Anchor line failures
Norwegian continental shelf
2010-2014

PETROLEUMSTILSYNET

Rapport

Rapport	
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Sammendrag norsk – Norwegian summary Det har siden 2010 vært 16 linebrudd på norsk sokkel. Feilsannsynligheten tilsier at næringen har et stort behov for forbedringer. Rapporten gir en sammenstilling av hendelsene, og beskriver fellestrekk. Det er videre vist til en del områder der det særlig er behov for forbedringer.	
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ABSTRACT

16 failures of offshore mooring lines have occurred in the period 2010-2014 on the Norwegian Continental Shelf. The failures are caused by a mixture of overload, fatigue, mechanical damages and gross errors during the manufacturing.

All the line failures and failure statistics are presented. The statistics are compared with earlier Norwegian and available international statistics.

In the period 1996-2005 a high number of cases were observed. The industry reacted, and the number of incidents was clearly reduced for several years. In 2010 the number of cases started to increase again, rising questions on how to improve again. Some of the old failure modes have disappeared, as dragging of anchors and failures of chains above 20 years of age. But several other failure modes have appeared or reappeared.

The failure frequencies are highly uncertain, but the failure rate from 2010-2013 have been in the order of magnitude

- single line failures: $92*10^{-4}$ per line year and
- double line failures: $12*10^{-4}$ per line year.

No triple line failures have occurred in 2010-2013, but when using data from 2000-2013, the failure rate have been in the order of magnitude $2*10^{-4}$ per line year.

The report discusses possible changes in practice, regulations and standards, quality of materials, maintenance, ALS-, FLS- and ULS-design.

INTRODUCTION

14 December 2004 a severe incident occurred on the Ocean Vanguard. The brakes of two lines failed almost simultaneously in about ten metre significant wave height. The movements of the facility lead to failure of the drilling riser and a total collapse of the tensioning system. The BOP on the sea floor suffered a permanent inclination of six degrees, the anchor winch system was damaged and the well was lost (Solheim et al, 2005).

Afterwards, PSA started a process to improve the safety on anchor systems. In 2005 Nilsen and 2006 Kvitrud et al presented statistics of anchor system incidents based on incidents on the Norwegian continental shelf from 1996 to 2005. They were based on 48 incidents with varying degree of criticality. In 2005 the first ISO 19901-7 was issued, and has since been a part of our way of working. 16.1.2007 we issued a letter to the industry to assist in the improvement process, focusing on compliance with the present regulations, site specific assessments, dragging of anchors, inspections of chains older than 20 years, loose studs and competence.

Several years of detailed follow up from the responsible parties, reduced the number of incidents. The activities successfully gave a reduction and zero failures of anchor lines during in service use for a period. The new regulations from the Norwegian Maritime Authority (the former Norwegian Maritime Directorate) were issued in 2009 (NMA, 2009). However from 2010 the number of incidents increased again.

The number of failures is far too high, and the purpose of this report is to assist in the improvement process.

This report will also be a basis for our follow up of the industry.

The incident investigations have been performed by different personnel from one case to the next. This has several disadvantages and some advantages. The investigators have been drawn mainly from the owner and manager of each facility, but in some cases the operator has participated or carried out their own investigation.

Failure causes are not always obvious, and some have been identified as the most reasonable assumption.

OUR CONCLUSIONS IN 2006

Kvitrud et al (2006) concluded that the number of incidents related to mooring systems on MOUs was too high. We emphasized that training and organizational factors should get more attention. We believed that many incidents would not have happened if the industry had a better system of sharing experience, and the crew had more insight and was more familiar with anchor systems and their function. Maintenance of such systems should also be given more attention. We pointed out that many of the incidents occurred during critical operations, when the facility was connected to the well or alongside another facility.

Failures of the mooring line itself were the most frequent cause of incidents involving the mooring system during use. The quality and quantity of inspections and repairs in connection with the recertification of the chains were of major importance. Very much so, because chains that were more than 20 years old, were still in use. Recertification, inspections and repairs are therefore essential in ensuring that the chains satisfy the applicable quality requirements. The chain owners must know the history of each individual line (traceability) in order to ensure a successful recertification. Several fatigue failures occurred in chains, caused by bending stress. It was reasonable to assume that the bending stress had occurred at the fairleads. We believed this was a good reason to reconsider the design of the fairleads.

The number of shackle failures was about the same as on chains, and the consequences of both types of failures were the same. Since the number of shackles was small compared to the number of chain links, the failure frequency of each individual shackle was significantly higher. We are of the opinion that special attention should be given to the selection of shackles, as well as to the assessments of the condition of the shackles.

Fibre ropes have proven to be very vulnerable to mechanical exposure, e.g. when in contact with steel wires. We believed, as a consequence, that operations carried out within the area of the anchor pattern, should be supervised better.

FAILURES OF CHAINS AND CHACKLES

Transocean Winner semi, 2010

1 December 2010 a 76mm mooring chain with studs failed on *Transocean Winner* when it was working at 78m water depth on Norald for Lundin.

The failure occurred in connection with anchor handling operations (Transocean, 2010). It broke about 175m from the fairlead in a 195m-long section. Maximum tension registered was roughly 210 tonnes. The ultimate strength of the chain was about 610 tonnes. Lundin (2013) concluded that the main underlying cause was insufficient inspection or maintenance. On arrival at the DNV laboratory, the chain link was too heavily corroded for a meaningful material investigation (Transocean, 2013). The final failure was then most probably a sudden fracture caused by long-term fatigue loading and a crack developing over a lengthy period (Transocean, 2010 and Lundin, 2013).

The chain was manufactured by Vicinay in 1992 as NV K4 quality, and had been recertified in 2006. All the chains of this quality were removed from *Transocean Winner* afterwards.

Songa Dee semi in 2011

1 September 2011 *Songa Dee* was working for Marathon on the Alvheim field. During anchor handling operation, the line 8 was tensioned up by *Skandi Vega*. The anchor on line 8 was secured on the vessel, and the chain to line 8 was coupled to the chain on line 3. The tension was incorrectly adjusted, allowing the winch to tension the chain up to 460 tonnes (Acona, 2011). Data logs from the winch were automatically deleted after 12 hours (Acona, 2011). The winch had its challenges with monitors and winch settings, and performance data were distributed to several monitors (Acona, 2011 and YouTube (2012)). The chain broke at the shark jaw on the anchor handler vessel, and fell to the seabed.

The chain was manufactured by Ramnäs in 2005 to NV R4 quality. According to the certificate, it had passed a proof load test in 2005 with 4 753kN. Break load tests were conducted on pieces to 6 030kN. It was last inspected in 2009 (DNV, 14 Oct 2011). The failed member had a yield strength of 571MPa, an ultimate strength 925MPa and an elongation 18% (DNV, 14 Oct 2011).

Mechanical testing of the failed chain link was subsequently conducted by DNV. Results show that requirements in DNV-OS-E302 were met, except that the yield strength was slightly lower than the minimum required. The deviation was not considered significant (DNV, 14 Oct 2011). The observed fracture surfaces looked like ductile overload fractures with a bending moment. Although the outer surface of the chain link was damaged and corroded, none of the cracks or surface defects would weaken the link. All observations corresponded with overloading of the chain link (DNV, 2012).

The failure occurred with a lower tension than the proof test loads, but bending might have introduced additional stresses.

Transocean Leader semi in 2011

26 October 2011 *Transocean Leader* was on the Espevær field for Statoil when a mooring line failed in a significant wave height of 5.8m. The line broke at the upper end of five link adapters on the upper joining chain shackle (kenter link) between the steel wire and socket with swivel and five link chain adapters. The unit experienced a maximum offset of 5.5m,

equal to a BOP flex joint angle of roughly seven degrees. At the time of the incident, thrusters had been at 85 per cent pitch (Transocean, 26 Oct 2011).

This was a fatigue fracture in a three-year-old kenter shackle of the Trident thin joining shackle type. No information about the material quality, as strength or chemical composition compared with the neighbouring links is given in the investigation report. Transocean concluded that: "The main failure mechanism has been identified as stress-corrosion assisted fatigue which has initiated from the inside of the shackle fitting area in the junction to the threads and notches of the fitting lock connecting the two shackle halves. The initiation area has unfavourable geometry, with internal corners acting as stress raisers." (Transocean, 26 Oct 2011). The transverse dimension (k value) of the kenter link, measured at the fitting area, was 10 per cent less than the minimum requirement specified by ISO 1704, and it was considered possible that the kenter link had been forged with a k dimension smaller than the requirements. The reduced cross-section would have resulted in lower strength (Transocean, 26 Oct 2011).

Has the shackle functioned as a sacrificial anode for the chain?

Transocean Spitsbergen semi in 2012

2 August 2012 the *Transocean Spitsbergen* was on the Midgard field for Statoil, operating on Posmoor ATA. The chain failed about 10m above the fairlead. The total line length was 1593m. The tension in the line was 150 tonnes, the wind speed was 14m/s and the significant wave height was 2.1m (Transocean, 2012).

According to DNV (28 Nov 2012) and Transocean (2012) it was a fatigue failure. Elongation, the reduction in area and the Charpy impact test results differed significantly from the values in the certificate. Incorrect heat treatment had resulted in an inferior microstructure and deficient mechanical properties in the chain material, with high notch-sensitivity and low ductility. The extent of corrosion was considered remarkable, and it is possible that deficient heat treatment created increased susceptibility to pitting corrosion related to the microstructure or chemical composition of the surface layer. Fatigue cracking was initiated at corrosion pits on the external crown, which was exposed to high tensile stress with these pits acting as stress concentrations to initiate fatigue. Cracking propagated with a fast overload fracture mode. The root cause of the failure was improper heat treatment causing an inferior microstructure and mechanical properties deficient of the chain material with high notch-sensitivity and low ductility.

However, on the other side, Statoil (2012) concluded that "high strength steels (YS >1300MPa) are known to be prone to hydrogen assisted cracking, and the hydrogen source may be either from self-corrosion and/or CP (cathodic protection). Hydrogen assisted cracking may have introduced initial cracks in the chain surface under static and/or dynamic loads over a certain period of time. The root cause of the incident is however the inherently high tensile properties demonstrated for the failed link (and some of the neighbouring links); Yield Strength (>1300MPa), Tensile Strength (>1600MPa) and hardness (>400HB). When studying the hardness measurements performed in the area close to the fractured chain link, it was demonstrated high hardness (>400 HB) in several chain links. It was also observed both high and normal hardness levels within the same chain link, strongly indicating a local heat treatment."

The chain was a 84mm-diameter NV R4 quality, manufactured by Jiangsu Asian Star Anchor Chain in 2008 (Transocean, 10 Dec 2012). The line chain failed at about one-third of the tensile strength. Two breaking load tests have been performed after the failure and the breaking loads were 7491kN and 11702kN, respectively. Specified minimum breaking load was 7208kN. The fractured link had yield strength of 1270MPa, a tensile strength of 1670MPa and an elongation at failure of 12%.

Deepsea Atlantic semi in 2012

26 January 2012 the mooring line 8 failed on *Deepsea Atlantic* when working for Statoil on the Gullfaks South field. The rig was waiting on weather and disconnected from the well. It operated on Posmoor ATA.

Trust of 300-350 tonnes was used ahead of the incident, and the line tension was up to 300 tonnes. The significant wave height was 9.4m, Tp was 14.2 seconds, the mean wind speed (at 10m) was 28m/s and the surface current was 1.0 m/s. The weather was about a one-year storm, but a wave train with Tp of 9.1 seconds might have introduced additional horizontal movements of the unit (Odfjell, 2012). The ATA system reduced the thrust by about 100 tonnes just before the line broke.

Kaasen (2012 and 2013) concluded that the wave train introduced a large slow drift. Existing methods of calculating slow drift may have to be changed. Wave-drift force was estimated from the reconstructed wave and given wave-drift coefficients from Wadam. Newman's second-order approximation method was used. At its peak, the wave-drift force was 3 500kN, which is considerably less than the "true" value of 4 600kN obtained from the force balance. This indicates that the conventional quadratic response model for low frequency offset used in Newman's approximation method may underestimate the low frequency wave loads. Wave-drift coefficients from in-viscid refraction models (such as Wadam) were claimed to be insufficient and to underestimate the loads under certain circumstances, particularly for semi-submersibles. Furthermore, the presence of strong currents may affect the wave loads. Wave drift is also known to be dependent on the vessel's pitching motion. This is not always reflected properly in the calculated wave-drift coefficients.

Odfjell (2012) concluded that the most important contributors to the incident were the lack of weather data, the analytical tools (slow drift and line dynamics), how the thrusters were included in the mooring analysis, communication of pre-assumptions in the analysis and tuning of the ATA system.

It was an 84mm NV R5-chain with a breaking strength of 881 tons. It failed due to overload. The failure was 258m from the fairlead. Two other links in line 8 had permanent deformations afterwards indication a load above the yield load of 750 tons (Odfjell, 2012). The facility was built in 2009.

Norne FPSO in 2012

6 November 2012 an alarm on a line tension measuring cell on the Norne FPSO operated by Statoil indicated a mooring line failure. However, the initial diagnosis was an error in the alarm system. The load cells were regarded as unreliable. The significant wave height was 8-9m. The failure was confirmed four days later (Statoil, 2013).

The first failure was attributable to fatigue caused by abnormal loads on or bending of the chain. This fatigue failure was close to the weld. According to Statoil, it was caused either by incorrect location of the chain in the fairlead or by the failure of the fairlead to rotate. An

FEM analysis demonstrated that incorrect locations of the chain produce significant bending forces (Statoil, 2013).

The second failure occurred in the same chain link immediately afterwards, as a result of overload caused by the fatigue failure (Statoil, 2013).

The lines had operated with higher pretension (about 160 tonnes) than specified in the design (140 tonnes). The winch had not worked as it should since May 2012. Personnel had been unable to follow their own programme to change the length of the lines monthly to redistribute stress, and the chain member had unintentionally spent too long in each position. The chain was 114mm of the NV K4 stud less type, with a breaking load of 12 420kN. No deviation in the material quality was found in testing. The chain had been installed in 2007 (Statoil, 2013).

Petrojarl Varg FPSO in 2012

14 December 2012. Mooring line 4 broke on the *Petrojarl Varg* FPSO on the Varg field. Nine mooring lines remained intact. The heave was up to 25m and the significant wave height was 7.5m. The same line had also failed in 2006. The upper chain segment was led via a seven-pocket fairlead wheel at the lower side of the turret through a chain pipe up to the chain stopper on a turret deck level with the main deck.

The failure resulted from high-cycle, low-stress fatigue initiated on the external surface of the link. The wear pattern on several of the chain links, including the fractured link, was consistent with expected wear from relative movement against the fairlead. This fatigue had been initiated or propagated by bending the link around a pivot point, which may be the fairlead, a neighbouring link or out-of-plane bending. General surface corrosion was obvious, with extensive localised corrosion, significant wear and cracks on the external surface around the fracture surfaces. General and severe localised corrosion would have acted as stress intensifiers and initiation spots for fatigue cracks owing to roughening and pitting of the external surface (DNV, 3 Apr 2013). Teekay Petrojarl (2013) concluded that "the direct cause was that the broken chain link was exposed for out of plane bending (due to bending in fairlead or rotation of chain (twist)) over time in a fixed position of the fairlead …"

The chain was produced in 1996 by Vicinay, and installed in 1998 with a design life of 15 years. It was grade NV R4 stud less, with a nominal diameter of 100mm. The material was within specifications (DNV, 3 Apr 2013). The minimum breaking strength was 1 005 tonnes. The yield strength was 777MPa, tensile strength 872MPa at elongation 17.5%.

Leiv Eiriksson semi in 2013

9 December 2013 *Leiv Eiriksson* was at the Trell field for Total. A chain failed during cross-tension testing. When pulling up from 200 tonnes to a planned 416 tonnes, the mooring chain parted at 387 tonnes. All other lines were tested to 416 tonnes. The chains were produced by Vicinay Cadenas in January 2013 as 84 mm stud chain link of NV R5 quality. The failed link had a yield strength of 994MPa and an ultimate strength of 1050MPa. The ratio between ultimate and yield strength was then 5.6%. The minimum breaking capacity of the examined chain was as certified, approximately 850 tonnes.

Based on the results of the DNV investigation (DNV, 2014), the following conclusions were drawn: "The chain link has suffered a fracture of partly brittle behaviour along the crown / bend region. The most likely cause to the premature failure of the examined chain link is found to be overloading / shock loading in combination with stress concentrations in the region of failure. The results of this examination reveal a uniform microstructure typical for quench and tempered material for both the fractured and reference chain links and no material irregularities or defects were found. In addition, the chemical composition, and mechanical properties of the material fulfil the requirements."

DNV (2014) discussed how the failure could occur, and found that the fractured link probably originate from interactions with the windlass (gipsy) wheel during operations. Windlasses have the potential for serious mechanical damage to chain if the chain does not run smoothly over the windlass and if horizontal links in the pockets are not properly supported on the four shoulders of the links. Two chain pockets on the gipsy of winch number 6 showed considerable mechanical damage in the contact area for the chain (protruding ends). This may occur in the case of worn pockets or twist in the chain. Investigations on the remaining 7 winches showed twist. Shock load effects can be inflicted by links jumping in the pockets, e.g. when links "ride" on the wheel and eventually fall back into place. Twist in a chain will increase the probability of jumping.

Deepsea Bergen 2014

6 April 2014 a rig chain link failed on Deepsea Bergen at Åsgard for Statoil. The wind was about 26-29m/s and wave heights of 4.6-7.5m.

Deepsea Bergen had a 76mm R4 chain with minimum breaking load of 6030kN.The chain was produced by Ramnäs Brug AB in 2009, and certified by DNV. The line was within its first 5 years period.

In addition the line had R3S 133mm chains with breaking load of 14760kN and the fibre ropes had a breaking load of 7848kN. All ten lines were tested to a tension of 240 tons at the location. Normal line tension in the lines varied between 90 and 150 tons. The line tension at failure was 135 tons.

The failure started in surface defects (up to 3mm) at 6 o'clock (inner side of the link) and subsurface defects (pores). The crack propagated with a brittle or fatigue mode, and continued with a fatigue fracture mode. The root cause was the defects from the production process, not discovered during NDE inspections. The material properties of the base material in the fractured chain link, did locally not meet the yield strength requirements (down to 546MPa) and ultimate tensile strength requirements (down to 850MPa) of DNV-OS-E302 (requirements of 580MPa and 860MPa). The certificate stated the yield strength to be 831-850MPa and the ultimate tensile strength to be 916-941MPa. There was almost a factor of two between the highest and lowest yield strength in the same link. At the highest yield strength results, there were almost no difference between the yield strength and the ultimate tensile strength.

The base material was inhomogeneous with high porosity, low hardness, locally low yield/tension strength and large variations of mechanical properties. Reduced corrosion resistance are likely to be a result of the production process, but not believed to be the main cause of the failure (DNV GL, 2014).

FAILURES OF STEEL WIRE ROPES AND SOCKETS

Regalia semi, 2010

A steel wire rope failed at some point between 18 and 20 June 2010 on the *Regalia* flotel working for BP on *Valhall* (Prosafe Offshore, 2010 and 2012). The anchor attached to a bolster (cowcatcher) was lost to the sea. The maximum significant wave height at the time was about 6.2m. Breaking just above the anchor, the steel wire rope was connected directly to it via a snub-nosed socket.

The anchor was attached to the bolster with 40-50 tonnes of tension. Inspection of the steel wire rope indicated that five of the six strands and the core parted just above where the socket was casted and the sixth and last strand was pulled out of the socket. The anchor was lost to the sea. The wire rope was 450m long, had a diameter of 86mm and a breaking strength of 528 tonnes in a test in 2001. The Delta Flipper anchor was of 12 tonnes. The socket and anchor were not found again. *Regalia* operated on dynamic positioning (DP), and two anchors had been stored in the bolsters for some time.

The fitting of the socket arrangement was identified as the root cause, since it was oversized for the wire. According to Prosafe Offshore, the resulting failure of the arrangement was likely to be caused by fatigue and failure of the socketing resin. All other wires and socket arrangements were subsequently inspected and the wires refreshed (cut back) and re-socketed with correctly sized sockets.

Later experience with anchors in bolsters has demonstrated that waves impose significant forces on anchors (Andersen et al, 2013 and 2014).

Navion Saga FSO in 2011

20 June 2011 *Navion Sag*a FSO lost two steel wire ropes on Statoils Volve field (Statoil in several documents 2011 and 2012). These failures were located on both lines at the bottom end of the upper steel wire segment, at the bending stiffeners and the socket. The failures probably took place on two different occasions in stormy weather, several months before the inspection. No active monitoring was conducted with single mooring line integrity during the operation (Statoil, 2 Dec 2011). Nine mooring lines were attached to the STL offloading buoy and connected in turn to *Navion Saga*.

The direct cause was ductile overload of the steel wire rope strands at the rope termination on the seabed, resulting from high local dynamic “snapping” loads after the line had temporarily gone slack. The ductile failures were of the “cup and cone” type (Statoil, 19 Jun 2011).

All the wire ropes were provided by Bridon, and were Spiral Beach without plastic coating. With diameters of 112mm and 106mm respectively, they were of the Xtreme type. The tensile strength for wires in the actual rope is about 2000MPa (Aksdal et al, 2013). The mooring system was installed in 2006. Its ultimate strength and elongation were better than the requirements (Statoil, 19 Jun 2011). Parts the upper wire rope segments were lying on the seabed in some load conditions and weathers. It was also evident that the system would experience slack in many circumstances (Statoil, 28 September 2011). The post-damage inspection made two further discoveries on the wire ropes in line 4. A kink and a wire bird-cage were found at the steel wire rope end against the STL buoy (Statoil, 17 Nov 2011).

Aksnes et al (2013) reported that: “High curvature was induced by large vertical motions of the wire-chain coupling segments. The maximum curvature was in the range of the specified capacity of the wire segment. Based on the sensitivity study, both seabed properties, drag on the coupling segments and rotation of the coupling segments affected the curvature of the wire rope during slack events.”

COSLPioneer semi in 2012

25 January 2012 *COSLPioneer* experienced a double line failure when working on *Crux* on block 30/06 for Statoil. The water depth was 109m. It was operating on Posmoor ATA. The wind speed was 28m/s, significant wave height 8-10m and the Tp 13 seconds (COSL, 2012, and Falkenberg, 2013).

Line 1 first paid out in the storm with a tension of 4 100kN. It was reinstalled. It paid out again 90 minutes later at a tension of 4 376kN. This second pay-out was followed by a break in line 8, with a recorded tension of 4 837kN. Another pay-out came 90 minutes later. Line 1 must have been reinstalled because it failed with a tension of 4 624kN. Both lines broke above the fairleads.

According to Falkenberg (2013), the capacity of the steel wire ropes was reduced by bending over the fairleads. The MBL of the wire rope was 6 622kN. The tensile strength was 1960 N/mm^2. The wire was produced by Bridon in 2009, and the wire diameters were 90mm. DNV (2012) discussed stress reduction with bending. The subject was complicated, but they recommended a reduction of the bending strength of 0.875 until better data was provided. It was in line with numbers used by API and Bridon. For COSLPioneer it gave an assumed strength of 5 794kN. Measured tensions at failure were lower.

The maximum capacity of the winches was said to be 750 tons when at least 850m of the wire was out. With 414-447m of wire out, winch capacity was reduced to about 70 per cent of maximum (Rolls Royce, 2013). The extreme tension may have been missed owing to a low sampling rate. Falkenberg (2013) concluded that the line breakages may be related to pay outs of lines at tension lower than holding load requirement. The main contributing factors were * a reduction of the capacity over the incident: * the ATA (DP) system was not run in an optimum way * high pretension * extreme drift cannot be disregarded * extreme wave groups * being outside the validity of applied theory.

Where corrective actions are concerned, COSL concluded (2012) that it was necessary to * set a wider (looser) line system earlier when the weather is coming up * accept that there will be more movement and that more thrust must be used in severe weather * not use damping or low gain in severe weather * let the line system take up heading forces with no yaw on axes control * evaluate the use of the manual thruster monitoring at an earlier stage in shallow water * position the unit between the point where it will end up if the thruster stops and the weather, which will produce steady thrust in one direction with no spinning of thrusters * full tuning and verification of the DP system * verify the correctness of the mooring analysis * double check that the line segments on each line entered in the DPM system is correct. With regard to the last point, there appeared to be errors on two segments which may have had an impact on the stiffness of the mooring line system. The DP system might have “thought” that the system was stiffer than it actually was.

DNV (11 Mar 2012) concluded that the failures were most probably caused by overload of the mooring lines.

Island Innovator semi in 2013

22 November 2013 *Island Innovator* was on block 16/2-20 for Lundin. A steel wire rope failed about 15-20m from the fairlead. Testing of the wire rope concluded that the failure was caused by external forces. Inspections demonstrated marks of bronze or brass on the wire. Underwater inspection of vessel Island Contender showed damage on the port aft thruster and propeller. The investigation team concluded that Island Contender had been in contact with the wire, and the port aft thruster of Island Contender mechanically caused the line to fail (Odfjell, 2014). The facility was built in 2012.

The root causes were found to be (Odfjell, 2014):

- Island Contender maneuvered too close to Island Innovator and the anchor line.
- The design of the anchor system of Island Innovator causing the anchor lines to be set high in the water.
- The risk of damaging or breaking the anchor lines by vessel has not been a subject in any risk analysis. And so no actions regarding this matter have been taken.
- Diagram showing the placing and depth of the anchor lines had not been established and distributed to arriving vessels.

FAILURES OF FIBRE ROPES

Transocean Winner semi in 2011

25 November 2011 *Transocean Winner* was in 314m of water on the T-Rex field for Maersk Oil when a polyester fibre line broke. It failed in the storm Berit with maximum recorded wind speed of 30m/s, wave height of 24m and heave of 11m.

The failure was about 5m away from where it was linked to the bottom chain, and about 795 m away from the rig top chain. The failure occurred about 1050 m away from the rig, and hence outside the 500 m safety zone (Maersk Oil, 2011). They had 800m fiber insert and 1000m rig chain on the bottom.

DNV (Maersk Oil, 2011) concluded: "... evidence was found on the rope and its sub-ropes, strongly indicating that an external object was leading to *external damage*, and subsequently leading to break of the rope by (partially) cutting it. This external object might have been a movable object which was "cutting" over the fibre rope, such as a trawler steel-wire from pelagic trawling, or a fixed object, such as a subsea installation where the fibre rope was then moved along a sharp edge. Based on the findings it is considered as most likely that the 'cut' must have happened quickly, i.e. within seconds or a few minutes. However, it cannot be ruled out that the 'cut' might have occurred days in advance of the break and elsewhere supplemented by assuming that minimum 3 sub-ropes remained intact after the 'cutting' event .. ". No foreign vessels were observed around the unit during the period from 4 November to 25 November (Maersk Oil, 2011).

The minimum specified breaking load was 800 tonnes. The mooring line had been pull-tested to 300 tonnes from the unit before use. This was a 158mm polyester rope parallel with 12 sub-rope cores, each comprising eight strands. It was manufactured in 2007 by Bexco Le Lis in Belgium (Maersk Oil, 2011). The fibre rope had been used on four previous jobs with a total of 853 days on hire. After its first job in 2007, a split in the protective Poly Urethane was observed and repaired. After its last job in 2009, red paint was observed on the jacket which was described as "melted", caused by offshore handling where the fibre experienced some friction, possibly combined with bending loading (Maersk Oil, 2011).

Mærsk (2011) stated "Actual fibre line tension during installation will determine the clearance of the eye of the fibre rope from the seabed. The eye of the fiber was designed to be lifted above seabed at all times but in reality this may be difficult to achieve, particularly during installation. Use of subsea buoys in case of small clearance of fiber from seabed is recommended for future installations." No buoys were used on this location.

Polar Pioneer semi in 2012

11 March 2012 *Polar Pioneer* was on *Cormorant* B/C for BP on the *Skarv field*, when a mooring line failed. *Polar Pioneer* experienced a 12m excursion from the initial position, and tilted 2.3 degrees. The angle on the lower flex joint was less than two degrees. The line was made up of two chains with the fibre rope in between. The line failed in the fibre rope section in the eye furthest from the rig and linked to the bottom chain, about 600m from the fairlead and roughly 38m above the seabed. The failure was located between the end of the eye and the crotch. Several subsurface buoys had twisted around the chains and the fibre ropes. The significant wave height was 6.2m.

BP (2012) concluded that the event was triggered by parts of the subsurface buoy shackles or chains coming into contact with the fibre rope. An external rusty object had cut the fibre rope on its outer side in the "flexible" section between the hard thimble and the stiff crotch on one branch of the fibre-rope eye. The cut started on the outer side, penetrated the braided jacket, progressed through 32 out of 36 sub-ropes and extended partly into the remaining four sub-ropes. This resulted in the final failure owing to overload. The cutting and final failure must have occurred within a few minutes.

BP (2012) noted that twist in mooring lines may have been initiated during testing of anchor holding capacity during pre-installation, and might have been stored when the chains were on the seabed. Twisting may have been induced by the winch wires on the anchor handling vessel. BP (2012) and Transocean (18 Jun 2012) concluded that the subsurface buoy shackle and the chain had been installed too close to the fibre rope. Furthermore, the rotational movement of the mooring line leading to the subsurface buoy arrangement got tangled up with the fibre rope.

Transocean (2012) recommended:

1. Install subsurface buoy to the bottom chain segment by "snotter" shackle in a safe distance to avoid the subsurface buoy to reach the fiber line segment connection point.
2. Install high tension swivels in both ends of the fiber line insert.
3. Evaluate use of swivels during test tension to avoid twist in pre-installed anchor lines.
4. Assess the use of ROV survey when the MODU has achieved work tension in the mooring lines.
5. All parties involved in the rig move process, is recommended to make themself familiar with industry learning related to mooring line failures and by doing so, bring learning forward in risk assessments and point-out potential weaknesses in rig move documentation issued for review.

Transocean Barents semi in 2012

13 September 2012. *Transocean Barents* was on the Jette field for Det Norske at approximately 128m water depth. A fibre rope failed about 350m from the unit. The BOP was not connected.

DNV (9 Nov 2012) concluded that a force had cut nine sub-ropes, destroying about 35 per cent of the cross section. This was most probably a fixed object, with the fibre rope moving along or bending over a sharp edge. The remaining sub ropes were pulled to break later, some over time and some during pretensioning. They were most probably unbalanced, since the residual strength only reached 295 tonnes or 37 per cent of MBS. The cut most probably occurred within seconds or minutes. Although the line had been subjected to external mechanical damage, the reason for this could not be determined (Det Norske, 2012). It could not be ruled out that the damage had been caused when deploying and connecting the mooring line. No fishing boats were in the area during the relevant period. Installation was done by Viking Seatech with the *KL Saltfjord* vessel.

The core of the rope comprised 12 triple strands parallel to each other. Half the cross section had left-stranded steel wires (S lay) and the other half were right-stranded (Z lay). This ensured that the rope did not twist during tensioning (Det Norske, 2012). It was produced in 2005 by Le Lis in Belgium and certified by Lloyds register. Minimum breaking load was specified to 800 tons. No requalification documentation after five years in use, were found.

A repair on the failed fibre line was performed in 2011, but traceability lacked to connect it to the failure. No repair procedure was found.

Det norske (2012) stated that is known that the Norwegian navy has been training with submarines in the area. It was however, assumed that no submarines have passed the area in this period.

STATISTICS OF FAILURES

In 2006, the PSA (Kvitrud et al, 2006) reported the observed frequency from the events in Norway to be 1 x 10^{-2} per line-year in 1996-2005. This gave an order of magnitude of one failure for every ten facility-years.

Data published by the HSE (Morandini and Legerstee, 2009, with reference to DNV Industry AS, 2003) suggest an average historical rate in UK for mooring failures of about once every seven operating years for FPSOs, about once every 17 for FSOs, about once every 1.5 for drill ships, about once every four for drilling semisubmersibles, and about once every eight for production semisubmersibles. Two accidents on the UK continental shelf (UKCS) have also actualised the need to reconsider mooring systems. These accidents occurred on 4 February 2011 on the *Gryphon Alpha* FPSO and on 10 December 2011 on the *Petrojarl Banff* FPSO (Brown, 2013). The initiating cause on Banff was probably a failure of the fairlead owing to overload (Statoil, 2013, page 29). The link failed at the fairlead (Brown, 2013). The first line failure on Gryphon Alpha was probably caused by fatigue failure of a flash butt weld in a chain below its design capacity (Statoil, 2013, page 29, and Brown, 2013). The FPSO moved 180m off location, resulting in significant damage to subsea equipment (Brown, 2013). Multiple line failures have also occurred worldwide, as described in Jean et al (2005), Wang et al (2009), Ma et al (2013) and Majhi and D'Souza (2013).

Table 1: Causes of the 15 failures on mooring line elements in 2010-13. Errors in winches or brakes are not included. (+2) refers to the second failure in the two double line failures. No dragging events are reported. Pay outs of anchor lines are not included. The number of reported pay outs the last ten years, have been about 35. The line failure in 2014 is not included in the statistics since the investigation report is not available.

	Fatigue	Overload	Mechanical damage	Manufacturing errors	Sum
Chains	3	3		1	7
Fibre ropes			3		3
Steel wires		2 (+2)	1		3 (+2)
Kenter link	1				1
Socket connection				1	1
Sum	4	5 (+2)	4	2	15 (+2)

We do not have information on how many components of each type have been used. Over the past four years, moored mobile units have numbered about 25 and floating production facilities about 19. Assuming the mobile units have eight mooring lines on average and production facilities have 12, the failure probability is about (15 failures / (4 years * (25*8 lines + 19*12 lines)) = $88*10^{-4}$ failures per line-year. The failure frequency has not improved over the past 10 years, since the observed frequency from the events in Norway was 100 x 10^{-4} per line-year in 1996-2005 (Nilsen, 2005 and Kvitrud et al, 2006). The difference is clearly within the uncertainty limits. Three incidents were on production facilities and the remainder on mobile units, giving mobile units a slightly higher failure rate ($150*10^{-4}$ vs. $33*10^{-4}$).

One double line failure occurred on a production facility and the other on a mobile unit. The frequency of occurrence has been (2 failures / (4 years * (25*8 lines + 19*12 lines)) = $11*10^{-4}$ double failures per line-year or about $100*10^{-4}$ double failures per facility-year.

We have experienced one triple line failure since 2000, with *Bideford Dolphin* suffering them during a summer storm on 13 June 2000. Shackles (CR links - Detachable Chain Connecting Links) failed owing to fatigue (Kvitrud et al, 2006). This indicates a frequency of about (1 failure / (14 years * 350 lines) = $2*10^{-4}$ triple failures per line year or $2*10^{-3}$ per facility-year. The two cases in the UK indicate that the probability of three line failures found from the Norwegian data alone might be an underestimate, providing the failures on the UKCS and the NCS have statistical properties of the same order of magnitude. Lower safety factors are applied on the UKCS than in Norway, indicating that the relevance of the British data to Norway might be questioned.

The cases with two or three line failure in Figure 1 are:

- 13.06.2000 *Bideford Dolphin*. Described briefly above.
- 24.12.2002 *Scarabeo 6*. One anchor dragged, caused the second to be torn off.
- 14.12.2004 *Ocean Vanguard*. Described briefly above.
- 24.11.2006 *Borgland Dolphin*. Two lines payed out.
- 31.10.2006 *Bideford Dolphin*. A chain failed due to fatigue, followed by another line paying out.
- 23.12.2008 *Scarabeo 5*. Two lines failed. Possible cause was loss of anchor, anchor dragging and line failure.
- 20.6.2011 *Navion Saga*. Described in detail above.
- 25.1.2012 *COSLPioneer*. Described in detail above.

The causes of pay outs and dragging, are not discussed in this report.

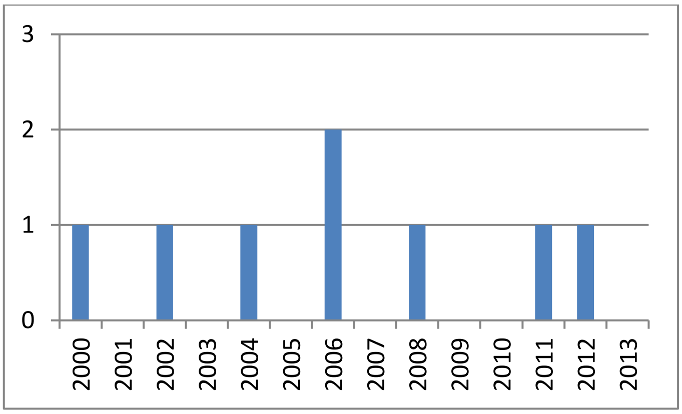

Figure 1: Number of cases with two or three line failures in the period 2000-2012 on the NCS. The cases are related to failures of lines, pay out from the winch, or significant dragging in combination with a line failure.

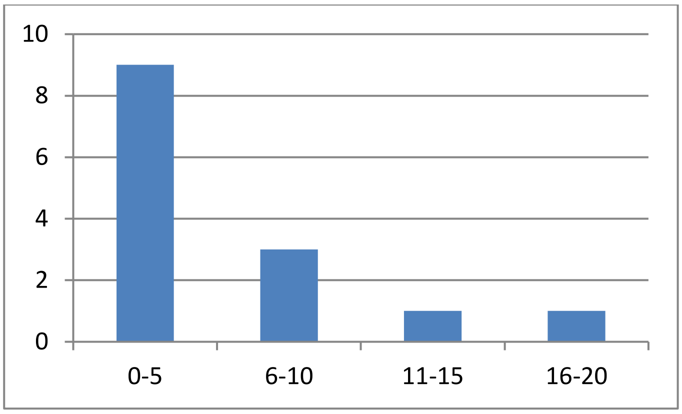

Figure 2: Number of failures as function of the age of the failed elements. The two double line failures are counted as one failure case.

Ma et al (2013, page 3) reported a worldwide failure frequency estimate of $30*10^{-4}$ per facility-year for major mooring incidents on production facilities, specifying that major incidents involved at least two line failures. It is not significantly different from the Norwegian data.

Roughly, about half of the failures are in platform specific anchor lines, and on the other half are in site specific lines.

POSSIBLE CONSEQUENCES

The safety of mooring systems on the NCS is mainly regulated by the facilities regulations and section 3 of the framework regulations. Section 63 of the facilities regulations on anchoring, mooring and positioning states that: “floating facilities shall have systems designed to hold their position at all times and, if necessary, be able to move from their position in the event of a hazard and accident situation. The mooring system shall be in accordance with the requirements in Sections 6 through 17 of the Norwegian Maritime Authority's Regulations relating to positioning and anchoring systems on mobile offshore facilities (the Anchoring Regulations 09*).*” Floating facilities subject to section 3 of the framework regulations must comply with the regulations of the NMA, together with supplementary classification rules issued by DNV GL.

The NMA regulations state, in general, that environmental actions must be specified with an annual probability of 10^{-2}, and a set of safety factors is specified with reference to ISO 19901-7 annex B. Technical requirements are given in the regulations, with reference to more detailed provisions in ISO 19901-7 and classification society rules. Compliance with the NMA regulations should prevent incidents to a reasonable degree.

Compliance with the NMA regulations from 2009 (NMA, 2009) has caused several failure modes to disappear from Norway’s event records. Examples are:

- dragging of anchors, as the NMA (2009) section 17 require testing of anchors holding to the 100 year loads or calculations according to DNV-RP-E301
- failures of old anchor lines, as the NMA (2009) section 15 give significant maintenance requirements for chains above 20 years of age.

Section 11 of the PSA’s facilities regulations and section 2 D103 of DNV OS-A101 require control of accidental loads not to destroy safety functions with an individual frequency of occurrence in the order of 10^{-4} per year.

Standardised quality improvements will only cover some aspects of the failures. One rig owner and one operator have each six of the 15 line failure cases (some in common). This may indicate that aspects other than the purely technical are also very important.

Selection of steel materials and fabrication

Nine of the failures have occurred on equipment having zero to five years in service. A timely question is whether the material requirements are sufficient. Almost all the material testing of failed lines confirms that material properties accorded to the rules. But did the steel have unintended properties? Are the ductility requirements sufficient to redistribute stresses? Can hydrogen cause unintended brittleness in high-strength steels? Steels with a yield above 700MPa are vulnerable to hydrogen. Even if the mooring system lacks anodes, the facility’s own CP systems produce sufficient hydrogen free of charge to the mooring lines. Higher steel qualities give opportunities to increase the tension, and greater variations in tension increase the possibility of fatigue failures.

Corrosion in chain links may call into question the adequacy of quality control, inspection, expertise and experience transfer.

Instead of increasing the strength, should the use of more lines be evaluated for mobile units?

The ratio between the ultimate strength and yield strength in one of the failed R5 chains was 5.6%. Normally, stress concentrations are not included in ULS-analysis, based on an assumption that redistribution of stresses occur at yield. It assumes that the ultimate strength is substantially greater than the yield stress and the elongation is significant. When the ratio between the ultimate strength and yield strength is in the order of magnitude of 5%, redistribution is more difficult. For wires (with ultimate strength up to 2000MPa) the ratio is close to one. Veritec (1991) stated "*I forhold til normaliserte stål er flytegrensen øket mer enn strekkfastheten, og høyfaste stål har derfor et høyere flytegrenseforhold (Re/Rm), som regel i området 0.81 - 0.90. Det er ikke kjent at dette har ledet til skader eller problemer i forbindelse med praktisk bruk av materialene*." Reitan et al (1991) skrev: "*Det foreslåes derfor at for høyfast stål skal faktiske prøveresultater ikke ha høyere flytegrenseforhold enn 0.9*". Eurocode 3 NS-ENV 1993-1-1 (first edition 1993, section 3.2.2.2) require the ratio between ultimate tensile and yield strength to be at least 1.2 if plastic analysis are used. High strength steels are also more vulnerable for low temperature and local surface imperfections (Pisarski and Stacey, 2014). Corrosion has also a more detrimental effect on high strength steel (Haagensen, 2013).

Should a ratio between the ultimate strength and yield strength be required? At which ratio should the stress concentration factors be *included or be taken into account in the ULS analyses?*

At least one chain failure (2009 and possibly also one in 2012) was caused by incorrect local heat input.

The framework regulation section 3 stipulate that *"... mobile facilities registered in a national ships' register, and which follow a maritime operational concept, relevant technical requirements in the Norwegian Maritime Directorate's regulations for mobile facilities (the Red Book), such as they read after the amendments in 2007 and subsequent amendments, and with supplementary classification rules provided by Det Norske Veritas, or international flag state rules with supplementary classification rules providing the same level of safety, with the specifications and limitations that follow from Section 1 of the Facilities Regulations, can be used as an alternative to technical requirements laid down in and in pursuance of the Petroleum Act. The chosen maritime regulations shall be used in their entirety*." When doing spot checks on lines used, we have found other standards than DNV GL used without deviation handling, as described in the framework regulations section 24 on use of recognised standards.

Is the understanding of a high quality sufficient?

Protection of fibre ropes against mechanical damage

Careful handling of fibre ropes had been given focus for years. But, it has not been successful. Other actions are also necessary.

Four lines have failed due to mechanical damage in three fibre ropes and one steel wire rope. Is it acceptable to use fibre ropes without protection? Protection of fibre ropes have recently been qualified or are on its way to be qualified for use at the field development at *Goliat* (Eni) and *Aasta Hansteen* (Statoil).

It might be reasonable to require protections for future fibre ropes, when it is properly qualified and tested in use.

The contact between ropes and equipments indicate that the safety margin for operation in the vicinity of a rope is too small. None of the cases seems to have been introduced by external activity, as fishing vessels.

Maintenance, inspection and maritime operations

It has turned up repeatedly that twist and bending of lines cause increased stress in lines. Twist is introduced during installation and in testing. Bending typically occur in connection with the buoys, fairleads and winches. Incorrect locations of chains in the fairleads introduce significant bending. If twist and bending are not eliminated, they shall be taken into the calculations according to the NMA anchoring regulation section 6 (3): "*The system shall be dimensioned to withstand the load that the selected solutions cause*".

Different means are used to avoid twist and bending. For MODUs, Statoil (7.3.2014) described that

- The platform crew control twist on the chain between the winch and fairlead. Twist is removed by means of a "twist removal kit" which always will be mobilized at the anchor handler vessel (AHV).
- Swivels are used between chains and wires to prevent twist.
- The crew of AHVs will visually check (part of the procedure during rig moves) that all fair leads have free rotation to avoid bending.

To make sure that twist can be controlled visual during installation of the STL-system on the Heidrun field, Statoil (29.4.2014) specified:

- The anchor chain will be marked (every second link),
- Wires have marking (longitudinal black paint),
- The upper connections (at the buoy) are via universal joints giving rotational freedom in all directions.

The experiences demonstrate that use of swivels alone is insufficient. Actions also have to be taken to prevent twist in the fairlead area (as twist removal kits).

Det Norske (2012) pointed to steel wire ropes comprised of 12 triple strands parallel to each other. Half the cross section had left-stranded steel wires (S lay) and the other half were right-stranded (Z lay). This should ensure that the rope did not twist during tensioning.

Bending of steel wire ropes have since 2013 been compensated for in the industry, by a reduction in the strength (the 0,875-factor). This is similar to the method used for wires in lifting equipments.

It might be question if the NORSOK N-006 in-service requirement that: “*the inspection intervals shall not be longer than that the cracks can be detected in due time before they grow to a critical size*”, are complied with.

The NMA anchoring regulation section 17 (7) state: "*An updated listing of every component of the anchoring system shall be available on the unit, and at the land organisation. The listing shall contain the age, quality, breaking strength, manufactures certificate, inspection certificate, possible re-certification date and re-certification agency of the different components of the anchoring system. The different components shall use a traceable* *identification system to ensure knowledge of where each component is located at any given time. It shall be possible to trace where the component has been used earlier and the history of the component, with regard to replacement, maintenance, inspections and breakage etc*".

After the incident on Scandi Vega in 2011, some captains on anchor handling vessels have reduced the possibility to do close visual inspections of anchor chains on the vessel decks.

Is the state of art on traceability adequate and according to the regulations, when the industry practice has not been to record where the individual elements have been located related to fairlead and where repairs have been done?

Accidental limit state (ALS) checks

The NMA regulation requires a check of damaged condition in the event of one failed line for mobile units in open water and two failed lines for production facilities and flotels. Requirements are also specified for weather conditions to be applied in the damage check calculations.

Experience from the Ocean Vanguard incident demonstrated that a two-line failure can produce substantial damage on mobile drilling units, and experience from the UK demonstrates that three-line failures can produce substantial damage on production units. A requirement to check the consequences of three-line failures should be evaluated. Three-line failure checks have already been introduced on the *Skarv* and *Aasta Hansteen* production facilities. A possible requirement to be assessed is, for example, that "three-line failures shall not produce unacceptable consequences". PSA has in 2014 repeatedly asked for a consequence evaluation of three line failures, based on the high failure rate, with reference to the framework regulation section 11 and the management regulation section 6.

Why do not all the incidents lead to accidents? Are some of the root causes less severe than others? Systematic errors will frequently have more adverse outcomes than random ones. Causes of systematic errors can include:

- systematically erroneous design of shackles as with Bideford Dolphin,
- wrong fitting of sockets, as with Regalia,
- manufacturing errors, as with Transocean Spitsbergen,
- errors or inaccuracies in the standard load calculation methods, as highlighted with Navion Saga, COSLPioneer and Deepsea Atlantic.
- Lack of consistency between the truster assistance system and the anchoring systems.

It may also be necessary to evaluate the frequency of line failures that pass unattended or where the reaction to disconnect the riser is slow.

Should a line failure cause an automatic disconnect? How much time do a human need to evaluate the situation and react?

Fatigue limit state (FLS) checks

Fatigue analysis has been required on production facilities and flotels for many years. The regulations require calculations to be conducted in accordance with the methodology specified in ISO 19901-7 chapter 9 (2005). ISO 19901-7 section 8.1.2.5 states that fatigue analysis is not required for MODUs. It is worth discussing if fatigue analysis should be required for mobile units. Good fatigue analysis is necessary to find the most critical areas for inspections. Is a MODU a MODU also when used for more than a year on a specific location?

Three of our fatigue failures were on MODUs and two were on FPSOs. Four failures were in chains and one in a Kenter link. The failed members were 18, 3 (the Kenter link), 4, 5 and 16 years old. These ages might indicate a U-curve. In practice, members more than 20 years old have been taken out of use owing to the strict inspection requirements in the NMA 2009 regulations. The main causes of the five failures identified by investigators are:

- insufficient inspection or maintenance (Transocean Winner)
- stress-corrosion-assisted fatigue and unfavourable geometry (Transocean Leader)
- bending of chains caused by either incorrect location in the fairlead or fairlead not rotating (Norne), plus to long time at the same location in fairlead.
- out-of-plane bending owing to bending in the fairlead or chain rotation (twisting) (Petrojarl Varg).

Three other fatigue failures have been reported since 2000 – on *Balder FPSO* in 2009, *Bideford Dolphin* in 2006 and *Deepsea Trym* in 2004. One was caused by unauthorised welding of chains at the manufacturer. Brown et al (2005), HSE (2006) and Næss et al (2006) describe additional causes of fatigue failures.

It must be questioned whether the present state of the art is good enough. Improvements might include:

- Detailed fatigue analysis are claimed to be unrealistic for site specific evaluations of MODUs. The traceability of history and where they have been used is already a requirement of the NMA anchoring regulation. Further the load history in known from the tension measurements, but they are at present only stored for a limited period.
- Higher focus on the fairlead was recommended by PSA in 2007, but no significant improvements have been done. All bending effects should be included in the analysis. The effects are known to the industry in relation to friction-induced bending, twisting, unbalanced set-up of pretensions, chain links fixed in the fairlead over a long time, etc. In addition operational precautions should also be done to reduce the amount of twist and bending to a minimum.
- Handling the consequences of possible fatigue failures in a reasonable way during the ULS and ALS checks if FLS analysis is not performed.
- The DNV-RP on fatigue is only valid for welds for yield stress up to 500MPa. Are the connections in the chains as good as the base material for high strength steel? What about the studs? Corrosion and local surface defects are more detrimental on fatigue for high strength steel than on mild steels.

Ultimate limit state (ULS) checks

The NMA's 2009 regulations prescribe that calculations shall accord with the methodology specified in ISO 19901-7 (2005), and that safety factors shall accord with the NMA regulations and the Norwegian annex B to the ISO standard.

Events more frequent than 10^{-2} per year are normally handled in ULS, and more infrequent events in ALS alone. ISO 19900 states: "*Extreme values and extreme <u>events</u> shall be used in* *design to verify ultimate limit states.... Extreme parameter values and* <u>*events*</u> *have a probability of being exceeded in the order of 10^{-2} per annum ...*" (my underlining). The definition of ULS does not restrict it to intact conditions. In NORSOK, collisions, waves and earthquakes are checked with both 10^{-2} and 10^{-4} loads. For a facility with 10 lines, a failure frequency in the order of 10^{-3} per line-year can then be included the ULS check. As an example, the fibre ropes have three failures in (four years * (25 + 19) facilities), giving $1.7*10^{-2}$ failures per facility-year if all the facilities had fibre ropes. This is not the case, and the frequency will be significantly higher.

Inclusion of one line failure as part of ULS is not a good solution, but should be evaluated if the high failure rate continues.

The main causes of the failures since 2010 identified by the investigators were as follows.

- Errors in socketing a steel wire rope (*Regalia*).
- Damage to fibre ropes during maritime operations as installation, removal or use of steel wires in the sea (*Transocean Winner, Polar Pioneer* and *Transocean Barents*).
- Loads causing slack (compression) in wire ropes near buoys (*Navion Saga*). *Should slack be avoided in steel wires?*
- paying out with low holding capacity on short wire lines from the winch (*COSLPioneer*). Could the lines be damaged by previous pay-outs? A line failure occurred a few hours after the pay-out on *COSLPioneer* and a week later on *Scarabeo 5* in 2008.
- Reduced strength in wires from bending (*COSLPionee*r).
- Twist of chain (Leiv Eiriksson).
- The ATA (DP) system was run in a sub-optimum way (*COSLPioneer*). Inclusion of thrusters in the mooring analysis and lack of weather data for the thruster-assistance system may cause incidents (*Deepsea Atlantic*).
- Communication of presumptions in the analysis and tuning of the ATA system (*Deepsea Atlantic*). Interferences drawn between the ATA and mooring systems are complex, and some of the failures indicate that the system as a whole did not function as expected. This might relate to the design of the systems involved, but also to the expertise of the people concerned.
- The analytical tools for extreme drift, extreme wave groups or outside the validity of applied theory, and lack of model testing (*COSLPioneer* and *Deepsea Atlantic*) and line dynamics (*Navion Saga*). Viscous loads are not included in all load calculation for semis, but shall according to the NMA regulation section 6 (3) be included. Statoil (Nybø, 2013) has made a description of how to include viscous effects in a simplified manner. A JIP (EXWAVE) will start up in 2014 to investigate the methods used for load calculations.
- Should there be a requirement to reanalyse all sea states above say 12m significant, to compare tension measurements with the calculation procedures for the unit?

In addition, UK investigations (Brown et al, 2005 and HSE, 2006, pages 13-14) point to factors as:

- "dog leg" or wavy mooring lines on the seabed
- excursion-limiting weighted chain and mid-line buoys
- unbalanced set-up of pretensions and lack of control with positions of the anchors.

The five overload cases indicate a failure rate of $3*10^{-2}$ per facility-year. This is too high by any standard.

One option is to increase safety factors in a way which promotes sound precautions. A disadvantage of this approach might be increased use of DP systems, which also have a significant failure rate or huge dimensions of anchor line components. Failures occurred in wires, chains, links and fibre ropes, and do not offer strong support for differentiated safety factors based on the material used. However, the failure frequencies might indicate a special need to increase safety factors for unprotected fibre ropes. A format for future safety factors might be to use the present ones, but to multiply them with an additional set of safety factors – if, for example, decent model testing or wind tunnel testing has not been performed, if unprotected fibre ropes are used, if ATA systems are used, etc. etc. (Kvitrud, 2013). The numeric values of factors must be based on expert evaluations and on what effect is wanted. These values should be stipulated conservatively, giving high credit for high quality. An order of magnitude might be 1.5-2 on each factor to secure a speedy improvement process (ALARP). For lifting equipment the safety factors for steel wire ropes are about 4.5.

Summary of possible future developments?

- The competences at the manufacturing and inspection companies are improved?
- Twist is reduced, and remaining twist is included in the analysis?
- Bending is accounted for in the analysis?
- Fibre ropes have protection?
- High strength steels are better understood (σ_F >800MPa)?
- Improved analysis tools for platform motions are used?
- Improved analysis tools for local line dynamics in vicinity of larger objects are used?
- The interaction between the thruster assistance systems and the anchor lines are better understood and accounted for?
- Three line failures consequence evaluations are required?
- The tension measurements and the line component traceability are used systematic to get the line loading history, and to verify assumptions in design?

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Aspects concerning material properties in the report have been discussed with my colleagues Ole Jacob Næss and Odd Hagerup. Major parts of the report were discussed during the Normoor JIP project meeting at DNV on 14 November 2013 and at OMAE on 12 June 2014. Valuable comments were achieved.

ABBREVIATIONS

ALS: accidental limit state; **ATA**: Automatic thruster assistance; **BOP**: blowout preventer; **DNV**: Det Norske Veritas; **DP**: Dynamic positioning; **FLS**: fatigue limit state; **FPSO**: floating production; storage and offloading unit; **FSO**: floating storage offloading unit; **FSU**: floating storage unit; **JIP**: Joint industry project; **MBL**: Mean breaking load; **Modu**: mobile offshore drilling unit; **MOU**: mobile offshore unit; **NCS**: Norwegian continental shelf; **NMA**: Norwegian Maritime Authority; **PSA**: Petroleum Safety Authority Norway; **STL**: Submerged turret loading; **ULS**: ultimate limit state.

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