Failures of offshore mooring steel wire ropes

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ABSTRACT

Steel wire ropes use individual wires moving relative to each other in a spherical structure. The behaviour of wire ropes exposed to loading, are not as beams or other structural elements. The ropes function is optimal when the individual wires can move in the rope. Several internal and external conditions can prevent the individual wires to move optimal, and change the behaviour of the rope. Based on two double overload failures, the paper describe the condition and behaviour of the failed steel wire ropes mainly as consequences of distorting the behaviour of the individual wires.

KEY WORDS

Steel wire ropes; twist; lubrication, wear; corrosion; bending.

INTRODUCTION

Offshore steel wire ropes are made of steel with typically 0.75-0.86% carbon content. The wires are galvanized using zinc. The individual wires are lubricated to fill the spaces between the individual wires. They are helically wound together to form a steel wire rope in specified combinations. If specified by the customer, they add polymer coatings outside the rope. They make end terminations, and the steel wire ropes are tested. The ultimate strength of offshore steel wires is typically about 2000MPa.

We have previously summarized the failures of Norwegian offshore anchoring lines, including the failures of steel wire ropes (Kvitrud, 2014). We have included information about Norwegian steel wire rope failures in lifting and drilling appliances. We are relying heavily on the industry investigative reports. Information about failures in offshore steel wire ropes are in e.g. Ma et al (2013), Leeuwenburgh and Brinkhuis (2014) and Leeuwenburgh (2015).

We describe the circumstances of the two Norwegian double mooring line failures. Then we describe the change of behaviour caused by violation of the individual steel wires possibility to move relatively to each other, as a function of lubrication, wear, corrosion, the distribution of loads over the cross-section of the rope, twist, bending, payout of lines and testing to 100-year load levels. We concentrate on the rope behaviour, and do not discuss the size of the tension. The size of the loads from the waves are currently investigated in the EXWAVE JIP project.

THE NAVION SAGA FSO FAILURES IN 2011

Navion Saga built in 1991, has been a FSO on Statoil's Volve field since 2006. She has a DNV GL classification, including POSMOOR. APL made the line design. The STL offloading buoy connect to nine mooring lines at 90m water depth.

On 20.6.2011 two steel wire ropes on the Navion Saga FSO failed. The failures were on both lines located at the bottom end of the upper steel wire rope segment, at the bending stiffeners and the sockets. The failures probably took place on two different occasions in stormy weather, several months before the inspection. This conclusion relies on the degree of corrosion. No inspections of the line integrity were done from the installation until the failures were found (Statoil, 2.12.2011).

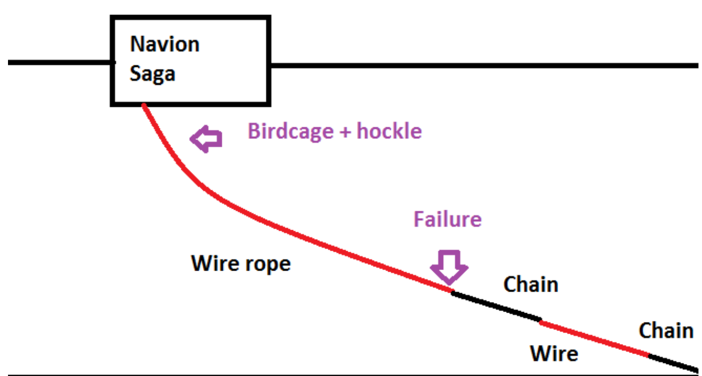

Figure 1: Schematic line set up at of line 1 and 4 at Navion Saga (not in scale).

Bridon provided the wire ropes of Spiral Beach Xtreme type (without plastic coating). The 106mm rope in line 4 was galvanized, 1*349 spiral strand, the ultimate strength was 1960MPa, and with a minimum specified breaking load of 1150 tons. The 112mm rope in line 1 was galvanized, 1*403 spiral strand, the ultimate strength was 1960MPa and with a breaking load of 1403 tons. It should be free from self-induced rotations. The production and installation of the ropes were in 2006. Swivels were not used.

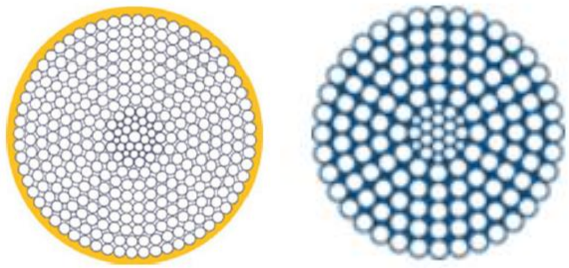

Figure 2: The investigative reports on Navion Saga do not show rope geometry. The pictures are examples of Bridon Xtreme spiral strand ropes found on Bridons internet pages. The Navion Saga ropes had no outer protection sheath in 2011.

Post failure testing demonstrated that its ultimate strength and failure elongation were higher than the requirements (Statoil, 28.9.2011). The yield strengths were 1564-1859MPa and the ultimate strengths were 2204-2263MPa. The ratios between the ultimate and the yield strength were 1.22-1.41. The elongation at failure were 7-9%. The lubrication was almost gone, but had some remaining inside. The wires were galvanized (Zn), but all the zinc was gone in the failure areas. It had some corrosion. Anodes had disappeared on the sockets.

All the failed wires in the outer layers showed ductile overload. Both lines showed global bending or permanent plastic deformation in one direction. This indicated that the failures did not occur in pure tension loads. The visible failure surfaces were of the types "cup and cone", 45 degrees shear and in addition much "topography and lamination". This is typical to pure tension overload failures and with significant plastic elongation and reduced area in the failure zone. Post damaged tests of wires in pure tension showed the same characteristics. The tendency to 45 degrees is typical for both ductile overload and shear failures (Statoil, 5.7.2011).

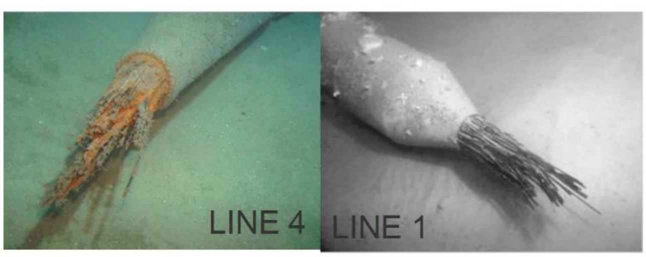

Figure 3: The failed areas of the ropes at Navion Saga (Statoil, 17. 2012).

The lines failed in significant milder weather conditions than what should cause problems. According to the analysis, parts of the upper wire rope segments probably hit the seabed in some drafts and weather conditions. Statoil did not report trenches on the seabed as was reported on the Bluewater's Haewene Brim platform, but the assumption is reasonable to us. It was also evident that the system would experience slack in many circumstances (Statoil, 28.9.2011). The post-damage inspections found a kink and a birdcage on line 4 wire rope, at the end against the STL buoy (Statoil, 16 Nov 2011).

Aksnes et al (2013) reported, "*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*."

Statoil concluded in 2011 that 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. The remaining wires had been deformed permanently (Statoil, 28.9.2011).

DNV (DNV, 2013) made experiments to reproduce the failures. The tests were in slow motion, not necessarily reproducing the actual failure situations. They tested samples from line 8 from Navion Saga. The rope in line 8 had the same size as in line 1 (112mm) and was produced in 2006. The wires had significant external corrosion close to the socket. The bolted connections to the bend stiffener to socket had some slack. Some bolts had heavy corrosion, and some bolts had failed on bend stiffeners. One bend stiffener had fallen off the socket completely. They tested bending, combined bending and axial compression, and the last one in axial compression. It was not possible to reproduce the failure modes. The rope had significant hysteresis in pure bending. After the testing it was found that the

- Lubrication had been pressed out on one side,
- Zinc was still present on the outer wires close to the socket,
- Wires had lost significant amount of material due to corrosion, possibly in combination with wear,
- The cross section of several wires were no longer circular.
- The loss of material was not uniform with large losses in small areas.

THE COSLPIONEER FAILURES IN 2012

COSLPioneer is a semisubmersible platform own by the COSL company. Yantai Raffles Shipyard completed the fabrication in 2010. She has DNV GL class including DYNPOS-AUTRO POSMOOR-ATA. She has eight steel wire rope winches from Rolls Royce. COSLPioneer experienced 25 January 2012 a double line failure when working on Crux on block 30/06 for Statoil. The water depth is 109m. It was operating in ATA mode (both anchoring and thrusters). The wind was about 28m/s and waves 8-9m. The wind direction was from 165 degrees. Some details of the Crux mooring (DNV, 09 Sep 2012):

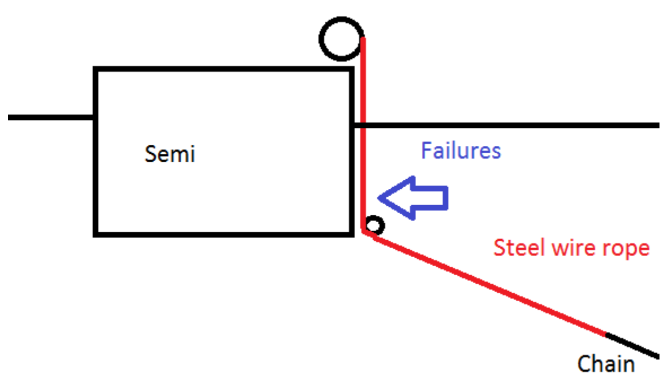

Figure 4: A schematic line setup on COSLPioneer. The figure is not in scale.

Line 1 was in the southwest direction:
* From the anchor 1250m: 76mm stud less chain with MBL 6004kN.
* Chase stopper of 13m 84mm stud less chain with MBL 7210kN.
* 401,6m platform steel wire rope.
Line 8 was in the southeast direction:
* From the anchor 1500m: 84mm stud less chain with MBL 7210kN,
* Chase stopper of 13m 84mm stud less chain with MBL 7210kN,
* 425m platform steel wire rope.
The investigative reports do not state if swivels were used.

The steel wire ropes were Bridon Diamond Blue rope: “88.9mm 6*47WS-IWRC (1-6/8+8-16) sZ B(Zn)”. It had a nominal diameter of 88.9mm. The rope had six strands each of 47 individual wires. It had an independent steel wire rope core (IWRC). It was cross-laid (sZ), and galvanized (class B) by zinc (Zn). The specified ultimate tensile strength was 1960MPa, but the actual values were higher. The rope had a stated minimum breaking load of 6619kN and an actual breaking load of 7019kN. The higher the strength the more vulnerable the wires will be for hydrogen especially in the splash zone. Bridon produced the steel wire ropes in 2009, and they were three years old at the time of the failures. The rope had been less than two years in seawater. The anchor chains were prelaid with drag anchors. The reports do not say if it was also pretensioned.

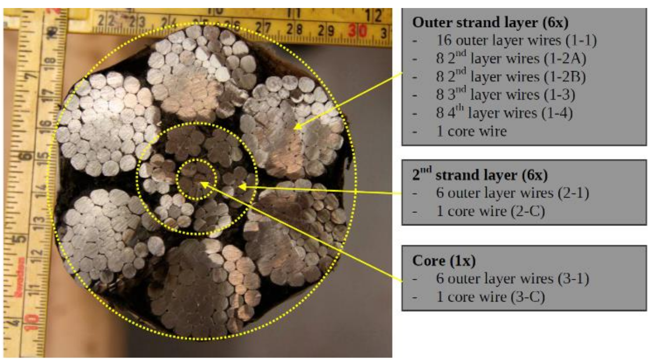

Figure 5: Geometry of one of the ropes after the failure (DNV, 12.3.2012). The strands seems is partly disconnected to each other on the left side of the picture. This might have been a post failure damage.

Line 6 and 7 had buoys attached. Line 1 and 8 had the shortest steel wire segments of all the lines, making them most vulnerable to payouts.

Unintentionally, the line 1 paid out (partly ca. 22-39 meter) with a tension of 4.100kN. Line 1 was reinstalled. It paid out (ca. 15-21 meter) again 90 minutes later at a tension of 4.376kN. The payouts were because of the design of the winches. The maximum capacity of the winches was 750 tons when at least 850m of the wire was out. With 414-447m of wire out, the winch capacity was reduced to about 70% of maximum (Rolls Royce, 2013) i.e. 5150kN. The payout tension was in fact significantly lower (about 55-60% instead of 70%). The winch capacity might have been significantly less than stipulated.

This second payout of line 1 was followed by a failure of line 8, at a recorded tension of 4.837kN. The measured failure tension was 69% of the tested breaking load! The sea state had Hs= 8.7m and Tp=12.6s.

Line 1 failed about 90 minutes later, with a tension of 4.624kN. The measured failure tension was 66% of the tested breaking load! The sea state had Hs= 8.5m and Tp=13s. Both wire ropes broke above the fairleads.

Bending over fairlead sheaves reduce the capacity of steel wire ropes. We will discuss this later on.

DNV (11.3.2012) at Høvik examined three of the four failed surfaces. The rig owner gave no cross references between the rope number and the line number. The fractures expanded over 4-6m. All the strands failed on different locations, mainly due to the strands have coiled away from the failure zone. Some of the failures of single wires showed signs of corrosion. The core strand had protruded from the rope and was laying on the outer surface, probably (according to DNV) due to stress release during the failure.


Figure 6: Representative picture of failed single wires, and on corrosion on a strand after two years in use (DNV, 11.3.2012).

The lubrication was mostly dried up, and small amounts of corrosion was observed. The strands showed signs of wear and deformations. The corrosion appeared in local areas with wear or deformations probably caused by the zinc wearing off. Single wire failures were especially where the single wires of one layer crossed the next layer. The rope had significant amounts of sand and corrosion products. The sand could be a post-damage consequence. The core strand contained a noticeable number of single wire failures. The single failures observed in the core showed failure surfaces angled at about 45 degrees. This is often associated with tensile overload or fatigue (DNV, 11.3.2012). According to Statoil (5.7.2011) the tendency to 45 degrees is typical for ductile overload and shear failures. The mechanical testing showed compliance with the DNV requirements (DNV, 11.3.2012). DNV (11.3.2012) concluded that the failures were probably caused by overload.

The failure mechanisms were not the same in all individual wires. A possible interpretation is that the development of the failures was:
* The loss of lubrication invited to internal wear taking away the galvanization, followed by corrosion. The ropes ability to react to the loading was no longer as intended. Disappearance of the lubrication with increased friction increased the effect.
* The lack of lubrication, wear and corrosion caused twist in the lines. The bending in the sheave of the fairlead cause increases in bending load or reductions in the bending capacity.
* The core wires might have failed first in a combination of twist, bending (shear) and tension.
* In the end, the strands failed in overload.

Falkenberg (2013) concluded that the exact extreme tension can have been higher, due to the sampling rate (2Hz). The main contributing factors were
* A reduction of the capacity over the incident.

* The automatic thruster (ATA) system did not run in an optimal way.
* High pretension.
* Extreme drift could not be disregarded.
* Extreme wave groups.
* Being outside the validity of applied theory.

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 use more thrust 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 ATA system was correct. The system might have “thought” that the system was stiffer than it actually was.

POSSIBLE CONTRIBUTING FAILURE MODES

The conditions before the failures

The metallurgical investigations of the two failures concluded that the failures were by overload. If hockles or birdcages existed before the failure, it would be difficult to find out after the rope and the involved wires have failed in tension. Hockles and birdcages reduce the capacity significantly (Leeuwenburgh and Brinkhuis, 2014 and Feyrer, 2015). On the Bluewater’s Haewene Brim FPSO, testing demonstrated that a birdcage reduced the capacity to about 2/3 of the MBL (Leeuwenburgh, 2015, page 8). This is in the order of magnitude the failure tension on COSLPioneer. Can birdcages have existed on COSLPioneer? Navion Saga line 4 had a hockle and a birdcage outside the failure area. They were near the STL buoy. It is unknown if they occurred before or after the failure. On Haewene Brim the birdcages were found before the failure (Leeuwenburgh and Brinkhuis, 2014), and it is reasonable to believe that they also existed on Navion Saga before the failures.

Birdcages occur when a strand separate from the core, and the strand gets a permanent damage. This may occur due to rotation when the line tension is relieved rapidly. It can also occur even if there is still tension in the line (Conway and Costello, 1990). Shock-loads in cranes often cause birdcages, but according to Roland Verreet (2002) in most cases improper geometry of sheaves caused twist as basis for bird caging.

A hockle (or loop) can occur at low tension and high twist. A twisted rope is vulnerable to hockle when it is unloaded (Chaplin et al, 2000). Hockles come by transfer of elastic energy between different forms of deformation (torsion, tension and bending). Hockles appear when deformations have opened up the wires. For the Navion Saga case, our interpretation are that twist and local geometry changes occurred in each repeated shock load situation. The deformations moved to the end terminations, stored there as increased deformation for each load cycle, and developed to birdcages or hockles.

Lubrication and internal wear

Typically, the lubrication in seawater will disappear in the outer areas first. The lubrication reduces the friction and reduce the wear. When the lubrication disappear or is only locally present, the friction will increase between the individual wires. In our two cases the lubrication were more or less gone on the outer parts.

Both our two cases had wear. Movements of the individual wires cause wear of the galvanization. The worn galvanization products will be present inside the rope, and accelerate the wear.

On Bluewater’s Haewene Brim FPSO, the overall diameter reduced with about 6% because of disappeared zinc (Leeuwenburgh and Brinkhuis, 2014). As a result, the pitch of individual strands changed, increasing the susceptibility for birdcaging to develop.

There are of course also other causes of wear as:
- Mistakes when reeling from the drum.
- Sheaves or swivels that does not work as it should or do not rotate.
- Individual wires rub against each other in the drum.

How frequent should steel wire ropes be relubricated? When is lack of lubrication critical? Inspection methods to find wear exist. It is difficult to relubricate a steel wire rope in the sea for production units. Site-specific equipment can be relubricated onshore e.g. using lubrication chambers, but it is expensive.

Corrosion

Both our two cases had internal corrosion. A steel wire rope has significantly larger surface areas than normal steel structures, making it more vulnerable to corrosion. When the galvanization worn of, the corrosion starts.

Lack of lubrication, wear products and internal corrosion inside the rope increase the friction. Again causing more wear, corrosion and twist. For lifting equipment, internal corrosion in a steel wire rope is a discard criterion. ISO 4309:2010 table 6 states as a discard criteria: “*Obvious visible signs of internal corrosion – i.e. corrosion debris exuding from the valleys between the outer strands*” and “*Assessment of internal corrosion is subjective; However if there is any doubt about the seriousness of any internal corrosion, the rope should be discarded*”.

Twist

When tensioning a stranded steel wire rope, it will produce twist. It is because of the helical design. The torque is approximately proportional to the tensile load. If swivels are used, they will not transmit torque at low load. When the load increase, the swivel locks and torque transmit to neighbouring line members, the anchor, the fairlead sheave or the drum. Ball joint swivels can avoid it. However, the Norwegian industry do not use ball joints, because strands loosens in its structure and give unintended stresses in the steel wire ropes.

We are told that Navion Saga, had problems with twist in the bottom chain during the installation. When the chains lift from the mud, it may release torsion to the steel wire rope in the opposite direction of the induced torque during installation. In addition, the steel wire ropes hit downwards into the seabed. The combination give torsion and stress release in the steel wire rope, and the rope might be vulnerable to bird caging.

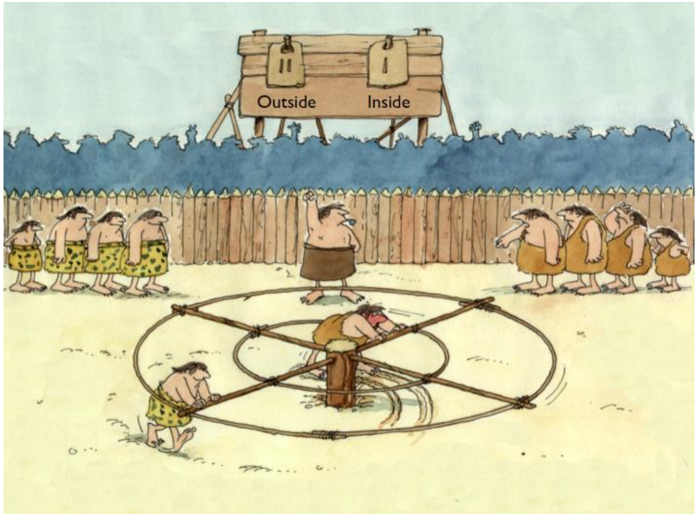

Figure 7: "*Due to their longer lever arms the outer strands have an advantage*" (Verreet, 2002).

The Navion Saga ropes had "nonrotational steel wire ropes". Some of the wires are right-hand wound, and some are left-hand wound. A design goal is to achieve torque balance. If this balance is disrupted, twist occurs. The balance is momentum balanced - with load multiplied by its arm. The balance disrupt by e.g.

- Reduction in the diameter by tensioning the line.
- Changing the friction by loss of lubrication, by wear, wear products, corrosion or coating.
- Hockles or birdcages.
- Yielding of individual wires with permanent deformations.
- Failures of individual wires.

Since the ropes are based on rotation of different layers in opposite directions, it is especially vulnerable to changes in friction, wear and corrosion.

The Bluewaters Haewen Brim FPSO mooring lines got combinations of abrupt tension reductions and small bending radii in the touchdown area (Leeuwenburgh and Brinkhuis, 2014). Trenches formed near the touchdown area for several lines. When the ropes lifted from the seabed and laid back on the slope of the trench, the line may roll back introducing torsion. At the Kumul buoy, a steel wire rope also failed at the seabed touchdown area (Ma et al, 2013).

The ropes at COSLPioneer had independent wire rope core (IWRC). These ropes were standard six strand ropes (6x47+IWRC). This design causes much wear during operations. The angle into the fairlead sheave and the size of the sheave also influences the wear.

Steel wire ropes in combinations with other type of elements

Chaplin et al (2000) described mechanisms including effect of twist on other elements in a line. The steel wire ropes will rotate. Swivels will prevent transfer of twist to neighbouring elements at small loads. When the load increases, the swivel locks and transmit twist to neighbour elements (chain or fibre). The fibre rope has a very low rotational stiffness and deform. The steel wire rope can open up permanently, and different varieties of shear failures can occur. The failure in the steel wire rope will frequently come on the most distant point from the neighbouring element absorbing the twist in the first case.

Ridge and Hobbs (2012) reported cases where the twist in steel wire ropes used during installation caused stored twist in a bottom chains.

At the line failures at Transocean Leader in 2011 and Petrojarl Varg FPSO in 2012 (Kvitrud, 2014), the failed chains were connected to steel wire ropes. The steel wire ropes may have contributed to twist in the lines.

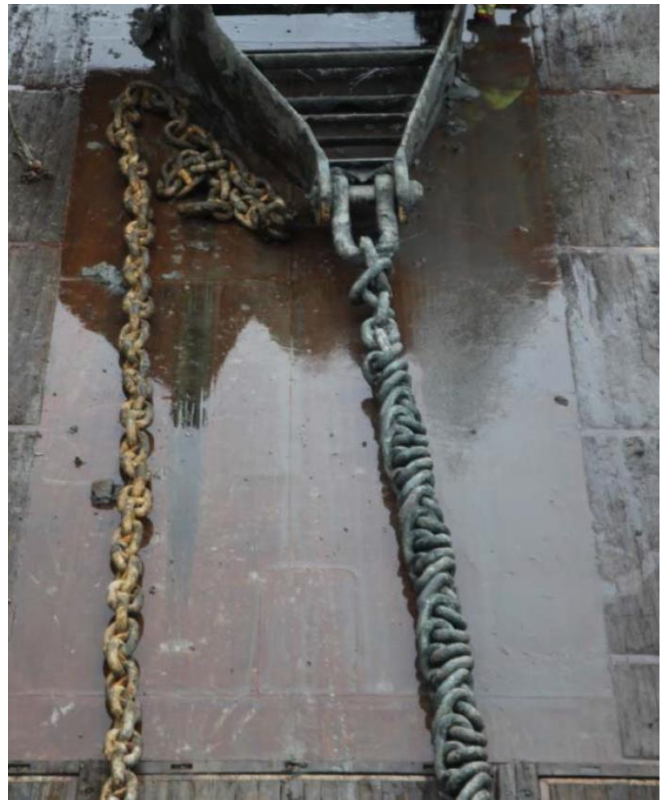

Figure 8: Twisted chain accumulated in a bottom chain during recovery using a six-strand wire rope (Ridge and Hobbs, 2012 and Norland et al, 2012).

Figure 9: Twisted chain on the deck of an anchor handler vessel (Norland et al, 2012).

At COSLPioneer, the failure came at the top of the line, while it came in the lower end at Navion Saga - both places at the end terminations. The reports concluded that the ropes broke due to overload. However, do we know enough of these failure mechanisms to say that our calculation procedures are conservative?

Steel cores

Dependent on the design, the upper end steel core can get the whole tension, with no loads in the strands. The lower rope end core can get large compression because the core normally cannot move laterally (Feyrer, 2015, page 135). In idealized six strand IWRC ropes in tension, the ratio between the load acting on the core wire and the outer wires can be a factor of two (Erdönmez and Imrak, 2011, figure 8).

The COSLPioneer ropes had several individual wire rope failures in the steel core, and the core strand had protruded from the rope and was laying on the outer surface.

Should the safety factor be on the most stressed element in the core wires, or is it ok to have plastic elongations or single wire failures in the core? Should we have a better understanding of what happens in the core? Some standards accept individual wire failures, - but when is it critical for offshore applications? Marine applications are vulnerable when lubrication disappears in the outer layers, with internal wear and corrosion.

Bending

When bending a steel wire rope over a sheave the steel wires connected to the sheave will experience friction against the sheave, and a friction force due to the load perpendicular to the individual wires. The individual wires will get a distortion of its possibility to move. When the diameter of the sheave is larger, the force distributes over a larger area, giving lower stress and less interference to the movements of the individual wires. Loss of lubrication results in internal and external wear and corrosion, the passing over sheaves cause reduced movements between the individual wires and strands. This may lead to internal wire failures, and cause reduced service life, as observed on a lifting steel wire rope at Statfjord A (Statoil, 8.11.2012) and on a steel drilling wire rope on the COSLPromotor semisubmersible (COSL, 2014). Both failures occurred by fatigue near the sheaves. The Statfjord steel wire rope (type *Bridon Dyform 34LR*) installed in 2008, had internal corrosion in 2012. At COSLPromotor, the 42mm steel wire rope from *Kiswire*, was installed in 2008. It had lack of lubrication on major part of the cross section, internal wear and "heavily corrosion".

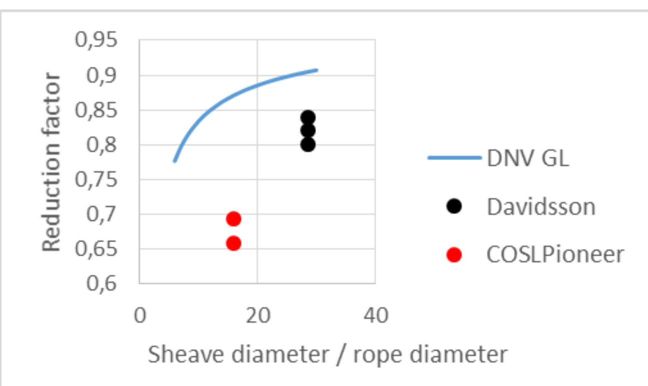

Figure 10: The DNV GL formula, the Davidsson (1955) results and the COSLPioneer data points from 2012. The COSLPioneer steel wire rope had lack of lubrication, wear and corrosion. A possibility that the measured load is too low is also present.

The DNVGL-OS-E301 chapter 13.3.2 account for the strength reduction in sheaves as:

$$= 1 - 0{,}5\sqrt{d/D}$$

Where D is the diameter of the sheave in the fairlead and d is the diameter of the rope.

The formula is based on static test results of ropes, made by Rairden in 1933 (sic!) on six strand wire ropes (6*19 and 6*37) (Chaplin and Potts, 1991, page 122f and 148, and Falkenberg, 2013). However, Chaplin and Potts (1991, page 122f) stated that the basis for these tests are static testing, and the formula is based on data for a *fibre* core rope. Steel cores and dynamic testing reduce the tensile strength significantly (Chaplin and Potts, 1991). Tests by Davidsson (1955, page 11) gave reductions of 0.80 – 0.84 with D/d of 28.5 on 1*295 ropes.

A much higher strength reduction factor might partly explain the COSLPioneer failures. Some suppliers recommend larger sheaves for rotation balanced steel wire ropes, because they are stiffer than stranded ropes.

Bending of the wire ropes over sheaves should be as in the next figure (right). However, the industry practice is to do it the opposite way (left figure). The bending in opposite directions can be detrimental for the steel wires, especially in fatigue.

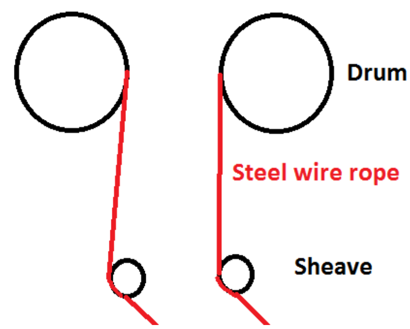

Figure 11: Good (right) and not so good bending directions (typical for offshore steel wire ropes) over sheaves. The geometry affect fatigue (Verreet, 2002), but the bending geometry might also reduce the general condition of the rope.

End terminations

End terminations influence the individual steel wires possibility to move. The effect will depend on the actual solution (Feyrer, 2015). Failures of offshore steel wire ropes at Navion Saga, Bluewater's Haewene Brim FPSO (Leeuwenburgh, 2015), Liuhua in 2006 (Ma et al, 2013) and Nan Hai Fu Xian in 2009 (Ma et al, 2013) occurred at end terminations.

Table 1: Capacity reduction factors for some end terminations (Feyrer, 2015, page 140).

Rope termination	Breaking force factor
Splice eye	0,50-0,80
Cylindrical aluminium ferrule eye	0,85-1,00
Flemish eye with steel clamp	0,90-1,00
Press bolt	0,90-1,00
Wedge socket (rope lock)	0,80-0,95
U-bolt clamp DIN 1142	0,85-0,95

Use of offshore sockets are assumed to give no reduction, but is it correct in all cases – with twist, bending, bird cages or knockles, at all temperatures and in sea water?

The socket connections may have weak points caused on manufacturing inaccuracies. We had a failure at Regalia in 2010, were the socket and the steel wire rope separated from an anchor in the bolster. Did the end termination and the bending in the fairlead interfere?

Payout of lines

From 2006 to 2013, we had 28 payouts. This indicates one payout every ten platform-years.

Did the payouts on COSLPioneer cause a loop or a birdcage? A slow payout when the winch pays out might not be problematic. However, a near free fall combined with a sudden stop of the movement might cause sudden fluctuations of tension and compression, similar to pile driving. The same might occur if the line hits the sea bottom. The movements might be too rapid for detrimented individual wires to follow the global behaviour of the rope.

There are major differences in the payout frequencies from our two major Norwegian suppliers of winches. Preventive technical solutions should be possible to find. We do not have any requirements to inspection of steel wires after payouts. Should there be?

Testing for 100 year loads

According to the Norwegian Maritime Authorities, anchoring rules, 2009, section 17 the anchor holding capacity at 100-year storm should be calculated or tested on each location. Arguments have been given that it frequently expose the anchor line components to very high loading. Earlier the anchor lines perhaps would meet such a load once in a lifetime. The equipment can get 100 year loading for each new location. During testing, the ropes can get tensions greater than the design values of the equipment. It also gets more wear. Part of the problem can be the procedure to tension to the 100-year load, and keep the load in 15 minutes. Then waves, currents and wind add to the 100-year load. Some companies have policies that they only will prove the holding

- Capacity by calculations.
- Prelay and pretension the anchors without use of site-specific equipment.
- Testing in specified maximum environmental conditions.

About 10% of examined kenter shackles in Norway had cracks after a few years use (Pedersen, 2014). There was no correlation between the number of cracks and the time at sea, but the number of anchoring operations. The tensioning of the steel wire rope cause twist and it might cause load combinations on the kenter link not taken into account in the design.

Our requirements may cause less opportunity to stress redistribution between the lines, than it would have if one allowed the lines to drag. However, the dragging have previously caused line failures in other lines.

Repeated high tension of the steel wire rope will introduce permanent elongations, and the rope will be stiffer (hysteresis). However, uneven distribution of loads between the core and the outer wires might give unwanted local yielding and deformations.

During the high tension testing significant twist can appear, almost proportional to the tension load. Disappearance of lubrication, wear and corrosion will increase the effect on the wire segments itself and on other segments in the line.

Should calculations or prelaying with pretension be the only choices when using steel wire ropes? Should the tensioning be less than the yield stress because the large differences in tension in individual wires (core vs. outer strands)?

UNCERTAINTIES IN RESPONSE AND CAPACITY OF STEEL WIRE ROPES

A main basis use of steel wire ropes is that the systems and components have a high standard. DNV GL classed both Navion Saga, COSLPioneer and Bluewater’s Haewene Brim FPSO. From our point of view, the cases represent possible situations that can also occur in the future. In none of the cases, it was possible with present knowledge, to state the exact causes of the failures. Is compliance to the standards sufficient to get a high quality?

Best practice analysis of the line tension and capacity of the failures of COSLPioneer indicate a significant underestimation of the tension (Falkenberg, 2013) and a significant overestimation of the capacity.

Disappearance of lubrication, internal wear and corrosion occur after a few years in service. The combination changes the characteristics of the steel wire ropes to produce twist in the lines. Do we account for it in a reasonable way?

Swivels can forward twist from the steel wire ropes to other line elements with low rotational stiffness. Do we account for it in a reasonable way?

Is the bending capacity in DNVGL-OS-E301 too high? Should we take into account the reduction of capacity in the drums and end terminations, together with the undesirable bending directions over the drum and sheave?

Should each steel wire rope design be qualified including bending over sheaves, twist, effect of disappearing lubrication in seawater, wear and internal corrosion?

Touchdowns can give sudden changes in the loading. The individual wires in all layers will not necessarily be able to follow up, because of increased friction in the outer layers. A precaution in the design phase might be, not to allow touchdowns.

Should all the anchors holding capacity tests be replaced by analysis or tensioning without use of the mooring line equipment?

CONCLUSIONS

The two double line failures seem to have occurred using accepted industry practice. This indicates that the present industry practice is insufficient.

This paper discuss a way to understand the behaviour of offshore steel wire ropes, using the individual steel wires as a basis. This point of view is useful in interpretation of the behaviour of steel wire ropes. A major limitation of our description is that we have not quantified the effects.

ACKNOWLEDGEMENT

We have discussed some aspects on the paper with our colleagues Rolf Hinderaker and Ole Jacob Næss. Terje Andersen has commented on the paper.

Main elements of the paper was presented at the Norsk olje og gass (NOROG) - Mooring integrity Workshop in Stavanger, a Normoor JIP meeting in DNV GL at Høvik, the PSA structural engineering day in Stavanger (*Konstruksjonsdagen*), the DNV GL technical seminar oil & gas in Bergen, and at PSA meetings with COSL in Sandnes, Transocean in Stavanger and Bridon in Doncaster. The discussions in the meetings have given us valuable feedback.

We have received acceptance from Roland Verreet to use figure 7 and from Vidar Norland to use figure 8 and 9.

ACRONYMS

ATA: Automatic Thruster Assistance; **COSL:** China Oilfield Services Limited; **DNV:** Det Norsk Veritas – at present a part of DNV GL; **JIP**: Joint Industry Project; **NMA**: Norwegian Maritime Authority; **PSA**: Petroleum Safety Authority Norway; **STL**: Submerged Turret Loading.

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