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DRAFT - OMAE2014-23095 -LESSONS LEARNED FROM NORWEGIAN ANCHOR LINE FAILURES 2010-2013

Arne Kvitrud
Petroleum Safety Authority Norway (PSA)
Professor Olav Hanssens vei 10
NO-4003 Stavanger, Norway

ABSTRACT
The paper describes 15 failures of mooring lines in Norway in the period 2010-2013. The failures are cause by a mixture of overload, fatigue and mechanical damage.
The paper gives failure statistics from the period 2010-2013 and compares it with earlier statistics. In the period 1996-2005 a high number of cases were observed. Several actions were taken to improve the standard in the industry. The industry reacted reasonably, 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 failure of chains above 20 years of age. But several other failure modes have appeared or reappeared. Differences between different types of units are found. The failure frequencies in Norway has been in the order of magnitude

- single line failures: $88*10^{-4}$ per line year,
- double line failures: $10*10^{-4}$ per line year, and
- triple line failures: $2*10^{-4}$ per line year.

The paper also discusses possible changes in the regulations and standards on requirements and formats:
* The limitation in the control in damaged (ALS) conditions to one line failure for mobile units and two line failures for production units might be insufficient.
* Several fatigue failures urge for improvements in FLS controls.
* For ULS analysis, more conservative safety factors than applied at present might be necessary to reduce the number of failures.

INTRODUCTION
14 December 2004 a severe incident occurred on the Ocean Vanguard. The brakes of two of anchor 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 et al 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 of 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. A new regulation from the Norwegian Maritime Authority was issued in 2009 (NMA, 2009). Several years of detailed follow up reduced the number of incidents. The activities successful gave a reduction, and also zero failures of anchor lines during in service use for a period. However from 2010 the number of incidents increased again. The present paper gives updates on the incidents the last years, and describes changes.
The number of failures worldwide and in Norway is far too high, and the purpose of this paper is to assist in the improvement process.
Major parts of this paper have previously been presented at a Normoor project meeting (Kvitrud, 2013).

OUR CONCLUSIONS IN 2006
Kvitrud et al (2006) concluded that the number of incidents related to anchoring 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 transferring experience, and the crew had more insight into 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.
The equipment on board the facilities is the owner's responsibility, and the site-specific evaluations are the responsibility of the operator.
Failures of the anchor line itself were the most frequent cause of failures in the anchoring system in use. The quality and quantity of inspections and repairs in connection with the recertification of the chains was of major importance. Very much so, because chains that were more than 20 years old, was still in use. Recertification inspections and repairs are therefore essential in ensuring that the chain satisfies the applicable quality requirements to the anchoring line. The chain owners must knew the history of each individual line (cf. traceability) in order to ensure a successful recertification. Several fatigue failures occurred on anchor 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 were 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 rope had 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.

FAILURE OF ANCHOR LINES 2010-2013

The incident investigations have been performed by different personnel from investigation to investigation. This has several disadvantages and some advantages. The investigators have mainly been from the owners and managers of the platform, but in some cases the operators have participated or done their own investigation.

The causes of failures are not always obvious. Several causes of the failures have been pointed at, some of them are supposed to be the most reasonable based elimination.

Regalia semi 2010

Sometime between 18 and 20 June 2010 a steel wire rope failed on Regalia flotel for BP at Valhall (Prosafe Offshore, 2010 and 2012). The anchor was attached to a bolster (cowcatcher), and lost to sea. The maximum significant wave height in the period was about 6.2 m. The wire rope broke just above the anchor. The wire rope was connected via a snub nosed socket directly on the anchor. The anchor was attached to the bolster with 40-50 tons of tension. Inspection of the wire indicates that five of the six strands and the core parted just above where the socket was cast and the 6th strand (left holding the weight of the anchor) was pulled out of the socket, as the socket and anchor was lost to sea. The wire rope was 450m long, had a diameter of 86mm, and had six strands and breaking strength of 528 tonnes in the test in 2001. The anchor was a Delta Flipper anchor of 12 tons. The socket and anchor were not found again. Regalia operated on DP, and two anchors had been stored in the bolsters for some time. It was identified that the fitting of the socket arrangement was the root cause, as the socket fitted was oversized for the wire. The resulting failure of the arrangement was according to Prosafe Offshore, likely to be fatigue and failure of the socketing resin. Subsequently all other wires and socket arrangements were inspected and wires refreshed (cut back) and re-socketed with correct sized sockets. Later experiences with anchors in bolsters have demonstrated that waves give significant forces on the anchors and in the anchor lines (Andersen et al, 2013).

Transocean Winner semi in 2010

1 December 2010 Transocean Winner a chain failed, when working for Lundin, in connection with anchor handling operations (Transocean, 2010). A 76mm anchor chain failed. It broke approximately 170m from the fairlead in a 195m long section. The failure occurred due to fatigue (Transocean, 2010 and Lundin, 2013). Maximum tension in the chain registered in connection with the operation was about 210 tons. The ultimate strength of the chain was about 610 tons. Lundin (2013) concluded that the main underlying causes were insufficient inspection or maintenance. On arrival to the DNV laboratory, the chain link was too heavily corroded to do a meaningful material investigation (Transocean, 2013). The final failure was then most likely a sudden fracture caused by long term fatigue loading, and a crack developing during a long time.

It was produced by Vicinay in 1992 in NV K4-quality, and was last recertified in 2006. All the chains of this quality were removed from Transocean Winner afterwards.

Navion Saga FSO in 2011

20 June 2011 Navion Saga FSO working for Statoil at the Volve field lost the steel wire ropes in line 1 and line 4 (Statoil in several documents 2011 and 2012). On both lines, the failures were located at the bottom end of the upper steel wire segment at the bending stiffeners and the socket. The FSO did not experience any abnormal excursion during the events. No damages to the import riser or any other equipment were experienced. It is likely that the failures took place in two different occasions in stormy weather, several months prior to the inspection. There was no active monitoring of single mooring line integrity during operation (Statoil, 2.12.2011). Nine mooring lines were attached to the STL-offloading buoy, and again connected to the Navion Saga.

The direct causes were ductile overload of the steel wire rope strands at the rope termination at the seabed resulting from high, local dynamic “snapping” loads after the line had experienced a temporary slack condition. The failures were ductile of the type «cup and cone» (Statoil, 19.6.2011).

All the wire ropes were provided by Bridon and were "Spiral Beach" without plastic coating. Their diameters were 112mm and 106mm, and were of the type "Xtreme". The anchoring system was installed in 2006. The ultimate strength and elongation were better than the requirements (Statoil, 19.6.2011). The design included that the length of the upper wire rope segments were lying at the sea bottom in some load conditions and weather situation. It was also evident that the system would experience "slack" in many situations. The fact that the rope was lying on the sea bottom and that it had "slack", did not violate rules or design requirements (Statoil, 28.9.2011). Two additional discoveries were found on the wire ropes in line 4 in the post damage inspection. A kink and a wire "bird cage" were found in addition in the wire rope end against the STL-buoy (Statoil, 17.11.2011). 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. Even though seabed properties and drag on coupling segments are associated with large uncertainties, the phenomenon causing large curvature appeared for all combinations of parameters and with similar magnitude of the curvature. The phenomenon is thus considered to be realistic. Compression in wire rope may lead to buckling. This phenomenon has not been modelled in this study. However, there are indications that compression may occur during slack events*".

Songa Dee semi in 2011

1 September 2011 Songa Dee worked for Marathon on the Alvheim field. During anchor handling operation, the anchor line 8 was tensioned up by the anchor handling vessel Skandi Vega. The anchor on line 8 was secured on board the vessel, and the chain to line 8 was coupled to the chain in line 3. The crew detected a shift in the chain to line 8 and corrected this. Then they all left the deck as a safe area, and gave signal that the deck was clear and further tensioning could continue. The tension control was incorrectly adjusted, and the winch could tension the chain up to 460 tonnes (Acona, 2011). The data logs from the winch were automatically deleted after 12 hours (Acona, 2011). The winch control station had its challenges as monitors and winch settings and performance data was distributed to several monitors. There were several opportunities for which settings and indicators to be used. The suggestion from the vessel crew was to make this more intuitive and avoid misunderstandings by changing the indicator or tension control setting from percentage to tons, independent of number of winch engines engaged (Acona, 2011). The chain broke, and 60 meters of the chain fell down on the seabed. The incident can be seen on You tube (2012).

The chain was manufactured by Ramnäs in 2005, as NV R4-chain. According to the certificate, it had passed a proof load test in 2005 with 4753kN. Break load tests were done on pieces to 6030kN. It was last inspected in 2009 (DNV, 14.10.2011).

Mechanical testing of the failed chain link was done afterwards by DNV. The results show that requirements according to DNV-OS-E302 were met, except for the yield strength which was slightly lower than the minimum requirement. The deviation was not considered to be significant (DNV, 14.10.2011). The fracture surfaces had the appearance of ductile overload fractures with a bending moment, due to the observed shear lips, morphology and orientation of the fracture surfaces. The outer surface of the chain link was damaged and corroded, but none of the cracks or surface defects could weaken the chain link. All observations corresponded with overloading of the chain link (DNV, 2012). *The failure seems to have 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 the Transocean Leader worked on the Espevær field for Statoil. The mooring line 7 failed in a sea state of 5.8m significant. The mooring line broke at the upper end of five link adapters at the upper joining chain shackle (Kenter link) between the steel wire or socket with swivel and five link chain adapters. The rig experienced a maximum offset of 5.5m equal to a BOP flex joint angle of about seven degrees. At the time of the incident thrusters had been at 85% pitch for approximately 24 hours in order to reduce tension in the mooring lines. It was observed when the wire cover disappeared and that the buoys on the line came to the sea surface. In order to reduce the tension in the second line, all thrusters were used keeping the unit on location. The well was prepared for disconnection. An anchor-handling vessel was used to normalize the situation (Transocean, 26.10.2011).

It was a fatigue fracture in a three year old Kenter shackle, of type "Trident Thin type joining shackle". Stress-corrosion cracks and micro-cracks had initiated in these pits. The shackle was in an exposed area of the mooring line, receiving rough treatment. 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 / notches of the fitting lock connecting the two shackle halves. The initiation area has unfavourable geometry, with internal corners acting as stress raisers*" (Transocean, 26.10.2011). The transverse dimension (k-value) of the Kenter link, measured at the fitting area, was 10 % less than the minimum requirement according to ISO 1704, and it was considered possible that the Kenter link had been forged with a reduced k-dimension compared to the requirements. The smaller cross-section would have resulted in lower strength (Transocean, 26.10.2011).

Transocean Winner semi in 2011

25 November 2011 Transocean Winner on the T-Rex field for Maersk Oil at 314m water depth. A sudden drop in the anchor tension line 8 was observed. The tension dropped from approx. 200 tons to 28 tons, indicating a broken line. The rig moved about 15 to 20m from the original position. The anchor line 7 and 8 crossed the production pipeline from Kristin. A polyester fibre line had broken.

Maersk Oil (2011) wrote: "*Although not believed to be the root cause of the incident, it must be noted that the failure occurred in the same area of the fibre where it had experienced high friction, possibly combined with bending loading during handling for previous client. It is uncertain what consequences this had for the breaking strength of the fibre*". 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. From that, the date and time of when the "cut" by the object occurred, can be identified. 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 in the period in the area around the unit (Maersk Oil, 2011).

The minimum specified breaking load was 800 tons. The mooring line had been pull tested to 300 tons from the unit before use, in order to confirm strength integrity. It was a 158mm polyester rope parallel with twelve sub-rope cores. Each sub-rope was made up of eight strands. It was produced in 2007 by Bexco - Le Lis in Belgium (Maersk Oil, 2011).

COSLPioneer semi in 2012

25 January 2012 COSLPioneer working at Oseberg for Statoil had a double line failure. It operated on POSMOOR ATA. The weather conditions were wind of 28m/s, significant wave height 8-10m and Tp of 13 seconds (COSL, 2012 and Falkenberg, 2013). They were waiting for weather with LMRP and riser disconnected from the BOP.

First, line 1 paid out in the storm, with a tension of 4100KN. It was reinstalled.

Line 1 payed out again one and a half hour later, at a tension of 4376kN. This last pay out, was followed by a break in line 8, with recorded tension of 4837kN. Another pay out came one and a half hour later, line 1 must have been reinstalled, because it failed with a tension of 4624kN. Both lines broke above the fairleads.
According to Falkenberg (2013) the capacity of the steel wire ropes should have been reduced because of bending over the fairlead. The MBL of the wire rope were 6622kN. Reduction over fairlead of 0.875 gave an assumed strength of 5794kN. The measured tensions at failure were lower. The wire diameters were 90mm, and were produced by Bridon in 2009.
The winches maximum capacities were 750 tons when at least 850m of the wire was out. With 414 to 447m wire out, the winch capacity was reduced to about 70% of maximum (Rolls Royce, 2013). The extreme tension may have been missed due to a low sampling rate. In addition the following may have contributed to the incident: * the ATA (DP) system did not run in an optimal way, * high pretension, * extreme drift cannot be disregarded, * extreme wave groups and * being outside validity of applied theory.
On corrective actions COSL concluded (2012) ea. to * set a wider (looser) line system earlier when the weather is coming up. * Accept that there will be more movement and that they had to use more thrust in severe weather. * Not to use damping or low gain in severe weather. * Let the line system take up heading forces with no yaw on axes control. * Evaluate to use manual thruster control at an earlier stage in shallow water. * Position the unit between the position where it will end up if the thruster stops, and weather. This will lead to steady thrust in one direction with no spinning of thrusters. * Full tuning and verification of the DP system. * Double check that the line segments on each line put in the DPM-system is correct; it appeared to be errors on two segments. This may have had an impact on the stiffness of the anchor line system. The DP system might have “thought” that the system was stiffer than it actually was. * Verify the correctness of the mooring analysis.
Falkenberg (2013) concluded that the line breakages may be related to rush-outs of lines at tension lower than braking requirement. The main contributing factors were a reduction of the capacity over fairlead sheaves, the ATA (DP) system did not run in an optimal way, high pretension, extreme drift could not be disregarded, extreme wave groups and the analysis were "*outside validity of applied theory*".
DNV (11.3.2012) concluded that the failures most likely were due to overload of the mooring lines.

Deepsea Atlantic semi in 2012

26 January 2012 anchor line 8 failed on Deepsea Atlantic on the Gullfaks south field, when working for Statoil. The platform was waiting on weather and was disconnected from the well. It operated on POSMOOR ATA.
Trust of 300-350 tons was used ahead of the incident, and the line tension was up to 300 tons. The significant wave height was 9.4m, Tp was 14.2 seconds, the mean wind speed (at 10 meters) was 28m/s and the surface current from the Miros radar 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 platform got an offset of 18m before the chain broke. The ATA-system reduced the trust about 100 tons just before the line broke.
Kaasen (2012 and 2013) conclusion was that the wave train introduced a large slow drift. The present methods of calculation 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 2nd-order approximate method was used. At its peak the wave-drift force was 3500kN, which is considerably less than the “true” value of 4600kN obtained from the force balance. This indicate that the conventional quadratic response model for low frequency offset used in Newman’s approximate method, may underestimate the low frequency wave loads. Wave-drift coefficients from in-viscid refraction models (as Wadam) was claimed to be insufficient and to underestimate the loads under certain circumstances, in particular for semi-submersibles. Further, the presence of strong current may affect the wave loads. In addition, wave-drift is known to be dependent on the vessel’s pitching motion. This is not always reflected properly in the calculated wave-drift coefficients.
It was a 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 platform was built in 2009.
Odfjell (2012) concluded that the most important contributors to the incident were: lack of weather data, the analytical tools (slow drift and line dynamics), inclusion of thrusters in the anchoring analysis, communication of pre-assumptions in the analysis and tuning of the DP (ATA) system.

Polar Pioneer semi in 2012

11 March 2012 Polar Pioneer worked on Cormorant B / C field for BP. The tension on anchor line 5, fell from 145 to 45 tons. Polar Pioneer got an excursion of 12 meters from the initial position, and it 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 that was furthest from the rig and which was linked to the bottom chain, about 600m away from the fairlead and about 38m above seabed. The location of the failure was between the end of the eye and the crotch. Several subsurface buoys had twisted around the chains. The significant wave height was 6.2m.
BP (2012) concluded that the trigger for the event was that parts of the subsurface buoys shackles or chains came into contact with the fibre rope and lead to losses of two fibre ropes. An external, rusty object had cut the rope, on the outer side of the fibre rope in the "flexible" section between the hard thimble and the stiff crotch on one branch of the eye of the fibre rope. The cut started on the outer side, penetrated the braided jacket and progressed through 32 out of 36 sub-ropes, and partly into the remaining four sub-ropes. This resulted in the final failure due to overload. The cutting and the final failure must have occurred within a few minutes.
BP (2012) noted that twist in anchor lines may have been initiated during testing of the anchors holding capacity during pre-installation, and twist might have been stored when the chains was on sea bed. Twist may have been induced by the winch wires on the anchor handling vessel

(AHV). The AHV specifications did normally not include requirements for rotation free winch wires.

BP (2012) and Transocean (18.06.2012) concluded that the subsurface buoy shackle and the chain had been installed too close to the fibre rope. Further that rotational movement of the mooring line lead to the subsurface buoy arrangement got tangled up into the fibre rope.

Transocean Spitsbergen semi in 2012

2 August 2012 Transocean Spitsbergen worked on the Midgard field for Statoil. It operated on POSMOOR ATA. Chain 7 failed about 10m above the fairlead. The total line length was 1593m. The tension in line 7 was 150 tons, the wind of 14m/s and sea 2.1m significant (Transocean, 10.12.2012).

According to DNV (28.11.2012) and Transocean (10.12.2012) the failure was due to fatigue. The elongation, the reduction of area and the Charpy impact test results were significantly different from the values in the certificate. Improper heat treatment had resulted in an inferior microstructure and mechanical properties deficient of the chain material with high notch-sensitivity and low ductility. The extent of corrosion was considered remarkable, and it was possible that deficient heat treatment had caused increased susceptibility to pitting corrosion related to microstructure or chemical composition of the surface layer. The fatigue cracking was initiated at corrosion pits on the external crown which was exposed to high tensile stress and with these pits acting as stress concentrations to initiation of fatigue. The 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.

Statoil (11.12.2012) 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. When the hydrogen crack has reached a critical depth, the chain link finally has broken in a brittle manner, likely since the chain material exhibit impact toughness below requirements. 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). The reason for these high tensile properties are only associated to heat treatment performed on the chain links in question; i.e. austenitizing of the steel followed by quenching and no or insufficient tempering. When studying the hardness measurements performed in the area close to the fractured chain link, it is demonstrated high hardness (>400 HB) in several chain links. It is also observed both high and normal hardness levels within the same chain link, strongly indicating a local heat treatment*."

The chain was a Ø 84 mm NV R4 quality, and it was manufactured by Jiangsu Asian Star Anchor Chain in 2008 (Transocean, 10.12.2012). The line chain failed at about one third of the tensile strength.

Transocean Barents semi in 2012

13 September 2012 Transocean Barents worked on the Jette field for Det norske. During testing of line 3, the tension in the rope fell from 300 tonnes to 60 tonnes. It was a line failure in a fibre rope about 350m from the unit. The BOP was not connected.

DNV (9.11.2012) concluded that a force had cut nine sub-ropes, destroying about 35% of the cross section. Most likely, it was a fixed object where the fibre rope had moved along or bent over a sharp edge. The remaining subropes were pulled to break either, some over time and some during the pretensioning. The remaining subropes were most likely unbalanced as the residual strength only reached 295 tons or 37% of MBS. The cut occurred most likely within seconds or minutes. The line had been subjected to external mechanical damage, but the reason for this could not be determined (Det norske, 2012). They did not rule out that the damage could have been caused during launching and connecting the anchor line. No fishing boats had been in the area during the relevant period. The installation was done by Viking Seatech with the vessel KL Saltfjord.

The core of the rope was made of twelve triple strands parallel to each other. Half of 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 get twist during the tensioning (Det norske, 2012). The age of the line and the name of the producer are not given in the report.

Norne FPSO in 2012

An alarm on an anchor weight cell 6 November 2012, on the Norne FPSO for Statoil, indicated an anchor 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. However, the failure was confirmed four days later (Statoil, 2013).

The first failure was caused by fatigue, caused by un-normal loads or bending of the chain. The fatigue failure was close to the weld. It was explained by Statoil to be caused by either incorrect location of the chain in the fairlead, or the fairlead had not rotated. A FEM analysis demonstrated that an incorrect location of the chain, would give significant bending forces (Statoil, 2013).

The second failure came in the same chain link. It came immediately afterwards caused of overload, due to the fatigue failure (Statoil, 2013).

The lines had operated with higher pretension (about 160 tons) than presupposed in the design (140 tons). The winch had not worked as it should, since May 2012. They had not been able to follow their own program to change the length of the lines monthly to redistribute the stresses, and the chain member had been unintentionally too long time in each position. The chain was 114mm of type NV K4 stud less chain, with a breaking load of 12420kN. No deviation in the material quality was found in the material testing. It was installed in 2007 (Statoil, 2013).

Petrojarl Varg FPSO in 2012

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

The failure was due to high-cycle, low stress fatigue that had initiated on the external surface of the link and propagated due to bending of the link. The fatigue initiated or propagated as a result of bending of the chain link, and the bending moment was most likely introduced due to a rotation or incorrect position of the chain link in the fairlead, or as a result of out of plane bending (DNV, 3.4.2013). Vicinay (Teekay Petrojarl, 2013) concluded: "*Due to a high tension working conditions cold working could cause locally interlink over hardness that has led to nucleate cracks in the surface. As per the result of the fatigue test the tension-compression cycles in normal condition would not make the inner bend crack to growth*." 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 in the period March 2008 to October 2012. Most probable scenario is that crack has developed over time (we were not able to quantify this period) before the link was cracked more or less completely through during the high loads experienced in a September 2012 storm and that the link was opened up during the winter storm experienced 2012-12-14. This theory is based upon the appearance of the link fracture surface just after pick up from sea*." The wear pattern on several of the chain links, including the fractured link, was consistent with wear expected due to relative movement against the fairlead. The fatigue had initiated or propagated as a result of bending of the link around a pivot point which may be the fairlead, a neighbouring link or due to out of plane bending. General surface corrosion was obvious, with extensive localized corrosion, significant wear and cracks on the external surface around the fracture surfaces. General corrosion and severe localized corrosion would have acted as stress intensifiers and initiation spots for fatigue cracks due to roughening and pitting of the external surface (DNV, 3.4.2013).
The chain was produced in 1996 by Vicinay, and installed in 1998 with fifteen years design life. It had grade NV R4, stud less and with a nominal diameter of 100 mm. The material was within specifications, thus material properties did not contributed to the failure of the chain link (DNV, 3.4.2013). The minimum breaking strength was 1005 tons.

Island Innovator semi in 2013

22.11.2013 Island Innovator worked block 16/2-20 for Lundin. A steel wire failed about 15m from the fairlead. The investigation report is not available 2.1.2014. The text will be updated.

Leiv Eiriksson semi in 2013

9.12.2013 Leiv Eiriksson worked on the Trell location for Total. Anchor line no 6 failure during cross tension testing. When pulling up from 200 tons to planned 416 tons, the anchor chain parted at 387 tons. All other lines were tested to 416 tons. The winch was operated from the bridge during the test. The investigation report is not available 2.1.2014. The text will be updated.

FREQUENCIES OF FAILURES

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

Data published by the UK HSE (Morandini and Legerstee, 2009 with reference to DNV Industry AS, 2003) suggests an average historical rate of FPSO mooring failure about once every seven operating years, of FSU mooring failures about once every 17 operating years, of drillship mooring failure about once every 1.5 operating years, of drilling semisubmersible about once every four operating years, and of production semisubmersible about once every eight operating years. Two accidents on UK Continental Shelf have also actualized the need to reconsider the anchoring systems. The accidents occurred 4 February 2011 on the Gryphon Alpha FPSO and 10 December 2011 on the Petrojarl Banff FPSO (Brown, 2013). The initiating cause on Banff was probably a failure of the fairlead due to overload (Statoil, 2013, page 29). The link failed at fairlead (Brown, 2013). The first line failure at Gryphon Alpha was probably due to fatigue failure of a flash butt weld in a chain below its design capacity (Statoil, 2013, page 29 and Brown, 2013). The FPSO moved 180 metres off station resulting in significant damage to subsea equipment (Brown, 2013). Multiple line failures have also occurred worldwide, as described in e.g. Jean et al (2005), Wang et al (2009), Ma et al (2013) and Majhi and D'Souza (2013).

Table 1: The causes of 14 failures on anchor line elements in the period 2010-2013. Errors in the winches or brakes are not included. (+2) is referring to the second failure in the two double line failures. The causes of the last two failures are not found 2.1.2014. To be updated.

	Fatigue	Overload	External damage
Chains	4	2	
Fibre ropes			3
Steel wires		3 (+2)	
Kenter link	1		
Socket connection		1	

We do not have information on how many components of each type that has been used. The last four years the number of anchored mobile units has been about 25 and the number of production platforms about 19 units. Assuming the mobile units have in average eight anchor lines and the production units twelve lines 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 have not improved the last ten years, since the observed frequency from the events in Norway was 100 x 10^{-4} per line year in the period 1996-2005 (Nilsen, 2005 and Kvitrud et al, 2006). The difference is clearly within the uncertainty. Three incidents were on production units and the remaining on mobile units, giving mobile units a slightly higher failure rate (150*10^{-4} vs. 33*10^{-4}).
One double line failures has been on a production unit and one 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 platform year.
Since year 2000 there have been one triple line failure in Norway. In a summer storm 13 June 2000, the Bideford Dolphin suffered three anchor line failures. It was shackles (CR-links) that failed due 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

platform year. The two cases in UK indicate that the probability of three line failures found from the Norwegian data alone might be underestimated, provided the failures in the UK and the NCS have the same order of magnitude of statistical properties. Lower safety factors are used in UK than in Norway, indicating that the relevance of the UK data applied in Norway might be questioned.

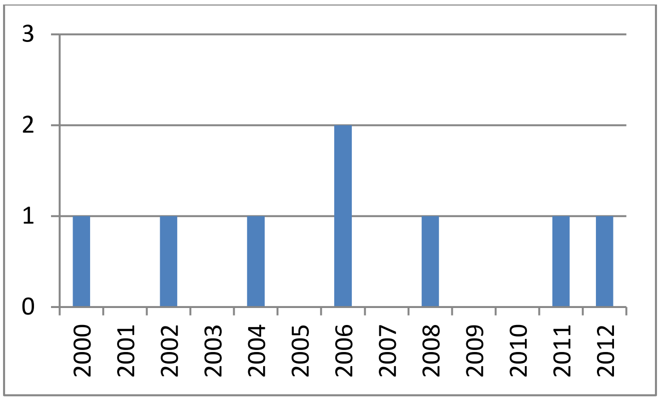

Figure 1: Cases with two or three line failures in the period 2000-2012 on the NSC. The cases are failures of lines, pay out from the winch, or significant dragging in combination with a line failure.

Ma et al (2013, page 3) reported a worldwide failure frequency estimate of $30*10^{-4}$ per platform year for major mooring incidents on production unit, describing a major incident to have at least two line failures. This is not significantly different from the Norwegian data.

CONSEQUENCES ON THE REGULATORY FRAMEWORK

The safety of anchoring systems on the Norwegian continental shelf is mainly regulated by the facilities regulations and the framework regulations section 3. The facilities regulations section 63 on anchoring, mooring and positioning, state 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 anchoring 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 that follow the framework regulation section 3, shall comply with the regulations of the NMA, together with supplementary classification rules issued by Det Norske Veritas.

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

Compliance with the NMA regulations from 2009 (NMA, 2009), have caused several failure modes to disappear from our event records. Examples are

- Dragging of anchors, prevented by pretension and standardized dragging calculations.
- Failures of chains older than 20 years, prevented by increased and frequent inspections.

The PSA facility regulation section 11 and the DNV-OS-A101 section 2 D103 are generally based on accidental loads affecting safety functions which have an individual frequency of occurrence in the order of 10^{-4} per year.

Standardized quality improvements will only cover some aspects of the failures. One of the rig owners and one of the operators are overrepresented each with six out of 14 line failure cases (some in common). This may indicate that other aspects than the pure technical are also very important.

Selection of materials, fabrication and use

A question timely to ask is also if the requirements to the materials are sufficient? Almost all the material testing confirms that the material properties had been according to the rules. But, *do we use steel with too high strength, or with other unintended properties*? Are the ductility requirements sufficient to give redistribution of stresses? Can hydrogen give unintended brittleness in the high strength steels? Steel with yield tension above 700MPa are vulnerable to hydrogen. Even if the anchor system does not have anodes, the platforms own CP-systems produce sufficient hydrogen free of charge to the anchor lines. Higher steel qualities give opportunities for higher tension, and higher tension variations increase the possibility of fatigue failures. General and localized corrosion in chain links may question if the quality control, inspection, competence and transfer of experience is sufficient.

Two of our failures were due to improper heat input, and have caused the chains to be non-ductile. Is the competence and is the quality control in the industry sufficient?

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

The accidental limit state control (ALS)

The NMA regulation require a control in damaged condition with one failed line for mobile units in open water, and two lines failed for production units and flotels. In addition requirements are given to the weather conditions to be used in the damage control calculations.

We have experienced several two line failures for mobile units and on production units. None of them caused severe damage. However, the experience from UK demonstrates that a three line failure can give substantial damage. A requirement to control the consequences of three line failures should be evaluated. Three line failures control, have already been introduced on the Skarv and the Aasta Hansteen production units. A requirement to be assesses is i.e. "*Three line failures shall not give unacceptable consequences*".

An obvious question is why don't all the incidents end up in an accident? And are some of the root causes less severe than others? Systematic errors will frequently give more adverse situations than random errors. Causes of systematic errors can be e.g.:

- As at Bideford Dolphin when the design of the shackles were systematic in error,
- As at Regalia with wrong type of sockets,
- Heat treatment errors as on Transocean Spitsbergen,

- Errors or inaccuracy in the standard load calculations methods as highlighted for Navion Saga, COSLPioneer and Deepsea Atlantic.

The fatigue limit state control (FLS)

Fatigue analysis has been required on production units and flotels for many years. The regulation requires calculations to be prepared 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.*

Three of our fatigue failures were on mobile drilling units and two on FPSOs. Four failures were in chains and one in a Kenter link. The ages of the members were 18, 3 (the Kenter link), 4, 5 and 16 years. The ages might indicate a U-curve. Members older than 20 years have in practice been taken out of use, due to the strict inspection requirements in the NMA 2009 regulations. The main causes of the five failures, found by the investigators are

- Insufficient inspection or maintenance (Transocean Winner).
- Stress-corrosion assisted fatigue and unfavourable geometry (Transocean Leader).
- Improper heat treatment combined with hydrogen (Transocean Spitsbergen).
- Bending of chains caused by either incorrect location of the chain in the fairlead or the fairlead had not rotated (Norne).
- Out of plane bending due to bending in fairlead or rotation of chain (twist) (Petrojarl Varg).

Since year 2000 there has also been reported three other fatigue failures, on Balder in 2009, Bideford Dolphin in 2006 and Deepsea Trym in 2004. One of them was caused by unauthorized welding of chains at the manufacturer. Brown et al (2005), HSE (2006) and Næss et al (2006) describe additional causes of fatigue failures.

With five cases of fatigue failure, questions have to be asked if the present state of art is good enough! Improvements might include:

- Detailed verifications of fatigue analysis and assumptions.
- Inclusion of bending effects in the analysis. The effects are known in the industry related to friction induced bending, twist, unbalanced set-up of pretensions, chain links fixed in the fairlead over a long time etc.
- Higher design fatigue factors due to high uncertainty.
- If FLS analysis is not performed the consequences of possible fatigue failures have to handled in a reasonable way in the ULS and ALS controls.

The ultimate limit state control (ULS)

The NMA regulation (2009) prescribe calculations to be in accordance with the methodology specified in ISO 19901-7 (2005), and safety factors to be in accordance to the NMA regulation and the Norwegian annex B of the ISO standard.

It is normal that events more frequent than 10^{-2} per year are handled in ULS, and more infrequent events in ALS only. 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 ULS to intact conditions. In NORSOK both collisions, waves and earthquakes are controlled both with 10^{-2} and 10^{-4}-loads. For a platform with ten lines, a failure frequency in the order of 10^{-3} per line year can then be in the ULS control. As an example the fibre ropes have three failures in (4 years * (25 + 19) platforms) giving $1.7*10^{-2}$ failures per platform year, if all the platforms had fibre ropes. This is not the case, and the frequency will be significantly higher. *Inclusion of one line failure as a part of ULS should be evaluated.*

The main causes of the five failures since 2010, found by the investigators were caused by:

- Errors in socketing of wire rope (*as Regalia*),
- Damage of fibre ropes during maritime operations as installation, removal or use of steel wires in the sea (*as Transocean Winner, Polar Pioneer and Transocean Barents*),
- Loads causing slack (compression) in wire ropes near buoys (*as Navion Saga*),
- Pay out, with low holding capacity on short wire lines out from the winch (*as COSLPioneer*). Can the lines be damaged by previous pay outs? At COSLPioneer the line failure occurred a few hours after the pay out and at Scarabeo 5 in 2008, a week later.
- Reduced strength of wires in bending (*as COSLPioneer*),
- The ATA (DP) system did not run in an optimal way (*as COSLPioneer*). Inclusion of thrusters in the anchoring analysis and lack of weather data to the thruster assistance system my cause incidents (*as Deepsea Atlantic*), Communication of presumptions in the analysis and tuning of the DP (ATA) system (*as Deepsea Atlantic*). The interferences between the ATA system and the anchoring system are complex, and some of the failures indicate that the system as a hole did not function as expected. This might be connected to the design of the systems involved but also on the competence of the parties involved.
- The analytical tools for extreme drift, extreme wave groups or being outside validity of applied theory and lack of model testing (*as COSLPioneer and Deepsea Atlantic*).
- Line dynamics (*as COSLPioneer*).

In addition other investigations (Brown et al, 2005 and HSE, 2006, page 13-14) point at e.g.:

- “Dog Leg” or wavy mooring lines on the seabed,
- Excursion Limiting Weighted Chain and Mid Line Buoy,
- Unbalanced set-up of pretensions or lack of control with positions of the anchors.

The five overload cases indicate a failure rate of $3*10^{-2}$ per platform year. If the three fibre rope failures are included the failure rate will be $5*10^{-2}$ per platform year. This is by all means too high.

An option is to increase the safety factors in a way that promote sound safety precautions. A disadvantage of higher safety factors might be an increased use of DP systems, also having a significant failure rate. Failures occurred both in wires, chains, links and fibre ropes, and the failures does not strongly support differentiated safety factors based on material. The failure frequencies might though indicate a special need for increased safety factors for unprotected fibre ropes. A format of the future safety factors might be to use the present safety factors, but multiply them with an additional set of safety factors e.g. if decent model testing or wind tunnel testing has not been performed, if fibre ropes without protection are used, if ATA-systems are used etc. (Kvitrud, 2013). The numeric values of factors must be agreed on by expert evaluations. The values should be stipulated conservatively, giving high credit for high quality; an order of magnitude might be 1.5-2 on each factor to get a fast improvement (ALARP) process.

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ACRONYMS

ALS: Accidental Limit State; **DNV**: Det Norske Veritas; **FLS**: Fatigue Limit State; **FPSO**: Floating production; storage and offloading platform; **FSO**: Floating storage offloading unit; **FSU**: Floating storage unit; **MODU**: Mobile Offshore Drilling Units; MOU: Mobile Offshore Units; **NCS**: Norwegian continental shelf; **NMA**: Norwegian Maritime Authority; **PSA**: Petroleum Safety Authority Norway; **ULS**: Ultimate Limit State.

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