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SS: Deployment of Subsea Equipment: Qualification of Large Diameter Fibre Rope for Deepwater Construction Applications

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Abstract

This paper describes the SIRIUS (Safe Installation with Ropes In Ultradeep Sea) JIP full scale testing program conducted to determine the bend fatigue performance of large diameter fibre ropes with HMPE fibres (Dyneema®) on small diameter sheaves, together with a summary of the results and the impact the results have on installation operations. The test rig has previously been used for testing of Ø109 mm steel wire ropes and these results will be used as benchmark for the fibre ropes tested at similar Safety Factors.

Steel wire rope together with active heave compensation has been used for subsea deployment applications for many years. However, with the requirement to install heavy subsea hardware in increasingly deeper water, there is a need to use large diameter fibre rope as part of the deployment system.

As the water depth increases, the high self-weight of steel wire rope limits the maximum payload of conventional steel-based deployment systems. Fibre ropes with HMPE fibres such as Dyneema® are however buoyancy neutral and can therefore carry the same payload at ultra-deep water, whereas steel-wire ropes generally reach a self-weight limit at around 2000 meters with SF=5. During the deployment of subsea equipment, the fibre rope will be subjected to bend fatigue loading when it is bent over the heave compensated sheave. This failure mechanism is the dominating factor in the degradation process of the rope. At present no generally accepted design standard for bend fatigue of fibre rope exists.

In the SIRIUS JIP, cyclic bend over sheave fatigue tests were performed within normal industry range of safety factors. The bend fatigue tests show a slightly better fatigue life for the engineered fibre ropes tested at higher safety factors when compared to multi-strand steel wire ropes. These promising results are illustrating that large diameter fibre ropes on sheaves have a potential to be used in subsea deployment systems containing active heave compensation. Hence, the work performed in the SIRIUS JIP is an important step on the way towards developing safe usage for fibre ropes during subsea installation in ultra-deep sea.

Background

The trend to produce oil in increasingly deeper water has led to development of subsea fields imposing challenges on the lifting appliances in terms of capacity, weight, size and space constraints on the construction vessels. The installation of the subsea equipment is often performed by hoisting the equipment by steel wire ropes running over a heave compensated sheave. In recent years, however, the use of fibre ropes for this application has been more and more accepted. During subsea installation, the fibre rope will be subjected to bend fatigue loading over the sheave. Present design routines for fibre ropes are based on safety factors related to the static breaking load and no generally accepted design standard for fatigue lifetime exists.

The main objective of the SIRIUS JIP is to benchmark the large diameter fibre ropes against previously tested Ø109mm steel wire ropes under identical conditions and with the same sheaves (D/d of about 20), see ref Vennemann et al 2008-1, Vennemann et al 2008,-2 and Vennemann et al 2008-3. Cyclic Bend Over Sheave (CBOS) testing with fibre ropes with as large diameter as 100mm has never been conducted before and the tests presented in this paper are therefore ground breaking.

Test program

In the SIRIUS project five CBOS tests were performed in 2009-2010. Four additional CBOS tests are planned in early 2011. The tests have been performed at different typical safety factors from 6 down to 3, which is comparable with steel wire rope operational values. In the first five tests the ropes were cycled to complete failure. Residual break strength at different life levels will be tested in 2011.

During the CBOS tests, water cooling was applied to the four bend zones in order to avoid heat build up in the fibre rope during the cycling. If the rope temperature becomes too high the HMPE fibre will re-crystallise and loose its strength. It was therefore of importance that during the tests the rope temperature was measured continuously. Hence, in the first three tests several internal thermocouples were used together with an Infrared-camera to monitor the temperature inside and outside the rope.

Prior to the bending fatigue tests, the rope was pre-tensioned and allowed to settle in over a period of 12 hours. Also, during tensioning the rope was slowly cycled back and forth to allow the rope on the sheaves to be equally loaded.

The tests were stopped at regular intervals and visual rope inspections were carried out. After testing, the least damaged ropes from the cycling tests were residual break tested at DNV Bergen.

The following values were measured constantly and recorded in a data-acquisition software:

- Rope tension and elongation
- Required force to move the rope and drive cylinder position
- Bend cycles
- Temperature

Test ropes

The Ø100mm fibre rope is made out of Dyneema® HMPE and ePTFE fibres and is tested in DNV's CBOS test rig. The rope construction is a 12x3 design, which in small scale testing has shown good resistance to cyclic bend fatigue and were the addition of ePTFE fibres was found to further enhances the cyclic bend fatigue resistance (see Thomas, R. and Gilmore, J.) This design offers possibilities to produce endless ropes in the rope manufacturing process. In addition, full performing splices can be made on strand level in the field. The high performance fibre used in this rope is Dyneema® SK78 XBO, a fiber optimized for bending related applications (see Smeets). A proprietary rope coating is used to further improve cyclic bending fatigue performance.

The physical properties of the test rope were as follows:

Rope design:	12*3 (12 strand braided rope consisting of 3-strand laid strands which can be respliced)
Nominal Diameter:	Ø100mm
Linear Density (coated):	814 Kg/100m
Theoretical Effective Cross Sectional Area:	6449 mm² ("voids" not included)
Estimated Modulus of Elasticity @ 20% MBL:	22.37 GPa

Figure 1. Test sample with end sockets

The ropes are terminated at the ends with sockets in order to reduce the test sample length for testing purposes, see Figure 1. A socketed solution has never been used on this large rope diameter before. However, the socket termination has proved to have sufficient strength for the CBOS testing . The socket termination consists of the socket, a centre spike and a thermoset resin. One of the points of attention is to distribute the rope yarns equally around the socket and spike so that they are all equally stressed when the rope is tensioned. The break strength efficiency of the socket termination will be further examined in the SIRIUS JIP project.

The socket solution for large diameter fibre rope may have several benefits compared to spliced end termination, including the significantly reduced termination length.

In order to determine the break load of the rope, new ropes with eye splices were break tested. Special attention was needed for the end splices as the rope is engineered to have a very low friction, meaning a simple splice design would have a tendency to slip at lower loads than anticipated.

Test rig

A bend fatigue test rig has previously been constructed and built for Subsea7 “then Acergy” at DNV Oslo for the bend fatigue tests of Ø109 steel wire ropes, see Figure 2 (see also Vennemann et al 2008-1, Vennemann et al 2008-2 and Vennemann et al 2008-3). The bending fatigue test rig at DNV is capable of performing bend over sheave testing of Ø100-Ø109 mm steel wire and fibre ropes, with a tension load ranging from 50 Tonnes to a maximum rope tension of 330 Tonnes. The ropes are bent over the 2.2 m diameter sheaves, which are the same sheaves that are used on an offshore construction vessel for steel wire ropes. The groove has a radius of 58mm with a 60° opening, see Figure 2. The travel length of ropes in the CBOS fatigue test is 2.5m which means that the rope is subjected to a single bend during a load cycle.

The test rig is able to perform one cycle (forward and back again) within 8 to 20 seconds, which is similar to the conditions the vessels encounter offshore during installation tasks. Two rope samples with a length of 10.1 m are tested at the same time in the rig and are connected with two pre-tensioners. Furthermore the length of these rope samples is designed to match the 2500 Te tension test rig located at DNV in Bergen, where the residual strength of the test ropes was determined after the bend fatigue tests.

The test rig is further capable of constant running around the clock, which required several hardware and software safety features included into the test rig for safe operation.

A major advantage of conducting the fibre rope testing in the same test rig used for steel wire tests is that the test gives a one-to-one benchmark towards steel wire rope even though the groove may not be optimized for fibre rope. Indeed, since the fibre rope has a diameter of Ø100 mm, the D/d ratio is now 22 and not 20 as it was for the steel wire ropes.

Figure 2: CBOS test rig at DNV Høvik, Oslo (Left). Sheave groove detail (Right)

Test results

Five CBOS tests have been performed so far in the SIRIUS JIP and the bend fatigue tests show a slightly better fatigue life for the fibre ropes tested at higher safety factors, when compared to multi-strand steel wire ropes. The multi-strand steel wire ropes tend to fail from the inside and very little visual signs can be seen when the rope is close to the life time limit. On the other hand, the fibre ropes have clear visual indications that the rope is close to the life time limit. These promising results are illustrating that large diameter fibre ropes on small diameter sheaves have a potential to be used safely in subsea deployment systems containing active heave compensation. Additional tests during spring 2011 will be conducted to determine how the residual break strength is affected by different levels of the cycling life-time.

Generally, during the first thousand cycles the rope elongation increased rather rapidly. Subsequently the rate of rope elongation slowed to a steady pace. This initial increase is due to bedding in of the rope strands and setting of the sockets. At the end of the rope bend fatigue life, the rope elongation started to increase more rapidly again, which indicates that the rope starts to deteriorate.

Observations During Tests

The CBOS tests clearly demonstrated that the ropes were subjected to abrasion and that the wear increased with the number of cycles. The ropes in the bend zones had several yarn and strand failures at the end of the tests. The ruptured yarn and strand ends were sticking out of the ropes on the opposite rope side of the contact area with the sheave, indicating that yarns and strands were broken somewhere along the bend zone. In Figure 3 the evolution of the abrasion is illustrated. At the end of the life time several broken strands are clearly seen. Furthermore, the rope-sheave contact area has a clear wear pattern and the fibres are recognized by a combination of squeezed and dislocated strands, with some broken yarns and fibres coming from the rope. The rope contact surface is also very hard and appears almost as if the fibres have been compressed and solidified.

The main cause of failure is believed to be abrasion between rope strands and not directly between the rope and sheave. When the rope is cycled, the difference in load required to move the rope back and forth is measured on the sheave and initially it is relatively low. However, as the rope becomes more worn, higher load is needed to move the rope and bend it over the sheave. The load increase starts to take place after about 50% of the rope life time and for some of the tests the load difference increased with a factor of 10 from the start till the end of the test. This clearly indicates how the rope efficiency is decreasing as the internal abrasion is getting worse. The reason for this is not completely clear, however it is most likely due to increased friction in the rope due to lack of coating or that the e-PTFE fibres are worn out. The increased friction further speeds up the degradation of the rope and the rope eventually fails.

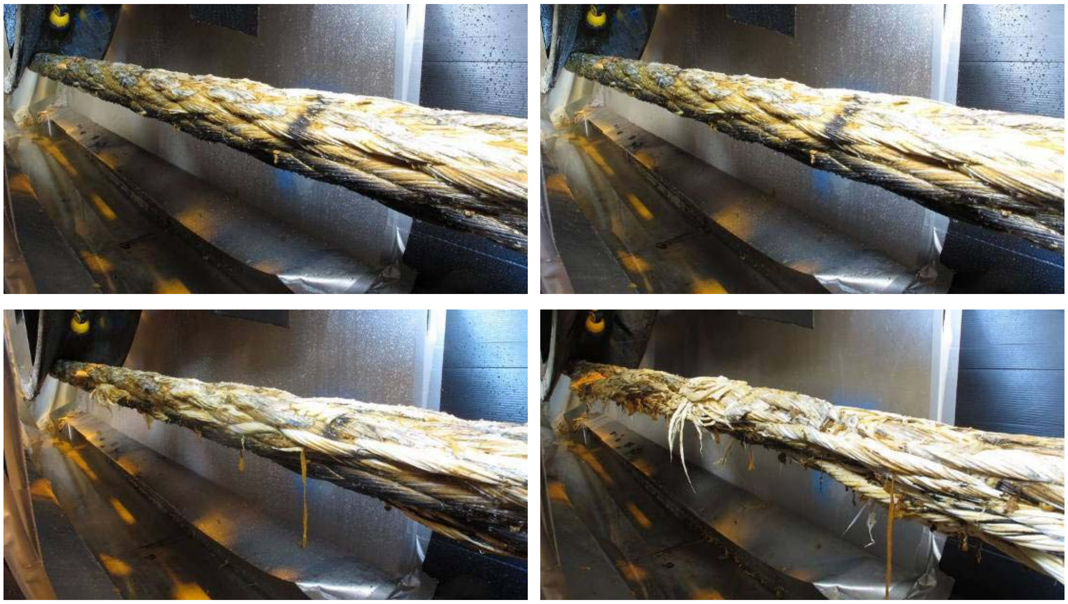

Figure 3. Rope wear at 25%, 50%, 75% and 100% of lifetime

The CBOS tests showed that water cooling is needed at the bend zones for large diameter fibre ropes on small diameter sheaves in order to keep the temperature at acceptable levels during repeated cycling operations associated with active heave compensation. This cooling is a similar approach to that required for steel wire ropes. Two dry tests at a high safety factor indicated that the temperature increases within an hour to the critical temperature of 70ºC where the rope properties start to degrade. The temperature will increase more rapidly for lower safety factors. The temperature is built up inside the rope, mainly due to friction from the internal movement of the strands, and in Figure 4 it is clearly seen in that higher temperatures are found between the strands.

During the testing it was believed that thermocouples inside the rope might influence a slightly premature failure of the rope and were therefore not used for higher Safety Factors.

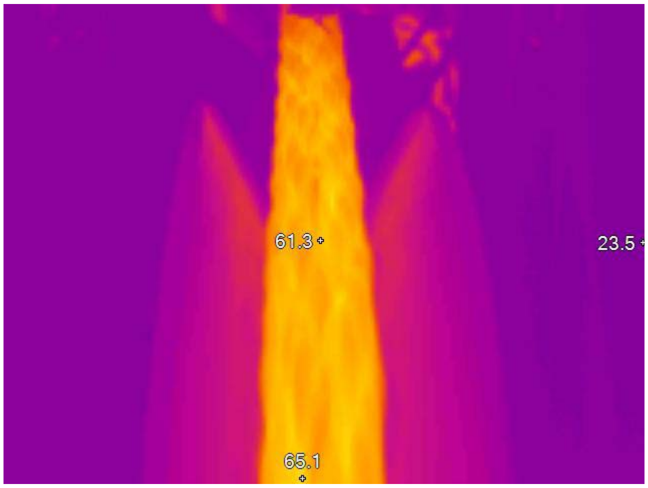

Figure 4. IR image of the temperature at dry testing (i.e. no cooling applied)

The temperature measured with thermocouples inside the rope and with IR camera indicated that when the water cooling was applied, the temperatures stabilized at an intermediate level between room temperature and water temperature, for the whole cross section.

One objective of the testing is to determine a retirement criterion. Except for the obvious number of cycles to rope failure, determined in the testing and combined with a safety factor, it is clear that visual inspection is going to be important to determine if the rope has been subjected to a critical amount of bend cycles. A retirement atlas of typical critical failure modes to be used during visual inspection is likely to be an important tool, as for all the tests one could observe major abrasion and cross sectional loss before the rope strength was significantly reduced. Generally, at around 50% of the lifetime some yarns started to stick out from the rope and at around 75% the strands started to stick out from the rope. The ability to observe minor damages easily, as indication of the future onset of failure is a great advantage compared to multi-layered steel wire ropes, which tend to fail from the inside and for which visual inspections can be misleading. Furthermore additional options for inspection and retirement like elongation during life time and rope stiffness have been identified.

After the completed CBOS tests, residual break strength tests were carried out at DNV Bergen, see Figure 5. Break tests were performed using the least damaged rope from each CBOS test demonstrating a reduction in strength of about 30-60%. The higher reduction was associated with the lower safety factor tests.

Figure 5: Break test 1 (left), Break test 2 (right)

Rule development

As mentioned earlier, the challenges related to deep water installation of subsea equipment are increasing and new standards addressing the safety concept pertaining to such installation work are needed. Today, the technical knowledge and competence within the fibre rope industry is sufficient to establish performance-based standards for installation. In order to achieve this, it is of vital importance that the knowledge and experience of the fibre rope industry (manufacturers and contractors) are included in the preparation of new definitions of safety, in order to apply the qualification methodology with the best results for lifting applications. Furthermore, it is important to follow a recognised technology-qualification methodology in order to achieve requirements for certification of deepwater installation systems. Through close cooperation with the industry the critical issues can be identified and addressed in the resulting offshore standard As a result of this DNV has launched a Joint Industry Project (JIP) on Certification of Deepwater Installation Systems. The existing DNV Rules for Lifting are currently being re-formulated into the newer Offshore Standard concept which shall be applied consistently to wire rope and fibre rope deployment.

Conclusion

The SIRIUS JIP is benchmarking large diameter fibre ropes against steel wire rope as well as looking at various failure modes. This is an important step on the way towards developing safe usage criterions for fibre ropes during subsea installation in ultra-deep sea. The bend fatigue tests show a slightly better fatigue life for the engineered fibre ropes tested at higher safety factors, when compared to multi-strand steel wire ropes on similar tight D/d ratio. Fibre ropes with Dyneema® are also buoyancy neutral and can therefore carry the same payload at ultra-deep water, whereas steel-wire ropes generally reaches a self-weight limit at around 2000 meters at safety factor = 5. The tests have helped to initiate a visual inspection methodology based on the modes of failure and remaining strength. These promising results are illustrating that large diameter fibre ropes on small diameter sheaves have a potential to be used safely in subsea deployment systems containing active heave compensation.

The initial work performed during the SIRIUS JIP has given confidence to investigate fibre rope dynamic performance further - also in relation to several winch and crane concepts for deep-sea installation.

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