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Abstract

In the history of offshore industry, position keeping has been an essential part for allowing operations to be performed, and production to be maintained. This is often done by connecting mooring lines between the vessel and placed anchors on the seabed. Although the history of the mooring line goes back several decades, or even centuries if considering ships, the technology is far from optimal even today. Failures does happen at what can be considered a regular basis in this context. Looking at reports from these occurrences, this thesis will elaborate on what happened, why they happened and what to be learned from what happened. Furthermore, they will be compared to each other to check if they have some sort of similar causes, alas trending failures. These trends will be discussed and evaluated, and given some personal suggestions for improvements if possible or if reasonable to improve. A risk elaboration on the loss of integrity of one or more mooring lines is also an important aspect of this thesis, as it gives an understanding of how serious an event a failure of this kind can be. In this section, simple risk methods will be illustrated like a bow-tie diagram showing preventative measures that can be used for loss of integrity of a mooring system.

1. Table of Content

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Abbreviations

DP	Dynamic Positioning
GPS	Global Positioning System
MODU	Mobile Operating Drilling Unit
NDT	Non-Destructive Testing
FPSO	Floating Production, Storage and Offloading
FSO	Floating Storage and Offloading
AHT /AHV	Anchor Handling Tug / Anchor Handling Vessel
PM	Position Monitoring
BOP	Blow Out Preventer
LMRP	Lower Marine Riser Packer
ATA	Active Thrust Assistance
NCS	Norwegian Continental Shelf
MBL	Minimum Breaking Load
JIP	Joint Industry Project
PSA	Petroleum Safety Authorities
HSE	Healt and Safety Executive
SRB	Sulphate Reducing Bacteria
ALARP	As Low As Reasonably Possible
AUV	Autonomous Underwater Vehicle
ROV	Remote Operated Vehicle

2. Introduction

In the offshore industry, station keeping is an important aspect for floating structures. Maintaining a stable position in the sea enables the facilities to have a continuous production or operation even when the weather is close to storm conditions. Without a reasonably stable position above a specific location on the seabed, well drilling and transportation of hydrocarbons from the reservoir to the surface would be impossible. Without a stable position, drifting of the drilling or production unit would have overstressed and ruptured either the drilling pipes or risers, depending on the activity. This could lead to an environmental disaster, huge economical losses, and in worst case, loss of human life/lives. Managing this problem, where fixed structures isn't an option, can be done by either mooring the unit to a location with anchors and mooring lines or by using DP (Dynamic Positioning). The DP system uses active thrusters to keep the unit in a given position. The given position is being monitored by for example GPS signals, and deviations from the wanted position will be sorted with the use of thrusters. Mooring, on the other hand, establish a physical connection between the floating structure and the seabed below with the use of wire, chain and in some cases fiber ropes as well. This physical connection "locks" the unit in place

This master thesis concerns one of the major problems with using the mooring alternative, "loss of integrity on one or more mooring lines". Mooring is done by having multiple lines span several hundreds of meters away or even kilometers away from the unit, down to the seabed where it is locked in place by anchors or piles.

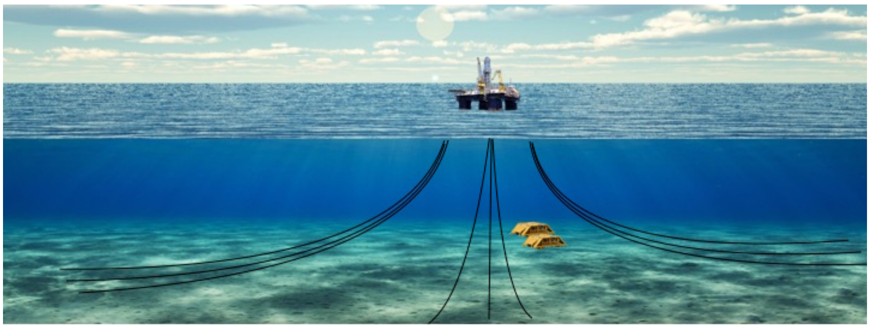

Figure 2-1: Illustration of a field. The black lines indicate the mooring lines and can stretch for several hundreds of meters away from the unit. (created using PowerPoint combining [1] [2] [3] [4])

Having such a large structure, often in metal, beneath sea level poses several threats to its continuous service, which often spans for two decades of designed lifetime. The sea behavior results in cyclic loadings inducing the danger of fatigue. If really rough seas it's possible for overloading events. water in combination with oxygen has the potential to cause corrosion on steel. Faulty equipment can lead to unspooling/pay outs or increased stress.

With events like the ones mentioned above, the production may have to be reduced or in worst case, completely stopped. If dangerous situations for the crew are possible, depending on further development, personnel may need to be evacuated to ascertain a minimum risk. It is highly unwanted to initiate these measures as they lead to a loss of revenue, and in some cases bad publicity.

With integrity loss of one or more mooring lines, the risk level increases drastically for both personnel and the facilities that are dependent on a functioning mooring system. A failure of one or more lines results in an increase in the loading on the remaining lines. This increase may be outside the capacity of the remaining lines, which can then lead to a domino effect of several other lines failing. Consequences connected to mooring failure are numerous. It can be from damaging subsea equipment, to completely uncontrolled platform drifting in the sea. This drifting isn't only a potential problem for the unit it is happening to, but also to other existing units in close proximity. In regard to the possible consequences of mooring failure events, a chapter in this thesis will be consisting of a study of risk connected with integrity loss on the mooring system.

The mooring system is placed high on the list over the most critical systems for offshore facilities, if the position keeping is done by mooring. Even though it is placed high on this list, mooring line failure does occur frequently. It happens more often than what one would think. Adding up all reported failures between year 1980 and 2001 resulted in an expected failure of mooring every 4,7 operating year for semi-submersibles [5]. This expected failure rate is high when considering that most of these mooring lines were actually designed to last for the entire operating period of the unit, which often extends to more than 20 years.

This thesis will investigate into previous mooring failures, and look for tendencies between incidents. Possible tendencies will be evaluated and studied, and possible ways of improvement will if possible be suggested for future practice. This will be done by doing documentation research from previously reported incidents. The studied incidents will be given a brief presentation and an evaluation of failure. Any tendencies between incidents will later be discussed. Failures that are classified as a so called system failures will be given a more thorough presentation than ones classified as component failure. This is done because the fact that the risks connected to these events are proportionally larger than a single line losing its integrity.

This thesis will start off by giving an explanation of basic mooring theory to give sufficient understanding of the topic to help understand what is being presented in this thesis. An introduction to a few common failure mechanisms will then be presented. They will give an indication of the complexity of designing an adequate mooring line system. Following the theory section, comes the presentation of previous incidents that are publicly known. The most severe cases are presented first, where more than one mooring line have experienced loss of integrity. To further classify them, they have been split in two sections, permanent installations and non-permanent installations. The less severe incidents (classified component failure) will not have an extensive presentation, but rather put into groups where the failure cause are close to similar and presented as a group. This is done to reduce the extensiveness of the report. The following section will be about risk connected with mooring systems, where also some statistics are presented. After the risk section comes a discussion chapter and a conclusion which ends the thesis.

3. Position Keeping of Floating Offshore Structures

Doing offshore work often involves having continuous contact with a certain specified area on the seabed. With currents, waves and wind acting on the unit, maintaining a constant location becomes a challenge that must be handled by cleverly engineered solutions. Without any measures to handle this station keeping problem, the offshore work becomes close to impossible to perform.

3.1 Maintaining Constant Position

There are two main ways to keep a constant position in the sea; Either mooring lines or by using Dynamic Positioning (DP). There are many possible configurations and solutions to do either of them, but the basic principles are close to the same for all of them. Mooring lines locks the unit to a fairly constant position by having physical contact with the seabed, while DP uses active thrusters to oppose drifting caused by the natural forces acting on the unit. DP won’t be evaluated to a great extent in this thesis, but a basic understanding is needed, as there exist some hybrid solutions that have had failures and in addition understand why it isn’t always chosen.

3.1.1 Basics About Dynamic Positioning

Dynamic Positioning is a way to keep a constant position by having active thrusters oppose drifting of the unit. This can be done by having a system like GPS to overlook that the location of the unit is locked to a given position. If movement away from this position is detected, the thrusters will be commanded to oppose the movement, and move back into place. This is done at a continuous rate, leading to a fairly locked in place location, where the work that is to be done can be performed within a relatively safe risk zone. Although this may sound simple, it can be demanding to do in reality. One of the problems is that GPS isn't always a perfect system in the way that it got full coverage of the oceans etc. This makes the DP alternative either unprecise or not functional at all. What can be done in these cases are to place probes on the seabed which the unit can use signals from to navigate its movements compared to the probes which are locked in place. However, this also isn't a perfect system; getting signals from the seabed to the surface becomes harder the deeper the water is.

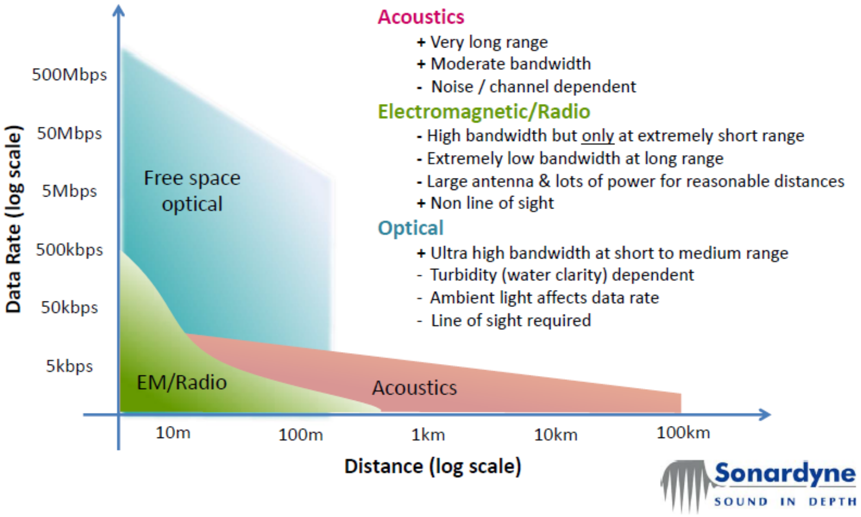

Figure 3-1: Figure showing possibilities of sending signals in water. [6]

With the increasing distance, the data transfer is greatly reduced, which may cause problems in case of interference. It isn't only the gathering of location data that can be problematic with a DP system, also the fact that it is dependent on engines with moving parts. It is a well-known fact that with moving parts, sooner or later things will start to wear down and cause failures. Knowing this leads to a necessity of risk management of the systems, ranging from frequent maintenance to the extremes of installing multiple engines in case one breaks down. However, it is very difficult to design a system that is completely safe, even with multiple engines. They may actually not be completely independent of each other, and the bottleneck may be something like the cooling system. If this bottleneck equipment fail, the entire DP system will stop as well. However, it does have the huge advantage of easy and quick installation of unit at the operation location.

These are just some of the reasons why DP is mostly used for temporary operations. Operations lasting more than one year, are usually no longer considered a temporary operation, and a mooring system might become a better alternative for these operations. This means that DP is mostly used on Mobile Operating Drilling Units (MODU), service vessels and flotels.

Figure 3-2: The flotel Floatel Superior [7]

Figure 3-3: The MODU Eirik Raude [8]

Figure 3-4:The service vessel Seven Viking [9]

3.1.2 Mooring system

When Dynamic Positioning (DP) is no longer an option, usually meaning operations lasting more than a year, the alternative is using mooring lines (as long as a fixed structure is out of the question). Mooring systems can be of different configurations, depending on what the most suitable is for the specific location. Factors that have an impact on the configuration are type of unit, water depth, seabed layout, soil, the water contamination(?) etc. With all these acting factors, what can be concluded is that no mooring systems are configured completely similar to each other between different fields. This can be problematic because of spare parts, and will be discussed further at a later point.

Mooring lines are made of a combination of chains, wires and fiber ropes. Each configuration has pros and cons, and must therefore carefully be considered when designing the mooring system, especially the placement of sections consisting of fiber rope. Fiber rope should at no point be in contact with the seabed, due to the fact that the seabed may contain rocks that have sharp edges. These edges will wear down or maybe even cut the rope, which will result in a more rapid mooring line failure than what it's designed to last. This will be discussed more thoroughly at a later point, but what must be noted is that the mooring line setup must be carefully planned. Done properly, it can be considered as a risk reducing measure.

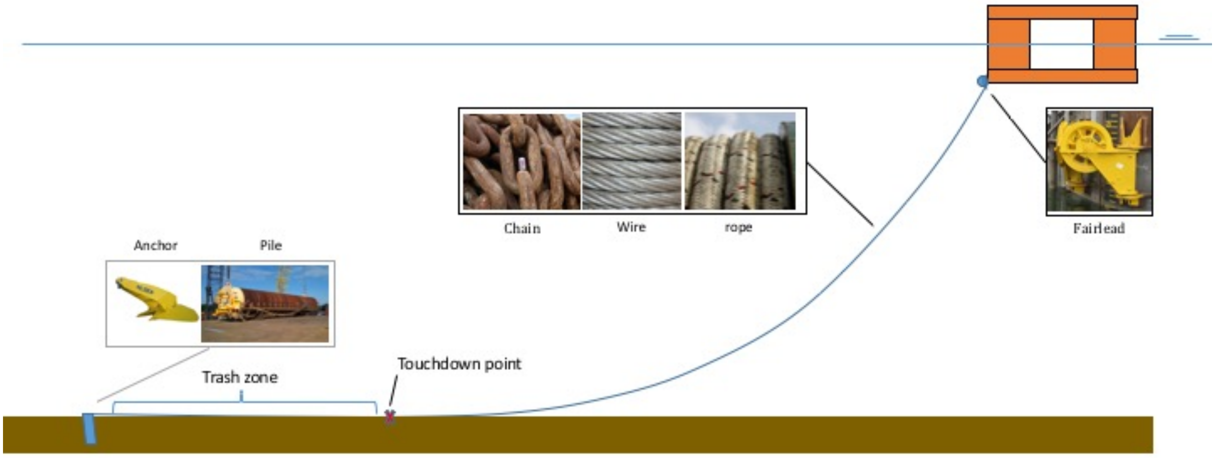

Figure 3-5: Illustration of possible layouts of a mooring line with a catenary design. This illustration is excluding possible shackle joints etc. (created using PowerPoint by combining pictures [10] [11] [12] [13] [14] [15])

3.1.2.1 Chain

Chain has been in use in the industry for decades. It is known for its high strength while still being almost completely freely maneuverable. This makes it ideal for doing heavy lifts, locking equipment in place, towing etc. When not in use, it is able to be stored in a limited amount of space. The downside in many cases is the weight distribution, which is very high compared to wire and fiber ropes. When it comes to mooring lines, this weight may be a positive characteristic. The weight of the line is used as a force for position restoring as long as it is used in a catenary configuration. In deeper water it becomes less favorable as a taut line becomes the best option, more about this in the next section. Another good point about chains is that the design makes it simple and reliable when having a transition from example wire to chain. In the interconnection point between two segments a joint section is necessary. The chain is a simple procedure to connect to the joint, however the wire and ropes require more effort with additional constructed solutions. The wire and rope need end splicing, and won't have a fully trustable connection point as it is often only a press fitting or something similar to it. When designing a chain mooring section, the capacity of chain links can be problematic to both calculate and to be completely certain about, when in proximity of the fairlead. This is because the interaction between chain segments causes interlink friction, resulting in a moment in the chain link. More about this problem later.

3.1.2.2 Wire

Wire has the advantage that it is very compact, but still free enough to be sufficiently elastic to be able to be rolled around a wire drum, making the storage, installation and decommissioning a simple affair. The wire is close to as durable as the chains, but has a downside of some more complex failure modes. A weakness with wires is that it isn't constructed to handle any torsional forces, which may be hard to avoid. The torsional forces create either compression or expansion of the wire, depending on the twining direction. If it is expanded, sea water may flow inside the wire and remove internal lubrication which will increase friction. This increased friction will lead to an increased wear as the protective zinc layer will be removed and lead to an even faster wear effect due to the induced corrosion problem with a lacking zinc protection layer. This a very problematic issue with the usage of wire ropes. Doing inspections of the wire won't give any pre-indication that it is internally corroded, and even doing the inspection can be challenging due to marine growth covering the steel. With the marine growth, doing thorough internal NDT requires long lasting operations and large investments in both equipment and personnel. It is not only the corrosion that is a problem with torsion in wires, but also a phenomenon called bird caging. This problem can occur if the wire is twisted and experience a sudden load change.

Figure 3-6: Picture showing a steel wire with a phenomenon called bird cage caused by twist in wire in addition to a sudden load change. [16]

If this occurs in the wire, it can be approximated that a third of the wire capacity is lost [16]. For this reason, twisting of wire should at any point be avoided so that the wire will be ascertained to have the required capacity.

3.1.2.3 Fiber Rope

Using fiber rope as mooring line has become more common over the years with the increasing knowledge about behavior of both floating platforms and the fiber rope material itself. It has mostly been in use in parts of the world with calmer sea states, like the coast of Brazil, but in recent years it has also become more common in harsher areas like the North Sea. The fiber rope material is fairly cheap to produce, and its elastic characteristics makes it highly viable to be used in many industries. When used as mooring line, it has the advantage of not being affected by corrosion over time like steel material would be. This makes the failure modes a lot simpler and predictable and much can be discovered by a simple inspection. Some weaknesses with fiber rope are that over time they will stretch, and more frequent readjustments on the lines becomes necessary. Extreme care is needed when winding on to a spool, transferring to an installation and when doing installation as the fiber rope is very sensitive to damage and improper handling. This can be hard to achieve considering both the length and weight of a mooring line.

3.2 **Mooring Line Configuration**

To understand the possibilities of failures in mooring lines, it’s important to have a basic understanding of how a “standard” configuration of mooring lines work. The mooring lines can stretch for several hundreds of meters as mentioned, and with this distance, the weight of the line becomes very heavy. This weight is what will be used to resist the forces applied on the stationed unit by waves, currents and wind. The way this is done in normal cases is that the unit move in one direction, and the mooring lines that stretches behind in opposite direction of the movement, are lifted from the seabed. With the lifting of sections of the mooring lines that lies in the trash zone, more weight is added on the line. This is the so called catenary mooring line design. The added weight force is transformed to a horizontal force due to the curvature of the mooring line. This force transition is important because it ensures that the anchor or pile at the end of the mooring lines does not experience any form of vertical loading when the unit moves. This is of course as long as the movement is within a limited and designed range. Should the anchor experience vertical loading, it might be dragged out of the soil, and make the mooring line dysfunctional until reinstated.

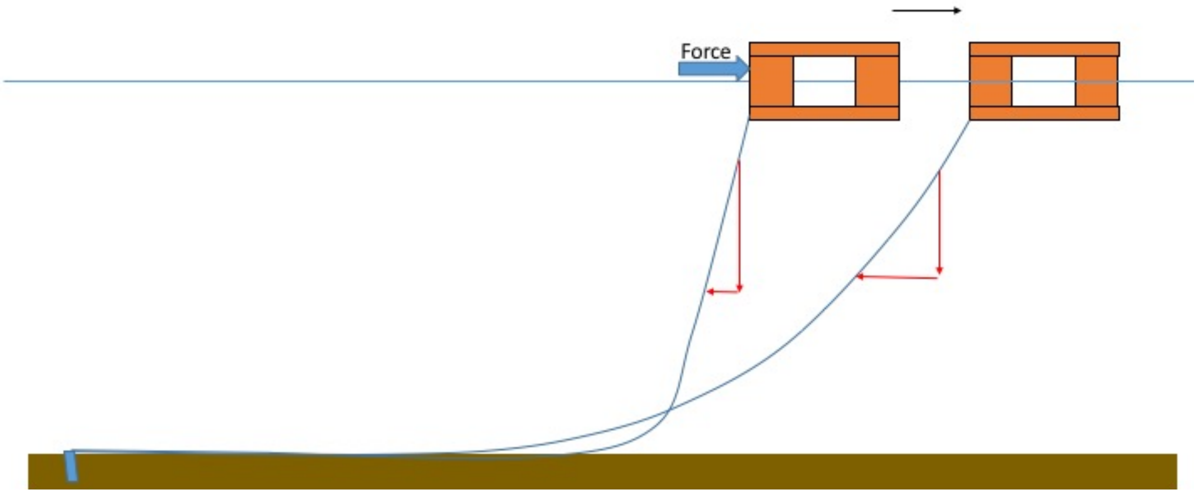

Figure 3-7: Illustration of increased horizontal force with movement out of place for the floating structure for a catenary layout.

Waves, currents and wind carries with them a lot of force on large structures like a semi-submersible. One mooring line on each side isn't sufficient to resist the movement due to these forces. In operable semi-submersibles today, 3-4 mooring lines are often placed at each corner of the structure. Adding up multiple of lines makes the system sufficient to resist the dislocation of the floating structure. With a turret configuration, it will gather all the mooring lines at a single location on the unit, and spread the lines out in a circular shape. Although circular, the working principle is still the same as for the spread mooring that's illustrated.

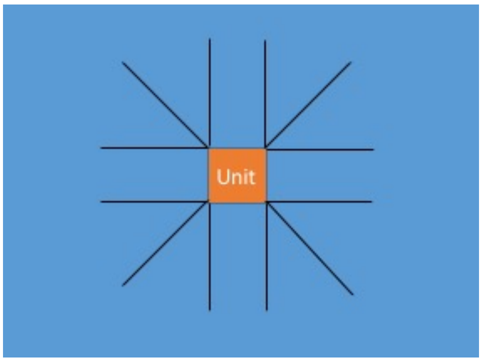

Figure 3-8: Illustration of a possible field layout where the mooring lines are spread out from each corner of the unit

From this layout it can be seen that movement in all possible directions will have multiple lines working against the displacement. This is, as mentioned, necessary for the large forces applied to be counteracted by the weight of the mooring lines. With this design of the mooring system however, the depth will be a limiting factor, as the weight becomes too excessive in larger depths. The movement of the floating unit would be larger than what is reasonable for drifting distances, and the line itself would have to stretch out for lengths that in itself would become problematic to design a field layout for.

Deeper waters require a different design, and the taut mooring line system is mostly used for these installations (unless DP is an option). This is a system that has a direct force transfer to the anchors/piles. This also means that the anchor will be affected by a vertical force, and to handle this, a more thorough research and planning has to be done for placing anchors/piles. The soil must be carefully studied to be certain that the anchor will not simply be dragged out by the forces applied, and make the whole line ineffective. Although it is a more complicated anchor design and anchor installation process, the upside for a taut mooring system is a reduced line weight, greatly reduced movement of unit, and shorter length of the mooring line itself compared to what a catenary design would require.

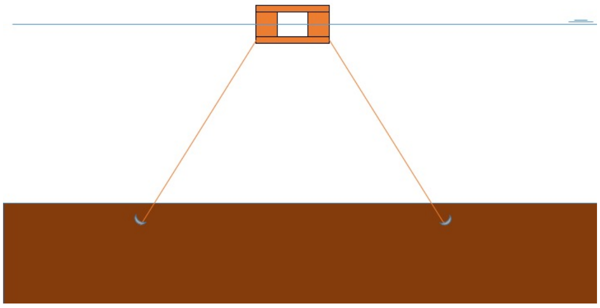

Figure 3-9: Illustration of a possible taut mooring design, where the forces are applied directly to the anchor, causing both vertical and horizontal forces.

3.2.1 Other Alternatives

There is also one alternative that is widely used, which combines thrusters with mooring for station keeping, called Automatic Thruster Assistance (ATA). This has the possibility of combining position restoring force from both mooring lines and a thruster. This leads to a lower load applied on the mooring lines. The drawback of this system is that it takes some of the drawbacks as mentioned in the DP section, into this alternative. Designers often use this system as a reason to lower the strength and/or size of the mooring lines. Should a failure occur with one system, often the other system usually won't be sufficient to supply the necessary restoring force for the unit. However, if used in a parallel, without reducing design criteria for either the thrusting force or the mooring line, it would make this system one of the safest and most stable alternatives. This solution however would be at at a very high cost. Appropriate reductions on the mooring lines are required for this to be a fairly safe alternative.

Another possibility is the use of tension leg mooring (TLP), where the mooring is done by having steel tubes going from the floating unit directly down to the seabed. This is referred to as a tendon mooring. This is a proven technology, but not widely used. The largest portion of units using this system is located in the Gulf of Mexico. [17]

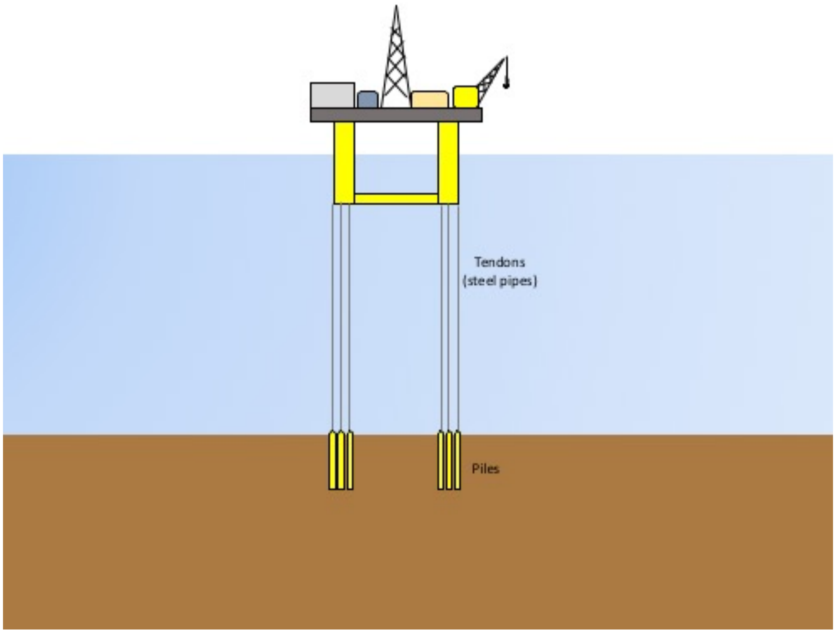

Figure 3-10:Illustration of a TLP platform, where the platform is locked at a location using tendons which is connected to piles at the seafloor.

3.3 **Common Failure Mechanisms**

Mooring lines are often the only barrier preventing an uncontrolled drifting of the unit. Therefore, they should in theory never fail, but in reality that is not the case. Over the years with an increasing offshore industry, there have been several cases of failures. Luckily most of the incidents ends up without any catastrophic outcomes, but the possibility exists to have large spills etc. because of these mooring system failures. More about consequences will be discussed in the chapter 5 concerning risks.

There are many reasons that a mooring line can fail. The most common failure causes can be sorted into sub-groups; natural causes, fatigue, overloading, impurities from production, design errors and external interactions. However, it should be noted, some of these sub-groups are able to affect each other as well, which in turn rarely makes the failure cause being only from one of these categories.

3.3.1 Natural Causes

In the natural causes category, it's the wear and tear from the local environment that is the concluded reason for a line failure. Corrosion is the major issue within this section. Mooring lines most often consist of either a chain or a wire rope. These components are made of steel, and it is well known that this material will corrode when in contact with water and oxygen and create rust. Even stainless steel may be affected by this [18]. Once the iron atoms in steel starts to react with oxygen and make rust (Fe_2O_3), the material capacity of the steel structure will gradually decrease.

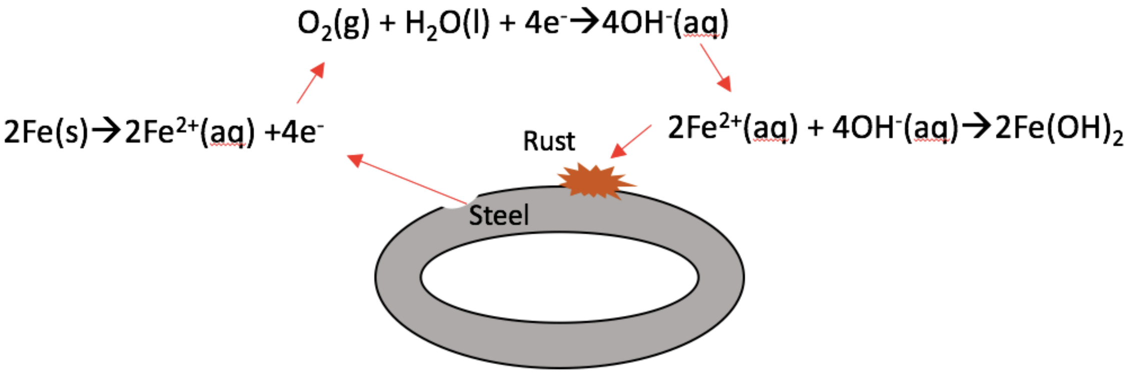

Figure 3-11: Illustration showing chemical process of rust formation.

A concern is that rust isn't necessarily proportionally distributed all over the surface, but may be more extensive in one area compared to another. This uneven rust distribution may cause large local stress concentrations in both chain and wire segments. Eventually this stress will be more than the remaining steel is able to handle, leading to a failure.

Corrosion is a problem that should be considered when designing both chains and wires, as it is close to guaranteed to occur. However, designing can also be a challenge, as you are depending on the environmental properties. What this means is that the corrosion rate varies depending on the location where the structure is placed. The responsibility to avoid problems caused by this variation should fall upon the national set standards, if no field data is available. For instance; NORSOK requires a design for a corrosion rate of 0.8mm/year in the splash zone for chains. [19] This splash zone is defined as 5 meters above to 4 meter below the still water level according to DNV GL [19]. Yearly corrosion allowance when designing this splash zone area will always be at a higher level than the remaining part of the mooring line. Access to higher oxygen concentrations causes an increased rate of the corrosion, thus the design in the splash zone must be of a more conservative level compared to the remaining mooring line. The requirements set by the NORSOK standard, which covers the regulations for the Norwegian Continental Shelf (NCS), is stricter than what is required for other locations in the world. The DNV standard states corrosion allowance should depend on inspection schedules. If the mooring line is regularly inspected, the requirements for corrosion allowance lower than if they are designed to almost never be inspected. However, the corrosion parameters should be based on at-field data. See table 10-2 in appendix for some more information regarding corrosion design according to DNV GL regulations.

The DNV GL requirements are fairly well based on lab tests etc. The problem is that lab tests may be based on assumptions that doesn't represent the real environment at the location that the mooring lines are to be designed for. For instance, the water can contain Sulphate Reducing Bacteria (SRB) which is known for causing pitting corrosion on equipment such as ballast tanks. [5] This may also affect the mooring chain/wire. Another possibility is an increased corrosion rate due to galvanic corrosion. This problem is usually handled by having sacrificial anodes connected to the floating unit, but as the mooring lines stretches a long distance away from this unit, the efficiency of the anodes can be questionable [20] [5]. This problem is challenging to handle because of the problem of attaching sacrificial anodes on a chain or wire and making it stay there, especially in the trash zone. The line is an object in almost constant movement, and this, over time, will cause additional wear on the anodes alongside the galvanic corrosion. Designing the line with anodes as major corrosion protection will, because of this wear effect, be a risky decision with added failure potential.

3.3.2 Fatigue

Cyclic loading above certain levels impose the risk of fatigue failure. This is highly relevant for mooring lines, as the movement of a floating structure can be close to periodic. This movement of the floating structure leads to cyclic loadings of the mooring line, which has an embrittling effect, and over time cracks can be induced in the material. These cracks again cause increased local stress loads, which in the end may lead to failure at a much lower load than what it is designed to handle.

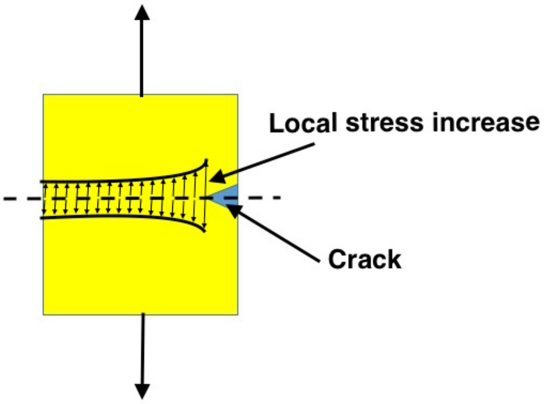

Figure 3-12: Figure illustrating local stress increase due to a crack.

Fatigue is one of the most common failures in engineered projects with moving parts. The reason for this is simply because fatigue is hard to predict and design against without doing a very costly and conservative design. Fatigue damage occur at loadings lower than the yield strength, and the resistance against fatigue depend on the load span variation, frequency it occurs at, impurities etc. This all adds up to a standard that can only give a percentage certainty that a failure won't occur at a specified load span and frequency. These probabilities are based upon multiple lab tests. There will be uncertainties until it converges to a point where it is close to completely assured not to fail due to fatigue. This is when another problem with a mooring system occurs; over-dimensioning of a mooring chain leads to an increased total weight of the mooring line. This weight must be managed by increasing the buoyancy force of the floating unit, which for a semi-submersible unit would be to increase the pontoon size. This increase in pontoon size would again lead to a larger necessary restoring force to hinder structure movement, which again leads to a necessary increase in chain/wire dimensions. This is a vicious circle that is challenging to end, and each "round" has a significant cost increase. This means that the mooring lines are designed to not have fatigue failure within its planned lifetime, but this is only in theory, as other failure mechanism/mode may also have an effect on fatigue, as manufactured impurities in the steel and corrosion.

3.3.3 Overloading

Overloading of mooring lines is a regular cause of failure, often during storm conditions. The most exposed point for this kind of failure are the links inside the fairlead or in close proximity of it. The reason why is the fact that these mooring links will take the entire weight load from the line itself, and in addition to being forced into a steeper bend, causing an added bending moment in the material. This makes the line experience a far larger loading on one side of the line while the other will have a slightly reduced load. The difficult part is to know how large an effect this added bending moment has, and how much it reduces the capacity of a link. This all means that there are higher loads on the section within the fairlead, and with the added periodic loading, causing fatigue cracking, the wear on this section is higher than the rest of the line. Because of this increased wear effect, it has become normal to rotate on sections that is within the fairlead. This ascertains that the wear effect not only affects a few links, but several. This measure gives an overall lifetime increase for each section that has this task in the fairlead.

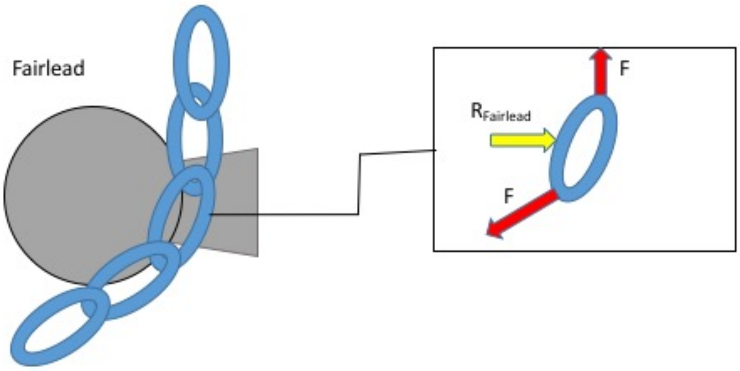

Figure 3-13: Simplified illustration of a fairlead and connected forces on a chain link.

It is during storm conditions that the lines are loaded the most as stated. Failures under these conditions might be catastrophic. A failure of a single line can quickly propagate to several line failures. The load increase in the remaining lines after the first one becomes inoperable is the cause behind this propagation. In some lucky cases the line fails after the peak storm has settled and the weather is going back to normal [5]. This makes the event less catastrophic as long as the affected unit is able to have a quick fix.

3.3.4 Production Impurities

Producing mooring lines that stretches several hundreds of meters with consistent material properties barely without faults is close to impossible to achieve. There will always exist a certain amount of structural impurities in the crystal structure or cavities, and the extent of the faults can be of a varying degree. Discovering, as well as judging, a fault in the material can be problematic because it requires a non-destructive testing method to not ruin the product. This can be done in several ways, like using acoustics, x-ray etc. These methods all helps in discovering internal and/or external cracks, but all kinds of material will have some internal faults. It is impossible to be completely certain about how these faults affect the material properties without doing destructive tests and read the measured results. This leads to the acceptance criteria for the existing faults within the material to be based upon previous experience. The faults must be judged as either acceptable or not acceptable by experienced personnel performing the inspections. Misjudgment is a risk that is problematic to handle and instate mitigating measures against. There isn't any fast feedback loop for line failures caused by production impurities. The failures are likely to occur several years after going through the inspection, and discovering the reason behind the failure can also be a time demanding effort. All this time leads to an unlikelihood that the person doing the inspection is even still in the same work position, and in case he or she is, the discovered faults will not be fresh in memory. Thus, experience in judging a material fault is hard to come by, and is mostly based on laboratory tests that is only approximated to be equal to the real working conditions.

3.3.5 Design Errors

In this category, the reason behind the failure is because of a mistake done in the designing process. This error might be as simple as a calculation mistake, but can also be as complicated as not being aware of the potential threat to the system. Errors with calculations can to some degree be easily solved by having colleague checks, ascertaining that the calculations are correctly performed. However, not knowing all the potential threats is usually caused by lack of experience or knowledge. This knowledge and experience can only be gained through trial and error. Because of this, it is important to keep knowledge and experience within the company, even through hard times, so that new employees will not make mistakes that an older “generation” has already done.

3.3.6 External Interaction

This point is mostly self-explanatory. The reason behind the failures are that external forces were applied to the mooring system. These problems are often caused by fishing trawlers, having their trawlers scratching and hooking onto the mooring lines segments that stretches outside the safety zone of the moored unit.

3.4 Discovering and Managing Loss of line integrity

There are multiple reasons that mooring line integrity loss should be discovered promptly. Early discovery and fix of failures avoids further damage to the mooring system as the increased wear effect due to missing or ineffective lines are reduced to a minimum. In addition, overloading is less likely to occur at a later event. A faulty line that is discovered at a relatively fast pace, with a quick response and fix time is desired to minimize the risk of overload on the other remaining lines. In practice, this is seldom achieved. The reason why it is rarely achieved is because of many different factors, line failure can be hard to even discover depending on where the line has failed. Failures in the trash zone for instance, will not result in a quick tension drop, startling the detection systems. A quick fix after discovery would require an Anchor Handling Vessel (AHV) at standby, ready to respond at any time. If it is only a single faulty chain link, a temporary fix can be done by a shackle joint, but if the fault/problem affects a large segment, a spare line close to identical to the failed line needs to be close at hand etc. Achieving this at any given time for a possible failure is very expensive. Because of the high cost of achieving all these conditions, it will most likely only result in financial losses, at least on paper, because of the designed parameters. The solutions often consists of compromises, where some are less well thought through than others. For instance; there was a case of having a spare mooring line, but without having a proper storing facility [5]. This resulted in the spare mooring line to be rusted away, and becoming inadequate to be used as a backup for a failed line, and thus ending up as an expensive “piece of junk”.

Having no backup at all can become a very costly affair as well. Should a line fail or having deteriorated to a state where it is no longer considered fit to continue its service, a replacement is needed. Having everything in place beforehand would stop/reduce the production/operation for only a brief time. If none of the factors mentioned above are accessible (AHV, spare parts etc.), a reduced production or in the worst case, with multiple line failures, a complete stop of production can go on for weeks or months. The downtime all depends on how fast the necessary equipment can be found or constructed and then transported to the operation site. Additionally, getting the weather conditions that’s necessary to have a safe installation might also take some time. This long lasting downtime can result in financial losses far larger than having one or two spare lines in a storage. Even though this large loss is a risk, many platforms don’t have any spares, or even detection systems, since the mooring lines themselves are often in theory designed to last more than the planned lifetime of the rig itself. Having one or more spare lines with this in mind may seem unnecessary. It would only seem as an added cost to manage for many that don’t have basic understandings of engineering design principles. See chapter 5 for statistics concerning numbers for handling mooring integrity loss incidents.

Should one line fail, it is usually not considered a severe incident as the remaining lines should be sufficient to handle the station keeping task, at least for a temporary duration. This, of course, is as long as the weather conditions aren’t too harsh. However, in the end, it is hard to be aware about the true conditions of the remaining functioning mooring lines. This is why a single mooring line failure can at times be hard to categorize, and evaluate if it is an event that prevents the continuation of an operation. A single line failure usually isn’t classified as critical, it is mostly categorized as a component failure. However, multiple line failures are a critical event, and it is categorized as a system failure. In the case of multiple line failures, risers and subsea equipment are at risk, and in the worst case; the platform itself and other units in close proximity. There are exceptions to this categorization; a single line failure can be a system failure if the remaining lines aren’t sufficient for maintaining the station keeping. Therefore, the managing part of loss of integrity of a mooring system becomes quite complex and thorough evaluations etc. must be done to decide further actions.

4. Cases of Mooring Failures

During the years with offshore hydrocarbon production, there have been several incidents of mooring failures. Some of the incidents are of course more severe incidents than others. Some of them has been of the kind that has been regarded as a simple component failure where only a single line is affected, while others have been of the complete system failure kind, often with several lines affected. In this section, some of the incident in more recent years will be listed and explained. The ones that are more than 15 years old (before year 2000) are excluded, as they can be considered as “old” technology and probably not still in use.

4.1 System Failure Incidents for Permanent Mooring Systems

There are a few incidents in recent history that has led to what can be classified as complete system failure, where multiple mooring lines have become ineffective. This subsection will cover most of the relevant incidents that are known to public. What must be noted in this section though, is that not all information is available to the public eye, and therefore this section will only cover what is available through publicized reports and public announcements. The illustrations in this section may not be entirely correct as they are often made using the brief and limited information that is available through these reports and announcements, but can be seen upon as a helping illustration to understand the failure.

Table 4-1: List of events that will be discussed in this section.

Events	Number of failed lines
Girasol Buoy – year2002	3(+2)
Nanhai Shengli – year 2006	6
Nan Hai Fa Xian – year 2009	4
P–34 Jubarte – year 2008-2010	3
Gryphon Alpha – year 2011	4
Navion Saga – year 2011	2
Petrojarl Banff – year 2011	5

The table above shows all the incidents on permanent installations that will be studied. Each case will have an explanation about what happened, why it happened, and what can be learned from the incident to help avoid getting a similar incident in the future.

4.1.1 Girassol Buoy

Table 4-2: Girasol buoy failure data. [5] [21]

Location	*Atlantic Ocean outside Angola*
Type of unit	*Buoy*
Installation year	*2001*
Failure year	*2002*
Age of mooring lines	*8 – 10 months*
Number of mooring lines	*9 (3x3)*
Number of line failures	*3(+2) (2 lines failed later)*
Finalized repair-work	*April 2004*

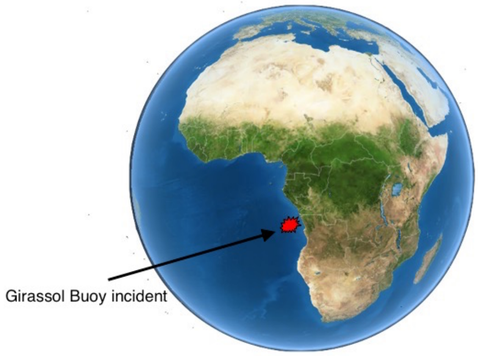

Figure 4-1: Globe illustrating where incident occurred. [22]

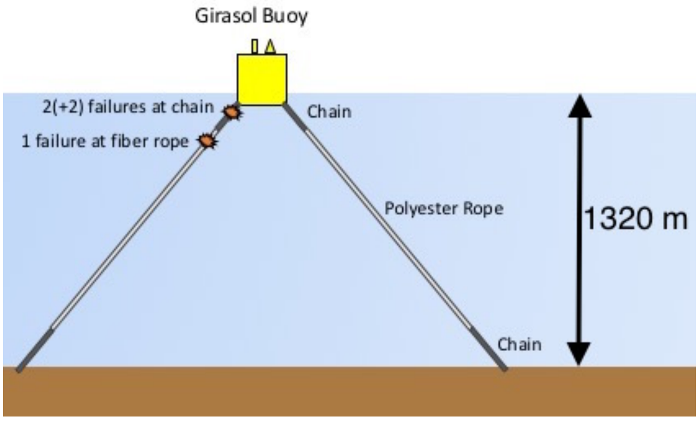

Figure 4-2: Figure showing Girassol Buoy failure locations.

4.1.1.1 What happened?

The Girassol incident was a highly unexpected occurrence, happening within a year after installation completion. The incident started with failure in one line at the 5th link from the chain stopper. This was rapidly followed by another failure in the same mooring group (3x3 groups), at exactly the same chain link, the 5th from chain stopper. With these two lines gone, the force became too large to handle for the last remaining line in the same group, resulting in a third failure. Although it would seem that the 5th link was the location experiencing the largest forces, the third and last line in this group failed at the polyester rope segment [23]. With this deviation it is reasonable to assume that the polyester rope got inflicted by a cut or something similar during installation, thus weakening it to some degree. Once these lines where lost, contingency measures were instated. However, not to a sufficient degree, which resulted in two additional failures occurring over time. Luckily this happened to an offloading buoy, and therefore didn't cause any rupture in risers nor did it drift off to cause potential collisions.

4.1.1.2 Why did it happen?

Although the deviation with the polyester rope is important, it isn't what is essential in this complete system failure. Inspection of the failed chain links revealed cracks in the metal, indicating fatigue damage. This should not occur this early in the field life, as the lines were designed for permanent installation according to API RP2SK with a designed fatigue life time of 60 years and more (3x designed life) [24]. The probable reason this failure occurred still, is because of out of plane bending (OPB). With the locking of the chain links at the exit point of the buoy, interlink friction caused a bending moment in the following link that could freely move. This added bending stress was not accounted for in design, and it lead to larger cyclic stresses in the chain than what was assumed to be caused by the environmental loadings. This increased loading caused a massive reduction in fatigue life of the chain link, and ended up with an early cracking of the metal and thus a reduced stress resistance.

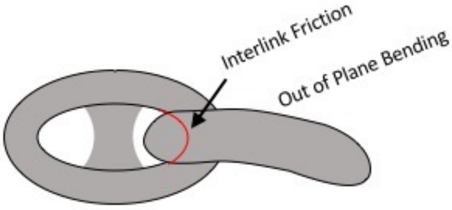

Figure 4-3: Illustration of Out of Plane Bending (OPB).

4.1.1.3 What to be learned from the incident

With the quick and unexpected failure of the mooring lines on the Girassol Buoy, it was shown some important aspects that needs to be taken into consideration in future designs. The most important point is to consider interlink friction that leads to an added bending moment. With this added moment, the stress at certain locations on the chain can be outside of what it is designed for in a cyclic loading environment, with the end result being premature fatigue failure. To avoid these kinds of surprises on future installations, a model test in a smaller scale with added strain gauges could be done. This will be able to confirm the applicability of the design. Another possibility is to use complex computer models. With the failure of the polyester rope, there isn't much to be done design wise, but extensive quality assurance and control (QA/QC) by a representative from the field operator(s) during fabrication and installation should be a mandatory measure. This will avoid "cheating" in acceptance criterias set by the field operators and their hired designers/engineers.

4.1.2 Nanhai Shengli

Table 4-3: Data for Nanhai Shengli Incident [25]

Location	*South China Sea*
Type of unit	*FPSO*
Installation year	*1996*
Failure year	*2006*
Age of mooring lines	*10*
Total number of mooring lines	*10*
Number of line failures	*6*
Finalized repair-work	*NA*

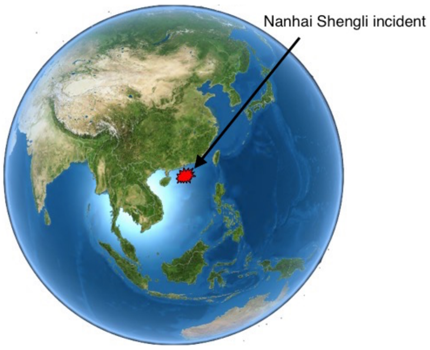

Figure 4-4: Globe illustrating where incident occurred. [22]

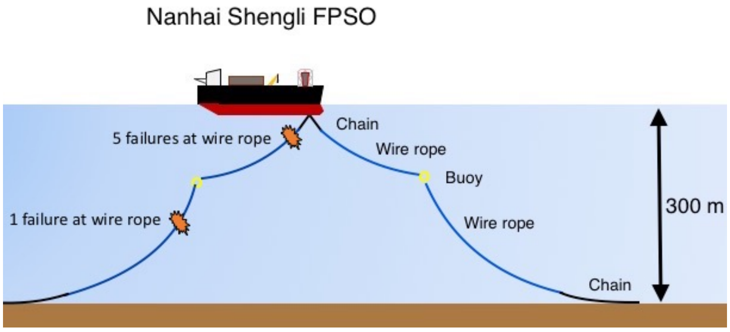

Figure 4-5: Illustration of system failure on Nanhai Shengli FPSO in the Liuhua field.

4.1.2.1 *What happened?*

In May 2006, the South China Sea was hit by a 100-year typhoon, the typhoon Chanchu. This typhoon had a 30-min mean wind speed at around 130 km/h (36 m/s) and wave heights that could reach more than 12m. This storm induced large strains on the mooring system on the Nanhai Shengli, and the FPSO had to initiate an emergency disconnect of the internal turret mooring system. Before the emergency disconnect had managed to disconnect the turret, mooring lines 1, 4, 5, 6, 7 and 8 had failed. [25] With all these mooring lines gone, a complete system failure of the mooring system had occurred. This caused a drifting of the unit that exceeded the design parameters, and resulted in riser ruptures. Once the turret was disconnected, the FPSO Nanhai Shengli had to be towed by several tugs in the harsh weather conditions to shore so it could be repaired. [25]

4.1.2.2 Why did it happen?

This incident occurred while the weather conditions were at the boundaries of the design parameters of the mooring system. However, it should still have been within the limitations. The system was designed to withstand waves up to 13.2m, currents around 6 km/h and a wind speed up to 160 km/h (45m/s). [25] The reason the lines failed are most likely connected to the discoveries that were done during an ROV inspection in May 2005. It was then discovered that several wire strands on multiple lines had been severed and was because of this ineffective. At the worst, 42 out of 168 strands were broken. The damaged wire sections were scheduled to be fixed in June 2006, but alas, a month before the planned repair work the typhoon Chanchu hit and caused the mooring system failure incident as described above.

4.1.2.3 What to be learned from this incident

In this case with the weather conditions at the design parameter boundaries, failures are hard to avoid. When this happens, the difference between withholding and failure are mostly dependent on the added safety factors and the wear conditions. In this case, with already damaged mooring lines, the resistance capacity was greatly reduced, and thus it was a basically a lost cause once the typhoon hit. What must be acknowledged in this case, is that the damage on the lines were know long in advance of the typhoon, and should have been replaced at a much quicker pace. A response time for a fix at above a year in these kinds of areas in the world is too long. The South China Sea is afflicted with yearly monsoons with strong winds etc. With a damaged mooring system during these conditions, the possibility of a system failure becomes far more likely. Therefore, the necessity of spare parts for the mooring lines in quickly accessible warehouses in a close proximity, as well as an installation vessel at station, is showcased greatly in this incident. Had the repairwork been done before the typhoon hit, restoring the mooring system back to perfect conditions, it is a far more likely that this disaster could have been avoided or only resulted in a single line failure. This is of course depending on the added safety factors in the system, as the storm was close to the design parameters making it hard to determine.

4.1.3 Nan Hai Fa Xian

Table 4-4: Data for Nan Hai Fa Xian Incident in the South China Sea. [21]

Location	*South China Sea*
Type of unit	*FPSO*
Installation year	*1990*
Failure year	*2009*
Age of mooring line	*19*
Total number of mooring lines	*8*
Number of line failures	*4*
Finalized repair-work	*2010*

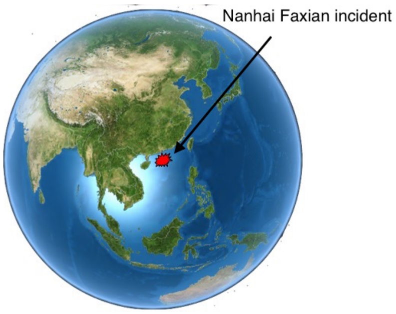

Figure 4-6: Globe illustrating where incident occurred. [22]

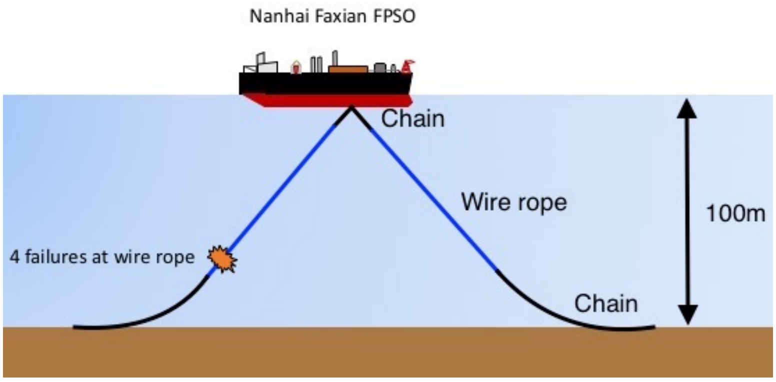

Figure 4-7: Illustration of system failure on Nanhai Faxian FPSO in the Huizhou field.

4.1.3.1 What happened?

The typhoon Koppu was raging in the Huizhou oilfield during September 2009. In advance of the coming bad weather, the FPSO Nan Hai Fa Xian tried to do an emergency disconnect of the turret to avoid it causing any major damage. However, the release mechanism of the turret didn't function, and the release failed. [21] With the failed release of the mooring turret, excessive loads were applied to the mooring lines during the bad weather. This ended with 4 failed mooring lines, where all the lines broke at the lower part of the wire rope segments. With all these lines parted, the mooring system had a complete system failure. This made it possible for the vessel to have larger drifting distances. With the increased drifting distance, the risers were overstressed, causing them to rupture. Luckily, the FPSO was prepared for the typhoon beforehand, initiating precautionary measures, and thus no lives were lost in this incident as stated by the operator CNOOC Limited. [26]

4.1.3.2 Why did it happen?

Not much data is officially released from this accident, but this occurred in components that were 19 years old. In that time, the lines had deteriorated to a certain degree, and as stated in "OTC 24025 A Historical Review on Integrity Issues of Permanent Mooring Systems" by Kai-Tung Ma et al. [21], it is likely connected with corrosion. However, the mooring line failure in this case could have been avoided if the mooring turret had been disconnected as it was designed to do. Had this disconnection function worked properly, the end result would have been much better, with the mooring lines and risers still intact. The large forces in this scenario wouldn't have been distributed from the FPSO on to the mooring lines.

4.1.3.3 What to be learned from this incident

This incident is a great example to show the necessity of reliable systems when they are connected to the mooring of the vessel. It is highly unlikely that this incident would have occured the way it did, had proper maintenance and routine checks and trials/tests of the disconnect system been done. The turret would in that case, close to guaranteed, have been properly released when it was initiated the disconnect procedure. This incident illustrates some of the dangers of having a system that is mostly in an idle state for a major part of the lifetime, especially for critical systems like the mooring system. Without frequent use, the components may deteriorate and get stuck in place due to corrosion, lack of lubrication etc. As a suggestion to avoid similar incidents for vessels using this kinds of emergency system, is to have frequent trials and inspections with necessary maintenance. Having this on emergency release systems is important to ascertain that it is fully functioning at all times, in a similar fashion to other safety equipment as fire alarms.

4.1.4 P–34 Jubarte

Table 4-5: Data for Jubarte fields FPSO system failure. [21] [27]

Location	*Offshore Brazil in South Atlantic Ocean*
Type of unit	*FPSO*
Installation year	*2006*
Failure year	*2008-2010*
Age of mooring line	*2-4*
Total number of mooring lines	*6*
Number of line failures	*3*
Finalized repair-work	*NA*

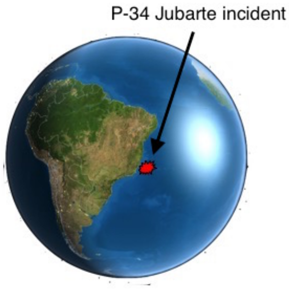

Figure 4-8: Globe illustrating where incident occurred. [22]

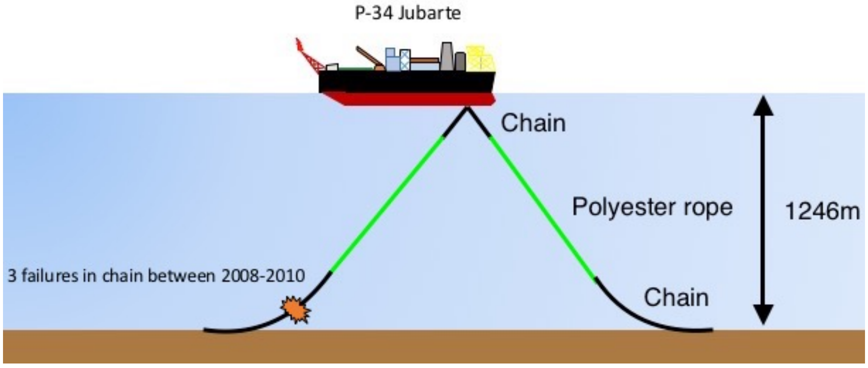

Figure 4-9: Illustration of system failure on P-34 Jubarte FPSO in the Jubarte field.

4.1.4.1 *What happened?*

Looking at the table above with data about the incident, shows us that this wasn't a close to instantaneous incident, but one that happened over a long period of time. As it isn't an instantaneous incident, the failures can't be locked down to when they happened, and what the environmental conditions were at the time. However, when looking at the installation date and time until the failures were discovered, it only stretches over a short period of 4 years. Early failures like these are an indication that something either wasn't properly designed or wasn't produced correctly. This is reasonable to assume in this case as well, as this is a permanent installation, and failures should not occur in such a brief amount of time. To the system in question here, there were two suppliers involved in the chain segments of the mooring system [27]. The chains were of the studded type with an R3 steel grade (see Appendix A for mechanical specifications). The lines that failed, all failed at the bottom chain segment because of fatigue.

4.1.4.2 Why did it happen?

It's been concluded that the cause behind the premature fatigue failure was because of the use of different materials between the studs and the links in the chain segments, which induced an electrochemical process. This process resulted in the occurrence of localized corrosion [27]. With the local deterioration on the links, an increased tension was experienced in this particular area. Over a short period of time the stress levels become larger and larger with the increased corroded material loss. As the stress levels became larger, the cyclic stress in this reduced state ran out of bounds of what it could handle. In the end the fatigue damage, in collaboration with the corrosion, became to severe and lead to failures in three mooring lines. A Further analysis of this failure case can be read in the OMAE report from2011 by Luiz Carlos Largura jr. et al., see referance [27].

4.1.4.3 What to be learned from this case

This case indicates a problem that can be considered a weakness with mooring systems there is no standardized construction of mooring chain links (materials to be used etc.). They are mostly especially constructed for that unit. Although chain technology is a known and well proven technology, the different layouts and varying vessel solutions leads to different requirements. This adds up to the fact that almost no mooring chains, or wire rope for that sake, are equal to each other, and thus there will always be a risk for unknown failure modes connected to the individual designs. This is what happened in this case, where there were design flaws with the stud's material being unsuited with the material which the link consisted of. This was shown with a test for electrochemical potential, where there was a difference of 45mV between the materials from one of the supplier, which proves that there could be induced a galvanic corrosion process [27]. This is also a problem with the use of studded links. The material deterioration over time. This deterioration makes the studs lose within the chain links, and thus inefficient. This in turn increases the possibility of failure, as this design is highly dependent on the stress distribution of the studs. In accordance to this fact, one needs to be careful when choosing this studded chain design, as they are highly dependent on fully functioning studs for the mooring lines to be adequate for their intended purpose.

4.1.5 Gryphon Alpha

Table 4-6: Data for Gryphon Alpha FPSO system failure. [21] [28]

Location	*North Sea (UK sector)*
Type of unit	*FPSO*
Installation year	*1993*
Failure year	*2011*
Age of mooring lines	*19*
Total number of mooring lines	*10*
Number of line failures	*4*
Finalized repair-work	*2012*

Figure 4-10: Globe illustrating where incident occurred.

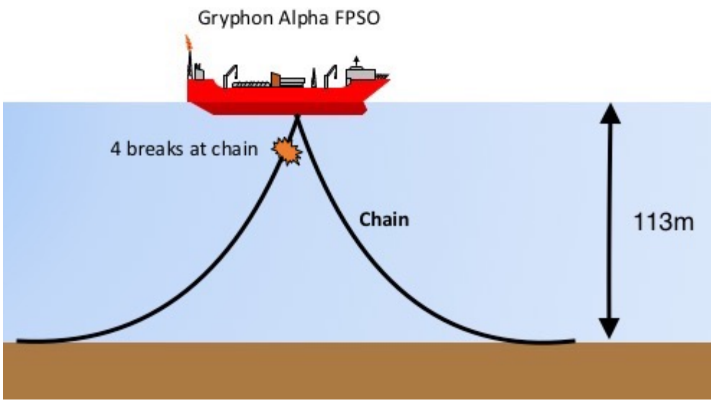

Figure 4-11: Illustration of system failure on Gryphon Alpha in the North Sea.

4.1.5.1 What happened?

This incident occurred in February 2011 during a storm in the North Sea, where the waves were at 10-15m significant wave height and a maximum wind speed reaching 110km/h (31m/s). The weather condition lead to a failure in mooring line no. 7. After this line failure, several coincidents occurred. In the end they lead to the PM (Position Monitoring) wrongly evaluated the heading it should take against the oncoming waves. The consequence of this faulty software was that the first failure was followed by another three subsequent mooring line failures. The mooring lines no. 6, 5 and 4, failed in the order as listed. After all these mooring lines failed, a complete mooring system failure was an undeniable fact. In the end, with the loss of a functioning mooring system, the vessel went out of control. The end result of the uncontrolled vessel was severe damage to subsea equipment. As an aftermath of this incident, a production shutdown was unavoidable. This shutdown was necessary to hinder a further development of the disaster, and personnel that was not essential after this shutdown were evacuated away from the FPSO. [28]

4.1.5.2 Why did it happen?

The initiating event was the failure of line 7. This failure occurred at a tension lower than what the design criteria stated it should have a capacity to withstand. It has been stated that the reason behind this lack of capacity was due to a flaw in a flash butt weld at a chain link [28]. The following three failures after the first one, are because of the PM system not functioning properly. Several factors (not explained in detail in the report) lead to the PM system making calculation errors of the forces and moment experienced by the vessel. These miscalculations made the system turn the vessel beam to a wrong position against oncoming waves. With the wrongly positioned vessel, the mooring chains experienced a larger tension than they should have and they were not able handle this increase. With the breach of the chain capacity, a propagating failure happened, and in the end resulted in failures in line 4,5 and 6 as stated in the previous section.

4.1.5.3 What to be learned from this incident

What is a well-known fact when it comes to mooring lines, is that they are only as strong as their weakest links. This case is a clear example that with a single link (on line 7) not up to the required specification can lead to a disaster. Although, it in theory should have only been a single line failure (component failure), where the remaining lines are supposed to be sufficient to withstand the forces, yet another weakness with this system showed itself. A system that is dependent on computer programs will to a certain degree always be unreliable. In cases that the computer system is challenged with obstacles it doesn't encounter on a regular basis, it can react differently than what it was thought to do. This faulty reaction can be hard to discover and fix, as these bugs/flaws in the system usually won't show up without actually experiencing these kinds of rare and variable cases beforehand. Therefor being too dependent on a computerized system can be an added risk. In this incident, the computerized system turned what would most likely only have been a "minor" failure into a severe incident. The computer system propagated the single line failure into a complete mooring system failure, which in turn resulted in damage to subsea equipment on the field. However, it must also be noted that these were fairly old mooring lines, and with the wear they've experienced over time, it is still a possibility that they would have failed even if the computer system had worked properly, but this is a possibility that's impossible determ.

4.1.6 Navion Saga

Table 4-7: Data for Navion Saga FSO mooring system failure at the Volve field. [20] [21] [29]

Location	*North Sea (NOR sector)*
Type of unit	*FSO*
Installation year	*2008*
Failure year	*2011*
Age of mooring lines	*3*
Total number of mooring lines	*9*
Number of line failures	*2*
Finalized repair-work	*NA*

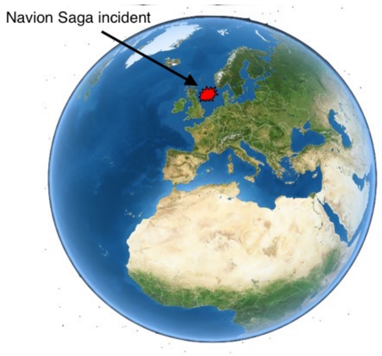

Figure 4-12: Globe illustrating where incident occurred. [22]

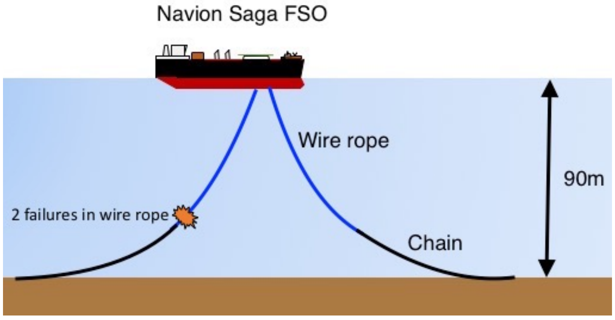

Figure 4-13: Illustration of system failure on Navion Sagain the North Sea at the Volve field.

4.1.6.1 What happened?

It's believed that the mooring line failures connected with Navion Saga happened on two separate occasions during storm conditions. The failures were not discovered until an inspection was performed after what is assumed to be a couple of months after the failures had occurred. The failures were discovered at the bottom end of the wire rope segment in both lines, close to the junction between the wire rope and chain segment. There are no active mooring monitoring systems on this vessel, so the events and forces experienced which resulted in the failures are to some degree unknown. Luckily this incident didn't cause any damage to equipment. The discoveries lead to a temporary shutdown of production until a fix of the mooring system had been completed. [29] [21] [20]

4.1.6.2 Why did it happen?

The reason behind the failures are believed to have been overload of the wires near the termination of the wire rope segments. It's assumed to have occurred due to a snapping load, which happened when the wires went slack at certain instances [20]. This snapping load caused a massive stress in the wires as it gained a larger velocity, and then instantaneously being deaccelerated in what can be considered as an impact load. This impact load will in turn stretch out the wire rope, and the circumference starts to reduce and a lesser area becomes available to withstand the forces. In the end the capacity of the remaining area wasn't sufficient, and resulted in line failures.

4.1.6.3 What to be learned from this incident

The leading cause for this mooring system failure is mainly a design fault, where it probably wasn't properly simulated using sufficiently accurate numerical models. Because of this, the possibility of the lines going slack wasn't uncovered. This shows that there are always uncertainties connected to designing against possible failures, where some of the possibilities can be unforeseen. This is a risk that will always exist within design work, where unknown failure mechanisms can occur, and are therefore not checked for. Further on, this incident gives a clear indication of the importance of a properly functioning mooring monitoring system, which alerts the personnel about line failures. In this case, it went on for several months without detecting that some of the lines had failed, and far worse consequences could have occurred if this had been undetected before harsh weather conditions. In addition, without a monitoring system, precautionary measures/routines can't be instated in case of line failure propagation, thus risking consequences far worse than what is necessary.

4.1.7 Petrojarl Banff

Table 4-8: Data for Petrojarl Banff FPSO mooring system failure at . [21] [30] [31]

Location	*North Sea (NOR sector)*
Type of unit	*FPSO*
Installation year	*1999*
Failure year	*2011*
Age of mooring lines	*12*
Total number of mooring lines	*10*
Number of line failures	*5*
Finalized repair-work	*2014*

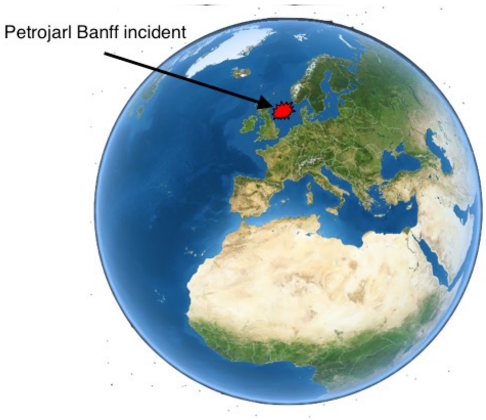

Figure 4-14: Globe illustrating where incident occurred. [22]

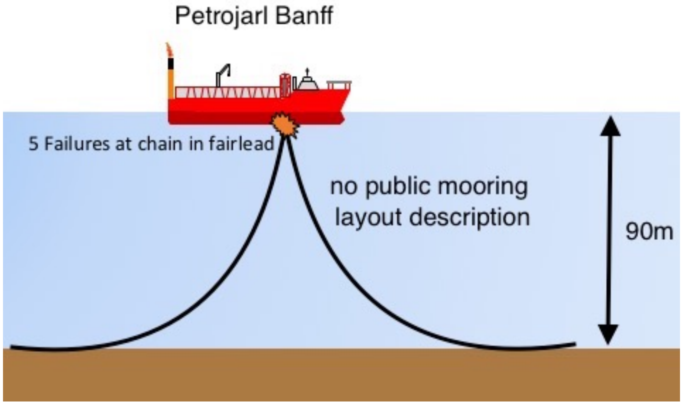

Figure 4-15: Illustration of system failure on Navion Sagain the North Sea at the Volve field.

4.1.7.1 What happened?

There’s scarce information available about this incident. What is known is that it happened during storm conditions. The forces applied on the vessel caused 5 out of 10 mooring lines to loose tension. Without a fully functioning mooring system, the vessel started to drift, and in the end it had drifted 250 m away from position. The few official statements about the consequences this drifting caused, coming from the Teekay Petrojarl 2011 and 2012 Sustainability Reports [30] [31], states that subsea equipment was damaged during the incident leading to a leakage of 1,56 metric tons of crude oil. The FPSO had to be towed to shore as a result of this incident for repair work. The damaged subsea equipment in the field either had to be repaired or replaced because of this incident, and alas all production was shut down for a long period. [21] [31] [30]

4.1.7.2 Why did it happen?

In the report by Arne Kvitrud [20], it is stated that the initiating event of this incident is a failing fairlead, which in turn resulted in an overloading of a chain link in the fairlead. Because this failure occurred during storm conditions, the remaining mooring lines had to withstand a much larger force than originally. It can be assumed that the forces became too large, and the incident propagated to become a total of 5 failed mooring lines, resulting in the mooring system failure.

4.1.7.3 What to be learned from this incident

Without sufficient data and details behind this failure, it is hard to state exactly what to be aware of from this event. It should be noted however, that this incident is assumed to be caused by a faulty fairlead on the turret. This fault can be problematic to get an indication of beforehand, as it can be a dangerous affair to perform an inspection close to the fairlead, often requiring a diver if it is below sea level. If the fairlead is submerged in water, the visibility is limited and it will most probably be covered by some marine growth making it even harder to perform the inspection and the likelihood of overlooking indicating factors of a faulty part becomes larger. With these kinds of obstacles in mind, the inspections may not be as frequent as it should be, as it is a quite demanding procedure. Strain gauges in critical sections in the fairlead might be a suggestion to monitor stresses, and possibly get indications of stress concentrations that is out of place and leading to an unscheduled inspection to uncover possible faulty parts needing a repair or change before failure occurs. Possible new technologies for performing the inspection should be investigated, and invested in if possible. This may prevent similar accidents.

4.2 **Mooring System Failure for Non-Permanent vessels**

Within this category, mainly MODU’s are being considered. Flotels would also fall under this section, but no incidents were found for these types of vessels, which is very likely due to the fact that they mostly use DP systems. The MODU’s experience mooring line failures more frequent compared to permanent installations. This is reasonable, as the lines are more frequently roughly handled with placing and retracting for each field they are operating in. When it comes to the spill danger with a drifting incident, it might be slightly less risky than for permanent installations. This is because the connection between the unit and the well has a BOP during drilling to prevent larger accidents. However, if large drifting occurs, damage to wellheads is still possible, and a BOP will not help in those instances. Although more frequent failures occur on MODU’s (see statistics in chapter 5), few of them are publicly reported. Because of this, the events in this chapter are based on incidents on the NCS because of the openness on events mandatory by governmental acts.

Table 4-9: List of events that will be discussed in this section

Event	Number of failed lines
Bideford dolphin – year 2000	3
Transocean Prospect – year 2001	2
Scarabeo 6 – year 2002	2
Ocean vanguard – year 2004	2
Bideford Dolphin – year 2006	1 (+unspooling/pay out)
Borgland Dolphin – year 2006	1 (+unspooling/pay out)
COSL Pioneer – year 2012	2 (+2 unspooling/pay out events)

The table above lists all the non-permanent installation incidents involving mooring system failure that will be studied in this section. The setup will be the same as the previous section for permanent installations, with an explanation about what happened, why it happened and what can be learned from the incident.

4.2.1 Bideford Dolphin

Table 4-10: Data for Bideford Dolphin MODU mooring system failure close to Snorre . [29]

Location of failure	*North Sea (NOR sector)*
Type of unit	*MODU*
Failure year	*2000*
Age of component	*2*
Total number of mooring lines	*8*
Number of line failures	*3*

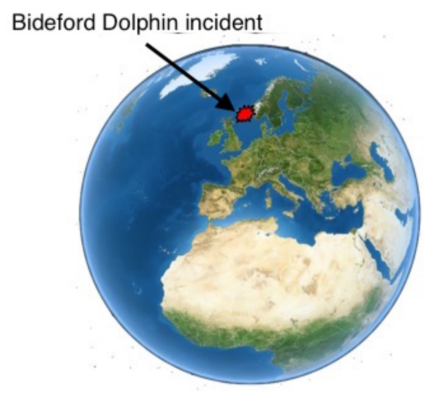

Figure 4-16: Globe illustrating where incident occurred. [22]

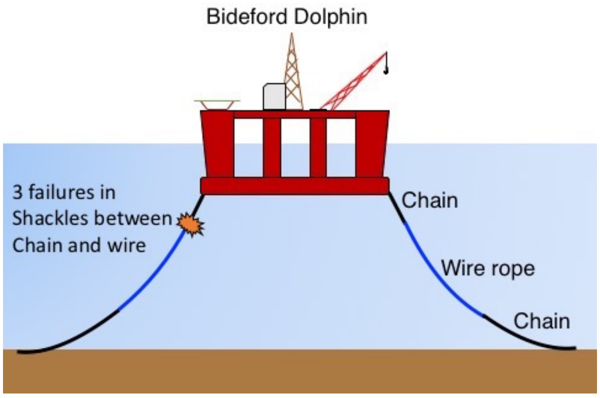

Figure 4-17: Illustration of system failure on Bideford Dolphin in the North Sea close to Snorre.

4.2.1.1 What happened?

This incident happened when the 10 min average wind speed was at around 70km/h (20m/s) and the significant wave height was close to 8,5m, which can be considered as fairly rough weather. The forces by this weather on the mooring lines lead to premature failures in two mooring lines at the shackle connections (CR-links) connecting the chain to the wire, and they both occurred at approximately the same time. 15 minutes later, the failure propagated, leading to a third shackle being broken, and thus a third line lost its functionality as well. With all these lines gone, a mooring system failure had occurred and the vessel started drifting. In the end, the vessel had drifted a total of 310m off its original location. During this incident, 56 persons were evacuated out of a total of 77 crew members. [29] [32]

4.2.1.2 Why did it happen?

The reasons behind this failure are fatigue cracking and tear-off fractures. The shackles (CR-links) that failed were only 2 years old. That is a clear indication of the shackles not being sufficiently robust and fit for their intended purpose. This reasoning is backed up by the knowledge that another of these shackles had failed previously the same year, only 3 months earlier than this incident.

4.2.1.3 What to be learned from this incident

This incident happened in the connection point between two different line segments, in a component that was only 2 years old. There are therefore two different options for this failure, insufficient design, or a manufacturing weakness. Without proper test results on these shackles, it's hard to differentiate between which of the two are the faulty party. However, what is certain is that a shackle shouldn't fail after only 2 years. This incident indicates that there is a need for a reform of the procedures in both of the suspected sections. The design section should design proof their solutions, by ascertaining that their solutions are actually able to handle what it is designed for over a long period of time. In addition, they must also be aware of the electrochemical potential between the materials, to avoid increased corrosion rates. The Manufacturing part should have more extensive QA/QC to be completely sure that what they are making actually withstands the parameters set by the design department. As a suggestion, shackle joints should be allowed to have more conservative design, as they will not greatly affect the total load of the mooring line.

4.2.2 Transocean Prospect

Table 4-11: Data for Transocean Prospect MODU mooring system failure close to Heidrun. [29] [32]

Location of failure	*Norwegian Sea (NOR sector)*
Type of unit	*MODU*
Failure year	*2002*
Age of component	*NA*
Total number of mooring lines	*8*
Number of line failures	*2*

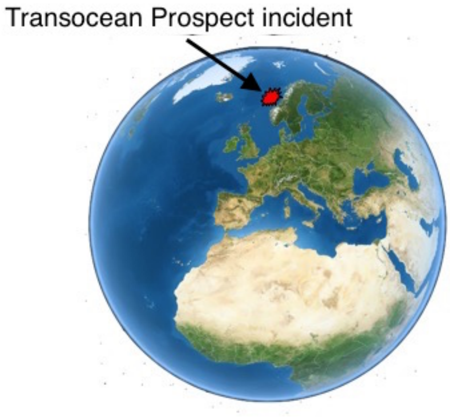

Figure 4-18: Globe showing where incident occurred. [22]

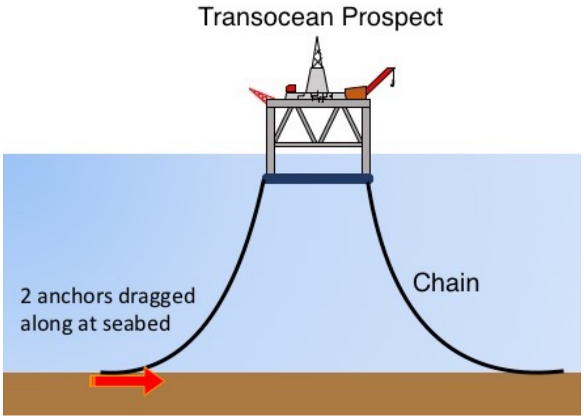

Figure 4-19: Illustration of system failure on Transocean Prospect in the Norwegian Sea at the Heidrun field.

4.2.2.1 *What happened?*

The Transocean Prospect MODU was stationed at the Heidrun field during harsh weather conditions in year 2002. The 10 min average wind velocity was at 76km/h (21 m/s). The significant wave height however is more uncertain, as there are conflicting data between units in close proximity, but was measured to be at around 13-14 m. While experiencing this weather, enough load was applied on the mooring system to cause 2 out of the 8 anchors to get dragged out of location and dislocated to around 50m out of their original position. [32] [29]

4.2.2.2 *Why did it happen?*

The reason behind this incident is not the mooring lines themselves, but rather the environment they were placed in, and the solution for solving this. The soil at the seabed turned out to be insufficient in keeping the anchors locked in place. This is likely caused by wrongly evaluated conditions of the soil resulting in wrongly chosen anchor solutions. This is a challenge with MODU's, they are not meant to be stationed at the same location for an extensive amount of time, thus doing a full and thorough field survey for placing mooring lines becomes too expensive and time consuming. Therefore, these types of events are more of a common problem for MODU's than for permanent installations which often relies on suction pile instead.

4.2.2.3 What to be learned from this incident

This type of event is to some degree hard to ward off. With the difficult process of evaluating the entire field in proximity of where the anchors are to be located. To be sufficiently protected against it would require a large investment of resources that is not always arguable to spend for only a short term operation. To increase the redundancy to the anchor location, enlarging the anchors is a possibility. Making them larger would make them able to resist larger loads, but this also has a few consequences. It would require a suitable winch able to handle the increased weight. In addition, the mooring line itself must be able to hold its own weight in addition to the anchor and the forces induced on the mooring line during anchor installation. Adding this all up, it becomes a problem that can to some degree be hard to mitigate, as the cost increase for doing so can be quite large. However, using good scanning equipment to do surveys of the field should be able to give a certain indication of how firm etc. the soil is, and should be carefully studied before placing the anchors. Doing this work with experienced personnel would greatly reduce the chance of it happening, but there will always be a slight possibility.

4.2.3 Scarabeo 6

Table 4-12: Data for Scarabeo 6 MODU mooring system failure at the Grane field . [29] [32]

Location of failure	*North Sea (NOR sector)*
Type of unit	*MODU*
Failure year	*2002*
Age of component	*NA*
Total number of mooring lines	*8*
Number of line failures	*2*

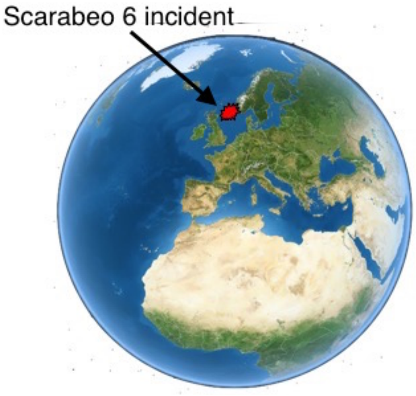

Figure 4-20: Globe illustrating where incident occurred. [22]

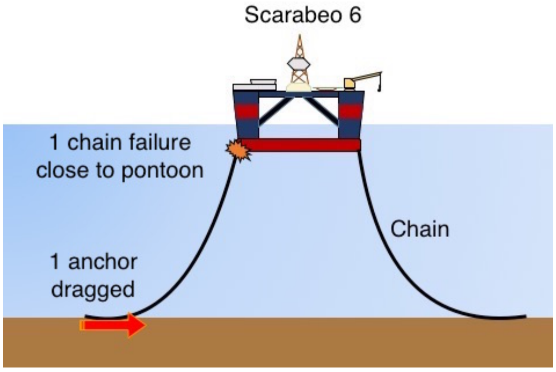

Figure 4-21: Illustration of system failure on Scarabeo 6 in the North Sea at the Grane field.

4.2.3.1 What happened?

The MODU Scarabeo 6 were drilling at the Grane field during rough weather in December 2002. During these rough weather conditions on the 24th of December, an anchor dragged along the seabed, causing a mooring line to become ineffective. The wind during this weather had a 10 min average of around 80km/h (22 m/s) and a significant wave height around 9-9,5 m. The anchor dragging resulted in a force increase in the seven remaining lines, which ended in a repercussion of the initial incident. The added load on the remaining lines resulted in an additional mooring line failing because of overloading. This second line failure was a chain link that broke inside the fairlead. With two out of the eight mooring lines ineffective, a mooring system failure was a fact. 38 Non-essential personnel were evacuated as a response to this, and the crew went from being 78 to only 40 persons. The well that was being operated on was also secured by disconnecting the rig from it, with the riser hanging freely in the ocean. This was done to avoid a risk for a riser rupture or even damage to the well head, in case the vessel should drift uncontrollably out parameters. [29] [32]

4.2.3.2 Why did it happen?

This incident was caused by a failure type that is a lot more regular for MODUs than for permanent installations as can be understood from this and the previous incident. As a MODU is only temporarily placed at location, there is not an extensive evaluation of the

seabed properties as stated in the previous incident with Transocean Prospect. Thus there is a higher risk for an anchor not staying fixed at the wanted location in the ground, but instead being dragged out of location as the applied forces breaches the resistance capacity of the soil covering the anchor.
The failure in the link happened at approximately 80% of its total holding capacity. However, this can't be blamed on bad production as it happened within the fairlead. In the fairlead, the chain link experienced an additional bending effect, and because of this, a reduction of the load capacity in the axial direction, which was also anticipated during design phase. [32]

4.2.3.3 What to be learned from this incident

The events that occurred in this incident are hard to prevent, as was stated in the Transocean Prospect incident. Spending much time on checking the seabed to be close to completely ascertained that there is no possibility of anchor dragging would be too costly for temporary operations. Spending days offshore with a full crew, expensive equipment etc. without production or performing the intended operation is very expensive. Should the anchor dragging happen however, the remaining lines should have been designed to be able to withhold with one line being ineffective. This was not the case here, where a failure occurred in a sequence to the anchor dragging. Although it happened in the fairlead, it wasn't what can be considered extreme weather conditions in this area during this time of the year. Based on this fact a more robust design would have been appropriate. No public information was available for the condition of the link that failed, or how old it was.

4.2.4 Ocean Vanguard

Table 4-13: Data for Ocean Vanguard MODU mooring system failure at Haltenbanken field. [29] [32]

Location of failure	*Norwegian Sea (NOR sector)*
Type of unit	*MODU*
Failure year	*2004*
Age of component	*NA*
Total number of mooring lines	*8*
Number of line failures	*2*

Figure 4-22: Globe illustrating where incident occurred. [22]

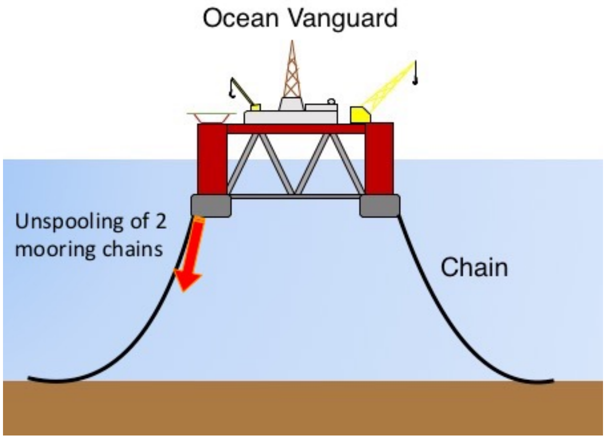

Figure 4-23: Illustration of system failure on Ocean Vanguard in the Norwegian Sea at the Haltenbanken field.

4.2.4.1 *What happened?*

The Ocean Vanguard MODU was at the Haltenbanken field in December 2004 drilling a new well. Bad weather with wind speeds up to 100 km/h (28m/s) and wave heights up to 15 meters occurred during this operation. As a response to the bad weather, they were preparing to disconnect the rig from the well. However, two winches in the same corner of the rig malfunctioned before this disconnect procedure could be finished. These malfunctions resulted in unspooling/pay out of the mooring lines. The lines connected to these winches were completely lost to the sea. With the two lines gone, a mooring system failure had occurred. This failure resulted in the rig getting a list between 7° to 10° and a total drifting of 160m away from its original position above the well. As the vessel had yet to disconnect the riser when this drifting incident occurred, the result was a riser rupture. It wasn't only the riser which was affected because of this drifting, the BOP also got impaired by the bending moment from the riser, and ended up being bent a total of 6°. This incident lead to the evacuation of 23 persons, who were brought to the Heidrun platform, that was close by. [29] [32]

4.2.4.2 Why did it happen?

Although none of the mooring line themselves failed in this case, another critical component connected to the mooring system malfunctioned, the winches. A system is only as strong as its weakest link, and in this case the winches was the faulty factor. The winches malfunctioned in the breaking function, leading to no resisting force on the chain from unspooling/paying out and being lost to the sea. The unspooling/pay out event had enough force behind it to severely damage the winches even further. They were damaged to such a degree that later investigation deemed it impossible to ascertain the reason why the breaking system malfunctioned. However, it was suspected to be because of improper adjustments. The company which had supplied the rig with the winches had in advance of the incident recommended that the braking band should be changed, and this had still not been done at the time of the event. In addition, the pawl stopper wasn't installed according to instructions, which had made the device unable to function properly and stop rotations in the wrong direction. [32] [29]

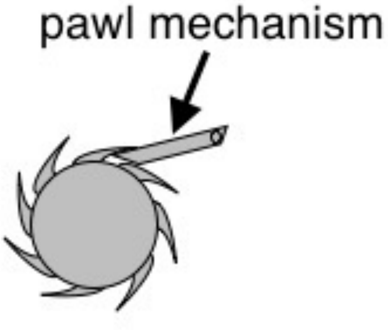

Figure 4-24: figure showing how a pawl mechanism works, allowing the wheel to only spin one way.

4.2.4.3 What to be learned from this incident

The cause behind this failure is mostly a lack of devotion to the work that needs to be done and taking initiative for immediate response by the responsible personnel to maintain the system. The required repair/change(es) should have been done by the personnel responsible for initiating the repair/maintenance of the winching system immediately after it had been discovered to be faulty. This is especially important on operations done in the North Sea at winter time, as this area is frequently affected by storms during this season. A component that has already been judged to be unfit for further service can't be blamed for malfunctioning, especially when it is being affected by stresses outside the regular working boundaries. From this incident the importance to learn the significance of every component in a mooring system, not only the lines themselves. With the lack of immediate action when critical systems like the mooring system is of concern, it may lead to devastating results. In this case, there were huge consequences, but they were also very lucky with the BOP in mind. If they had reached the reservoir and the bending of the BOP continued until rupture, a blowout could have occurred. This event would have ended up in spilling huge amounts of hydrocarbons on the seabed, similar to the Deepwater Horizon incident. As a consequence of the bending that was actually caused on the BOP because of these unspooling/pay out incident, the well was lost and abandoned, at a huge financial cost [32]. With the problem of the pawl not functioning because of improper installation may indicate a missing quality control/assurance on the performed installation of the winching system. An increase of procedures when doing inspections and having inspection-personnel with sufficient knowledge of the system might be some of the suggestions to avoid further events like this from occurring.

4.2.5 Bideford Dolphin

Table 4-14: Data for Bideford Dolphin MODU mooring system failure at Oseberg Sør. [29]

Location of failure	*North Sea (NOR sector)*
Type of unit	*MODU*
Failure year	*2006*
Age of component	*9 years*
Total number of mooring lines	*8*
Number of line failures	*1(+ Some unspooling)*

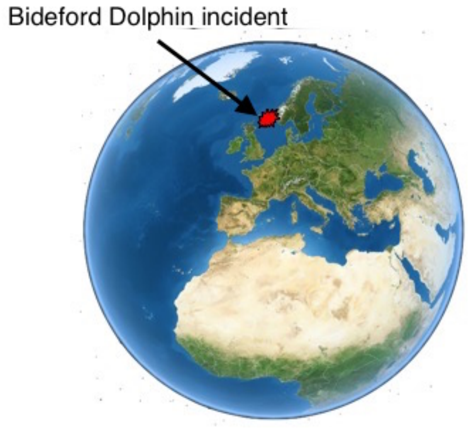

Figure 4-25: Globe illustrating where incident occurred. [22]

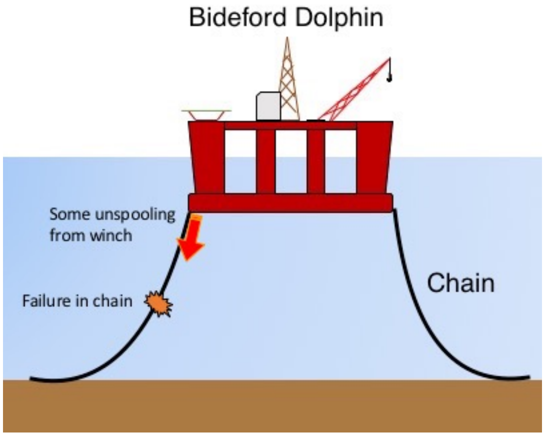

Figure 4-26: Illustration of system failure on Bideford Dolphin in the North Sea at Oseberg Sør.

4.2.5.1 *What happened?*

This incident can be considered to be in the gray area between a mooring system failure and a component failure. The weather was rather harsh during the time of the incident, and it is stated in the PTIL document [29] that there was a measured wind speed of 150 km/h (80 knots or 42m/s) although with uncertainty about where the measure has been done(at what height), but it's believed to have been from the mast. The significant wave height is stated to have been between 8m and 9,5m. During this weather there was a single line failure, which was later discovered to be caused by a chain link failing 671m away from the rig. The line failure was discovered after 40 min when the monitoring system indicated only around 25 tons, but no alarms had been observed during this time. This failure resulted in the MODU drifting a total of 40m away from the well. With this drifting, another mooring line was heavily strained, and it started to unspool/pay out, and a total of 23m of chain was dragged out before it was stopped by the breaking mechanisms. It wasn't only this line that was affected by the initial drifting, other were also affected. Although not with such consequences as unspooling/pay out, but a second winch had a burnt stench and was probably heavily strained as well during this incident. With the added unspooling/pay out event, the rig drifted even further, and in the end it had drifted around 80m away from the well they were operating in. The rig uncoupled from the well and a complete operation stop was initiated. [29]

4.2.5.2 *Why did it happen?*

The reason behind this incident is believed to be fatigue cracking which in turn lead to local stress concentrations and in the end resulted in a link failure. The MODU was both lucky and unlucky with the unspooling event in mind. With one line gone, there was a huge force increase in the remaining lines, which can be disastrous as shown in previous incidents. Luckily the remaining chains were in good enough condition to withhold the force increase without failing. However, there was also a large increase of strain on the winches. A winch reached its maximum capacity, which unluckily resulted in an unspooling/pay out event. In this case, compared to many other incidents (see section 4.3), the breaking system functioned properly and managed to stop the chain from being completely lost to the sea. Because the control of the unspolling mooring line was regained, this incident can only be considered a temporary mooring system failure situation. The crew managed to regain the control of the situation with the use of safety features installed on the system. [29]

4.2.5.3 *What to be learned from this incident*

This incident happened because of fatigue cracking that occurred during 9 years of service. This is close to half of the standardized intended lifetime of a mooring line, however fatigue is also one of the major weaknesses of metal, refer section 3.3. When it comes to fatigue design, one can never be to certain about how much it will actually handle as it is mostly probability based. With an unfavorable grain structure or cavity inside the metal, the capacity can be greatly reduced and one can never be completely certain about this structure when creating metals. It's reasonable to believe that this was just an unlucky event, as the failure happened 671m away from the rig, which is not an extensive stress zone of the line unless something out of the ordinary circumstances occurred (VIV, interaction from external forces etc.). Further on, this case shows how properly functioning mitigating measures should work in comparison to the previous incident (Ocean Vanguard −2004). Although some chain was unspooled/payed out, the breaking system properly functioned and was thus able to stop the chain from being completely lost to the sea and thus prevented a permanent mooring system failure from occurring. This shows how important it is to have these features properly functioning at all time. The negative part from a risk reducing perspective in this incident was that no alarms were observed from the monitoring system during the 40 minutes it took to discover the line failure. Had this happened, the crew could have been ready to initiate an emergency disconnection from the well much sooner than they did, and would then have prevented a disaster, if the breaking system had instead failed.

4.2.6 Borgeland Dolphin

Table 4-15: Data for Borgland Dolphin MODU mooring system failure at Tordis. [29]

Location of failure	*Norwegian Sea (NOR sector)*
Type of unit	*MODU*
Failure year	*2006*
Age of component	*NA*
Total number of mooring lines	*8*
Number of line failures	*1(+some unspooling)*

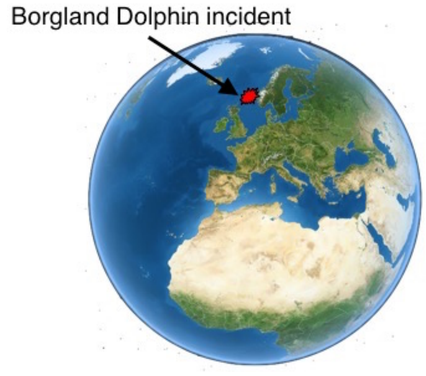

Figure 4-27: Globe showing where incident occurred. [22]

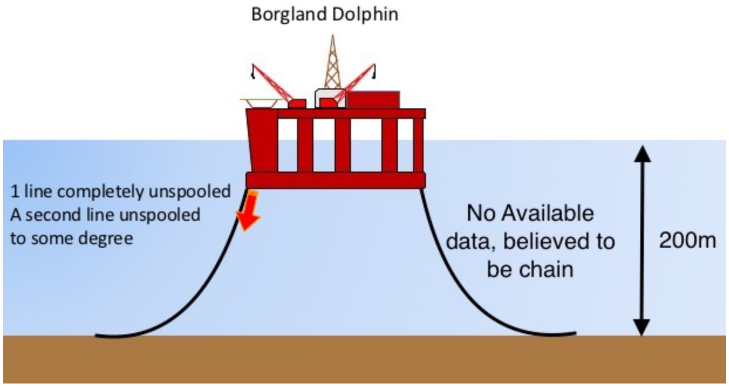

Figure 4-28: Illustration of system failure on Borgland Dolphin in the Norwegian sea at Tordis.

4.2.6.1 What happened?

This incident is as the previous one, in the gray area of being defined as a system failure. The incident happened during preparation procedures of the MODU for oncoming bad weather that had been alerted. As a precautionary measure, it was decided to tighten the mooring lines. This initiative was supposed to reduce the movement of the MODU during the harsh weather conditions. During this tightening procedure, one line had already been tightened and was about to be locked in place, as a loud boom sound was heard from another line. The line which had made the boom sound started to unspool/pay out, and the personnel on duty was unable to stop the unspooling/pay out of this line, and the line was lost to the sea. Immediately after this line had been lost, the line that was about to be locked in place beforehand also started to unspool/pay out. This second unspool/pay out however, was stopped by using the breaking mechanisms. This incident resulted in the MODU moving 12m away from the position above the well, and the BOP was disconnected as a response to this drifting, avoiding any disaster from occurring. [29]

4.2.6.2 Why did it happen?

There is little information about the cause behind the incident, other than that it was the winches which failed. As this happened during a tightening process, it is probable that some of the safety features were put on standby mode on the winch that was being used as not to interfere with winding process of the line tightening. The first winch failure, with the boom sound, however, is unclear. It happened during a tightening process of a line, which resulted in a load increase in the other lines as well, making the strain increase on other winches larger. The cause behind the initial unspooling might have been caused by improper configuration, breach of capacity, failing breaks etc.

4.2.6.3 What to be learned from this incident

This incident happened in the preparation phase of the oncoming weather that was alerted. This shows that incidents will not necessarily only happen during bad weather, but might also occur in what can be seen as a relatively calm sea state. This incident occurred with waves hitting only 4 meters [29] which is comparatively low compared to storm situations. Looking at the event, it is likely that the tightening of one line also increased loading in another line, which caused it to unspool/pay out. *Was proper live tension monitoring used during the tightening process to give alarm of excessive strains and thus a possibility of aborting any further tightening?* This is one of the unanswered questions regarding this incident.

4.2.7 COSL Pioneer

Table 4-16: Data for Borgland Dolphin MODU mooring system failure at Oseberg. [29] [20]

Location of failure	*North Sea (NOR sector)*
Type of unit	*MODU*
Failure year	*2012*
Age of component	*NA*
Total number of mooring lines	*8*
Number of line failures	*2(+2 unspooling's)*

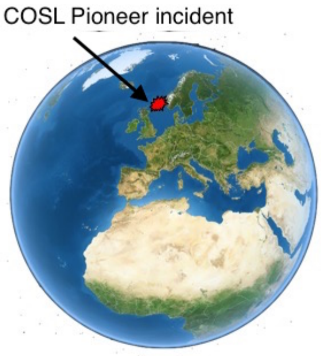

Figure 4-29: Globe illustrating where incident occurred. [22]

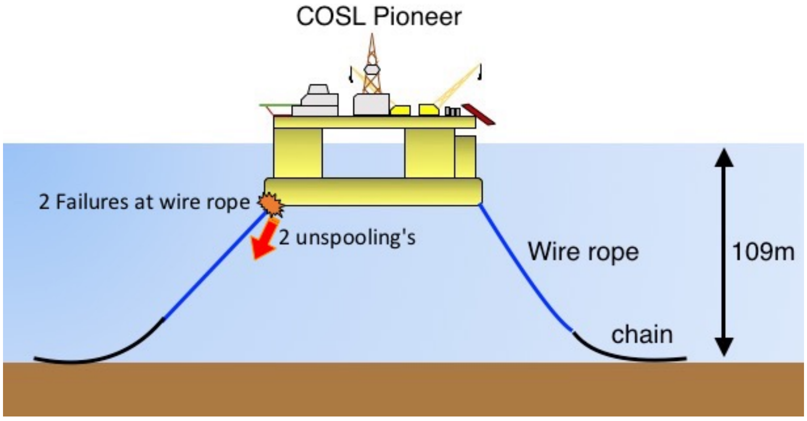

Figure 4-30:Illustration of system failure on COSL Pioneer in the North sea at Oseberg.

4.2.7.1 What happened?

This incident occurred during a storm, where the wind speed was at 100km/h (28m/s), and the significant wave height between 8 and 10m. The first thing that happened was that a line unspooled/payed out. This line was picked up again and re-installed by a AHV. However, after just 90 minutes of service after being reinstalled, it unspooled/payed out a second time. After the second unspooling/pay out of the line, another mooring line failed close to the fairlead. The mooring line which had unspooled twice by now, had been picked up yet again. Only an hour after the first line had failed, so did this “problematic” mooring line, however not by unspooling/pay out. This time it failed by breaking close to the fairlead like the other mooring line that failed. When these incidents occurred, the riser with the LMRP (Lower Marine Riser Package) had already been disconnected. It was done as it was originally planned to wait for the weather to calm down before reconnecting to the well and reinstating the drilling operation. [29] [20]

4.2.7.2 Why did it happen?

The failures themselves are believed to have happened due to overloading. Although the lines failed, the wire rope themselves aren’t the real cause behind the failures, even though it did occur below the assumed designed capacity. It is reasonable to accept this failure below the capacity because of the additional stress caused by the fairlead. What can be considered as one of the main reasons this incident occurred, is the Active Thruster Assistance (ATA) system. This system did not function optimally, along with a too high pre-tensioning of the mooring lines beforehand. These factors, in addition to a slow drift that was larger than expected, resulted in load conditions that was close to the capacity of the mooring lines themselves. The capacity of the wire rope inside the fairlead had been set, in cooperation with DNV, at 0,875 of the bending strength. This number was only meant as a temporary number until further data was acquired, as it was set with large uncertainties due to the insecurities caused by the added fairlead stresses. These factor lead to the lines failing at a load lower than the assumed Minimum Break Load (MBL). [29] [20]

4.2.7.3 What to be learned from this incident

One thing that's understandable, is that the fairlead complicates the work of setting a capacity of the line going in the fairlead. This incident proves that the capacity that is to be set for the mooring line inside the fairlead has to be very conservative. In this case a factor of 0,875 of the original bending strength turned out to be insufficient. Further on, when using ATA systems, they have to fine-tune the system to work at optimal conditions at all time. If they don't, they can go from being of great assistance, to be the cause behind a devastating incident. This incident shows that with the ATA system not working under optimal conditions, the stresses on the mooring lines become quite large, and in this case so large that failures occurred. In addition, as stated in the report by Arne Kvitrud [20], one must consider to allow more movement of the vessel (as long as the riser etc. are disconnected from the well), so that a lower pre-tension can be used on the lines for incoming bad weather. Had this been done, the ATA system might not have caused the failures as the mooring lines had been a bit slacker with lower initial stress. These slacker lines would give the ATA system a larger working space to do corrective actions.

4.3 Incidents Affecting the Mooring Integrity Without Causing a System Failure

There are many incidents which are closely related to the mooring systems that haven't affected the operability of the system at a complete level. Although these incidents may not be as critical as the previously discussed cases, some of them are still dangerous cases where the consequences could have been much worse than they were. These events aren't easy to get information about, as they happen frequently, and is often handled internally in the company without any information releases unless reporting to governmental organs are mandatory and publicized through this organ. Due to this fact, this section has been limited to events on the NCS like the previous section. Operators which operates in this sea are required to be reported to the Petroleum Safety Authority (often referred to as PTIL) which is more open to public information. Discussing each individual incident thoroughly is out of the questing as there are a total of 94 cases that can to some degree be connected to the mooring systems, and this is only on the NCS. Instead, the cases will be categorized and discussed in groups where they have common ground with each other. All of these incidents are gathered from the internal document sent from PTIL(PSA), [29] *DFU8 1990–2015 Forankringshendelser* written and provided by Arne Kvitrud, and discussed based on the information listed in this document.

The categories that has been decided to be used to divide the incidents are the following:

- Anchor handling incidents; where the anchors/mooring lines are being used by a third party, or used as a means for repositioning the rig.
- Line Failure; where there is a failure on the mooring line itself.
    - Shackle failure: as a subsection to line failure, where the failure is in a shackle joint either used as a repair for previous failure or as a connector between two segments.
    - Fiber rope failures: also a subsection for line failures, as these incidents often have a completely different cause than wire or chain failures
- Incidents where the winch, fairlead or other onboard equipment is the main cause for the incident.

- Incidents that happens during testing or maintenance.
- "Wrongly pushed button" incidents; where there have been pushed a button by accident, causing for instance; an Unspooling/pay out incident.
- Loss of Anchor incidents; where the anchor has been lost.

Some of the incidents may be categorized under multiple of the categories, but what was judged as the "essence" of the incident was a deciding factor in these cases. With this sorting, the following diagram was achieved from the 94 cases mentioned above.

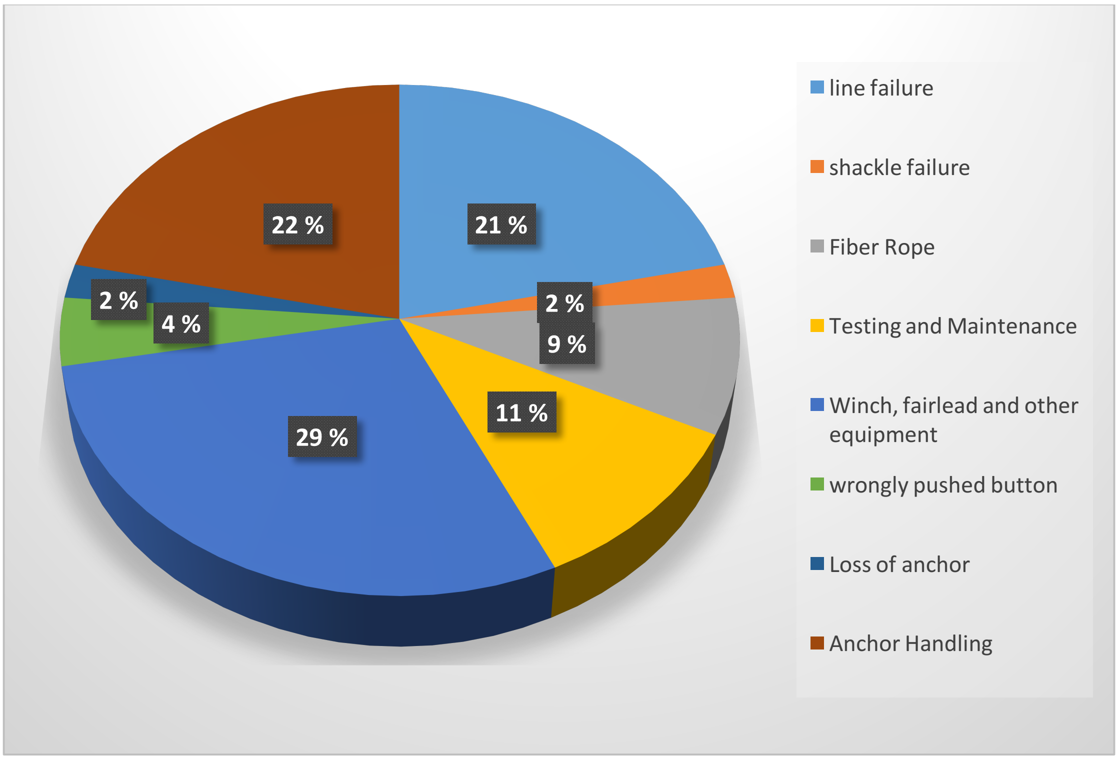

Figure 4-31: Pie-chart showing percentages of types of "minor" incidents on NCS since year 2000.

4.3.1 Wrongly Pushed Button

The events involved in this section are some of the more "funny" stories, however they are quite serious events. Two incidents in this section involved doing work on something completely different than the mooring system itself. One of them involved repair-work on a wind shield wiper. The electrician performing the repair work accidentally dropped the wiper engine on the emergency/quick release button of a mooring line. Pushing this button caused the line to unspool/pay out a total of 80m before he was able to initiate the brakes and restore the system back to normal. The other case involved the installation of a printer, where a close to equal event occurred. The person doing the installation accidentally bumped into a keyboard which dropped onto the emergency release button. In this event unfortunately, the accident went on undiscovered, and ended up with the entire mooring line going out to in the ocean.

Other cases in this section involves the operating of the winch, where the operator mistakenly activates incorrect functions. One event happened during switching of a section on a mooring line. To be able to perform this operation, it was required to cut a wire section. By mistake, the operator of the control panel activated the wire cutter on the wrong mooring line. This resulted in about 20% of the wrong wire line being cut, instead of the one that was supposed to be cut. Another event was an operator who was supposed to be pushing the clutch in a relocation operation, but instead of pressing the clutch, he activated the emergency release function. Around 30m of the line was unspooled/payed out to the sea before it was able to be stopped and restored to normal again.

These events are clear examples of human mistakes, and they are hard to avoid. To some degree, even harder than land based operations. The work hours are longer and more exhausting while offshore, making mistakes more likely close to the end of a shift. Even though the causes are human mistakes, the events mentioned here are serious to such a degree that they should have been designed to not have been possible to mistakenly happen. A redesign of the control panel(s) should be evaluated. As a suggestion, make the emergency release button in to a rotating switch or similar (marked with a distinguishable color and tag to not mistakenly activate it). This way, dropped objects won't cause an impact that can unintendedly activate the function. The Same action should be considered when it comes to the wire cutter function, where it could be placed at separate locations for each line etc. These functions have critical impacts on the integrity of the mooring line, and avoiding mistakenly activations reduces the risk overall on the rig to some degree.

4.3.2 Loss of Anchor

Losing an anchor isn't a frequent occurrence, at least not on the NCS. However, if it happens, it does possess a certain threat to the subsea structures down on the seabed. An anchor usually weighs between 10 and 20 tons, and with this freely and uncontrolledly falling on a subsea field could end up in a disaster. There are many exposed structures on the seabed, and an anchor impact has a potential for breaking and damaging these structures.

The two incidents found in the complete list of documented incidents in the NCS [29], are not closely related. One of the incidents occurred while the vessel was operating on DP. During the finishing stages of this operation, a chain link at around 3m above the anchor, which was located close to the fairlead failed. This failure indicates either excessive stresses in the fairlead or worn out chain links, where the second point is the most likely, as it wasn't operating with mooring lines at the time. This incident might have been avoided if a thorough inspection had been done on at least the chain parts going from the winch and down to the anchor. Luckily the anchor hit the ground 40m away from the well location on the seabed, and didn't cause any damage.

The other incident is one that is much harder to handle. The anchor in this case was torn from the mooring line just above the socket due to what can be assumed to be internal wear on the wire. This is something that can be hard to discover by simple inspection, as everything may seem ok from the outside, while the core on the inside might be worn down by corrosion. In these cases, only NDT methods are applicable (ultrasound, x-ray etc.), which can be very time consuming and costly. A suggestion could be to frequently do readjustments on the wire rope that's in contact with the anchor. The reason behind this suggestion is because of the twisting of wire rope the anchor causes while being dropped or raised. The spinning anchor may cause the threads in the wire rope section, in close approximation of the anchor, to unwind (refer bird caging in section 3). This would thus give free pass for water to enter into the wire core, and cause corrosion.

4.3.3 Testing and Maintenance

A large portion of the failures in this category occurs after the anchors and mooring lines have been set and installed, and a tension test is being done to check that it is capable to withstand the necessary forces. Although a mooring failure may be a costly affair, but if it does happen, it is quite fortunate if it does occur during this testing phase. The reason for this is simply related to the risks involved. In this phase, no operations should have started on subsea equipment, meaning no possibility of breaking risers etc. However, it may lead to an extension of the required days for offshore work, as the integrity of the mooring system is greatly reduced. If a line failure does happen during this phase, the mooring system on the rig must be reevaluated to check if it is still able to handle the expected loadings in the oncoming predicted weather. It may be necessary to instate some precautionary measures like a reduced flow in risers if it is deemed able to continue service. If the fault is in the winch's breaking system, it gives the opportunity to sufficiently fix and recalibrate them before critical operation phases start. Unspooling/pay out events are then less likely to occur in the near future.

When maintenance is in question, the events are usually connected to maintenance work on the winch system, which for various reasons leads to unspooling/pay out events. These events can to a certain degree be dangerous to the personnel doing the maintenance. If he or she is in a close proximity of the winch when the incident occurs, a fatal accident is possible. As a suggestion for these kinds of events, a secondary, non-permanent breaking/locking system could be installed to help out while maintenance is being performed.

4.3.4 Winch, Fairlead and Other Surface Equipment

Figure 4-32: Picture of a mooring winch. [33]

A large portion of the 94 incidents falls within this category, as it is a fairly wide and open category. A majority of these incidents are related to the winching system. The winching system can be fragile to some degree as it is designed with moveable parts. In accordance to these large loads on movable parts, it should be ascertained to be at close to perfect conditions at all times, or else a failure of a component is a likely occurrence. If a winch failure happens, it can often be considered as just as serious as losing a mooring line. With this kind of failure, unspooling/pay out is a possible event, or a wrongly tensioned mooring line which makes the line ineffective. A lot of the events connected with the winching system within this category, comes from a wrongly calibrated band breaking system on the winch. This results in insufficient resistance against the loads caused by the environment on the rig. As is known from basic physics, once something loses its grip, the friction factor is greatly reduced making it harder to regain the grip. This event will thus likely end up completely unspooling the mooring line and losing it to the sea, as the causing factor is the breaks themselves. Therefore, it's important to include opinions of the creators of the winching system in the calibration work, as they are the ones with the most knowledge about the equipment. However, they aren't necessarily always correct, and therefore a cooperation between experienced operators and the creators should be done to optimize the equipment's "abilities".

Other components on the winch that has seen a few incidents are winch shafts and couplings. On a few occasions shafts in the winch has broken or started to crack, causing the winch to be inoperable until repair-work has been done. On other occasions, couplings have caused problems, like gear couplings jumping out of position or clutch couplings not connecting properly, making the winch unable to get into for instance 1st gear. Some of these events are of course more severe than others, but all of them inhibit the system from functioning optimally, thus affecting the integrity of the complete system to a certain degree. Completely avoiding problems like these aren't easy. Many of the parts are moveable mechanisms, and dynamically loaded parts often experience an increased wear effect in comparison to stand-still loaded parts. A more conservative design is a possibility, however the cost increases proportionally as both material needed increases, as well as necessary spacing for the system, which is of a limiting factor on offshore structures. In addition, the equipment becomes heavier and more demanding to operate.

Fairleads are also represented in this category (mooring line failure caused by added fairlead stresses are not included in this section). The problem that involves the fairlead often have the same cause, although it's not always a serious matter at the time of the discovery. The implied problem are the bolt fastenings on the fairlead. They may loosen up over time, and some are even lost to the ocean. On the MODU Transocean Leader, the bolts had loosened up to such a degree that the fairlead wheel was standing at a bent position. In this situation, the drilling operation was stopped and well disconnected so that the bolt could be jacked up into right position again and fastened without any further concerns of harming subsea equipment or losing integrity of a mooring line. Incidents like these shows the importance and possible benefits of a cheap and simple inspection. Without the inspection, this incident could have turned out to a more disastrous event. With the rapid development of drones and similar equipment, this kind of inspection can become very simple. There are even drones that are being developed for both flying and submerging into water (see [34]). This creates an opportunity for further simplifying the work of doing inspections on mooring lines and other equipment that's hard to approach.

In addition to the stated causes above, there are as well some other components in this category that has caused an impact on the integrity of the system. To list a few; control panel losing electrical power, DC motors shutting down/breaking, hydraulic leakages and so on. Most of these problems are caused by failing components that are "smaller" and more standardized. These failures also resulted in events that have been or could have been devastating to the mooring system integrity. As previously mentioned, a system is only as strong as its weakest link, and for these “cheap” parts, it can be considered quite unnecessary for them turning in to the weakest link. A well evaluated and engineered change/maintenance program is a possible option to improve in this area. This could be done on hydraulic hoses/tubes (or other minor parts) connected to the hydraulic system, electrical components connected to engines/control panels and so on. Doing this will reduce the probability of leakages from the hydraulic system, or electrical components losing power/ malfunctioning. Changing or maintaining DC engines, if these are used, on a planned basis might also save a huge sum of money in a long term basis. Doing emergency replacements/repairs may be very costly and long-term procedures, with maybe even a stop in production/operation. Having it on an engineered and planned schedule with the part always at hand is a great saving and risk reducing program. Then it can be planned to be done while a production/operation stop is already planned, like in transition between fields.

4.3.5 Anchor Handling

This category is a little side step of incidents directly connected to the mooring system. However, it is the cause of many incidents of lines breaking or being lost to sea. In some occasions it reduces the availability of a mooring line for the rig, due to it being broken/lost with no spares available. If this happens, the integrity of the mooring system is reduced. Within this category are also the cases with the worst outcome, the events where the consequence was loss of human lives. This risk is easily displayed in a short video posted on the Norwegian news page VG.no (see [35]), where a chain breaks during anchor handling on the AHV Skandi Vega. As can be seen in this video, a crew member is barely able to get into safety zone before the snapback of the the chain hits with a massive force at the rear end of the deck, where he stood just seconds before. The reason this event happened was because a twist had occurred in the chain, which the crew needed to fix. Once a clear signal was given for continuation of the operation, the winch was wrongly adjusted for reinitiating the winching procedure again. This wrongly adjustment resulted in a pull force of 460 tons, which overloaded the capacity of the chain. In other incidents, the crew wasn’t as lucky as the one in this event. In 2001, on the AHV Viking queen, an anchor didn't have sufficient holding capacity in the seabed soil during a winching procedure, and a shackle came from behind a crewmember and hit the person in the head. This unfortunately resulted in a fatal accident.

Some of the incidents in this category involves mooring lines failing. The causes are rarely explained, but the most likely reason is the rough handling the mooring lines experience during anchor handling procedures, compared to the normal operation conditions. Because of this rough handling, it is more likely that links that has experienced excessive wear or have production faults, will fail. These failures aren't as positive as the ones during testing procedures, because of the risks to the personnel are often larger on an AHV, or it inhibits movement of the rig to safety zones. Not much can be done about this however, as one can never be completely sure about the conditions that the mooring lines are in when initiating the procedures, and when it comes to handling older chains, failure becomes even more likely. For instance, this kind of failure happened on Transocean Winner in 2009. The chains that were 18 years old and closing in on the mark of exceeding their designed life time. An inspection can be done on the mooring lines beforehand, but as explained on multiple occasions in this thesis, it can't uncover all possible faults. In accordance to this problem, the crew must be precautious and strictly follow safety procedures when handling mooring lines. This is especially essential for old mooring lines because of the mentioned wear. New mooring lines are also a greater risk, because of the statistics showing that an excessive amount of lines fail during the first 5 years in service due to faulty production, design etc.

Some of the incidents with losing the lines to the ocean and lines failing, can be traced back to not having sufficient procedures or them not being strictly followed. Not being precautious when performing the anchor handling by sufficiently and safely locking line/anchors that is onboard the vessel may end up in disasters. Although, some of the incidents can to some degree be traced back to malfunctioning equipment, most of them could have been avoided. With more thought on assuring the lockage of the lines onboard the vessel and having other safety measures to assure equipment won't be lost to the sea many of these incidents wouldn't have been a problem even with malfunctioning equipment.

4.3.6 Line failures

In this category, there could be several subcategories, however summarizing all of them would require in depth study of every single event as they all have, to some distinction, varying faults. If this type of work is of interest, a suggested reading would be the report "Floating Production Systems: JIP FPS Mooring Integrity" distributed by HSE (UK) [5]. Instead, the most common or the essential initiation of the failure causes will be handled in this section.

4.3.6.1 Fiber rope failures

When it comes to fiber rope, there are very few cases where the rope themselves are overloaded, at least as can be seen on the NCS. This can be concluded to be because the design and usage of fiber rope is very strict. The capacity of the fiber rope is very conservative and the placement and handling of the rope segments are mostly ruled by standards. As stated in DNVGL–OS–E303 [36]:

> "*4.3.2 Mooring lines should in general not be in contact with the seabed during installation or handling. Provided the protection against soil ingress has been duly qualified, lines may be placed on the sea bed as part of the installation and handling procedure, pending retrieval and final hook up."*

> "*4.3.3 The load-bearing parts of the line shall be adequately protected from marine growth. Hard marine growth shall not occur on load-bearing yarns."*

These regulations are clearly stated to avoid the possibility of anything causing any harm to the rope, as this would greatly affect the overall capacity. This leads to the fiber rope segments usually being placed in the middle section of the line, where the strains are at their lowest, and few possible external wear possibilities exists. The only thing one must be aware of while using fiber rope is that it can be very elastic, and over time require more frequent readjustments than mooring lines only consisting of only steel segments.

Even though it is strictly regulated in use, failures do occur. Some of them are caused by wrongly calculated distances, leading to the rope touching the seabed. If in contact with the seabed they will get cut or worn down by sharp edges at the seafloor. Other incidents are caused by what's often assumed to be improper handling during anchor handling operations. Fiber ropes requires very gentle and close to perfect handling during installation to not lose any capacity, and this is hard to achieve. Therefore, QA/QC during both production and installation is very essential for fiber rope segments, and this measure should be greatly invested in, if fiber ropes are to be used in the mooring system.

Even though the problems discussed above is of huge importance, there's another one that is far more devastating, when it comes to using fiber ropes. The problem is fishing trawlers or similar ships with their dragging wirelines. When they cross a fiber rope mooring line segment, they have steel wires tearing with large forces on the fiber rope. Fiber ropes are weak to this type of external forces; they are usually cut or greatly damaged because of it. This has happened on many occasions: Transocean Winner (2008), Bideford Dolphin (2006), Bideford Dolphin again (2003, but uncertain if it was actually a trawler), Safe Scandinavia (2003, also uncertain if trawler, but most likely), and these are only the NCS incidents. With the dangers connected to offshore oil production, this possibility could, by governmental regulations, be completely eliminated. Either by increasing the safety zones for rigs where fiber is in use, or by distributing highly detailed maps where these types of lines are located and vessels are not allowed to cross these marked areas with submerged wires. This may seem strict, but the risk reduction can be considered a great improvement if placed in a risk matrix (see chapter 5). With the Norwegian coastal area being as large as it is, it is only a very small area that becomes "forbidden" and unavailable to other interests, like fishing vessels, when compared to the overall available area for the fishing industry.

4.3.6.2 Shackle Failures

Shackle failures can be considered to be a rare event, with very few incidents in recent history, with the most recent in 2011. There are many types of shackles (D-shackles, kentar-links etc.), but in general they work as connection points between two sections, and thus requires a locking mechanism which again requires loose parts/sections. These movable parts enforce the design to be very robust and wear resistant, as this joining point often have more possible failure mechanisms. Designing a few shackles to be more robust won't have an excessive effect on the overall weight, or cost for that sake, of the mooring line, and therefore barely affecting the design parameters for the whole floating structure. Since the shackles won't affect the design parameters of the rig to a large degree, they can be allowed a more conservative design with minor drawbacks. Still, failures do occur on some occasions. The mentioned failure in 2011 happened due to corrosion inside the shackle fitting point, which induced larger stress concentrations. These increased stress concentrations in a cyclic loading environment, resulted in a fatigue failure. This is one of the complicated problems with shackles, just the same as with the wire ropes internal core, they have areas that can't be inspected from the outside. This obstacle makes it hard to uncover excessive corrosion, as it may occur "out of view". The shackle joint that failed in the mentioned event had design parameters less than the requirements, which signifies that either QA/QC did not function properly, or that the link was wrongly designed and specified to the producer. It is also a suspicion that it functioned as a sacrificial anode leading to the excessive corrosion.

4.3.6.3 Chain and Wire Rope Failures

Common failure causes for this category have been mentioned many times previously in this thesis. Because of this, this section can be seen upon as a summarization of the most common causes of failures that have been reported in the NCS.

The most occurring failure cause is not surprisingly; fatigue failure. This is one of the most difficult and problematic challenges when it comes to designing and constructing a long lasting mooring line. The metal can be designed to withstand massive forces, but with sufficient cyclic loadings, it can fail at loads greatly below its resistance capacity. Only a slight impurity can have a great impact on the fatigue capacity of a wire strand or chain link (or Shackles). This also implies that the reason behind the fatigue failure can be many; impurity from the construction, dents from installation operations, crevices or pits from corrosion etc. Adding all these possible causes together, will lead to the requirement of improvements within multiple divisions to "fix" the issue. In the end, no matter how much is spent, nothing will ever be totally perfect, so a certain risk must, in the end, be accepted. The ALARP aspect is important in handling this issue (see chapter

5). Even though it can’t become perfect, the trend in recent mooring line failures indicate a need for improvement of the fatigue resistance.

One of the causes for the reduced fatigue life is corrosion. This problem is often handled by designing for corrosion. What this means, is that the links/wire ropes are designed with extra material that can be corroded and lost without the link or wire rope going below its required capacity, see figure 10-2 in appendix, or DNV standard [37]. However, studies have shown that at certain locations, the corrosion process may be above the estimated values (even above the criterias required on NCS which are larger than the rest of the world). When this rapid corrosion happens, the extra material becomes insufficient over time, and stress concentrations above the designed capacity will occur a lot quicker. This can to some degree be handled by coatings and/or using stainless steel. However, no steel will ever be completely corrosion free, and some corrosion will occur in stainless steel as well (hence the less part in the name). Coatings on the other hand, are worn away over time by the friction forces, and becomes close to useless. As a response to this corrosion problem, the chain link must be ascertained to have good and clean welds, without contaminations, or studs of same material as the link, to avoid parts acting as a sacrificial anode. This will, to some degree, ascertain that the corrosion will not be even faster than the “regular” rate. The mooring line itself must be evaluated as a whole, not in segments, to ascertain that there are no “conflicting” (large electrochemical potential) materials. This avoid one of them ending up acting as a sacrificial anode, same as with the welds and studs in a single chain link. If this is a possible problem, additional equipment/material should be put in place to act as the sacrificial anode instead of the parts that is of importance.

Storage is also an important aspect. If the chain or wire is stored in unfavorable conditions while not in use, they may experience increased corrosion rates. This reduces the service life to some degree, and if pitting or crevices occurs due to the corrosion, the fatigue life may be greatly reduced, and of course, the danger of overload increases. To avoid this problem as much as possible, the environmental conditions in the storage must be so that minimal corrosion can occur before installation. This is important especially for spare parts, as they may be stored for an extensive period of time. If the integrity of the parts is lost to corrosive effects during this period, they become pretty much useless and just a waste cost.

Production flaws are the cause of many failed mooring lines, hence the large failure rate during early service life (see chapter 5). In production, material flaws are impossible to avoid completely. During production internal cracks and cavities will always form to some degree, or grain formations could form that are unsuited for this type of use. Localized stress concentrations could occur around these material flaws, and unwanted grain formations could have inadequate fatigue resistance. These faults then lead to a reduced fatigue life. Even though it's impossible to completely avoid these flaws, they can be managed to some degree and kept to a minimum. This can be done by having strict routines and procedures in construction, with high focus on QA/QC. The quality can be assured by random destructive testing and NDT to ascertain material properties. (see OTC report 24181 [38] for a suggestion of tests that could be done.) In addition, lowering the acceptance criteria in NDT will also help, but the cost of this is large, as more links or wire strands becomes unusable. However, by implementing these measures, the risk of bad quality is greatly reduced. QA/QC is the essential aspect for the chain and wire rope having the necessary material properties when coming out of fabrication.

Installation of mooring lines requires what can be considered rough handling of the mooring line. If this isn't done properly according to procedure and with the use of improper functioning equipment, the mooring line may be afflicted with significant dents, which in turn gives an area with increased localized stress. Stationing inspectors to ascertain that the work is correctly performed, is a possible measure that will help as there won't be an option to "cheat" with the procedures. This is a simple and fairly cheap measure and it can at least maintain the risks of accidents to a minimum as correctly performed procedures will be a close to guaranteed result.

5. Risk

Offshore structures can have a major impact on the local environment, company financials, and people's well-being if a disaster should occur. With this in consideration, there are some major concerns connected with offshore operations, and these concerns needs to be handled in a scientific and logical way. By establishing risk reducing measures may the concerns and dangers connected to the offshore industry be lessened. With mooring lines in mind, the risks connected to failure are multiple, and many of them have devastating outcomes. Accordingly, the mooring lines are, as previously stated, rated high on the list of the most critical components of the structure.

5.1 Statistics

Over the years, many authorities (and at least one JIP) have been gathering information about failures connected to mooring lines. From the numbers published from the UK sector by HSE (Healt and Safety Executive), the expected line failure varies between different structures. They report that a FPSO will have a line failure every seven (7) operating year, while a FSO on the other hand only has an expected line failure for every seventeen (17) operating years. For drilling ships, more frequent failures can be expected, as it was calculated to be one around every one and a half (1,5) operating year. This number is slightly improved for drilling semi-subs, with an expected failure around every four (4) operating year. [20] The differences between the permanent established floating platforms (FPSO and FSO) and MODU's, may be caused by the rougher handling of the mooring lines, as they are more frequently placed and recovered again on MODU's when switching between fields. The difference between the MODUs themselves (ship vs. semi-subs) can be caused by many different factors. For instance; different motion characteristics or different connection point designs like a turret compared to spread mooring around the semi-sub. To establish an exact cause of the varying expected lifetime is hard. Not a single unit has the exact same layout as another unit. However, what is clearly shown, is that they all have expected failure below what one should expect and want, except the FSO lines, which has a very high expected service time. When it comes to mooring lines, it is in most cases usual to design the lines to last up to 20 years or more, which means that most of the expected lifetimes are between a forth and up to around a half of this. The reasons for this are mostly because of impurities in production, faulty design or damage to the line during installation operations. This is indicated by the early failure compared to the designed lifetime. With this knowledge, it is expected from an outsider's point of view that proper risk reducing measures are established in every unit. The reality, however, is actually quite different from this common assumption. Data originating from year 2006 from the North Sea shows that on FPSOs stationed there, 50% have no real time tension monitoring, 50% are unable to adjust the line lengths, 67% have no spare lines in case of failure, and 78% don't have any alarms to indicate a line failure [5]. Even though these numbers are to some degree old, they can still be considered fairly reasonable today, due to the cost and the technical difficulty installing the necessary equipment subsequent to the building process of the offshore structure, and the time span an offshore vessel is in service.

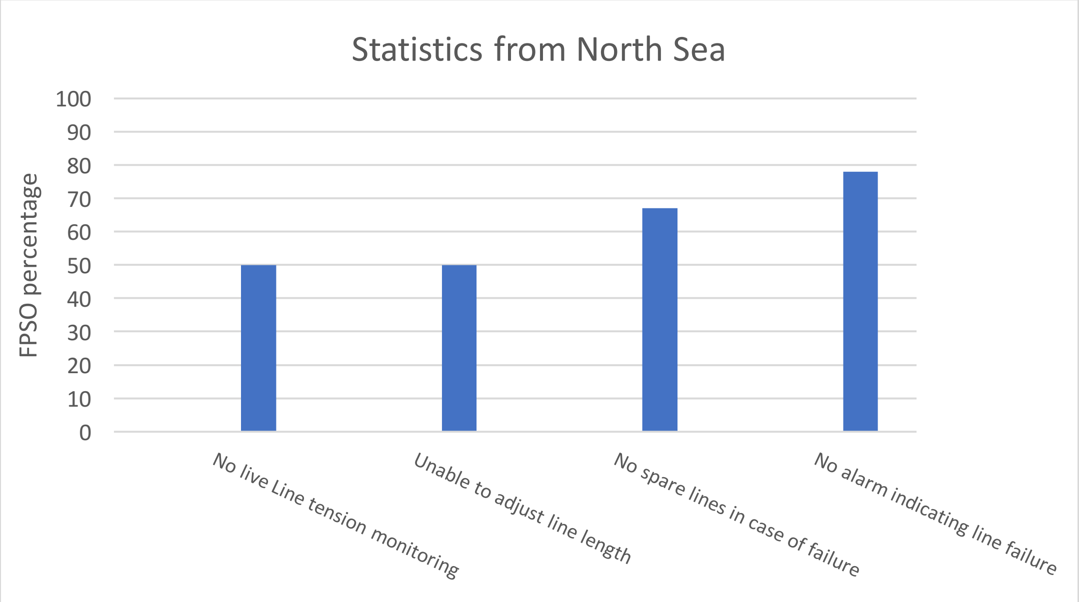

Figure 5-1: Figure showing data from 2006, indicating the percentage of FPSO missing essential equipment for maintaining safe operation when mooring lines are used.

5.2 Possible Consequences Connected to Mooring Failure

Mooring lines are as previously stated ranked as one of the most critical sections of a floating unit that is supposed to be stationed above a certain location, for an extended amount of time. This statement is based on the necessity of a permanent uptime of the mooring system. A failure of one or more mooring lines have many possible outcomes should it occur, and these failures have all aspects connected to it when considering risk; People's well-being and maybe even life, environmental and/or equipment damage, financial losses and a blow to the reputation of the companies that are connected with the mooring failure. This is why risk management is a necessity when considering mooring lines. With knowledge about possible scenarios comes the opportunity to establish precautionary measures to lessen or maybe even avoid the assumed possible consequences.

5.2.1 Financial loss

The cost connected to a line failure can be hard to estimate. There are many reasons why this estimation is a challenge. For instance; the line requirements changes depending on where in the world it is supposed to be placed, making the material cost to vary between each installation. Different governmental requirements for precautionary measures for a further development, in case of a line failure, may also have an effect. When, in the lifetime of the unit, the mooring failure occurs, where the worst possible time would be at peak production, has an impact on the revenue of the field. In case it is a MODU, the losses are to some degree simpler to figure out, as they usually have a day rate, and every day that it isn't operating, this amount is lost. It is often required to reduce the production in the period that a mooring line is missing or ineffective, or a complete shutdown in the case of multiple line failure. This also leads to more excessive losses for large quantities producing units, compared to units that produce lesser quantities. Whatever the cost may be, it still leads to a reduced profit from the field. For this reason, some investments into mooring lines should be reasonable, to ascertain they last longer, and minimize downtime in case of a failure by having spare parts at hand.

If disaster strikes, and uncontrolled drifting causes severe damage to equipment in the ocean, the cost would increase even more. In worst case, hydrocarbon spills causes damage to the local environment probably resulting in large fines. Maybe even worse could happen, if the hydrocarbons ignite and causes an explosion on the platform, lives would be lost and expensive equipment would be ruined. This would add up to a huge cost from a mooring failure incident. If the unit drifts completely uncontrollably towards other units in close proximity, the financial losses have the potential to increase even further. Even if it doesn't hit other units. If it has a heading towards another unit at some point, an evacuation has to be instated on the other vessel, which costs most likely has to be covered by the operator of the drifting unit.

5.2.2 Damage to Environment and/or Equipment

There are many possible outcomes if multiple lines fail. They are depending on the mooring configuration, where the failures occur, the kind of vessel it occurs on etc. There are two severe incidents at least that could occur due to mooring system failure which are of major concern. The first one is a blowout due to damaged riser/subsea equipment like what almost happened in the Ocean Vanguard incident written about in section 4.2. The second possible severe outcome is an uncontrolled drifting platform. The first incident is, however, often dependent on the second happening to some degree.

The first mentioned incident can be caused by damage and rupture on one or more risers or even the wellheads themselves. This is equipment that is used to transport the hydrocarbons from the seabed to the unit, and a rupture would mean large spills into the ocean. Spills in these quantities can have a major impact on the local ocean environment. This kind of spill did happen on Petrojarl Banff because of riser rupture, as described in section 4.1 The damage or rupture of risers or wellheads can occur due to excessive movement of the platform, which would cause large bending and axial stresses. Another possibility for spills to happen because of mooring failures are if the failed mooring line causes an impact on subsea structur(es) and causes damage. If large quantities of hydrocarbons are gathered in close proximity of the platform due to spills (like a methane gas cloud), a single spark could cause an explosion. This would be a terrible incident, and most likely many lives would be lost.

The second incident with an uncontrolled drifting unit has the potential to cause large damage to other structures in close proximity, on either the surface or in the ocean as described above. If this drifting should occur, there are several possible outcomes. If the failed mooring lines failed, or remaining mooring lines fails in the trash zone, or anchors get dragged out of position, heavy chain, wire or anchor would be dragged along the seabed. This event has the potential to cause large damage to the infrastructure placed on the seabed due to possible impacts, and in worst case lead to large spills of hydrocarbons. Another problem with an uncontrolled drifting unit of thousands of tons, is the potential to cause large damage to other structures or vessels in proximity. If it crashes into a platform or ship, the following disaster would be tremendous. Explosions, hydrocarbon spill, considerable damage to both units, are just some of the possible outcomes. This was a possibility just recently in the North Sea, although not by an uncontrolled floating platform. It was motor- and captainless barge that went drifting uncontrolled. The incident occurred in rough weather on new year's eve 2015, where the Eide Barge 33 of approximately a hundred meters (300 ft) had dethatched itself from the tug Eide Wrestler and went uncontrollably adrift into the North Sea. [39] This lead to the evacuation of around 400 persons from two different oil-fields; Ekofisk (ConocoPhillips) and Valhall (BP). [40]

Figure 5-2: The uncontrolled barge Eide Barge 33 passing by the Valhall field. [41]

Because of this incident, the two oil-fields had to stop production and initiate emergency evacuation of non-essential personnel. These are costly procedures to initiate and the longer it last, the more revenue is lost. Because of this event, the company that is responsible for the incident may end up with a several million fine to be paid to the two operating companies (ConocoPhillips and BP) for their financial losses because of this incident. Looking at this incident, it is clear that the consequences to a freely drifting vessel can be quite large, even if it doesn't actually hit anything like in this event.

5.2.3 People's Well-being

It isn't only for station keeping that a mooring failure is a very risky event. While doing anchor handling on Anchor Handling Vessels (AHV), a mooring failure can quickly become a fatal accident. This is easy to understand by watching the video mentioned in section 4.3.5. This means that also the consequence of losing a human life is connected to the integrity of a mooring line. Insufficient strength in mooring lines, faulty winches and other possible aspects that could lead to a mooring failure must therefore be avoided. If a person is hit by a flying mooring line, he or she doesn't stand much of a chance of survival, as the forces in this chain or wire is very large, and not something the human body can handle. This risk can to some degree be reduced by the implementation of strict routines, safety areas, proven technology that can give load readings in the mooring line and regularly inspections and maintenance of the equipment that are essential for the procedures.

5.2.4 Loss of Reputation

Reputation loss usually isn't that much of a problem in connection to mooring lines unless a devastating incident should occur. However, if the mooring failure causes a devastating incident and the fault mainly lies in the hand of the operator, it could get a lot of media coverage, affecting the reputation. This loss of reputation would lead to fewer persons interested in working for the company as it for instance indicate lack of safety, and maybe even make it harder for them to be awarded with new fields in the future. MODU's have it a bit worse than permanent installation, as they are more dependent on their reputation to get new contracts and work orders. A mooring incident that can directly be blamed on lacking effort by the MODU's personnel could cause a great blow to the reputation. As the failure of the mooring line/system might affect the operators schedule, increased cost and maybe even affect their reputation as well, if the incident is really severe (refering to Deepwater horizon incident, where the contractor Transocean was the responsible as the owner of the MODU, but BP was accountable as it was the operator). If this kind of incident happens, it would make it harder to get renewals on existing contracts and get new work orders.

5.3 **Risk Assessment — Foreseeing the Unexpected**

When conducting a risk study, an important aspect is to be able to predict possible future problems that might occur and evaluate if the risks are acceptable. This should be done so that precautionary measures against the possible problems can be established. Should the predicted problem occur, a guideline on how to act in response to this problem could be developed, in order to lower the consequence. The probability in combination with the possible consequences must then be evaluated too see if the design of a structure, operation, routines etc. are acceptable. Although a simple job in description, but a hard and mentally exhausting work to perform. The personnel handling risks are loaded with the heavy burden of often evaluating if safety levels are sufficient on costly equipment/systems or in dangerous operations. These evaluations often come with pressure from leaders and other stakeholders with personal interests. The stakeholders with financial interests want the evaluation to approve of the safety at lowest possible cost, while on the other hand human lives may be depending on a thorough and well done evaluation and righteous judgment.

When considering mooring lines, the task on foreseeing the possible problems which may inhibit it from performing as intended, demands a wide knowledge into many different areas; chemistry, mechanics, biology(marine growth, SRB) etc. The most common failure causes were mentioned in section *3.3 Common Failure Mechanisms* and these can each be handled in different ways. The more problematic part of a risk study when considering mooring lines, is the necessity to foresee the more unexpected events that might occur, and establish procedures against them. These events may involve external interaction on one or more mooring lines, electrical power black outs, hydraulic leakages etc. To make a complete risk assessment of the mooring system, a team consisting of persons with varying backgrounds is a necessity to foresee and handle as many possibilities as possible. They should also evaluate the criticality of these possible problems and suggest possible mitigating measures. These mitigating measures should also be evaluated, and stated by how much it will reduce the risk level. This evaluation can be presented in a risk matrix (see section 5.3.1). By doing this properly, the risk connected with mooring failures can be kept to a minimum without too high costs.

The possible failures that are more obvious can however be managed to some degree to avoid problems from occurring completely or at least minimizing the consequences. For instance, an offshore installation has a safety zone of 500m radius (at least in NCS), where no unauthorized traffic is allowed to trespass. This is a good and well established risk reducing measure which reduces possibilities of collisions with the installation by other vessels.

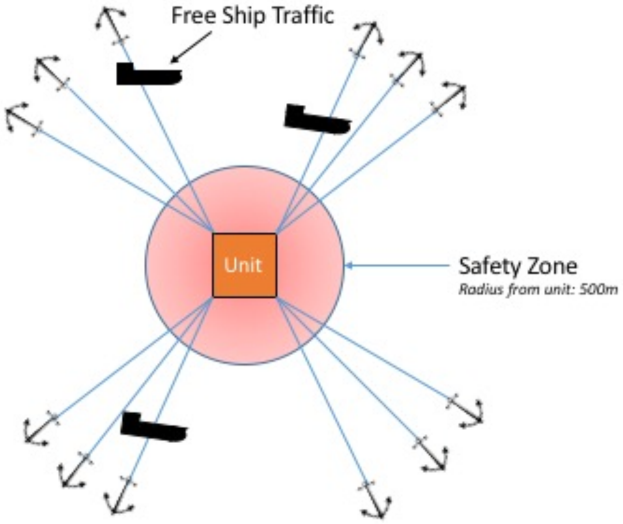

Figure 5-3: illustration of regulation against ship traffic within the safety zone. Notice that the mooring lines stretches outside of this zone.

When it comes to mooring lines though, the safety zone area often isn't sufficient to cover the whole area where the mooring lines are stretched. A mooring line may stretch several hundreds of meters if it is of a catenary design. With this catenary design, this safety zone isn't even nearly sufficient to cover this. This leads to the possibility of having ship trafficking above the mooring lines. If one of the ships, traveling above the mooring lines, drags something like an anchor or other equipment on the seabed, it's a possibility that it can hook onto one or more lines. If a heavy equipment like an anchor is dragged along the seabed, it has the potential to cause a severe blow to the integrity of the mooring line(s). Some of the possible outcomes are that the mooring line or lines get dragged out of place, damaged or even a completely torn of chain link or a cut wire or other possibilities that will compromise the lifetime of one or more of the lines. The risk assessment must strive to foresee all the possible consequences of an event like this, and elaborate on mitigating measures. By foreseeing an event and and preparing against it, will make the event, to the lowest possible degree, inhibit the operation or production that is being done if it should occur.

As a side note, the mentioned safety zone should be greatly considered to be increased, at least for operating MODU's (and installations using fiber rope segments in their mooring lines). The MODU's are only temporary stationed at an area, and they are often performing more complex and dangerous operations inside the wells compared to regular production. An uncontrolled drifting may cause large environmental damage as stated in the previous section. This safety zone increase would then be a great measure for reducing risks connected to drilling new wells and doing workovers on existing wells.

Doing risk assessments on the mooring design layouts are another challenge. There are many different potential threats to varying designs and getting a clear view of all of them is important in order to choose the design with the lowest probability of failure without too large costs. For instance, a danger with mooring lines is that they are often dug to some extent down into the seabed in the trash zone area. This can be a problem over time, as there can be large rocks that the chain or wire will grind on, causing a slowly propagating wear on a fairly concentrated area of the line. To avoid this problem, a massive research and clearing process would have to be done of the soil at the bottom. This can be a huge cost, and if the unit is only stationed temporarily, a simple inspection of the top layer of the seabed and a clearing of this area is what is often done. This problem has to be thoroughly assessed, as this is a deciding factor between choosing wire rope or chain in this trash zone. For the units meant to be permanently stationed, a more thorough research and clearing will likely be done. For the MODUS however, this is still a problem, and has an impact on the expected lifetime of the mooring lines, as can be seen in the statistics.

5.3.1 Risk Evaluation

In a risk study, it's not only important to discover all possible problems, they also need to be evaluated to establish the criticality of the possible problems. This can be understood from the definition of risk, that is defined as Risk = Uncertainty x Consequences [42]. This means that although the consequences can be huge, the chance of it occurring can be so low, that it can to some degree be excluded. Should the predicted consequences be considered too high however, some measures should be done to lower the risk, so that it is contained within a predefined acceptance limit. For a good and clear presentation of risks connected to an event, the evaluated results should be displayed in a risk matrix. The matrix should illustrate where the acceptance limit is, define where tje ALARP (As Low as Reasonable Possible) region is and set a limit to where the risks are too high to be acceptable. If an event is judged to be within the ALARP region, risk reducing measures, that are within reasonable cost parameters, should be instated. Issues that are judged to be outside of both the acceptable and ALARP region are considered non-acceptable and risk reducing measures no matter the cost must be instated to get it at least within the ALARP region. If it is not possible to get it within at least ALARP region, a redesign or even complete cancellation must be decided on.

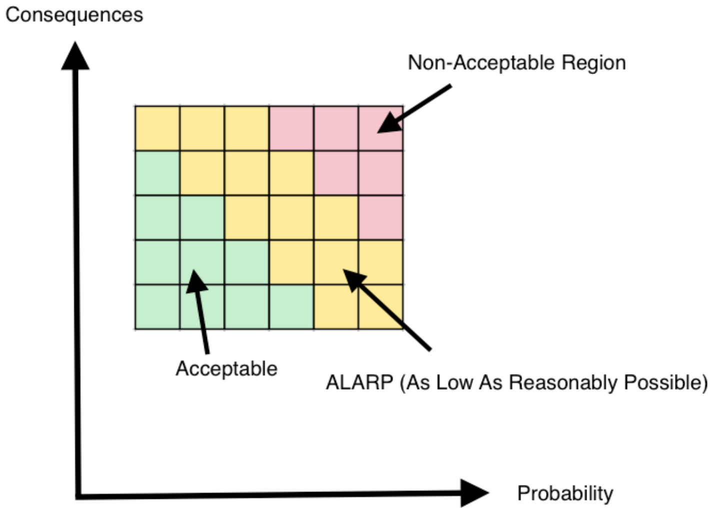

Figure 5-4: Illustration of a risk matrix, where the colors show the predefined acceptable region, an ALARP region and a non-acceptable region.

When doing this type of evaluation for mooring lines, all the possible problems that can inhibit one or more of the mooring lines from operating, must be evaluated. Each possible event can be evaluated in at least 4 different categories; Human risk, environmental risk, financial risk and reputational risk. This evaluation will be what is called a subjective based risk evaluation. The decision of placement in the matrix is based upon the background knowledge of the person doing the evaluation, and its relevance must thus be considered in perspective to his/her/their background(s). If this assessment is properly carried out, it will give a good indication about the risks connected to a design or a project. If it is used correctly, the safety levels will greatly increase while still having the costs within acceptable limits (refer ALARP). If it is considered too risky, it will give a clear indication about this.

When considering mooring lines, this risk evaluation is important to do for every type of vessel and projects that are going to use mooring lines. Even though the design may be of a similar type to another vessel or project, the possible risks connected to it may be different. For instance, the layout of the mooring system may be close to equal between two vessels operating at a field, however, one of them may be, for instance, a flotel, while the other may be a MODU. These two vessels have completely different tasks, which in turn leads to different risk aspects connected to failures. Eg. If a flotel drifts some distance off of location, its isn't really a huge deal as long as it is able to regain control before a collision is a possibility. However, if a MODU experience the same problem, the aspect is completely different, as it has a riser connected to a well, and leakages or blowouts are a possibility if a drifting out of location occurs. In addition, it may cause damage to subsea equipment, like bending the wellhead etc., making the well inoperable and thus a huge financial loss. The same principle, with varying risk, goes for using semi-subs compared to using FPSO, and all other combinations. Therefore, a thorough job is necessary for each case, to be both aware of the risks and to be able to establish necessary precautionary measures.

Adding all the possible risk aspects together, should in turn give an impact on how much should be invested in the mooring system, assuming it is a vessel that uses mooring lines. The greater the risk, the larger the investment. With sufficient investments, the risks connected to the system should be at a minimum, and disasters should in theory rarely occur. The risk assessments might be a factor that isn't considered and depended on to the degree it should be for the mooring system, as the failures are as frequent as they are.

5.4 **Risk Reducing Measures**

When it comes to mooring systems, risk reducing measures are often very simple to suggest, but many are hard and/or costly to implement. Something as simple as having a routine inspection, which is often considered as the simplest and cheapest possible measure when it comes to risk reduction, is a challenge to perform. One of the reasons for this is marine growth close to surface covers the mooring lines, making it close to impossible to study the condition of the material. The sinking of chain/wire into the soil at the seabed is another problem, unless it's a taut mooring system. With a dug down mooring line, the inspection becomes difficult to perform. So how can an inspection be done, on something that can't even be seen? This requires additional, extensive, measures to be performed in order to just get a clear view of the mooring line itself. If it is an anchor which is dragged with the chain/wire far down into the seabed, it becomes close to impossible to inspect the dug down mooring lines. Although it is an extensive operation for something as simple as just getting a clear view, it is a measure that should be invested in for the areas that can be inspected. Although not all parts can be investigated, but doing a thorough investigation on the most stressed section close to the fairlead on a regular basis, will have a great, positive, effect. The inspection is also important for the top segments, as they are often more exposed to corrosion effects due to the excessive amount of oxygen available. Just a “simple” inspection, with a clear image, gives a good indication if some sort of wear effect out of the ordinary is occurring, and just being able to discover this is a major risk reduction.

As stated in section 3.4, a single line failure usually isn’t considered a critical event, but only as a component failure. However, with the unknown condition of the remaining mooring lines, could make it a mooring system failure, as they might be worn to such extent that they aren’t sufficient to withstand the force increase. For this reason, cautionary measures should be executed to lessen the consequences, in case the failure should propagate and affect several lines, when a single line failure has occurred and been detected. These measures may to some degree vary in severeness. If integrity of a single line is reduced/gone and operation shall still continue, reducing production to lessen possible spoiling quantities in case of drifting is a possible measure. If Drifting occurs during drilling operations, an emergency disconnect from the well is a great measure. Evacuation of non-essential crew to lessen number of people that will be involved, is another measure that should be considered should a disaster occur. Station tugs in a close proximity to help out with the station keeping to lessen the forces on the mooring lines is a third measure to be considered. Basically all possible measures that can reduce the risks needs to be considered. If the failure occurs in a chain segment, a temporary fix is a possibility, where, for instance, a kenter link can act as a temporary replacement for the failed link. An alert message to other vessels in close proximity should also be issued, as it will make them aware of the possibility of an uncontrolled drifting platform. A colission is a highly unlikely event, as the rig has a safety zone of 500m (at least on the NCS) and drifting outside of this zone seldom occurs, but it is a measure that makes other vessels close by aware of the danger.

Figure 5-5: Picture showing a kenter-type joining link. [43]

As guided by all kinds of engineering standards, safety factors are added when considering the loads that the components must be able to withstand. This is of course a large risk reducing factor, but as it is a universal measure for risk reduction in all kinds of engineered structures, a thorough discussion about this measure will not be done in this thesis. However, as insinuated in previous sections, just increasing the mooring lines aren't a good way to invest. Increased effort in QA/QC, creating spare parts, having proper storage for these spare parts etc. is an equally important and maybe even better investment. With proper investments, there aren't necessarily much larger costs, than today that's required, but smarter investing.

The largest risk reducing factor that has been become a standard feature for mooring systems, is the redundancy of at least one possible line failure without causing a complete system failure. The earliest floating semi-subs only used two mooring lines for each corner. This practice lead to a high risk with only a single line failure, and most often a complete shutdown of operation if it should occur. With three or more mooring lines at each corner, the redundancy becomes far more excessive, although with the downside of a significant cost increase for construction of the system. With more mooring lines, comes an increased weight, and this requires larger columns for more buoyancy. But with the increased column, comes yet more added weight which may lead to the necessity of a larger chain for more restoring force if a catenary layout is used. This is the evil spiral as previously mentioned in section 3.3, that can be quite troublesome to manage. However, with the added redundancy, the risks connected to a single mooring failure is greatly reduced, making it worth the expenditure. Although the single failure isn't a critical failure with this redundancy, it is still a serious matter, and precautionary measures should be put into effect. These precautionary measures may involve, as previously mentioned, a reduction of production, disconnecting MODUs from the well or production facilities from risers, evacuating non-essential personnel and so on.

There are also many other efforts that can be done to reduce the risks when position keeping is concerned. A good and functioning sensor system on mooring lines to ascertain the existing tension within the lines, and in case of failure, the loss of tension. It is also a great help when doing a relocation of the vessel, as it can warn about increasing stresses. These systems have become better and more precise within recent time, and is worth the investment to be able to have a well-controlled mooring system. Another measure is adding sacrificial anodes on metallic segments to avoid excessive corrosion. This is important on steel line segments that's too far away from the floating unit to get an effect from the installed anodes on that structure. However, keeping control of these anodes again, is a challenge because of the earlier mentioned problems in doing inspections, and changing them is a hassle to do as well. Previous events, as stated in section 4 in this thesis, also gave an indication that a redesign of the mooring control panels might be necessary. The moored vessels are equipped with emergency release on the mooring lines, which is a good thing to have if excessive drifting does occur. This function makes it possible to reduce consequences in these events by avoiding having mooring segments or even anchors dragging along the seabed and causing damage to subsea templates or pipelines/umbilicals. However, with this function being activated by a button, it becomes a larger risk for an accidental activation. A suggestion would be to make it into a turning switch, preventing falling objects to accidentally release the mooring line(s).

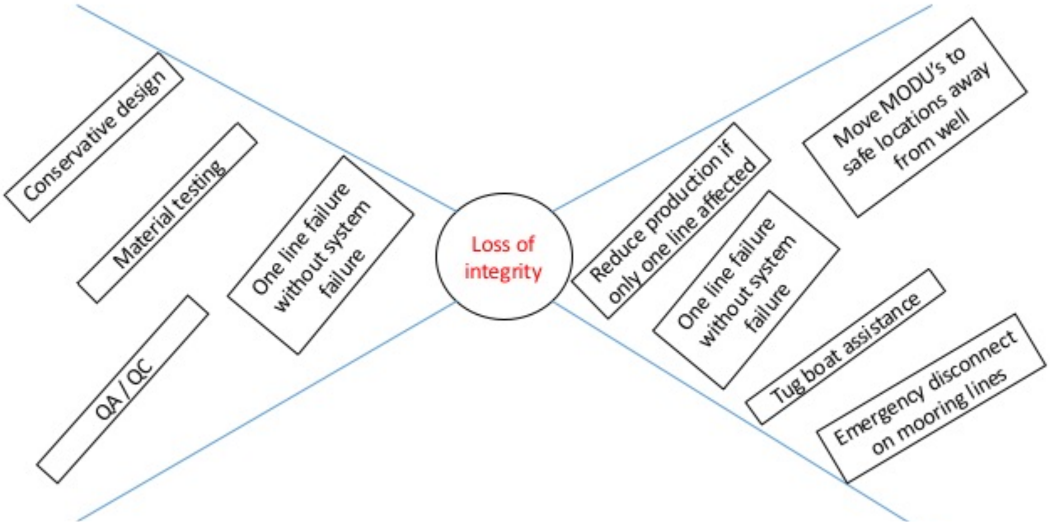

Figure 5-6: A bow-tie diagram for loss of integrity on mooring system, where some probability reducing measures are on the left side, and some consequence reducing measures on the right side.

6. Discussion

Looking back at all the incidents described in this thesis, it’s clear that mooring accidents happens more frequently than what’s desired. A majority of the accidents were only from the Norwegian Continental Shelf, known for its focus on safety on both structures and for the personnel. Only considering that “small” section of the world, there have been several accidents over the years. With this taken into consideration, it can be imagined what the actual numbers would be if everything was publicly announced and reported all over the world.

There have been several attempts to improve the structural integrity of the mooring system, it results in gradual improvement. Some of them are still ongoing projects, like the JIP which findings etc. has been sited frequently in this thesis. The problem with the findings and resulted suggestions by these kinds of projects, is that they are often ignored to a large degree. In addition, there is rarely a compulsory force to instate the suggested improvements. The rules to be implemented are solely decided by the local governments, therefore, the safety measurements connected with the offshore industry are highly dependent on the mindset of these governing organs and their interests.

A falling oil price is a danger that is claimed to result in an increasing downfall in the safety for the offshore oil industry at least, but many third party companies, which is also connected to the offshore industry, are also likely to be affected. This is due to the fact that companies cut down the costs to an absolute minimum to “survive”, resulting in many workers getting fired, early pensioned, redundancy packages and so on, and also a reduction in production costs. This often comes at the cost of safety, due to the personnel doing the cuts often lack the necessary insight and knowledge in the areas where they are cutting costs. This tends to result in unforeseen losses. There might thus be losses of essential knowledge within the company, reduced quality in design and other factors that may have severe influence on future projects, like reduced procedures in critical safety routines. In Norway, some signs are already showing this trend, and have been getting media coverage during the recent weeks due to a helicopter accident. After this accident had occurred it was uncovered a contract was being negotiated to reduce the downtime between landing and takeoff on the rigs, which reduce the time available for safety routines [44]. Norway has for a long time been considered one of the safest nations when it comes to offshore industry, but in recent time there has been a trend for a downfall, and there is a worry that it has been developed an increased acceptance for a safety level equal to the British sector [45]. Considering all the mooring incidents that's been listed in this report from just the last 15 years on the NCS, this will be a dangerous way trend when mooring systems are in question.

Taking this in consideration when looking into the mooring system, it is unlikely that there will be much of an improvement in the coming years, as few companies are interested in new investments. However, it is important that the companies connected to the mooring system tries, as much as possible, to maintain the gathered knowledge and experience of mooring systems within the company, even through these hard times. Further increase of mooring failures may turn into an expensive affair for both creators and operators. The manufacturer loses reputation with an increased failure rate and with it, customers as well. The operators will get more frequent downtimes on production/drilling operations and therefor a loss of revenue. To be able to at least maintain todays level, the authoritive figures in the companies should be briefed about the importance of the mooring system and its challenges. Doing this will make them aware of the problems connected to all phases of the mooring systems, and its importance for operations to be successful and profitable. That way, the budget reductions are less likely to affect the most important divisions and personnel, when it comes to the mooring system.

Fatigue has been an issue that's been mentioned and discussed many times in this thesis, and it is a trending failure cause. It is easy to understand that this is an issue of great importance for the engineers when doing design tasks, instructing installation operations and for general operation of the mooring system. As insinuated previously in the thesis, fatigue life is easily affected. Because fatigue is depending on many different factors, it is easily affected, and only one factor being below par is enough to reduce the expected lifetime. It will affect other aspects as well, like total capacity, but the fatigue life is the aspects that is the one that is most affected by it. Lack in procedures in one or several different divisions involved in the construction or handling of a mooring line (designers, producers, installers etc.) results in a reduced fatigue life compared to its planned and designed value. With this knowledge, it is understandable that QA/QC becomes and important aspect to maintain the fatigue value close to its designed parameter.

Corrosion is a problem that is either the sole reason or a “helping hand” behind many of the failures in the mooring system. The corrosion problem can be caused by many different factors. One possibility is that a chain or wire rope section become a sacrificial anode due to electrochemical potential between elements. SRB (Sulphate Reducing Bacteria) is a possibility in some areas of the world, that could increase the corrosion rate. The normal process with water and oxygen reacting with the metal is unsurprisingly also a common issue, where environmental conditions has a major impact on the rate it occurs. Avoiding all the causes for corrosion on a mooring line is close to impossible as long as the line contains a metal segments and not made entirely of fiber rope. What at least should be done are surface corrosion tests in the area the facility is to be installed, with the same metal composite that is to be used. This is especially important when a permanent installation is the considered structure. The reason this should be done is to evaluate the quickness of the corrosion process in the area. As mentioned, it varies to some degree all over the ocean due to different environmental conditions, and knowing the rate helps the engineers to know their minimum design parameters. Just blindly following the standards may end up as a great mistake. Some tested places have proved to be at more than twice the rate of what is the minimum required rate to design for [5].

In addition, the designers must be careful and aware of the materials they choose to use in the system, to avoid electrochemical reactions between different segments. If the potential between the materials are too large, one of the parts becomes a sacrificial anode for the other part.

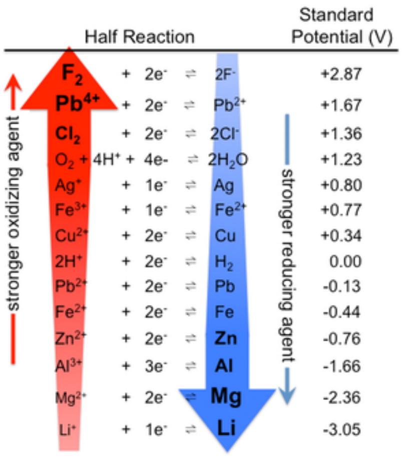

Figure 6-1: List showing electrochemical potential for different elements. [46]

Using anodes on the mooring line to act as sacrificial anodes should be considered if this type of corrosion is of concern. However, they need to be inspected and possibly replaced on a regular basis to ascertain its functionality. This inspection may become easier in the future as simpler AUV's / ROV's are being developed, like the recently demonstrated snake robot by Statoil, Kongsberg Maritime and Elume [47]. Hydrogen cracking might also be a problem caused by corrosion, although this hasn't been mentioned to a large degree in the studied reports, and thus no sections about it in this thesis. In addition, measures against this issue are mostly based on reducing corrosion.

Out of Plane Bending (OPB) is the cause of multiple failures. This is a problem with chain links when they are in proximity of the fairlead. The locking and bending of links close to the fairlead (refer section 3.3 and Girassol Buoy incident) results in a bending effect. This bending stress is added upon the already existing axial force, resulting in higher stresses on certain areas of the chain link. This stress increase may result in a reduced fatigue life, or overloading incidents at axial stresses lower than its designed capacity. The fairlead stress increase is a problem which is sort of a necessity for guiding the mooring line, and avoiding this problem is close to impossible. Conservative guidelines need to be instated regarding designing mooring segments going through the fairlead. In addition, frequent repositioning of the segments within the fairleads is a requirement, to avoid a single location getting all the additional wear. On COSL Pioneer, a correct procedure was attempted to handle the fairlead issue, where DNV was an external advisor(see section 4.2). However, the uncertainties with the stress increase made them underestimate the stress increase. This was a correct way of handling the issue, by bringing in third part experts, but it just goes to show how large the uncertainties are when mooring design are of concern.

With OPB in mind, it's frightening that many of the mooring systems aren't able to adjust the line length as mentioned in section 5.1. Without adjustable mooring lines, the increased load becomes constant on only a few chain links. This will greatly reduce the expected line failure time. In addition to fatigue failure, overloading is also most likely to occur in proximity of the fairlead, due to this increased load factor from a bending moment. Therefore, it is understandable why the links in segment in or close to the fairlead needs to be up to the expected standards at all time. Frequent inspections become important to ascertain that they are close to perfect. In installations that's being planned, a mooring system with locked in place mooring lines should be avoided. Having an adjustable system may result in great improvement on the expected line failure time, and make it worth the investment.

The anchor handling vessels must be careful not to create twists in the line during the installation. This operation is a crucial factor for the mooring lines to be able to maintain the integrity over a long period of time. Twists in the line will create more complex loading situations in the line due to the torque it applies, and the same problem as with OPB can occur because of this on chain links. In the case it's on a wire rope, the twisting may force the outer wires to expand, and thus letting water penetrate into the core, causing undetectable internal corrosion. Therefore, the anchor handling vessels must have good QA/QC for performing the installations. Lacking routines during the installation operations may prove fatal, as this is where most of the lives are lost when it comes to mooring line failures. This is because this is the phase where direct human interaction with the lines are often necessary. Because of this interaction, humans are more exposed than when the lines are in what can be considered as a normal idle operating state where they are mostly handled by a separate control panel.

Fiber rope has very few documented failures, at least that's publicly available. This can be explained by the fact that fiber ropes are often designed very conservative compared to metal wires or chains. This is because there are more uncertainties connected with fiber rope strength, durability etc. In addition, they are not as frequently used as chain or wire rope. They are mostly chosen when in deeper water where catenary mooring design isn't an option, only a taut mooring system is possible. Looking at all the failures that's been available for study, most failures concerning fiber rope has been caused by an external interaction. This interaction can be from fishing trawlers or even the vessels doing the anchor handling. The interaction isn't limited to human caused interaction either, because in tropical and sub-tropical locations, it has been discovered that fish and sharks have been biting on fiber ropes. For protection against the problem with fish/shark interaction, special designed fiber ropes have shown good results [48]. The problem with fishing trawlers has been discussed to some degree previously, and is at least a major issue while in the Norwegian Continental Shelf, where the fishing industry is a major business. The fishing industry wants as few limitations as possible as to where they can put out their trawlers. The 500m radius safety zone while in proximity of a rig, that's been instated by governmental regulations, is not sufficient when in deeper waters. In these depths, the mooring lines will go outside the safety zone, even for taut lines, and are therefore freely exposed to the ships trafficking above. As previously stated, this safety zone should be evaluated to extend over a larger area than what is done today, at least for deep waters above 600m. This suggestion is important for MODU's, doing drilling operations, with their blow out potential. This measure would greatly reduce the risk of trawlers or other vessels impairing one or more mooring lines, which again reduce the risk for spills caused by uncontrolled movement of the rigs, or leading to damage to subsea equipment.

Although some failure causes aren't necessarily trending failures, two of them should be discussed due to their significance. The two incidents are the ones in the Chinese Sea, described in section 4.1.2 and 4.1.3. In the Nan Hai Fa Xian incident, the turret wouldn't release. This indicates lack of maintenance and insufficient testing. When a rig is designed to rely on avoiding bad weather by dropping the turret, the mooring lines usually will not be designed to handle extreme weather conditions either. If this crucial design point isn't functioning, the safety feature ends up wrecking the robustness of the system, and become its weakest point instead. If the turret feature had been properly maintained and been ascertained to function, this would have been a system with very few incidents. Excessive wear and overloading would be avoided as bad weather could easily be avoided if deemed necessary. This incident is a good example to show the importance ascertaining the function of critical equipment, at all time, by the use of maintenance and testing procedure. The other incident with Nan Hai Shengli, is the one where an ROV inspection had discovered excessive damage on wire strands, with multiple strands being inoperable. From this discovery to the planned change of the damaged segments was approximately a full year. With so much damage on several mooring lines, expecting it to be able to withstand an additional year might be too optimistic. In this time, where it is likely for a storm to occur and even the regular monsoon, an incident, like the one that did in fact occur, is very probable. The importance of spare parts, and proper storing to maintain these parts, are shown to a great extent in this case. Had a complete set of spare parts been available, then it would have been a “quick” fix. With the fix, the risk for mooring system failure would have been greatly reduced. The issues in these two cases apply for all possible components connected with the mooring system, like the winch systems, fairlead etc. With the many cases of implications on the winch system causing pay outs, proper maintenance with correctly calibration is necessary. The availability for spare parts would also be a huge benefit, with reduced downtimes if parts are discovered to be faulty, like a shaft.

A slight trend was also shown in the winching system, where the breaks etc. weren’t being properly calibrated according to the producer’s recommendations. Not acting in compliance to the instructions set by the producer can be a dangerous affair. Doing it can result in faster wear effect on consumable parts, leading to failures before they expire their intended service life. Although a bit risky, this tuning might not always be a bad thing to do. In some cases, it might be necessary to fine tune/calibrate the system after gaining a long time of experience and increased knowledge about the limitations of the system. However, if this fine tuning/calibration should be done, it should be done in collaboration with the producers to avoid overloading the capabilities, or making it insufficient to withhold the applied forces. If done correctly, this fine tuning/calibration may result in a better performance of the winch system, and will thus slightly reduce the risks for loss of integrity on the mooring system.

Using computerized system are also a thing that should be considered carefully. With the procedures being done automatically, sometimes the results ends up in unwanted consequences. For instance, this was an issue on COSL Pioneer incident, where the ATA system wasn’t functioning optimally. This resulted in increased stress in mooring lines instead of reducing it. Other incidents have been counters which have miscalculated the length of mooring line, ending in pay-outs. If computerized systems are to be used, they should be updated/calibrated regularly to ascertain a proper functioning system, instead of a bug causing unspooling/pay out or in worst case mooring failure(s).

7. Conclusion

With the overview of all the incidents listed, studied and discussed in this thesis, there are clear signs that the mooring system are often insufficient for their required tasks. The reasons behind this insufficiency vary to some degree, but with the amount of failures connected with the mooring lines, a clear trend shows premature failures are a problem. A majority of these failures occurs during the first 5 service years. This is a frightening number, as the majority of the mooring lines are designed to have up to and even more than 20 years of service. This indicates a need for improvements. However, doing this is a very difficult task. Some of the challenges to complete this task is avoiding too large cost increase for possible solutions, and another one is gathering sufficient information in a business with scarce information sharing between companies to study what can be improved. There are some companies that have taken initiative to create a joint industry project (JIP) for improving this area, which have resulted in more openness for information and experience sharing.

The difficulty in improving the expected failure time for mooring lines lies mostly with the material uncertainties and chemical properties. As has been "revealed" and discussed at several points in this thesis, a major issue with mooring lines is the fact that it experiences cyclic loads on a regular basis. This cyclic loading leads to material fatigue wear, which again often results in premature failures. This trend is not that surprising, but it is still the largest issue when the mooring line itself is of concern. Handling the fatigue problem requires improvement in many different divisions. The fatigue resistance can only be designed according to statistics from several laboratory tests. These test often have what can be considered large variations between each test subject as the material will always have some impurities differing them from each other. Extensive effort in all divisions connected to design, production and installation is required to achieve an improvement. The suggested way to achieve this is through increased QA/QC in all connected phases.

Fiber rope, which is the alternative to using metal for the mooring lines, doesn't experience this fatigue trend. Its connected uncertainties and strict regulations, makes it designed in a very conservative fashion, resulting in fewer reported failures due to loadings. However, it is still not without any weaknesses. The incidents portrayed in this thesis showed that they are greatly affected by external interaction, and its integrity reduce significantly by unwanted dents and cuts. This means that shipping lanes above the mooring lines possess a major risk for loss of integrity. The ships passing may drag anchors by steel wire, or fishing vessels travel with trawlers out. The interaction between steel wire and fiber rope ends up badly for the fiber rope. Therefore, the usage of fiber rope must be carefully considered. When used, it should have no connection with the seabed to avoid any tearing effects from being dragged on sharp rocks, and ship traffic in a close proximity should be at a minimum to avoid damage from steel wires. In addition to being weak to interaction, it also has a tendency to stretch. This must be frequently handled, especially with a taut mooring configuration. If the lines become slack, they may end up experiencing impact loadings which can overload the capacity of the line. With the characteristics of the fiber rope, it is well suited for usage in deep waters.

Although not discussed to a large degree in this thesis, it should be mentioned that there were a few implications caused by digital equipment. A few of these were caused by a faulty chain counter, where the consequence was either failure or pay out. Active Thrust Assistance have also been the cause or a helping factor behind a few incidents. With a "buggy" software, it has the potential to result in the system doing the opposite of what it is intended for, causing larger loads on the mooring lines. Therefore, digital equipment must be carefully implemented, with frequent error checks and updates/fine tuning of the software. The checking of the system might help to avoid situations where it doesn't work as it is supposed to do in critical situations, like the one on COSL Pioneer event in 2012. It must be noted that a digital equipment can never be fully trusted and relied upon, and backup solutions should be available in case of a breakdown of the system.

Adding it all up, it can be concluded that there are many aspects connected to the mooring system that are to some degree lacking when compared to what is desired, leading to some trending failures. However, fixing them requires extensive work, good communication and cooperation between companies and what can be seen as the largest hindrance; financial investments. Improving problems like fatigue failures requires improvements in many different departments. This can to some degree be done by the suggested increase in QA/QC, but further improvement would most likely cause large cost increases for what can be seen as minor improvements. Other trends have a simpler solution in theory, like a regulation change for safety zones to avoid fiber ropes being cut or chain/wire rope damaged. In practice, however, it’s harder to implement, as there are conflicting interests between industries. It is important to have a good understanding of the risk assessment done for the mooring system solution that is of concern. Following suggestions from this assessment with smart investments may lead to safer constructions with fewer incidents, and greatly reduced consequences if a failure incident should occur. One important factor that should be improved, is the frequency inspections and maintenance procedures. They are often cheap and simple (to some extent) efforts that could lead to great improvements. In coming years, they might even become cheaper and even simpler to do, considering the new drone technology etc. that is being developed.

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8. Appendix

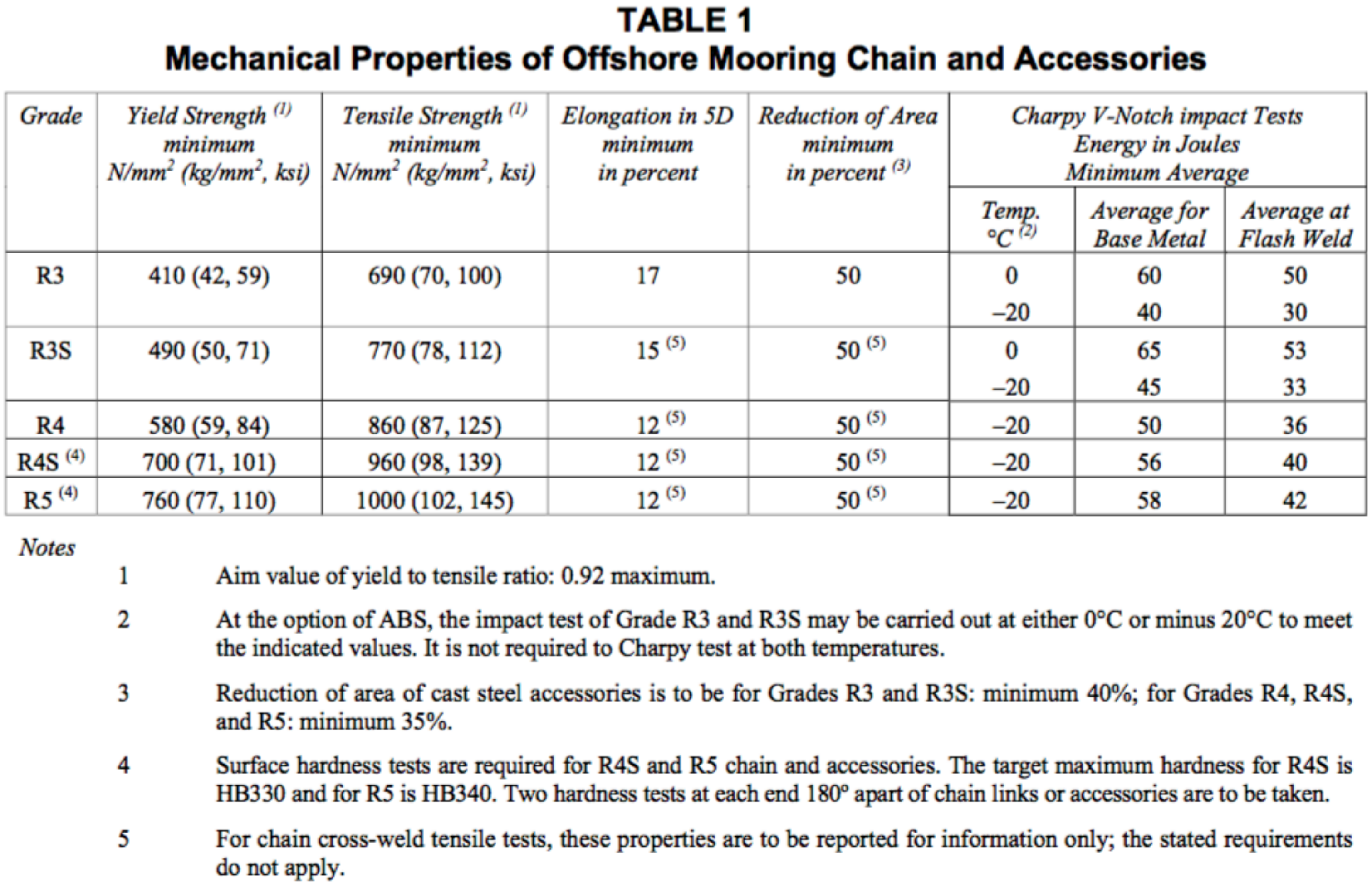


TABLE 1
Mechanical Properties of Offshore Mooring Chain and Accessories

Grade	Yield Strength (1) minimum N/mm^2 (kg/mm^2, ksi)	Tensile Strength (1) minimum N/mm^2 (kg/mm^2, ksi)	Elongation in 5D minimum in percent	Reduction of Area minimum in percent (3)	Charpy V-Notch impact Tests Energy in Joules Minimum Average		
					Temp. °C (2)	Average for Base Metal	Average at Flash Weld
R3	410 (42, 59)	690 (70, 100)	17	50	0 –20	60 40	50 30
R3S	490 (50, 71)	770 (78, 112)	15 (5)	50 (5)	0 –20	65 45	53 33
R4	580 (59, 84)	860 (87, 125)	12 (5)	50 (5)	–20	50	36
R4S (4)	700 (71, 101)	960 (98, 139)	12 (5)	50 (5)	–20	56	40
R5 (4)	760 (77, 110)	1000 (102, 145)	12 (5)	50 (5)	–20	58	42

Notes

1 Aim value of yield to tensile ratio: 0.92 maximum.

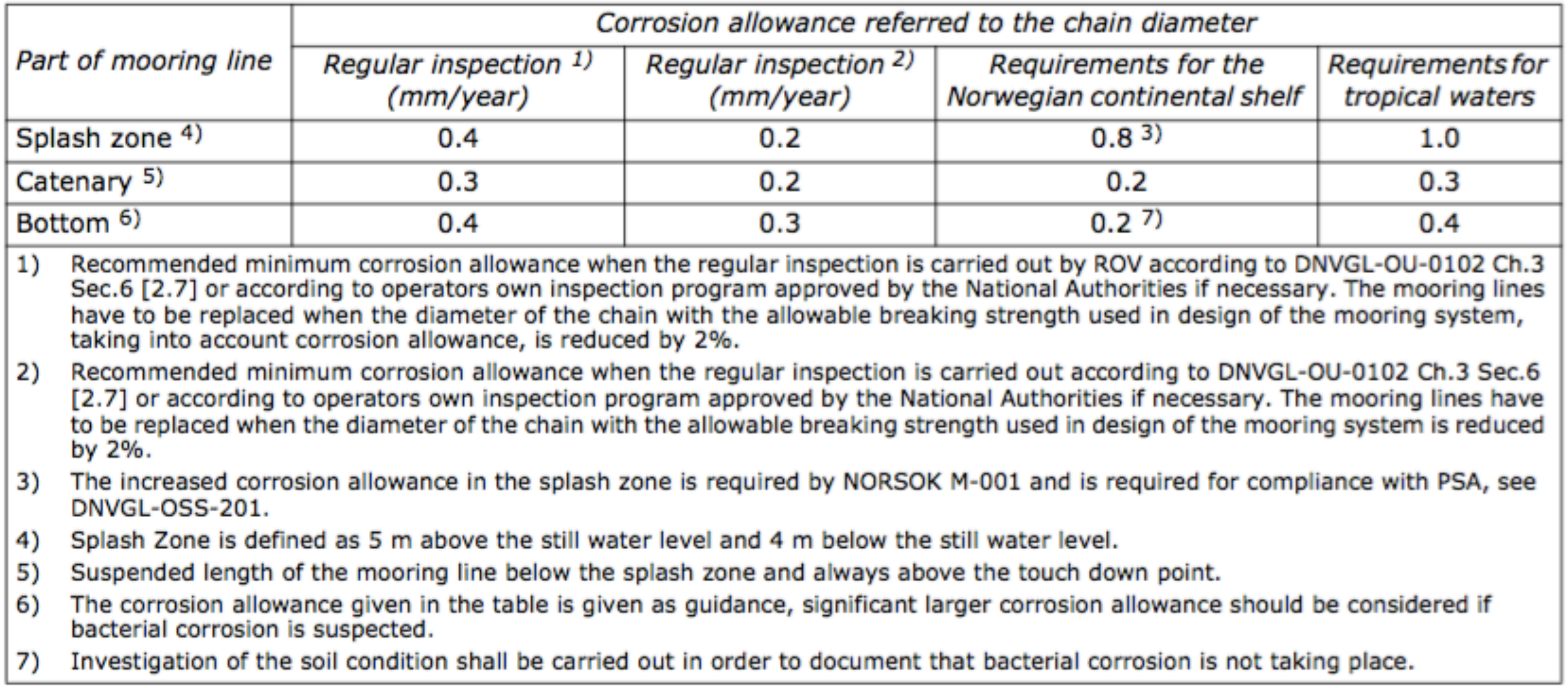
2 At the option of ABS, the impact test of Grade R3 and R3S may be carried out at either 0°C or minus 20°C to meet the indicated values. It is not required to Charpy test at both temperatures.

3 Reduction of area of cast steel accessories is to be for Grades R3 and R3S: minimum 40%; for Grades R4, R4S, and R5: minimum 35%.

4 Surface hardness tests are required for R4S and R5 chain and accessories. The target maximum hardness for R4S is HB330 and for R5 is HB340. Two hardness tests at each end 180° apart of chain links or accessories are to be taken.

5 For chain cross-weld tensile tests, these properties are to be reported for information only; the stated requirements do not apply.

Table 8-1: Steel grades used for mooring chains, taken from the ABS´s (American Bureau of Shipping) "Guide for the Certification of Offshore Mooring Chain"



Part of mooring line	Corrosion allowance referred to the chain diameter			
	Regular inspection 1) (mm/year)	Regular inspection 2) (mm/year)	Requirements for the Norwegian continental shelf	Requirements for tropical waters
Splash zone 4)	0.4	0.2	0.8 3)	1.0
Catenary 5)	0.3	0.2	0.2	0.3
Bottom 6)	0.4	0.3	0.2 7)	0.4

1) Recommended minimum corrosion allowance when the regular inspection is carried out by ROV according to DNVGL-OU-0102 Ch.3 Sec.6 [2.7] or according to operators own inspection program approved by the National Authorities if necessary. The mooring lines have to be replaced when the diameter of the chain with the allowable breaking strength used in design of the mooring system, taking into account corrosion allowance, is reduced by 2%.

2) Recommended minimum corrosion allowance when the regular inspection is carried out according to DNVGL-OU-0102 Ch.3 Sec.6 [2.7] or according to operators own inspection program approved by the National Authorities if necessary. The mooring lines have to be replaced when the diameter of the chain with the allowable breaking strength used in design of the mooring system is reduced by 2%.

3) The increased corrosion allowance in the splash zone is required by NORSOK M-001 and is required for compliance with PSA, see DNVGL-OSS-201.

4) Splash Zone is defined as 5 m above the still water level and 4 m below the still water level.

5) Suspended length of the mooring line below the splash zone and always above the touch down point.

6) The corrosion allowance given in the table is given as guidance, significant larger corrosion allowance should be considered if bacterial corrosion is suspected.

7) Investigation of the soil condition shall be carried out in order to document that bacterial corrosion is not taking place.

Table 8-2: Design criterias for designing agains corrosion taken from DNVGL–OS–E301: Position Mooring

List and sorting of incidents used in section 4.3

Shackle failure

1. 27.1.2000 West Venture
2. 14.3.2000 Bideford Dolphin

Anchor handling

3. 2.7.2000 Troll-C
4. 4.9.2000 West Vanguard
5. 25.2.2001 Deepsea Trym
6. 8.11.2002 West Vanguard
7. 22.1.2003 Transocean Searcher
8. 8.11.2003 Bideford Dolphin
9. 9.1.2005 Eirik Raude på Troll
10. 13.2.2005 Transocean Arctic
11. 29.7.2005 Transocean Searcher
12. 30.9.2006 Songa Dee
13. 16.6.2008 Transocean Winner
14. 2.12.2008 Transocean Arctic på Tyrihans
15. 3.12.2008 Transocean Arctic på Tyrihans
16. 26.4.2009 i forbindelse med Songa Trym på Troll
17. 28.4.2009 COSLRival
18. 27.11.2009 Transocean Winner for Marathon på South Kneler / Viper
19. 18. juli 2010 Transocean Winner for Lundin
20. 1. september 2011 Songa Deehttp://www.vgtv.no/#!/video/47827/her-ryker-den-flere-tonn-tunge-kjettingen
21. 4. mai 2012 Transocean Barents

Line Failure

22. 23.1.2001 Bideford Dolphin
23. 28.8.2004 Deepsea Trym på Ekofisk
24. 24.9.2004 Deepsea Trym på Ekofisk
25. 18.6.2005 Transocean Arctic på Norne
26. 10.11.2006 Transocean Winner på Albuskjell

27. 30.12.2006 Petrojarl Varg
28. 9.5.2007 Borgland Dolphin på Tordis
29. 3.6.2007 Scarabeo 5 på Kristin
30. 1.12.2007 Scarabeo 5 på Kristin
31. 18.12.2008 Scarabeo 5 på Alve Field
32. 27.12.2008 Transocean Winner
33. 9.3.2009 på Balder FPSO
34. 1. desember 2010 Transocean Winner
35. 26. oktober 2011 Transocean Leader
36. 26. januar 2012 på Deepsea Atlantic
37. 2. august 2012 Transocean Spitsbergen på Midgard
38. 6. november 2012 på Norne FPSO
39. 14.12.2012 Petrojarl Varg
40. 22.11.2013 ISLAND INNOVATOR
41. 6.3.2014 Deepsea Bergen for Statoil

Winch, fairlead and other equipment onboard related

42. 10.4.2002 Deepsea Trym – kontroll panel sviktet → bremser deaktivert
43. 18.12.2002 Borgland Dolphin – klokobling løsnet, for tregt bremsesystem →utrausing (2 hendelser på samme dag, andre pga slitte bremser)
44. 1.2.2004 Deepsea Bergen – ikke korrekt konfigurert bremser → utrausing
45. 30.9.2004 Transocean Arctic på Norne – ikke korrekt konfigurert bremser → utrausing
46. 11.12.2004 Stena Dee på Troll – mistet dyamisk bremser pga tannhjul mistet kontakt, ikke korrekt konfigurert band bremser → utrausing
47. 3.9.2005 Ocean Vanguard i Norskehavet – crack in shaft frame on the winch
48. 26.5.2006 Polar Pioneer på Snøhvitfeltet – breaks disconnected at start up of hydraulic pump → unspooling
49. 23.2.2007 Transocean Winner for Hydro – possible overload of capacity → unspooling
50. 25.2.2007 Transocean Winner for Hydro – inspection found ¾ bolts broken in connection to main shaft

51. 8.4.2007 Songa Dee for Hydro – hydraulic leakage resulted in ineffective breaks → unspooling
52. 9.4.2007 Songa Dee for Hydro – breaks on same winch did not work → another unspooling event
53. 4.10.2008 Deepsea Trym på Troll – uncontrolled deactivation of breaks
54. 14.11.2008 Bideford Dolphin på Fram – a connection point jumped out of its tracks → unspooling, stopped quickly by breaks
55. 15.12.2008 Transocean Winner – no clear reason found for unspooling, as inspection checked out everything about the winch being OK
56. 16.12.2008 Scarabeo 5 på Alve Field – no remaining chain in chain locker, weak end link broke →unspooling, caused by malfunctioning chain counter giving improper values.
57. 29.5.2009 Songa Delta på Grosbæk – breaks not properly working
58. 4.8.2009 Veslefrikk B – claw coupling not properly connected → unspooling
59. 14.8.2009 Polar Pioneer – faulty software in new control panel revealed to have resulted in damage on several winches.
60. 8.9.2009 Aker Barents på Geitfjellet – clutch coupling broken → adjustments on winch not possible as it cant be put into gear
61. 3.12.2009 Polar Pioneer for Statoil på Troll – intermediate shaft on winch broke
62. 13. mai 2010 West Alpha – DC motor failed
63. 28. mai 2011 Njord A – unspooling while moving rig, possible overload or not properly functioning breaks
64. 26. januar 2012 på Songa Delta – DC motor malfunctioned, had to be changed
65. 7. mars 2012 Bideford Dolphin – unspooling caused by possible malfunctioning breaks, had to be mechanically locked at a preset tension
66. 14.2.2013 SONGA DEE på Gullfaks – overload of capacity is very likely reason for unspooling
67. 7.12.2013 TRANSOCEAN LEADER – bolt on fairlead was loose, making the fairlead leading wheel standing at a bent position
68. 23.12.2013 West Alpha for ExxonMobil på Balder – leading wheel in fairlead lost to sea, unclear about reason, lose bolts?
69. 15.4.2014 Deepsea Bergen – broken shaft in winch

Testing and mainteance

70. 4.5.2002 Bideford Dolphin
71. 30.10.2004 Transocean Searcher på Åsgard
72. 28.12.2007 Njord A produksjonssemi
73. 17.1.2008 Transocean Winner på Grane
74. 22.8.2008 Polar Pioneer.
75. 12.8.2009 Aker Barents
76. 13. oktober 2010 Songa Trym
77. 13. juli 2012 Scarabeo 5 på Visund
78. 13. september 2012 Transocean Barents
79. 9.12.2013 Leiv Eiriksson på Trell
80. 8.4.2015 TRANSOCEAN BARENTS

Fiber rope

81. April 2003 Safe Scandinavia
82. 31.10.2005 Port Reval på Eldfisk
83. 28.2.2006 Bideford Dolphin
84. 9.8.2007 Port Reval på Eldfisk
85. 11.4.2008 Transocean Winner på 30/9-21
86. 26.6.2008 Borgland Dolphin på Vigdis Extension D-template
87. 25. november 2011 Transocean Winner
88. 11. mars 2012 Polar Pioneer

Wrongly pushed buttons

89. 9.07.2003 Borgland Dolphin
90. 10.3.2007 Deepsea Delta på Oseberg
91. 7.12.2008 Polar Pioneer på 7223/5-1A Obesum i Barentshavet
92. 28.10.2013 TRANSOCEAN SPITSBERGEN på NORNE

Loss of Anchor

93. 4.10.2005 Eirik Raude 1258 m vanndyp
94. 18. juni 2010 Regalia for BP på Valhall