighs 350 tons. This is equal for all the computer models. The tower is either connected to a larger jacket at 70 m water depth, a smaller jacket at 27 m water depth or a monopile at 25 m water depth.

3.8 General specifications for the foundations

3.8.1 The large jacket foundation

In this model, the tower is supported by an x-braced jacket foundation with five levels modeled with joint-to-joint elements. Seabed is defined to Z = - 61.5 m. The height of the

jacket is 89.5 m, making the total structure almost 152 m high (from seabed to top of the tower). The piles into the soil are 69 m long, with a diameter of 1 m and 30 mm thick.

3.8.2 The small jacket foundation

The small jacket foundation is basically the same as the large jacket but the lowest part of the jacket is removed. This leaves the jacket with four x-braced levels. Total length of foundation is reduced to 61.5 m, placing it at the seabed defined to Z = - 33.5 m. The piles have a length of 69 m, diameter of 1m and at thickness of 50 mm.

3.8.3 Monopile foundation

The foundation model for the monopile is based on details from the Belwind 1 offshore wind farm project. This is done because they are made for water depths for 20 m – 37 m. A wind turbine in the Belwind 1 farm has a rated power of 3 MW and consists of 130.8 tons head mass and a tower of 54 m, compared to 5 MW, 350 tons and 62 m used for this model. The transition piece structure and support structure therefore needed to be strengthened. The transition piece is increased from 4.3 m to 6.0 m in order to fit the tower. The monopile foundation is increased from 5 m and 70 mm thickness to 6.5 m and 80 mm thickness, respectively.

		Belwind project		This thesis	
Top head mass		130.8	tons	350	tons
Tower height		54	m	62	m
Transition Piece structure	Diameter	4.3	m	6.0	m
	Height	25	m	30	m
Support structure	Diameter	5.0	m	6.5	m
	Thickness	70	mm	75	mm

Table 3-2: Belwind 1 values compared with modified values for monopile model

Table 3-2 gives an overview of the modified model compared to the Belwind 1 project.

3.9 General ship specifications

The ship used for the analyses, as required by BSH, is a 160,000 dwt tanker. This corresponds to a displacement of 190,000 tons. This is a vessel of the Suezmax size. Fully loaded a tanker of this size can have a draught of approximately 15 m – 20 m. Assuming little or no roll motion of the tanker it is likely that it will hit the jacket with the top of the bilge keel at a depth of 13 m – 18 m. Further, the tanker has a sideways drifting speed of 2 m/s. At the moment of collision, the ship has no own propulsion, meaning longitudinal speed is 0 m/s. The kinetic energy of the tanker can be found with the following formula:

$$E = \tfrac{1}{2}(m + a)v^2 \tag{2}$$

When taken 40 % added mass into account, the energy becomes:

$$E = \tfrac{1}{2}(190,000 + (190,000 * 0.4))2^2 = 532000\ kJ = 532\ MJ \tag{3}$$

When the tanker not is loaded, and only traveling with ballast, the mass is assumed to be 70,000 tons. Adding the effect of 40 % added mass, the kinetic energy becomes:

$$E = \frac{1}{2}(70,000 + (70,000 * 0.4))2^2 = 196000\ kJ = 196\ MJ \qquad (4)$$

As seen from equation (4) the kinetic energy is a lot less for the ballasted ship. The draught will also be less, approximately 8 m.

3.10 Energy dissipation

There are mainly three design principles considering a ship – offshore structure collision; strength design, ductile design and shared-energy design, as shown in figure 3-1.
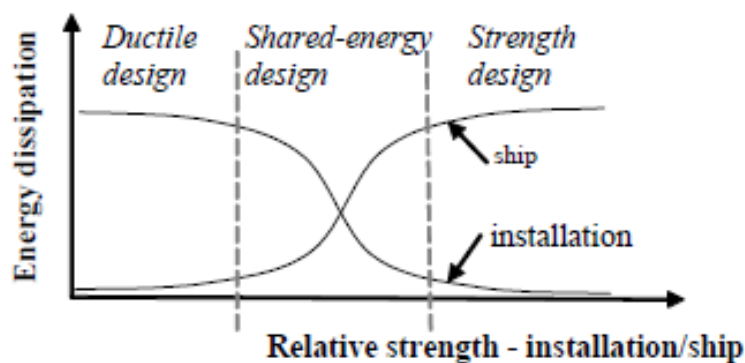
Figure 3-1: Energy dissipation for strength, ductile and shared-energy design

Strength design implies that the installation is strong enough to resist the collision force with minor deformation, so that the ship is forced to deform and dissipate the major part of the energy.

Ductile design implies the opposite, that the installation undergoes large, plastic deformations and dissipates the major part of the collision energy.

Shared energy design implies that both the installation and ship contribute significantly to the energy dissipation (DNV10).

Regarding this case, when having a ship with this enormous amount of kinetic energy, ductile design is assumed. This meaning that the OWT will dissipate the major part of the collision energy.

3.11 Other parameters to take into account
- Buoyancy. Buoyancy is switched on.
- Structural damping is represented by 0.5 % Rayleigh damping at 0.5 Hz.
- Relative velocity is specified in the dynamic analyses. This means that the relative velocity between the structure and the wave particles are accounted for in connection with the calculation of drag forces.
- Imperfections of 1.5 ‰ of the characteristic length.

3.12 Parameters that are not taken into account

The primary focus in this thesis is how the ship impact will affect the OWT. Therefore an analysis with a storm condition has not been accounted for; neither has any other ULS criteria.

During a storm, the turbine would stop rotating. This would be unfavorable with a possible impact. A storm that large would also causing the ship to have a higher velocity. In this thesis these things are not taken into account.

4 Calculation Model

4.1 General

The modeling technique used is reference point modeling; hence all geometric points in the model have unique names. This is done in order to make it easier to update or modify the models to suit the different analyses.

4.1.1 Tower, rotor and nacelle

The tower is modeled with specifications as given in chapter 3.5 using tubular elements. It represents the global behavior, but does not take local shell buckling into account. This can be solved by using nonlinear shell elements, which will take any local buckling into account. It will be satisfactory to only use shell elements at the bottom part of the tower to reduce computation time.

When the tower is connected to a jacket, the transition is modeled with equivalent box elements yielding correct representation of the stiffness of the real structure (ref figure 4-1). In this case the box elements are 3.5 m high and 2 m wide. The thickness is set to 50 mm.
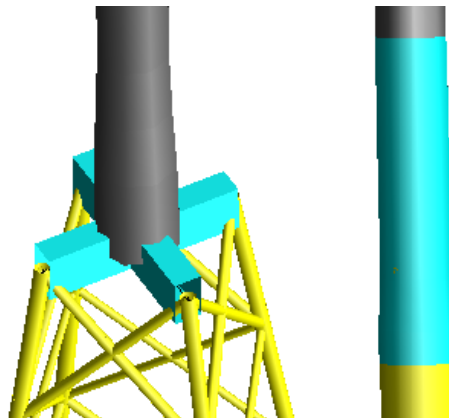
Figure 4-1: Transition piece for jacket (left) and monopile (right)

The 350 ton nacelle is modeled as a concentrated mass at the top of the tower. The rotor blades are neglected as they have a negligible influence on the response to the ship collision.

It is assumed that the turbine is in operation at the instant of impact and the mean downwind thrust of 500 kN is represented by a constant force.

4.1.2   Different foundation models
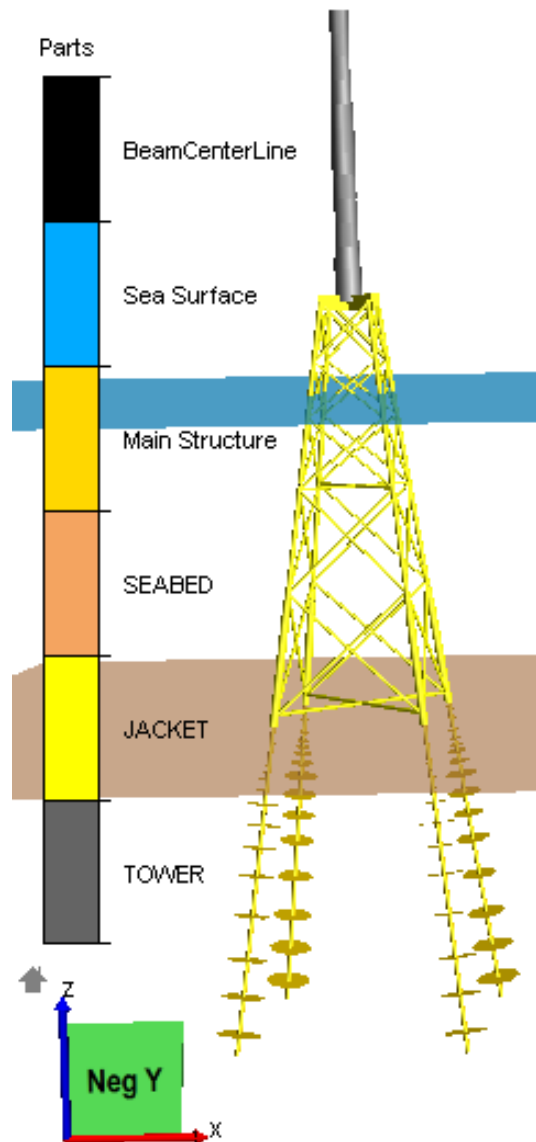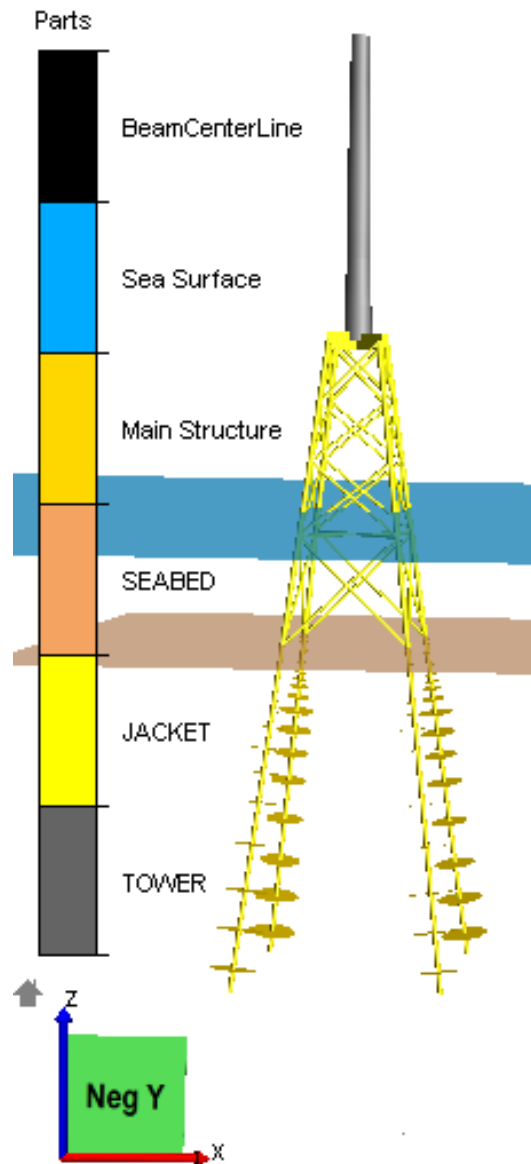
4.1.2.1 The large jacket

Figure 4-2: The computer model for the large jacket

The computer model is originally given by Virtual Prototyping, and modeled by specifications given in chapter 3.7 and 3.8.1. By increasing the surface level with 8.5 m the water depth is set to 70 m, making the hub 81.5 m above MWL.

Depending on the type of analysis, the jacket has two ways of being fixed to the seabed. In the first case, the jacket is fixed to the soil by 69 m long piles with a diameter of 1 m and 30 mm thickness at each leg. The foundation is modeled with tubular beams for the piles and nonlinear springs representing the p-y (lateral pile resistance), t-z (shear capacity) and q-z (end bearing) properties of the soil. In the second case, the jacket is fully fixed with respect to translations at seabed. The seabed consists in both cases of a 200 m x 200 m square.

4.1.2.2 The small jacket

Figure 4-3: The computer model for the small jacket

This model is also originally given by Virtual Prototyping but is based on changes done by Ramberg (Ramberg11). It is modeled by specifications given in 3.7 and 3.8.2. The surface level is in this case decreased with 6.5 m making the water depth 27 m, and the hub 96.5 m above MWL. That might give an unnecessary large air-gap between water level and bottom of tower, but it is done this way for simplicity reasons. The alternative was to make a completely new model. The changes will most likely only give more conservative results due to the inertia forces.

The soil conditions are the same, but the piles have increased their thickness to 50 mm instead of 30 mm as in the case with the larger jacket. The seabed for the small jacket is modeled as a 120 m x 120 m square.

4.1.2.3 The monopile
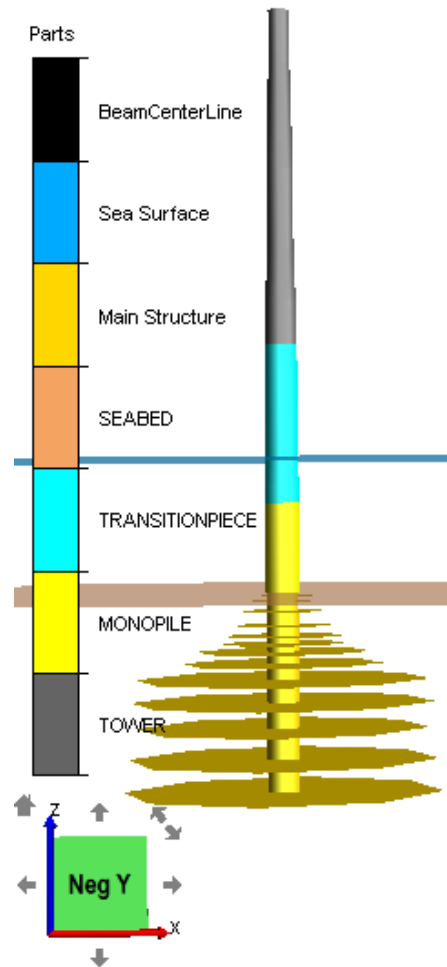
Figure 4-4: Computer model of the monopile

The model for the monopile is self-made by specifications given in 3.7 and 3.8.3. Same dimensions are used for the tower, nacelle and rotor as for the jackets. Although, at this point in reality there have not been built wind turbines of this size for monopiles yet.

In reality the monopile is hammered into the sea bed. In this model the monopile is modeled as a pipe beam either fully fixed regarding translations to the seabed or it is connected to one large pile corresponding the properties of diameter and thickness as the monopile into the soil. The soil conditions are the same as for the jackets, and the seabed is defined as a 120 m x 120 m square.

4.1.2.4 The ship

Ballast ship joint impact
The ballasted ship is modeled to hit the joints of the jackets at 5 m water depth. The same ship model is also used for the monopile, but then it is not designed to hit a joint, as there obviously are no joints on a monopile. It is all cases the ballasted ship is designed to only hit one node.

Loaded ship joint impact

The ship is modeled as a nonlinear spring. The spring is given a compressive stiffness of 500 MN/m. This ship impact is only considered when looking at the large jacket. Then it hits the jacket at a joint 20 m below the sea surface, hitting only one node. That is the absolute maximum draught for a tanker of the Suezmax size. This ship impact is not considered at the small jacket due to low water depth. The tanker would in that case hit the joint at seabed, and it is not likely that a ship of this size would travel in those waters.

Loaded ship column impact

The column is soft. The ship is modeled to hit at the midpoint of the element. This impact scenario will most likely create a yield-hinge, and after deformation of the element, the ship will hit the joint at 5 m depth. Therefore there is in this case modeled two springs that are connected with an infinitely stiff beam. The upper spring is modeled with a lower stiffness so that the force is zero until the ship hits the joint.

5 Results

5.1 General

In the following subchapters results from the different analyses are described. All analyses are performed using USFOS. Minor changes to the basic different analyses are not mentioned here. Larger and more figures are available in appendix A. For even more details regarding commands, models and soil options please look into the different head*.fem, model*.fem and soil*.fem files in the attached zip. file in appendix B.

5.2 The large jacket

5.2.1   Eigenvalue analysis

Eigenperiods large jacket	
Mode	Eigenperiods
1	2.592
2	2.592
3	1.105
4	1.105
5	0.922

Table 5-1: Five largest eigenperiod values for the large jacket
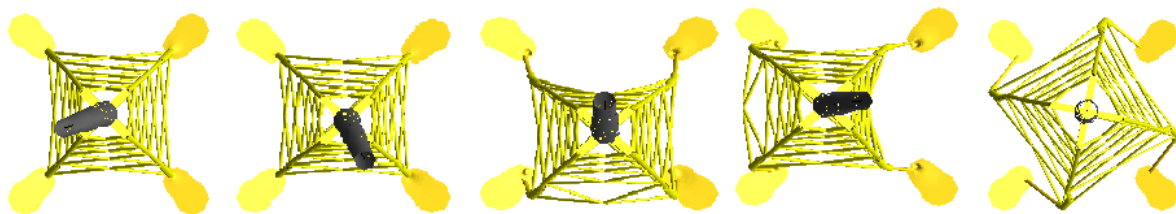
Figure 5-1: Mode shapes 1 – 5 (from left to right) for the large jacket

Table 5-1 shows the five largest eigenperiods for the large jacket. Figure 5-1 shows the corresponding five first different mode shapes for the large jacket. Mode 1 and 2 have cantilevered mode shapes, mode 3 and 4 have bending/sway and mode 5 has a torsion mode shape.

5.2.2   Ballasted ship impact on joint with large jacket

5.2.2.1 Static analysis
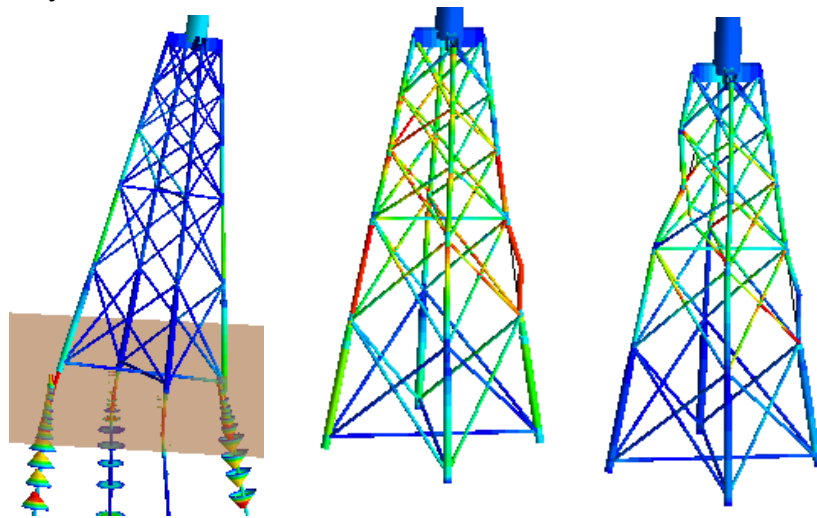
Figure 5-2: Static failure with piles (left) and failure pattern when fixed (mid and right)

As seen from figure 5-2, the static analysis of the ballasted ship impact on a joint on the large jacket shows that when the foundation is connected to piles it will merely be tipped over. An extra analysis with thicker piles (50 mm thickness) was also carried out, but only minor differences occurred. When the jacket is fixed to the seabed, failure pattern shows a buckling on the opposite leg at first, and then some more buckling will occur on the beams connected to the ship impact.

5.2.2.2 Dynamic analysis
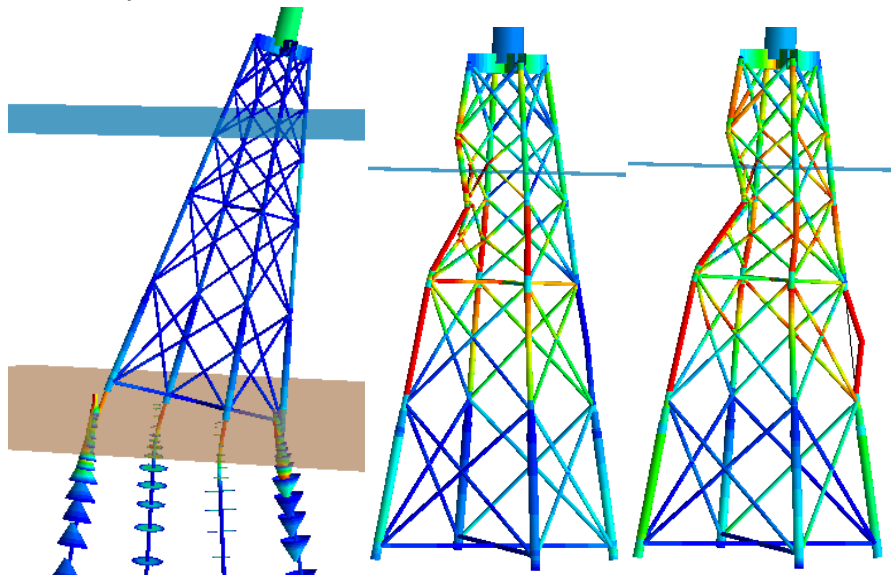
Figure 5-3: Dynamic failure with piles (left) and failure pattern when fixed (mid and right)

Figure 5-3 shows the similar dynamic results. They were about the same as for the static analysis, except this time the analysis showed buckling of beams connected to the ship first, and later on at the opposite leg of the jacket.

5.2.3 Loaded ship impact on column with large jacket

As both the static and dynamic analyses give more or less the same results, only the dynamic results are presented here.
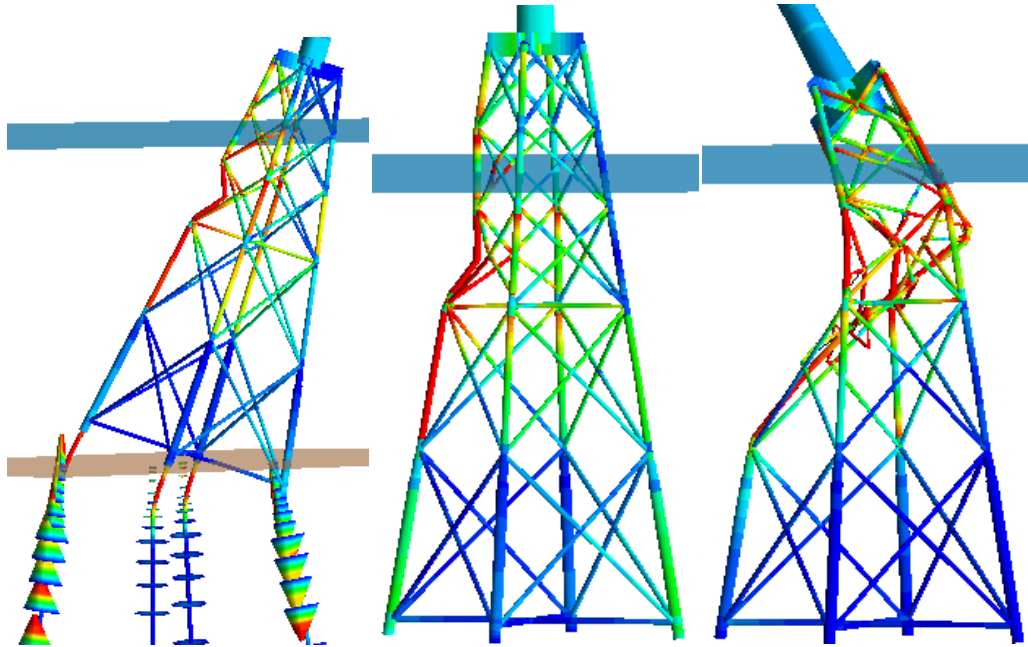
Figure 5-4: Jacket with piles (left) and fixed to seabed (mid and right).

Regarding the loaded ship impact on column with the large jacket, it would first get a small buckling on the column that was exposed to the impact, and thereafter collapse in the favorable direction when the jacket was connected to piles. When the jacket was fixed to the seabed, it collapsed in the dangerous direction over the ship. This is illustrated on figure 5-4.
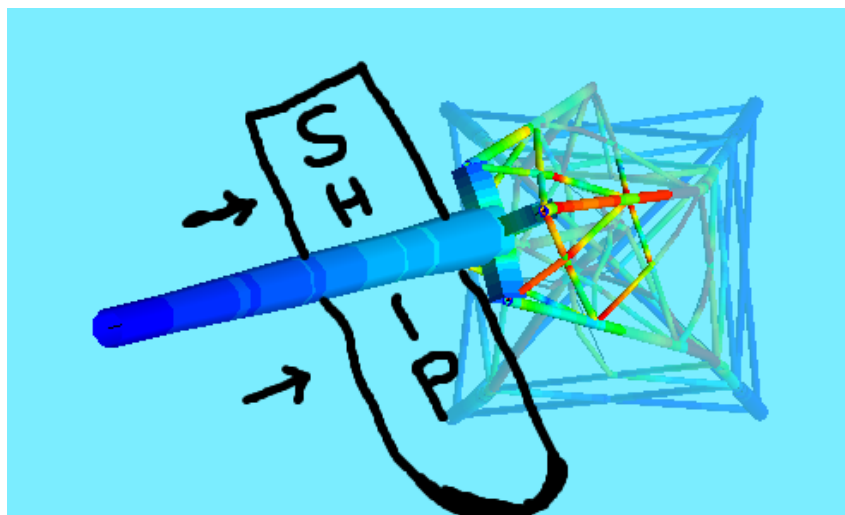
Figure 5-5: Jacket collapse over ship, seen from above

Figure 5-5 shows the same collapse mode, but seen from above. In addition, the ship is drawn on to the figure with arrows showing the drifting direction.

5.2.4 Loaded ship impact on joint with large jacket
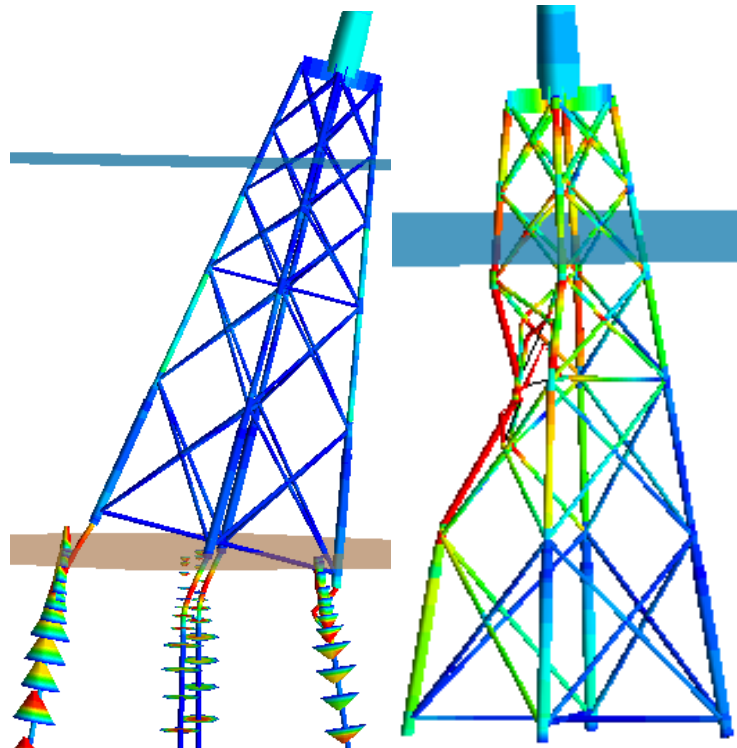
Figure 5-6: Jacket joint impact with piles (left) and fixed to seabed (right)

Both the static and dynamic analysis showed similar results regarding the loaded ship against a joint impact on the large jacket. Figure 5-6 shows the model with piles is pushed over, while the fixed jacket incurred some buckling at the hit joint.

5.3 The small jacket

5.3.1 Eigenvalue analysis results for small jacket

Eigenperiods small jacket	
Mode	Eigenperiods
1	2.520
2	2.520
3	0.826
4	0.826
5	0.642

Table 5-2: Five largest eigenperiod values for the small jacket

The eigenperiods for the small jacket are listed in table 5-2. The mode shapes are the same as for the large jacket (ref fig. 5-1).

5.3.2 Ballasted ship impact on joint of the small jacket
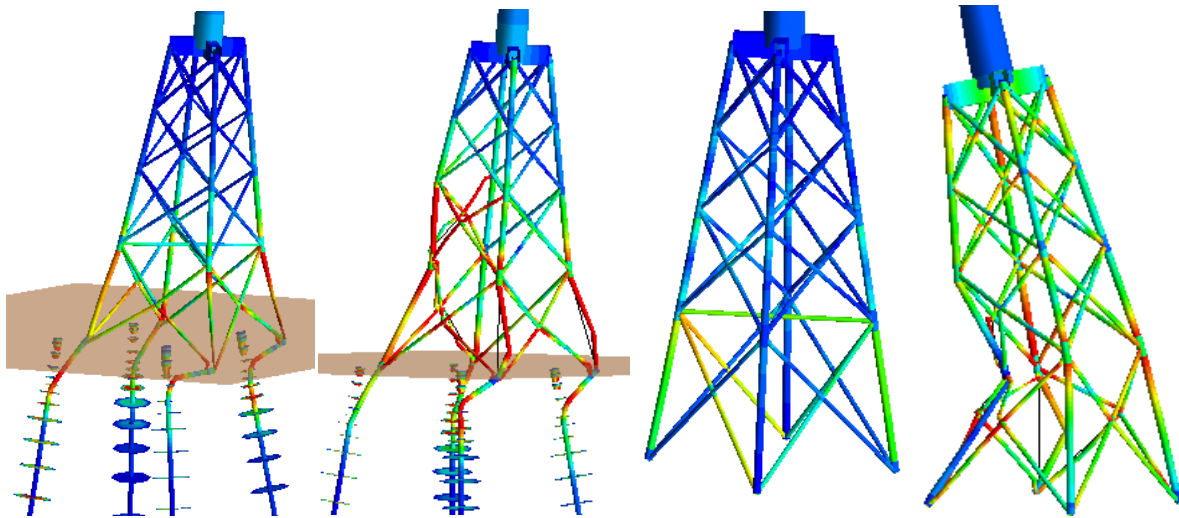
Figure 5-7: Four different ballasted ship impact scenarios against the small jacket

There are made four impact scenarios for the ballasted ship against the small jacket. The four different cases are:

- Jacket connected to piles with a horizontal x-brace between level 3 and 4.
- Jacket connected to piles without a horizontal x-brace
- Jacket fully fixed with regards to translations at seabed with x-brace
- Jacket fully fixed without x-brace

All four cases were analyzed both static and dynamic, which showed similar results. On figure 5-7 the different scenarios are shown in the order listed above. It is seen that less buckling occurs when the horizontal x-brace is used. Of these four cases only the last showed any potential danger regarding wind turbine falling over the ship.

5.3.3 Loaded ship impact on column of the small jacket
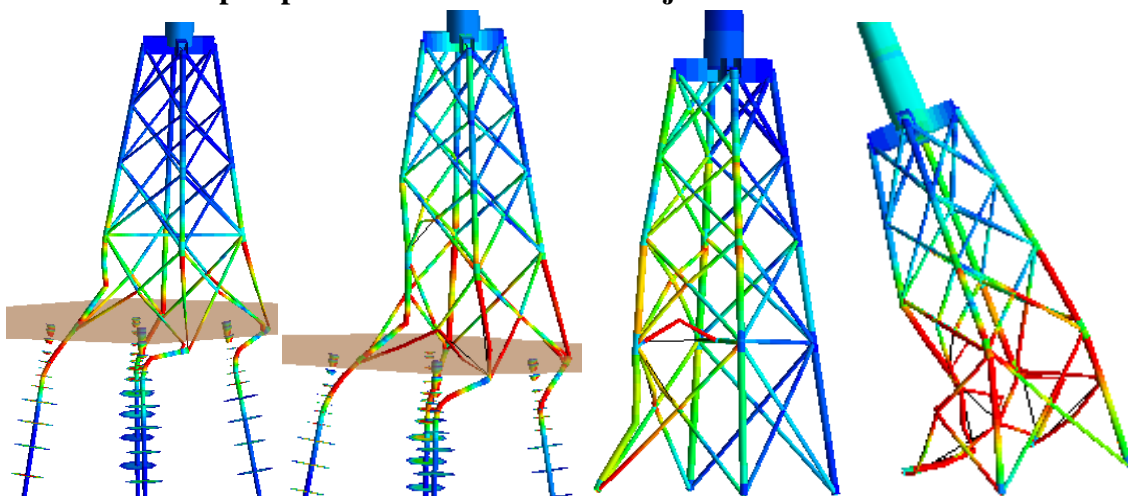
**Figure 5-8: Four different loaded ship impact scenarios against small jacket**

The same four impact scenarios (as in chap. 5.3.2) were made for the loaded ship impact against the small jacket. This time the ship hit the column instead of a joint at the jacket. Again, both static and dynamic analyses were performed giving similar results. The outcome of the results is primarily consistent with the other results showing that a jacket connected to piles will be pushed over due to a weak upper layer, while the fixed jacket will suffer of more buckling and possible collapse over the ship. This especially counts when there is no horizontal x-brace.

5.4 Monopile

5.4.1 Eigenvalue analysis

Eigenperiods Monopile		
Mode	Eigenperiods	Modeshapes
1	3.580	Cantilever
2	3.580	Cantilever
3	0.809	Sway/Bending
4	0.809	Sway/Bending
5	0.280	Sway/Bending

Table 5-3: Five largest eigenperiods for the monopile
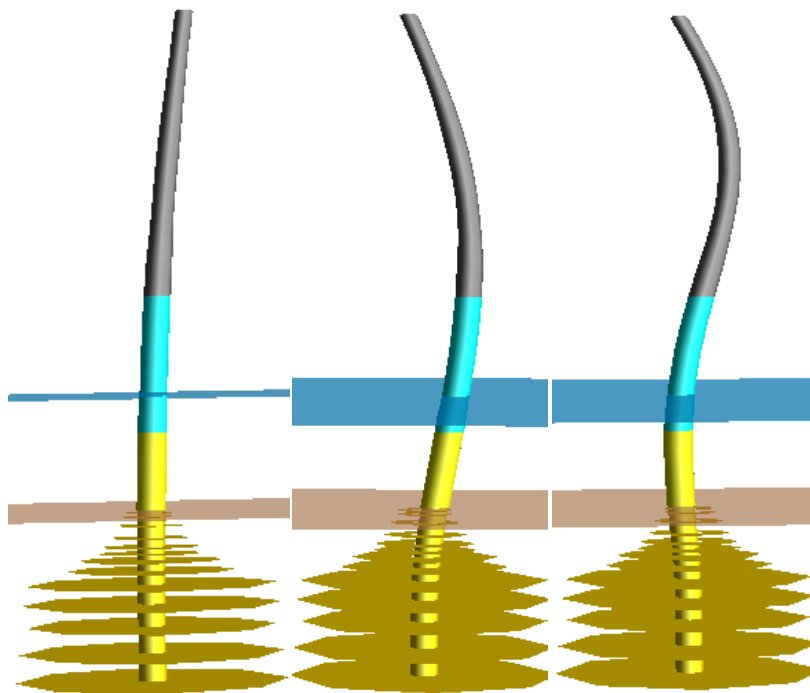
Figure 5-9: Mode shape 1, 3 and 5 for monopile

Table 5-3 gives the five largest eigenperiods for the monopile, while figure 5-9 shows the corresponding modeshape for mode 1, 3 and 5. Mode 2 had the same shape as 1 only in a different direction. The same was for mode 4 in comparison to mode 3.

5.4.2 Results of ballasted ship impact with monopile analysis
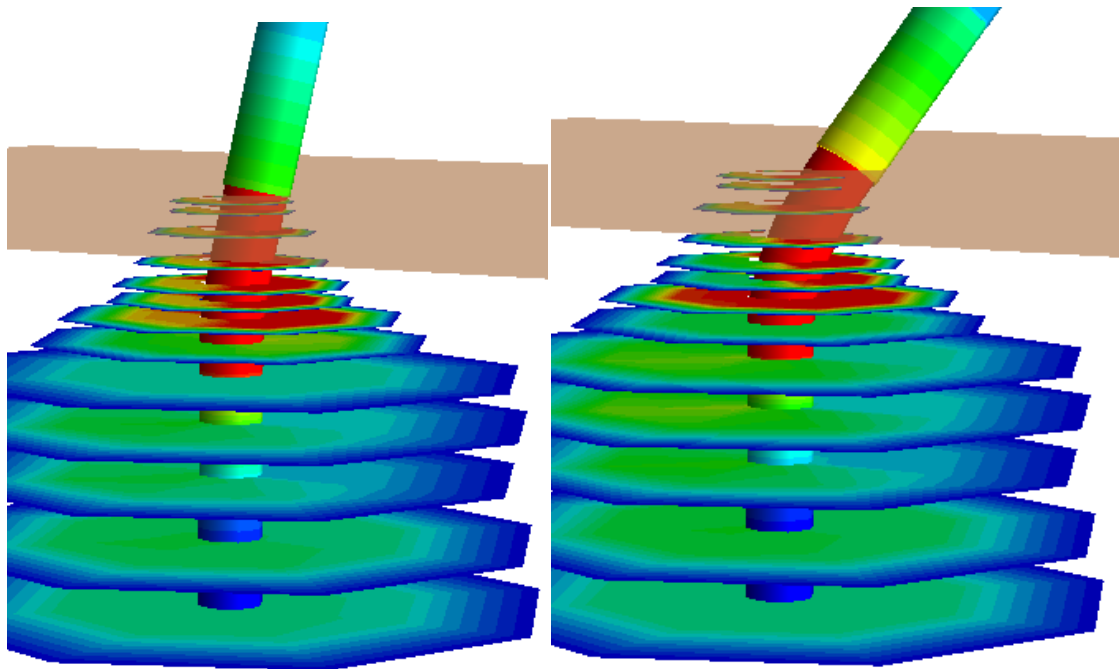
Figure 5-10: Monopile failure pattern

Figure 5-10 shows the static results from the ballasted ship impact with the monopile. As with the jackets the weakness is found in the upper part of the soil. The wind turbine is pushed over in the favorable direction away from the ship.

The dynamic analysis of the ballasted ship impact was not successful in the way that the results seemed accurate. This was also the case for the analyses of the loaded ship.

6 Discussion of results

6.1 General

The results in this thesis show how different parameters affect a ship impact with an offshore wind turbine. The main focus has been so see the how different water depths has affected the failure pattern of the OWT. Also the effects of horizontal x-brace and soil conditions have been looked closer into.

6.2 Eigenvalue problem

Jacket

It is stated in previous work (Ramberg11) that it is desirable to avoid eigenperiods within a 90% interval in the limit of 1.7 s – 2.7 s due to danger regarding a resonance problem with the rotor blades of the wind turbine. Looking at the jackets, they are both within this danger limit. To resolve this issue, one must look at the relationship between the eigenperiod and the eigenfrequency. This is given as:

$$T = \frac{2\pi}{\omega} = 2\pi\sqrt{\frac{m}{k}} \qquad [\text{s}] \qquad (5)$$

Where T is the eigenperiod, ω is the eigenfrequency, m is the mass and k is the stiffness (Larsen12). Looking at the formula (5) it becomes clear that one must either increase the mass or decrease the stiffness in order to increase the eigenperiod. A decrease in the stiffness could require a substantial change in the tower configuration; therefore is it easier to increase the mass. An increase in mass has the most effect when placed at the top of tower. This can be done by increasing the weight of the hub. The downside with placing the extra mass at the top is that it makes it easier for the tower to buckle. Therefore another solution can be to use the extra mass to reinforce the bottom of the tower. However, one would need quite a massive increase in weight.

	Eigenperiods large jacket		
Mode	Original eigenperiods	Increase in mass at bottom	Increase in mass at top
1	2.592	3.115	3.158
2	2.592	3.115	3.158
3	1.105	1.479	1.108
4	1.105	1.478	1.108
5	0.922	0.944	0.923

Table 6-1: New possible eigenperiod values for large jacket

	Eigenperiods small jacket		
Mode	Original eigenperiods	Increase in mass at bottom	Increase in mass at top
1	2.520	3.090	3.084
2	2.520	3.090	3.084
3	0.826	1.476	0.830
4	0.826	1.476	0.830
5	0.642	0.671	0.643

Table 6-2: New possible eigenperiod values for small jacket

Table 6-1 and 6-2 show an increase in either 200 tons (from 350 tons to 550 tons) at the top of tower or 2250 tons for the large jacket and 3000 tons for the small jacket at the bottom of the tower. It is also possible to divide the mass at the top and bottom. Other projects, as the Alpha Ventus for instance, has a top mass of 410 tons (AlphaVentus). If this top mass had been used, less is needed at the bottom of the tower.

Monopile
According to table 5-3, the monopile did not have any eigenvalues within the dangerous interval limit, and is therefore not further investigated.

6.3 Effect of water depth
When comparing the loaded ship impact on columns for the large jacket and the small jacket it is seen that even though both models get some local buckling of the hit jacket leg, the jacket at deeper water will still be pushed over in the favorable direction. This happens due to the fact that the impact hits further away from the soil, and the jacket still can be "tipped over". Therefore it seems that an increase in water depth is in favor for a more collision friendly offshore wind turbine design.

6.4 Effect of horizontal brace
The horizontal brace seems to have an overall good effect making the jackets stronger. The effect is not studied in detail on the large jacket, but on the small jacket the horizontal x-brace "improved" all failure patterns. In the case of the small jacket when hit by a loaded ship on a column, the failure pattern went from falling away from the ship when the jacket had the x-brace to potentially collapsing over the jacket when the x-brace was removed. This is a good sign as the loaded impact on the column has the most damage potential.

6.5 Effect of soil condition
This is the parameter that gave the largest differences in failure pattern. When the originally soil conditions were used, almost all simulations showed that the jacket would, if it would fall, fall in the favorable direction (away from the ship). One exception though, the loaded ship impact on the column of the small jacket where it would collapse over the ship. The reason that the jackets fall away from the ship is due to the weak upper layer. The kinetic energy from the ship is able to tear the pile out of the seabed of clay. An increase in thickness of the piles were tried out, but gave little effect.

When the OWTs are designed so that the wanted outcome is that that the OWT shall fall away from the ship, the weak upper layer is actually a good thing. When the jackets were fixed to the seabed, meaning that the soil would be infinitely stiff, the collision outcome was far worse for many of the cases. Several analyses showed that buckling occurred with potential to hit the ship.

6.6 Local buckling of the tower

This option is not looked deeply into. However, in appendix B, the files needed to perform one shell analysis is available. The result of the analysis shows that local buckling in the tower is not likely. In this case the tower had thinner walls to provoke a buckling, meaning this is not likely to happen. In addition, in order to get the eigenperiods high enough, extra mass can be used to strengthen the bottom of the tower, making it even less likely that this is an event that would occur.

6.7 Turbine fixation fail

This point is not looked into, but based on earlier work (Ramberg11) this is not of concern.

6.8 Monopile

The results from the monopile were few and even poor. In order to perform a good solution here more data is needed. As mentioned, there has in real life not been built a 5 MW wind turbine for a monopile. More engineering work is needed to make this possible. On the other side, there has been done a lot of research of smaller wind turbines with monopile foundation (ref Biehl05), showing that the monopile already is collision friendly.

7 Conclusions and recommended further work

7.1 Conclusion

Whether the offshore wind turbine models used in this thesis are collision friendly or not relies on different factors. When the given soil properties are used the analyses show in all cases except one that the offshore wind turbine models can be called collision friendly. The case were it could not be called collision friendly was a case with the small jacket at a water depth of 27 m getting hit by a loaded ship at a column of the jacket, but installing a horizontal brace on this jacket would make it also collision friendly.

If the soil had been stronger it is not certain that the outcome would be the same. When the jackets were fixed to the sea bed, several of the models could collapse in the dangerous direction over the ship.

A horizontal brace was seen to have a positive effect when installed on the different jacket models. It seems also that it is more favorable to use jackets at deeper water.

7.2 Recommended further work

Since the work in this thesis is based on beam theory there might be an idea to perform an analysis of the models using shell elements. Not only on the lower parts of the tower, but also around the impact location. One can for instance make a fine mesh around the potential buckling part of the tower and around the impact location. In the rest of the model one could use a coarser mesh in order to save computational space and time.

It is only looked a beam impact hitting a corner leg of the jacket. One could study the effect that a ship impact would have when hitting two legs at the same time.

During a storm the ship would have a higher drifting speed at the same time as the wind turbine would be shut off. This could be another scenario to look at. Also, in this thesis there is assumed that the ship is rigid, and that the turbine would absorb all the energy. A study of shared energy design could also be of interest.

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Pictures used on front page:
Ship Cap Victor: http://www.euronav.com/images/vessels/CapVictor.jpg
Wind turbine: http://ars.els-cdn.com/content/image/1-s2.0-S0951832012001160-gr1.jpg (Artist impression, Bjarne Stenberg/ CeSOS, NTNU, Norway)

Appendix A

A.1   Large jacket results

A.1.1   Ballasted ship impact with large jacket:
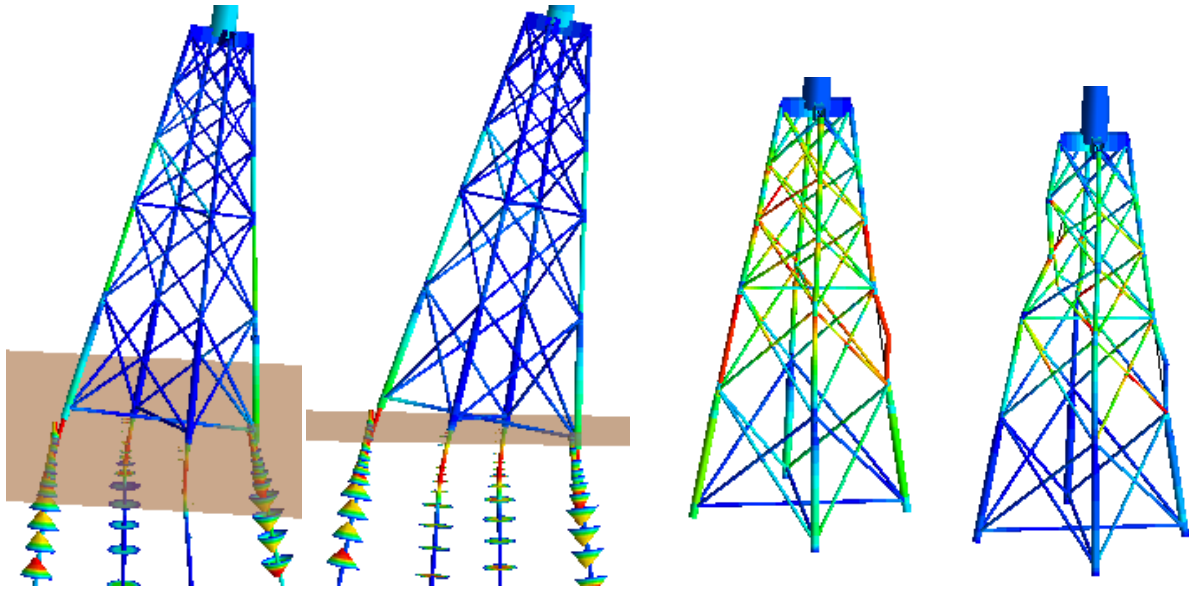
Static:

Large jacket, static, ballast, 30 mm pile (left), 50 mm pile (mid), fixed (two to the right).

Dynamic:
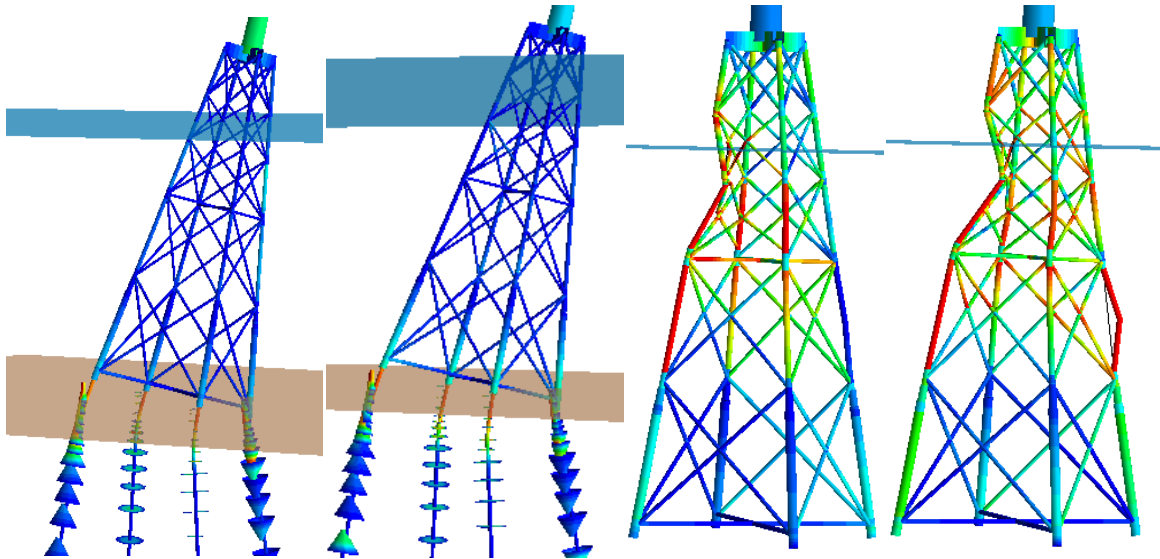
Large jacket, dynamic, ballast, 30 mm pile (left), 50 mm pile (mid), fixed (two to the right).

A.1.2   Loaded ship impact on column with large jacket:
Static:
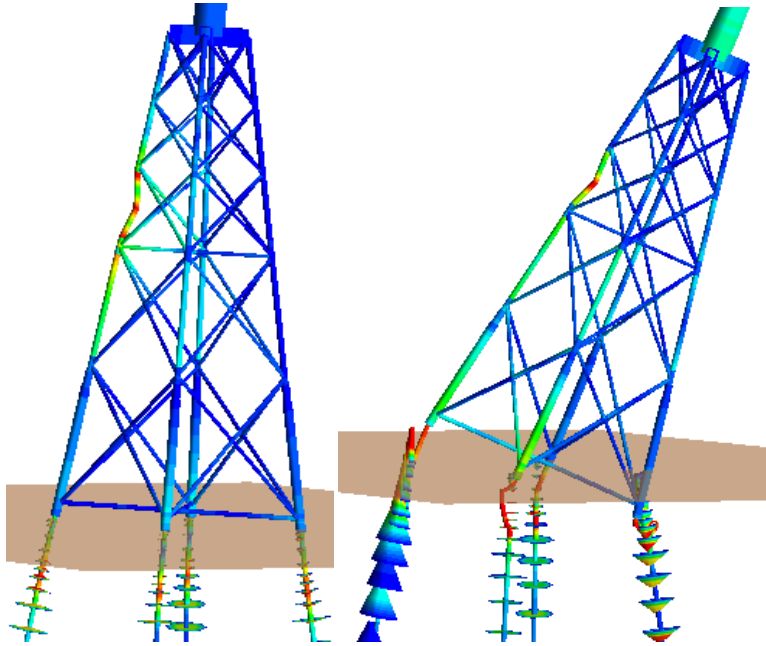
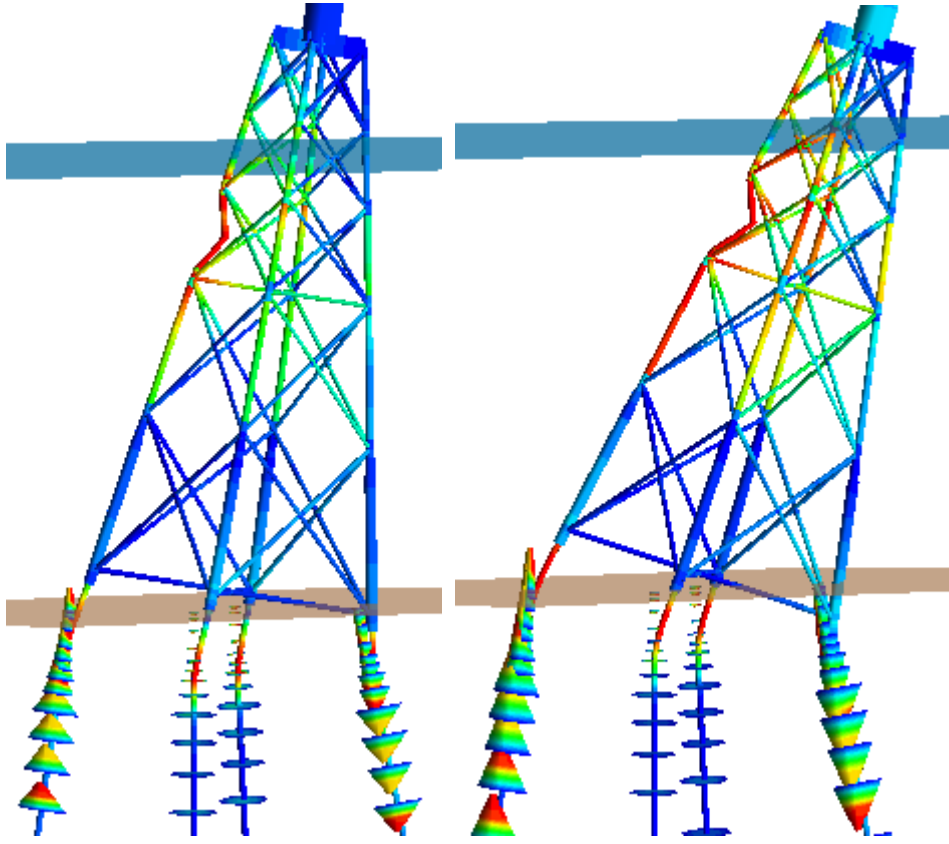Large jacket, static, loaded ship, column impact, basis, failure pattern.
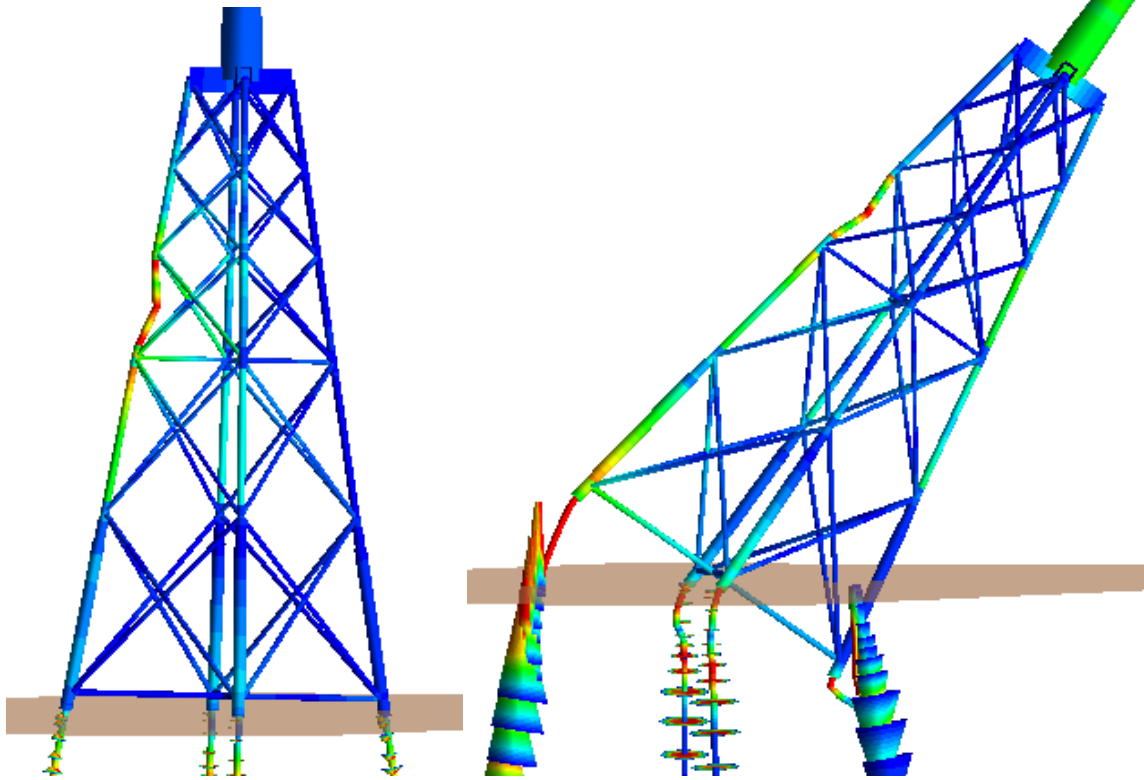
Large jacket, static, loaded ship, column impact, larger piles, failure pattern.
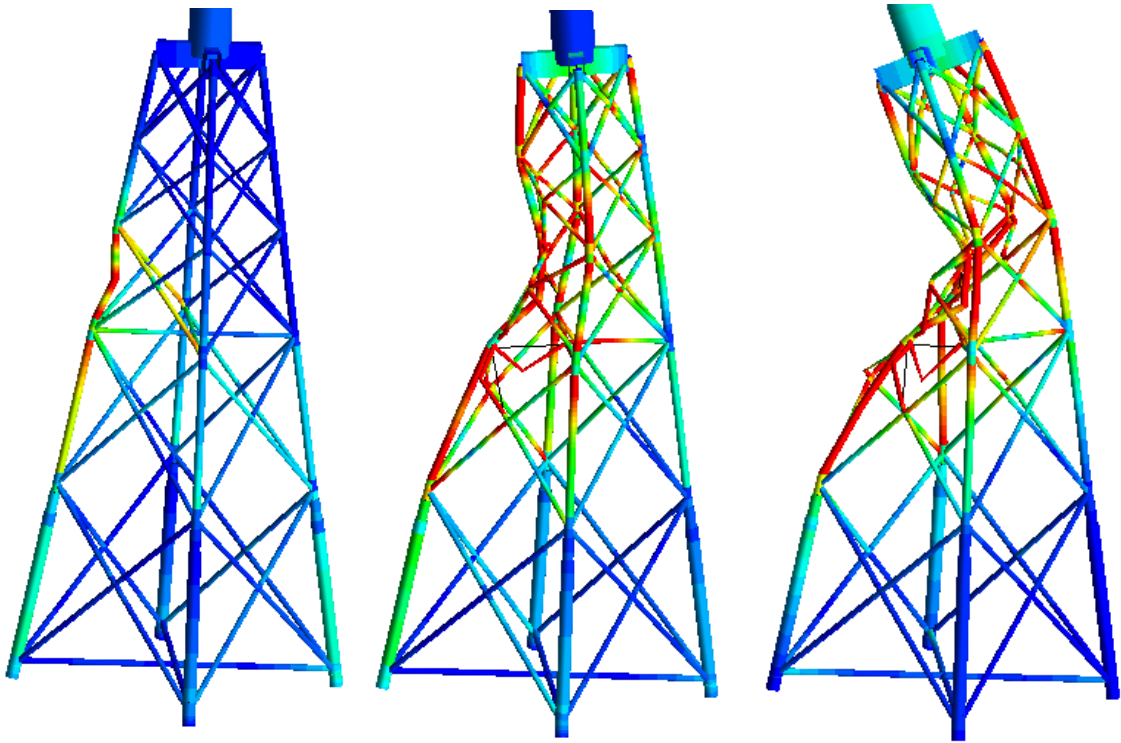
Large jacket, static, loaded ship, column impact, fixed to bottom, failure pattern.

Dynamic:

Large jacket, dynamic, loaded ship, column impact, basis, failure pattern.
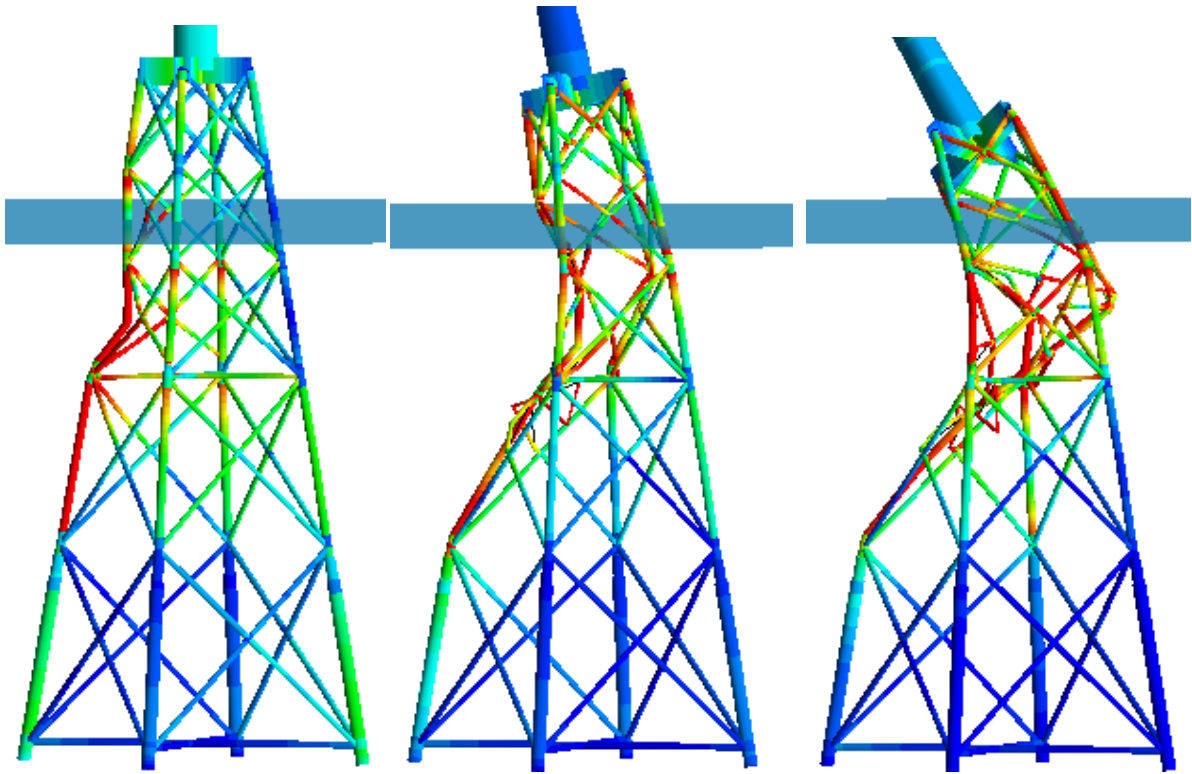
Large jacket, dynamic, loaded ship, column impact, fixed to bottom, failure pattern.
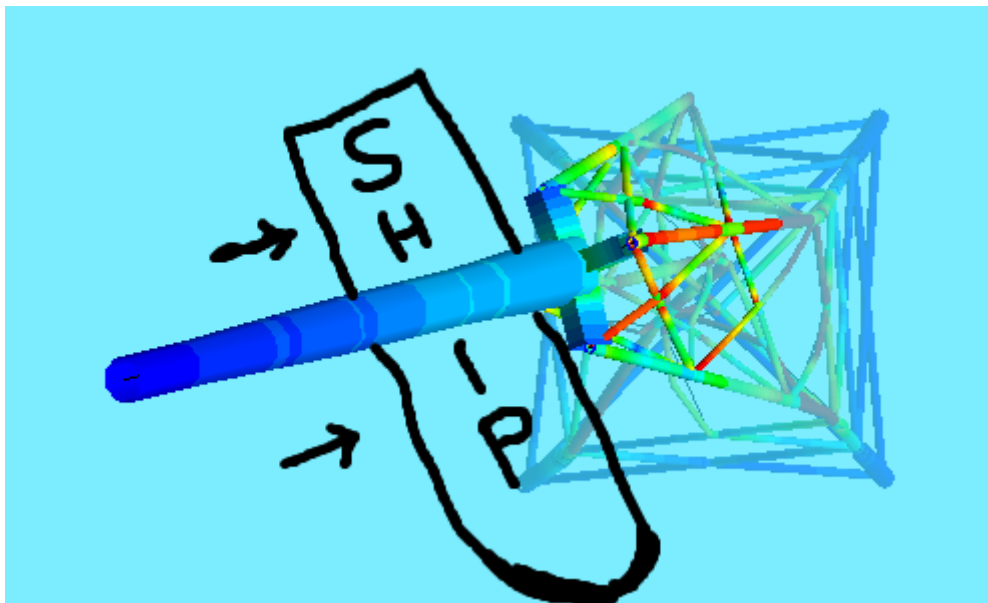
Illustration of failure pattern from above, different angle, showing potential fall over ship.

A1.3 Loaded ship impact on joint of large jacket:
Static:
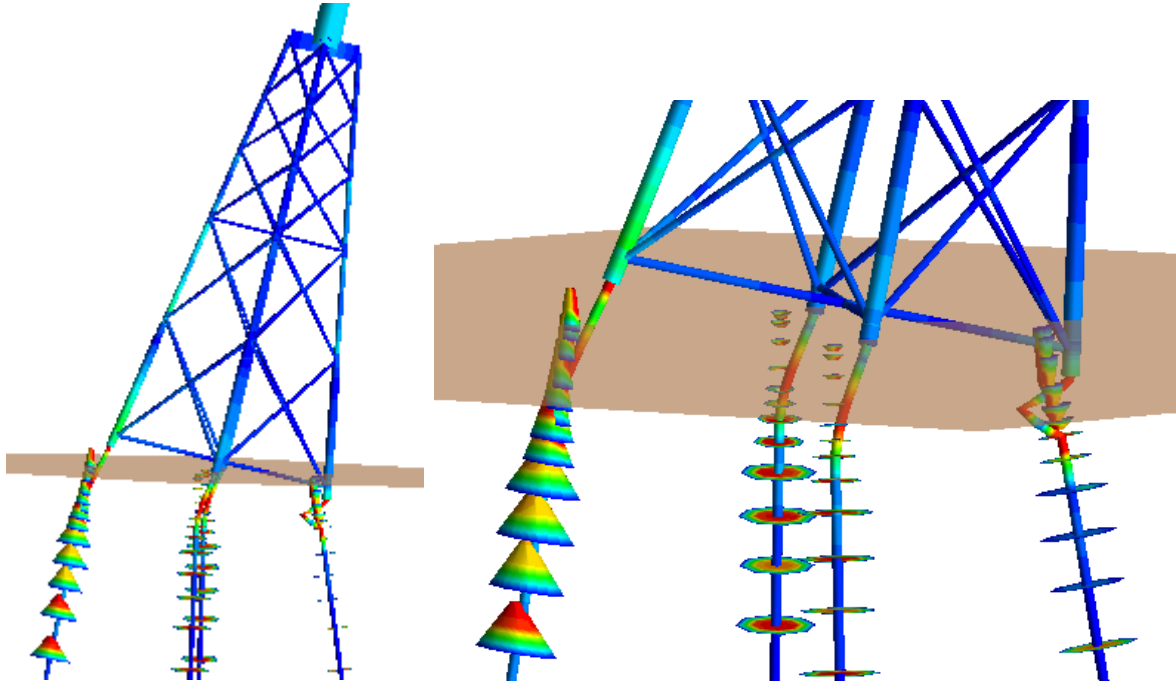
Large jacket, static, loaded ship, joint impact, basis, failure image (left), close up (right).
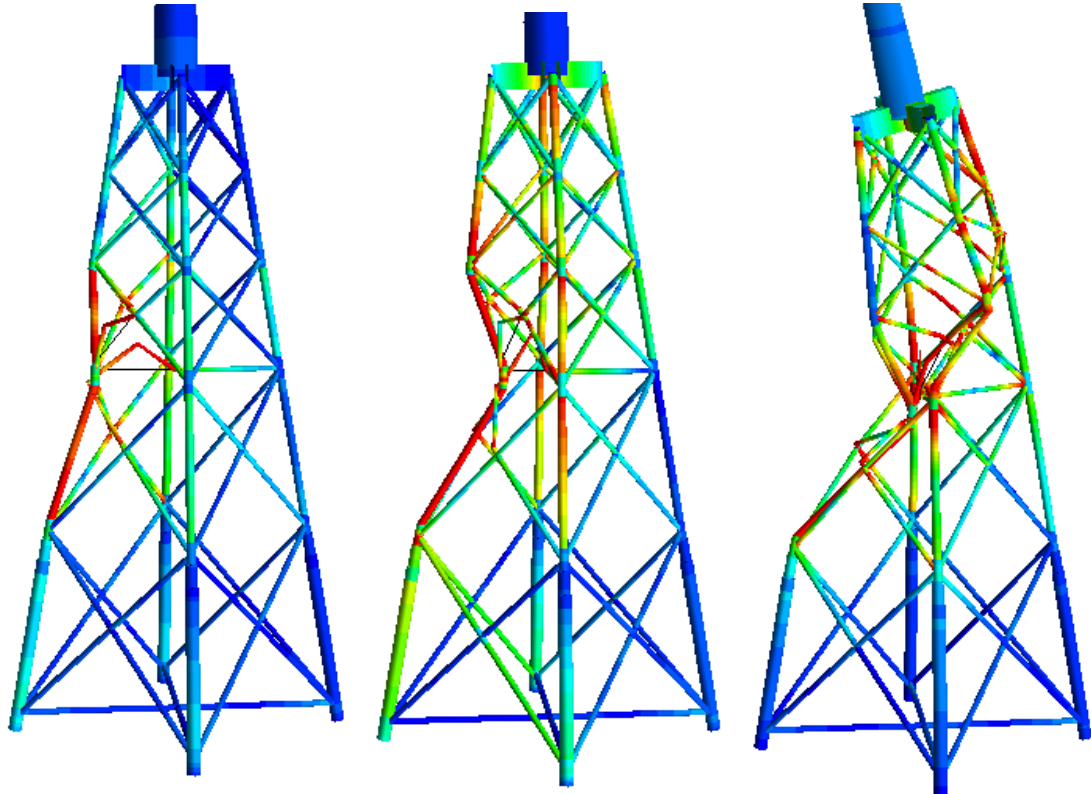
Large jacket, static, loaded ship, joint impact, fixed to bottom, failure pattern.
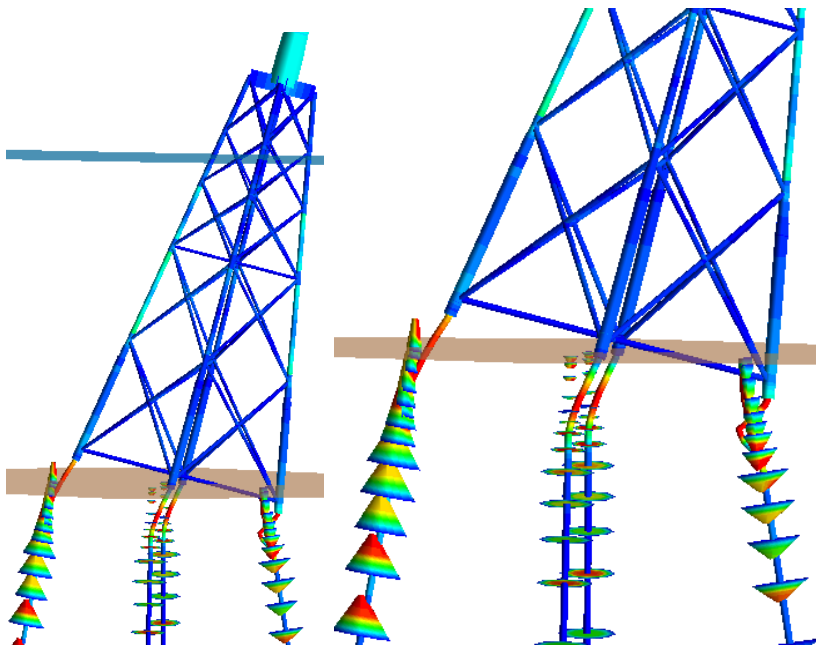
Dynamic:

Large jacket, dynamic, loaded ship, joint impact, basis, failure image (left), close up (right).
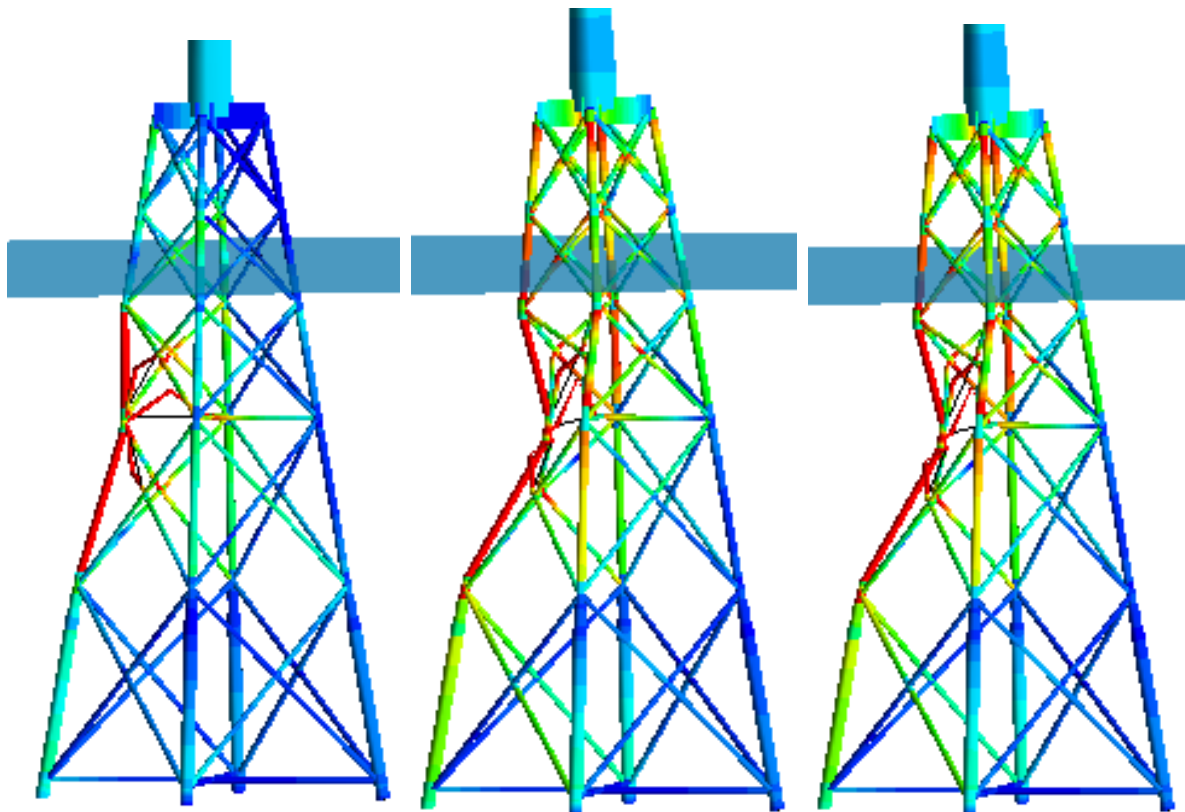
Large jacket, dynamic, loaded ship, joint impact, fixed to bottom, failure pattern.

A.2 Results of small jacket:

A.2.1 Ballasted ship joint impact on small jacket
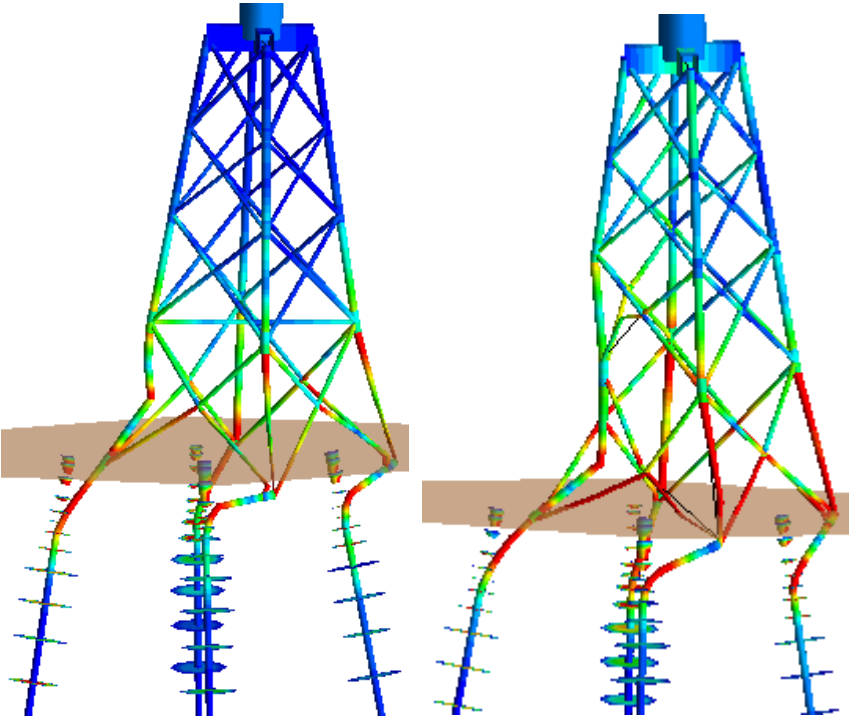### Static:
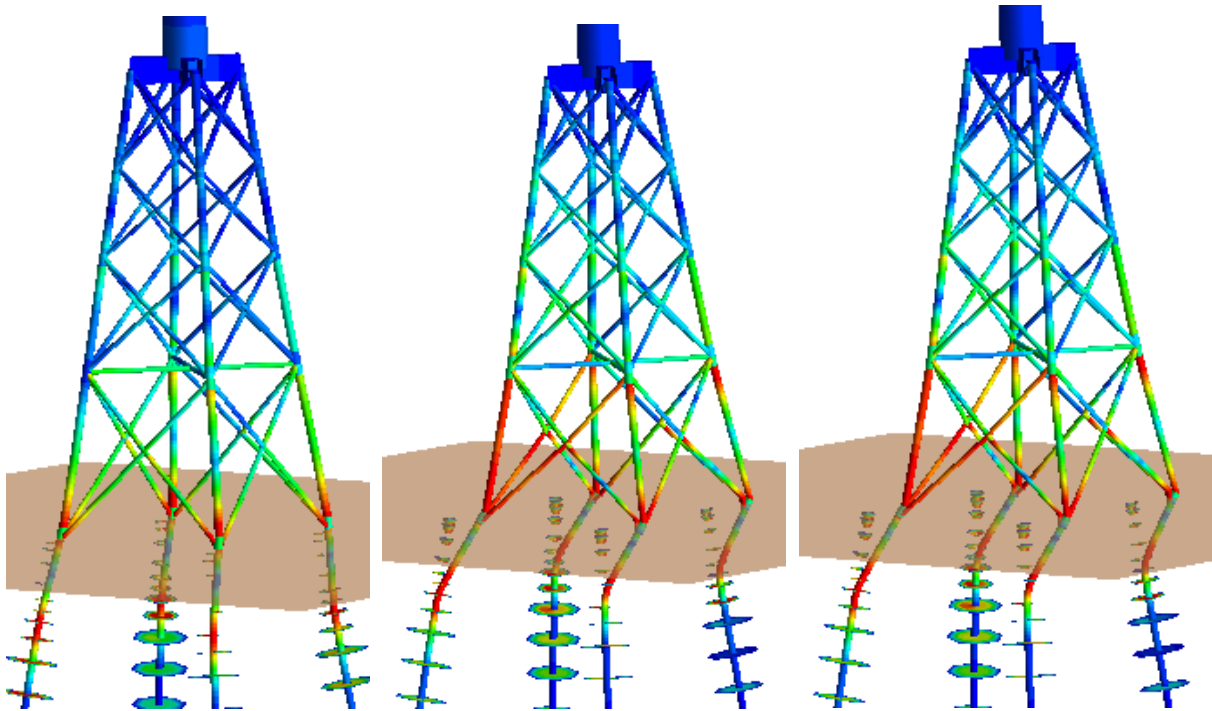
Ballasted ship, static, joint impact, failure pattern.
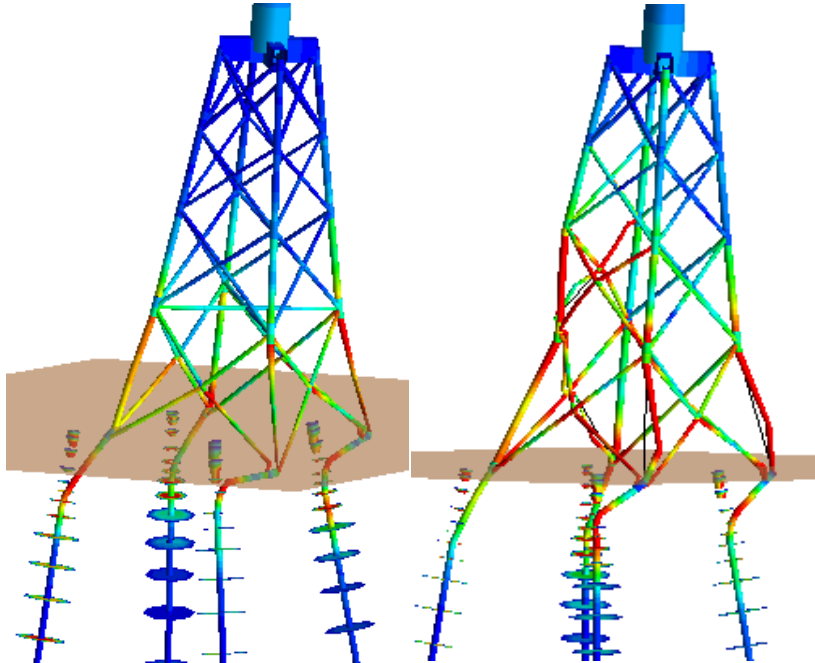
Ballasted ship, static, joint impact, with piles, with horizontal x-brace (left), without (right).
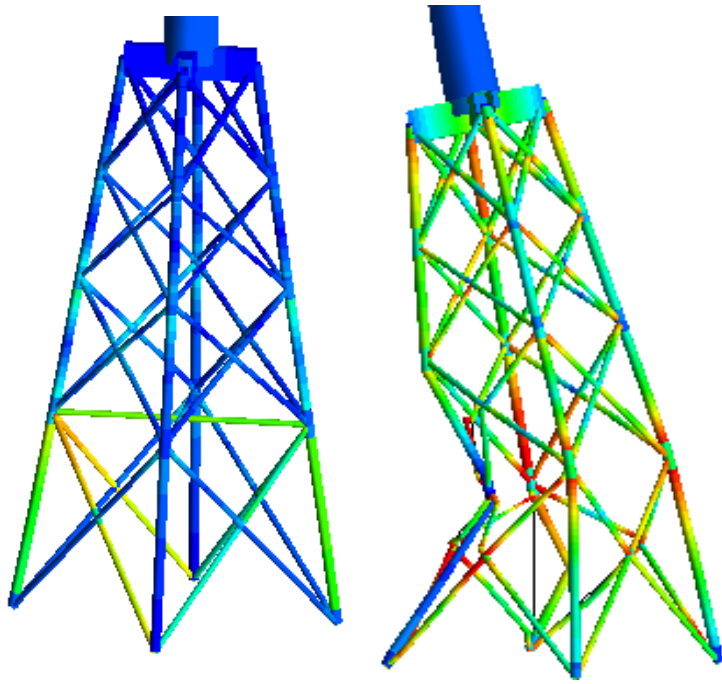
Ballasted ship, static, joint impact, fixed, with horizontal x-brace (left), without (right).
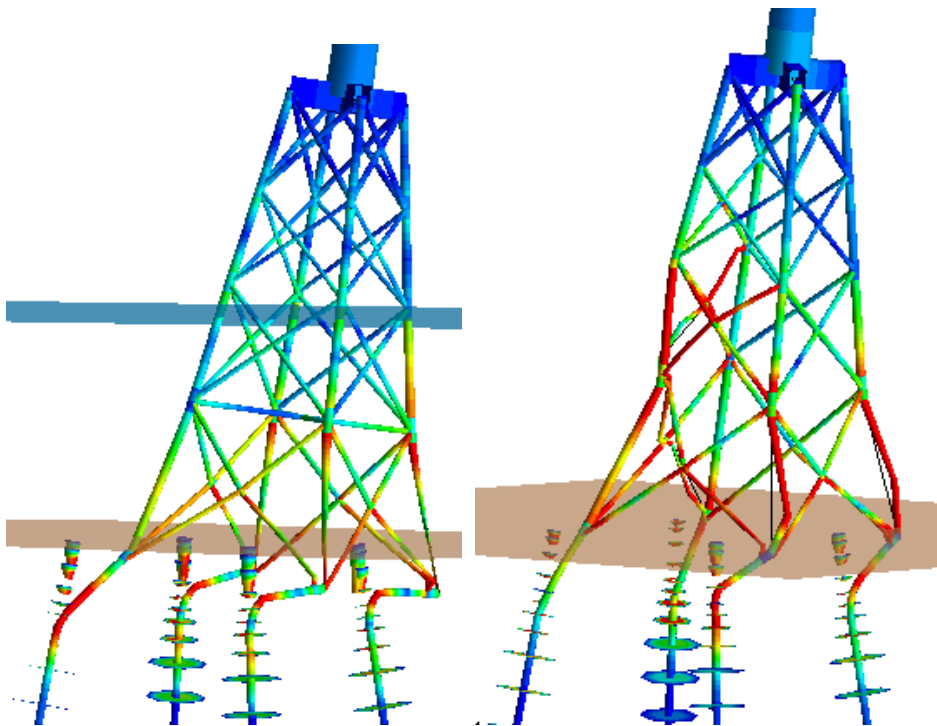
Dynamic:

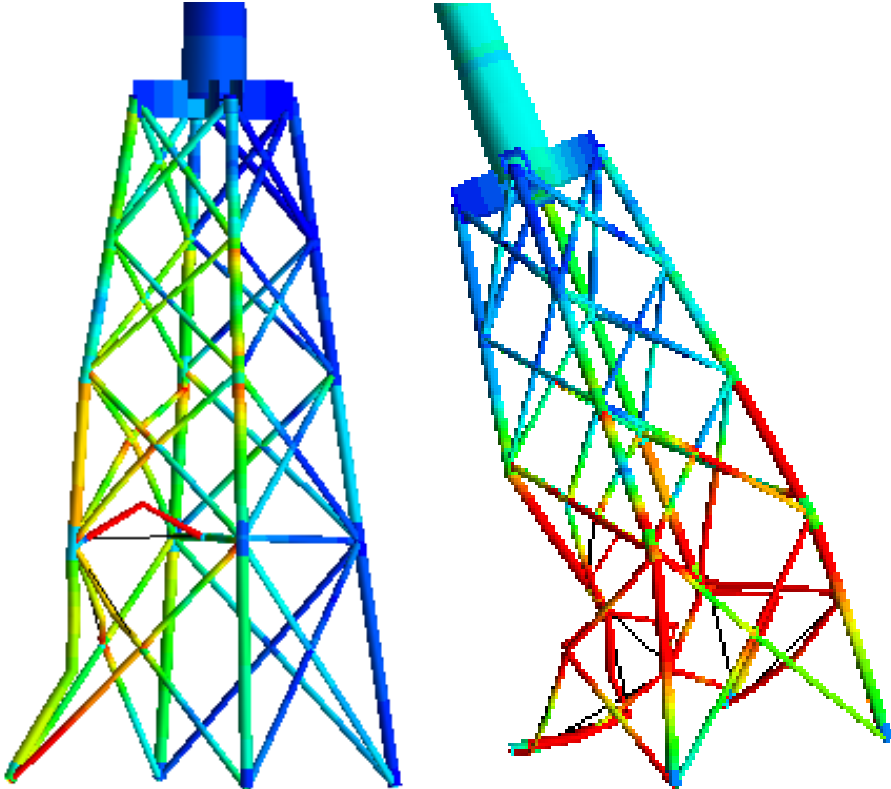Ballasted ship, dynamic, joint impact, with piles, with horizontal x-brace (left), without (right).
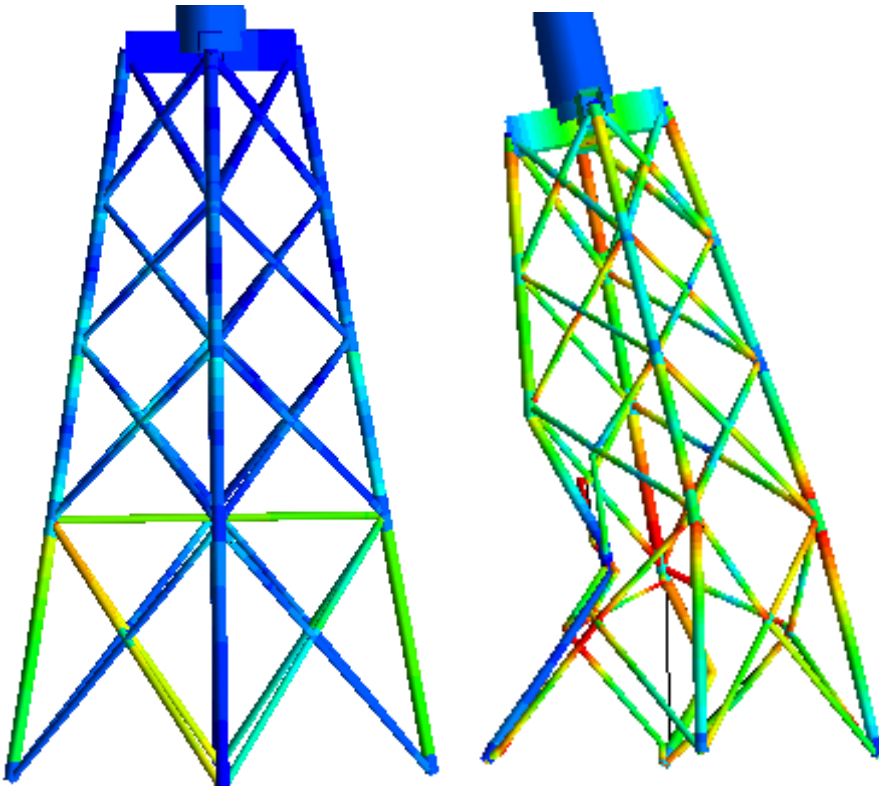
Ballasted ship, dynamic, joint impact, fixed, with horizontal x-brace (left), without (right).

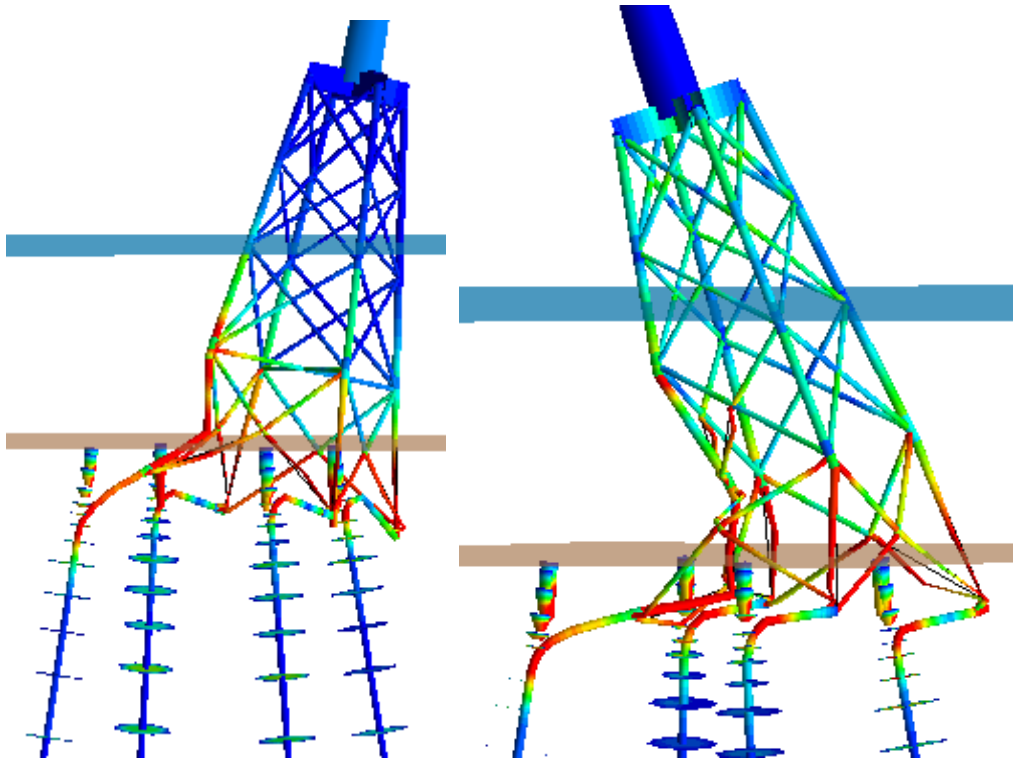## A.2.2 Loaded ship column impact with small jacket
Static:

Loaded ship, static, column impact, with piles, with horizontal x-brace (left), without (right).
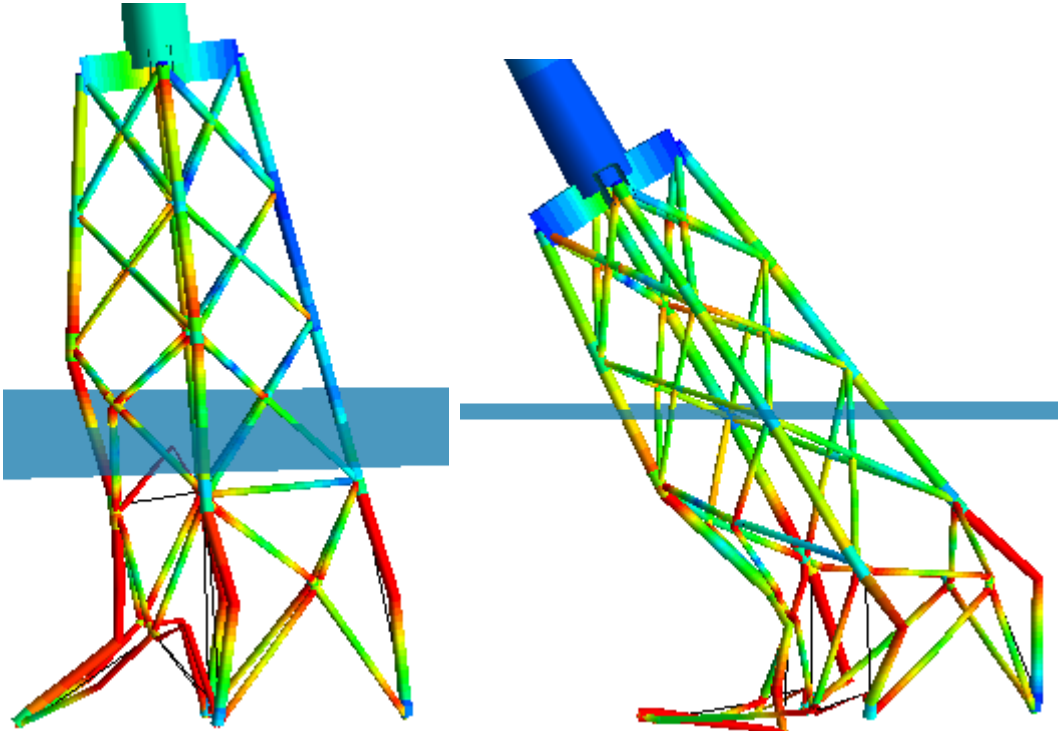

Loaded ship, static, column impact, fixed, with horizontal x-brace (left), without (right).
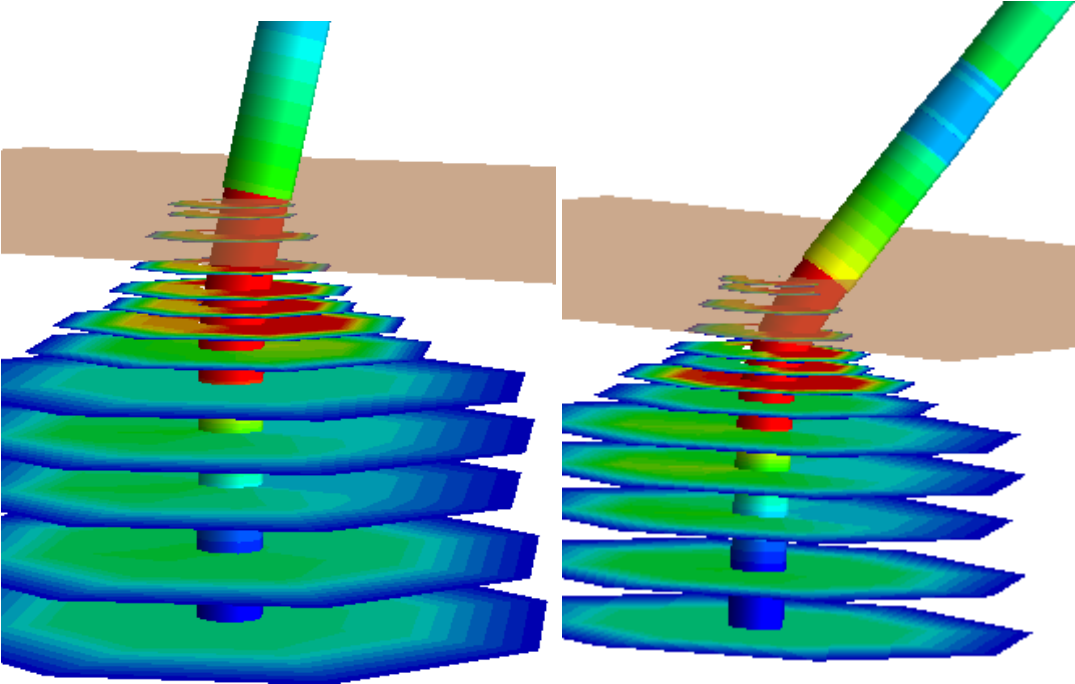
Dynamic:

Loaded ship, dynamic, column impact, with piles, with horizontal x-brace (left), without (right).

Loaded ship, dynamic, column impact, fixed, with horizontal x-brace (left), without (right).

A.3 Monopile results

A.3.1 Ballasted ship impact

Monopile, static, ballasted ship impact, failure mode.