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How UHMwPE fibers improve the service life of ROV tether cables

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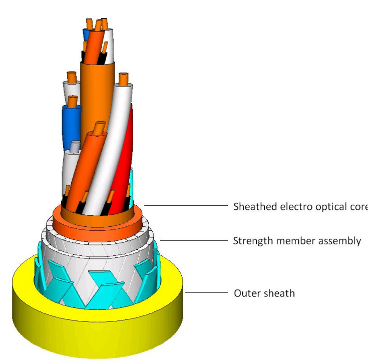
Abstract

This paper describes how the service life of Nexans' conventional ROV tether cable design can be improved by using a strength member made with a bending optimized Ultra-High Molecular Weight PolyEthylene (UHMWPE) fiber, manufactured by DSM Dyneema and branded as Dyneema®. Herewith opportunities for more cost-effective ROV operations and more flexibility in the design of ROV tether cables are created. The improved ROV tether cable is manufactured by Nexans and branded as ENABLE®.

As a physical connection between a Remote Operating Vehicle (ROV) and its tether management system (TMS), a ROV tether cable is exposed to both small bending diameters and relatively sharp directional changes in the TMS as well as axial loading, severe multiple bending in arbitrary planes and hydrostatic pressure during ROV operations. The internal friction, caused by these motions and hydrostatic pressure, induces mechanical deterioration of the strength member in ROV tether cables. Loss of functionality and regular cut-backs and re-terminations of the ROV tether cable are the consequence, leading to valuable downtime.

In conventional ROV tether cable designs aramid fibers are commonly applied in contra-helically stranded layers around an electro-optical core. After a while in operation the mechanical deterioration becomes apparent in the form of fibrillation, misaligned filaments and compression failures. Given this type of deterioration, the friction coefficient and axial compression sensitivity of high-performance fibers are key properties with respect to the service life of the strength member of the ROV tether cable. Comparing the tensile-elongation properties, coefficient of friction, axial compression resistance and bending fatigue performance of aramid fiber with (bending optimized) UHMWPE fibers, also referred to as High Modulus PolyEthylene (HMPE) fibers, shows that UHMWPE fiber provide a good opportunity to improve the service life of the ROV tether cable.

For the design and testing of the improved ROV tether cable a 'claim–argumentation–evidence' process was derived from the certification method as described in DNV-OS-E407. The contra-helically wound layers of the strength member assembly, wrapped around the electro-optical core in Nexans' conventional and currently used aramid-based designs, are made with an assembled bending optimized Dyneema® (SK78 XBO) fiber using a volume-based substitution and applying identical lay angles. With the outer diameter, break strength and load at Cu yield as key design criteria, the key mechanical characteristics of the improved ROV tether cable design shall at least be identical to the characteristics of the conventional design.



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For the provision of evidence regarding the intended performance improvement several steps have been taken, knowing:

- Finite Element Modeling (FEM);
- Material analyses (Differential Scanning Calorimetry (DSC), Size Exclusion Chromatography (SEC) & Scanning Electron Microscopy (SEM));
- Static testing (break strength & axial stiffness testing);
- Dynamic testing (Cyclic Bend Over Sheave (CBOS)); and
- Field testing of the improved ROV tether cable as key proof of principle.

DSC, SEC and SEM analyses, before executing static and dynamic testing, of virgin UHMWPE fibers probed from the improved ROV tether cable design have proven that the fiber characteristics were not affected by the over-extrusion of the outer polymeric sheath. The static testing, before and after CBOS testing, revealed that the break strength and axial stiffness of the improved design remains unchanged, whereas the break strength and axial stiffness of the conventional design reduced by 50-75%. SEM analyses of the UHMWPE fibers probed from the strength member of the virgin tether cable as well as the cable subjected to bend fatigue loading revealed that the UHMWPE fibers did not show any relevant mechanical deterioration as a result of this dynamic loading.

Following the static and dynamic testing of the improved ROV tether cable, Fugro Subsea Services executed field testing. After 700 hrs of operational use without any failure or loss of functionality, only one re-termination was ordered by Nexans for evaluation purposes. Static testing has shown that the ROV tether cable shows no significant loss of strength and stiffness. SEM revealed that the UHMWPE fibers only showed minor deterioration.

In Nexans' ENABLE® ROV tether cable aramid fibers, applied as strength member, are of is substituted by a bending optimized Dyneema® (SK78 XBO) fibers. A combination of Finite Element Modeling, material analyses, static and dynamic testing and field testing have shown that this substitution improves the service life significantly. This next generation of Nexans' ROV tether cables enables longer operational time between re-termination of the ROV end and longer operational time between replacements of tethers. Furthermore, other parameters, such as the axial stiffness and break strength of the ROV tether cable, were not significantly affected, while the linear weight in water of the improved ROV tether cable was reduced significantly. Given all results, the bending optimized Dyneema® fiber has become the preferred material for the strength member in Nexans' ENABLE® ROV tether cable.

1. Introduction

In Remote Operating Vehicle (ROV) operations the physical connection between the vehicle and the tether management system (TMS) is provided by a flexible and light-weight tether cable. Its primary function is to transmit electrical power and optical signals and carry mechanical loads. Between operations the tether cable is stored on a drum integrated in the TMS. From a cable perspective, TMS's are small due to space and weight constraints. Consequently, when the vehicle swims out the tether cable is pushed or pulled along its path of sheaves and roller devices, causing it to bend and make sharp directional changes. During subsea operations the tether cable is also exposed to hydrostatic pressure and follows vehicle motions thereby inducing many bend cycles at no, or low, load. This puts a constraint on the maximum achievable service life.

The strength member assembly in conventional ROV tether cables is made of contra-helically stranded layers around an electro-optical core. The required functions of the strength member are to provide torque balance and axial stiffness to protect the electro-optical core, breaking strength, and bending durability. In view of these required functions the layers are preferably made with flexible and lightweight (multi-filament) high-performance fibers of which aramid fibers are most commonly applied.

When the ROV tether cables are used, load and compression will be imposed in each layer of the strength member as well as the fibers in each layer. The magnitude of load and compression in the fibers is governed by the overall load and bending, water depth, lay lengths, placement in the cross section, and friction forces between the fibers. The type of fiber also determines the level of mechanical deterioration of the strength member during use. The deterioration is especially apparent in the section of the ROV tether cable closest to the connection with the ROV.

The friction coefficient and axial compression sensitivity of high-performance fibers are key properties with respect to the durability of the strength member of a ROV tether cable. This insight is based on the visual impressions of the most common failure modes for aramid fibers as probed from an actually used ROV tether cable. Figure 1 depicts internal abrasion, misalignment and compressive failures as these common failure modes intrinsically related to the high friction coefficient and axial compression sensitivity of aramid fibers. .

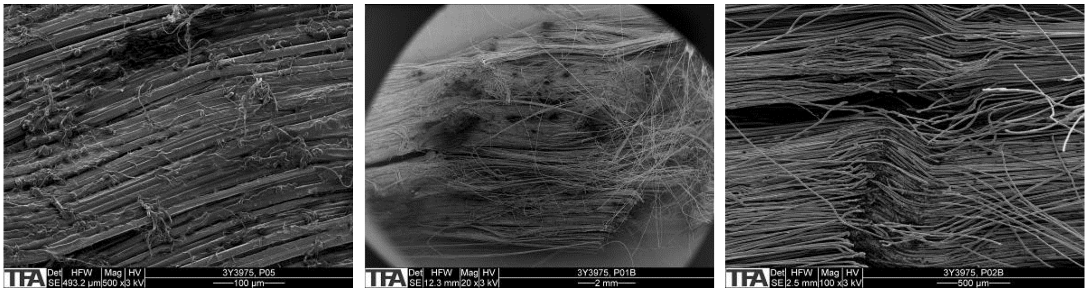


Figure 1. Impressions of internal abrasion *(left)*, misalignment *(middle)* and compressive failures *(right)* of the strength member made with aramid fibers from an actual ROV tether cable.

In Table 1 some key characteristics of common aramid and (bending optimized) Ultra-High Molecular Weight PolyEthylene (UHMWPE), also referred to as High Modulus PolyEthylene (HMPE), fibers are mentioned. This shows that bending optimized UHMWPE fiber, manufactured by DSM Dyneema and branded as Dyneema®, is a good alternative for aramid fibers applied in the strength member of ROV tether cables.

Physical characteristics	**Unit**	**Aramid fiber**	**UHMWPE fiber**	**Bending optimized UHMWPE fiber**
		Twaron® D2200	**Dyneema® SK78**	**Dyneema® SK78 XBO**
Density	kg/dm^3	1.45	0.98	0.98
Tenacity	GPa	3.2	3.4	2.8
E-modulus	GPa	118	113	98
Elongation at break	%	2.8	3.5	3.7
Coefficient of friction	n.a.	0.15	0.07	0.05
Axial compression resistance	n.a.	-	++	++
Bend fatigue performance	n.a.	-	+	++

Table 1. Characteristics of aramid and (bending optimized) UHMWPE fibers

Generally, high-performance fibers are sensitive for localized compression failures, also referred to as kink bands, which are formed due to buckling and slippage of polymer chains when exposed to axial compression. Amongst the high-performance fibers Dyneema® have the highest resistance against compression fatigue due to its smoothness and ductility [2, 3]. To improve the mechanical durability one should therefore aim to improve the bend fatigue performance of the strength member assembly without compromising the outer diameter, axial stiffness and break strength of the ROV tether cable. With the physical characteristics of (bending optimized) UHMWPE fibers attributes are available to accomplished service life improvement of an ROV tether cable.

2. Improved ROV tether cable design

For the design, and the execution of (field) testing, of the improved ROV tether cable, manufactured by Nexans and branded as ENABLE®, a 'claim–argumentation–evidence' process was derived from the certification method as described in DNV-OS-E407 [1].

Nexans' conventional and currently used aramid-based design provides the basis for the improved design as depicted in Figure 2. The contra-helically wound layers of the strength member assembly, wrapped around the electro-optical core, are made with an assembled bending optimized Dyneema® (SK78 XBO) fiber using a volume-based substitution and applying identical lay angles. With the outer diameter, break strength and load at Cu yield as key design criteria, the calculated load at Cu yield and linear weight of the assembled yarn are resp. approx. 20% and 30% less compared to the conventional design based on aramid fibers. The reduction of the load at Cu yield in the new design is not perceived as being critical. Table 2 illustrates the key calculated mechanical characteristics of the conventional and improved ROV tether cable design.

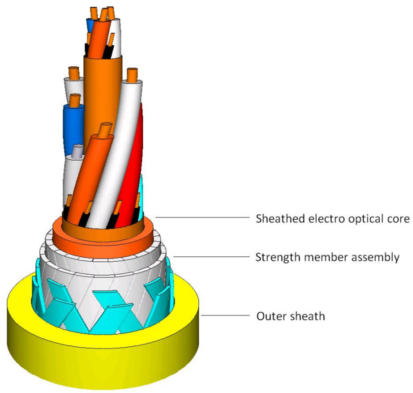


Figure 2. A three dimensional impression of the improved ROV tether cable design.

Physical characteristics of ROV tether cables	Unit	Conventional design (Aramid-based)	Improved design (UHMWPE-based)
Outer cable diameter	mm	30	30
Linear weight of ROV tether cable in *air*	kg/m	0.77	0.74
Linear weight of ROV tether cable in *water*	kg/m	0.05	0.02
Break strength of ROV tether cable (1)	kN	95	125
Load at Cu yield (2)	kN	15	12

Notes: (1): determined by means of empirical calculations; (2): determined by finite element modeling.

Table 2. Calculated physical characteristics of conventional and improved ROV tether cable designs.

3. Collecting the evidence for improved ROV tether cable performance

In this paragraph the steps taken to collect the appropriate evidence are described before and after field testing executed by Fugro Subsea Service.

3.1. Material analyses and mechanical executed prior to field testing

3.1.1 Type of analyses and tests executed

The outer sheath of the ROV tether cable is a thermoplastic elastomer (TPE). As the temperature of this TPE during extrusion exceeds the UHMWPE melting point, this final stage of the tether cable manufacturing process might induce recrystallization and thermo-oxidation. This may affect the physical characteristics of the fiber. Both the virgin UHMWPE fiber and UHMWPE fiber probed from the outer layer, closest to the TPE, were analyzed by means of Differential Scanning Calorimetry (DSC) to determine possible recrystallization. For comparison the endothermal peak(s) and melting enthalpy were derived from the first heating curves. The molecular weight parameter changes, possibly induced by thermo-oxidation, were analyzed by means of Size Exclusion Chromatography (SEC).

The break strength test was done by installing a 100 m virgin tether cable specimen in a large winch spooling rig. Each end of the cable was terminated by winding of more than 8 windings on a drum. By increasing the line load, the cable was loaded until failure while recording the line load. The sheave and drum diameter applied was approx. 2 m. With a ROV tether cable diameter of 30 mm the ratio of the sheave/drum diameter to the diameter of the cable is 67. This test was performed with both a virgin and a bending fatigue loaded specimen in order to verify the effect on retention strength.

One of the primary functions of the strength member is to provide sufficient axial stiffness, and consequently sufficient load at Cu yield, to protect the electro-optical core. The axial stiffness test was performed to determine the load at Cu yield on both as virgin specimen as well as specimen subjected to bend fatigue loading. The test specimens were approximately 3.5 m and mounted in the test rig by triple graded Kellum grips. Both the virgin and bend fatigue loaded specimen were axially loaded up to and slightly above the calculated load at Cu yields (≈ 12 kN). During this straight pull of the tether cable load and elongation, through extensiometers, were simultaneously measured.

Bending fatigue loading, also referred to as Cyclic Bending Over Sheave (CBOS) tests, were performed by cyclically loading the tether cable in order to simulate the overall load (axial and radial) and bending imposed on a tether cable during use without incorporating the effect of hydrostatic pressure. A specimen was mounted in the test rig by triple graded Kellum grips and loaded during four (4) predefined loading sequences with a cycle time of 15 seconds and a stroke length of 3.5 m. Each sequence comprises 500 bend cycles at a load of 5 kN followed by 25 cycles at a load of 12 kN, representing peak loads, using a sheave diameter of 400 mm and sheave grove diameter of 30 mm. The combination of the stroke length and sheave diameter implies that a zone in the tether cable is exposed to double-bending; the area where most of the mechanical deterioration is expected to occur.

The applied loads during the CBOS test are less than 5% of the tether cable break strength and 5 to 10 times the normal spooling load in a typical TMS. Therefore this test is an accelerated dynamic test without considering long-term static loading of the strength member during ROV operations. Under constant loading UHMWPE fiber show irreversible deformation that is strongly dependent on type of UHMWPE fiber, applied load and temperature. By selecting Dyneema® (SK78 XBO) the irreversible deformation of the strength member during the CBOS test and ROV operations can be calculated. Using the proprietary DSM creep design tool the creep proofs to be negligible. [6].

SEM analyses were executed of virgin UHMWPE fibers and UHMWPE fibers probed from the inner and outer layers of the strength member in the ROV tether cable in a double bend zone during CBOS testing. This to be able to visually check on any potential mechanical deterioration as a consequence of the dynamic loading.

3.1.2 Results of material analyses and mechanical testing

From the endothermal peaks in the DSC thermograms as well as the molecular weight (distribution) parameters (M_n [kg/mol], M_w [kg/mol], M_z [kg/mol], M_w/M_n [-] and M_z/M_w [-]), obtained from both samples by means of SEC, it can be concluded that the fiber characteristics were not affected by the extrusion of the outer sheath.

Table 3 shows the yarn strength determined before and after CBOS tests of yarns probed from the outside of the section of the cable that is exposed to the highest bending loads; the double bend zone. These results illustrate that the bending durability of the strength member comprising bending optimized UHMWPE fiber is significantly better than strength member of the conventional ROV tether cable. Based on this experimental difference in durability, we have illustrated the propagation of two of the important mechanical characteristics of the tether, load at Cu yield and break strength, in Table 4. Note that the decline in retention strength is not necessarily linear.

Retention strength [1]	**Unit**	**Conventional ROV tether cable (Aramid-based)**	**Improved ROV tether cable (UHMWPE-based)**
After 0 bend cycles	%	100	100
After 4,200 bend cycles	%	25	100

Notes: (1): determined by means of traditional yarn strength methods using socketed end terminations.

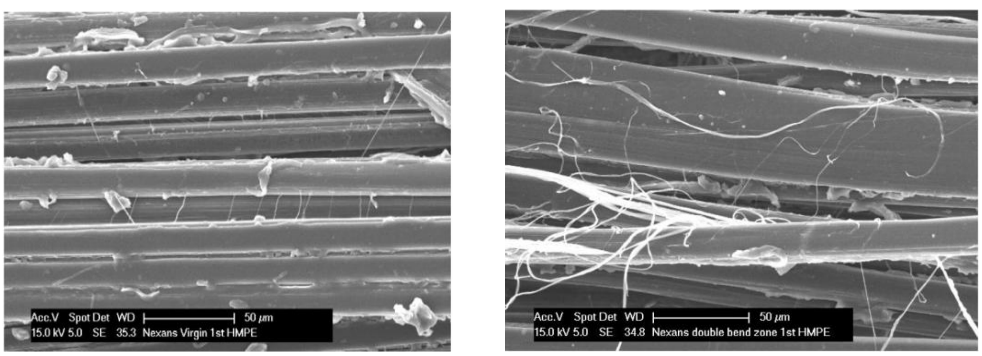
Table 3. Retention strength as function of number of bending cycles of yarns probed from ROV tether cables comprising strength members made with aramid fiber and bending optimized UHMWPE fiber.

The data in Table 4 illustrate that the initial load at Cu yield for the conventional ROV tether cable is approx. 25% higher than load at Cu yield for the improved ROV tether cable. As the spooling load is less than 5% of the tether cable break strength, implying less than 6.3 kN, the Cu conductors in the virgin tether cable will not yield. Hence, this difference is not critical for the improved design.

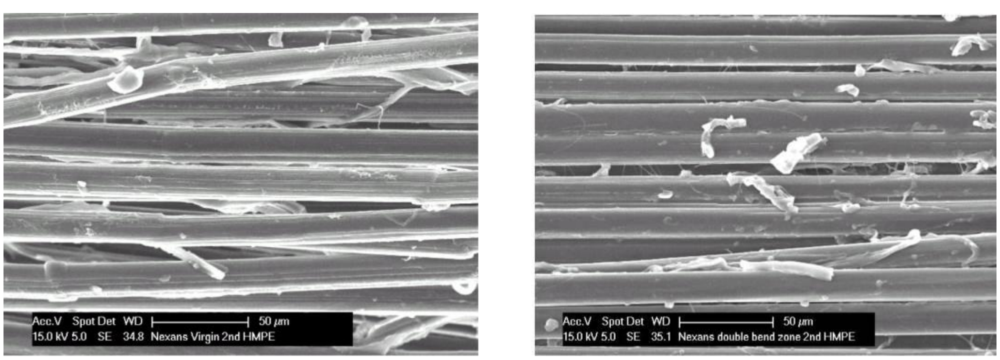
After 4,200 bend cycles of the conventional and improved ROV tether cable design the differences become evident. Where the load at Cu yield for the conventional ROV tether cable was significantly reduced to almost half the initial value, the load at Cu yield of the improved ROV tether cable was not affected at all. The same holds true for the break strength of these designs. The decrease in break strength of the conventional ROV tether cable reached a level of almost 75%. From the data in the Tables 3 and 4 it is evident that yarn retention strength, load at Cu yield and break strength of the tether cables are best preserved by armoring the ROV tether cable with bending optimized UHMWPE fibers.

Load at Cu yield and break strength	**Unit**	**Conventional ROV tether cable (Aramid-based)**	**Improved ROV tether cable (UHMWPE-based)**
Load at Cu yield after 0 bend cycles	kN	15	12
Load at Cu yield after 4,200 bend cycles	kN	7	12
Break strength after 0 bend cycles	kN	95	125
Break strength after 4,200 bend cycles	kN	22	125

Table 4. The measured load at Cu yield and break strength of ROV tether cables BS as function of the number of bend cycles for conventional and improved ROV tether cable design.



(A) Inner layer in virgin improved tether cable specimen *(left)* and CBOS tested (4,200 cycles) specimen *(right)*.



(B) Outer layer in virgin improved tether cable specimen *(left)* and CBOS tested (4,200 cycles) specimen *(right)*.

Figure 3. SEM images of bending optimized UHMWPE fibers probed from *(A) inner* layer and *(B) outer* layer of both virgin *(left)* and bend fatigue loaded *(right)* improved tether cable specimen.

Figure 3 depicts these SEM images of these fibers probed from the inner and outer layers of the strength member in the double bend zone. These impressions confirm that the overall load (axial and radial) under given CBOS conditions only caused minor internal abrasion. Misalignment of fibers and compression failures have not been observed. Figure 3 *(A; right)* illustrates that some outer filaments in the inner yarn layer seem to be 'fused' during bend fatigue loading. This is probably due to the radial forces imposed on the strength member. The 'fused' filaments created a shield on the interface between the inner and outer layer of the strength member, which restricts layer-to-layer abrasion to a minimum.

3.2. Evidence collected from the field testing

3.2.1 Field testing and material analyses

Following the promising results from the mechanical testing and material analyses, a cable length was provided to Fugro Subsea Services for field testing. Under subsea operations the ROV tether cable is exposed to hydrostatic pressure next to axial and radial load caused by axial loading and bending in arbitrary planes.. A first cutback sample, implying a first re-termination of the ROV tether cable, was created after approx. 700 hours in operation. The condition of this sample was evaluated by means of stiffness testing and SEM analyses of UHMWPE fibers probed from the inner and outer layer of the strength member. For stiffness testing the same method was used as before field testing.

3.2.2 Evidence collected from field testing and subsequent material analyses

During the first 700 hrs operational hours Fugro Subsea Services did not report any problem. Axial stiffness and load at Cu yield will decrease when the strength member deteriorates. So, this test will serve as a proxy for strength member deterioration.

Figure 4 depicts the axial stiffness measurement of a specimen retrieved from the ROV end of the field trial tether cable, overlaid with the graphs denoting different cases of retention strength as determined by means of Finite Element Modeling. Where this test with a virgin ROV tether cable revealed an axial stiffness following the green-dotted line in Figure 4, the results of the used cable show that the majority of the strength remains even after 700 hrs in operation.

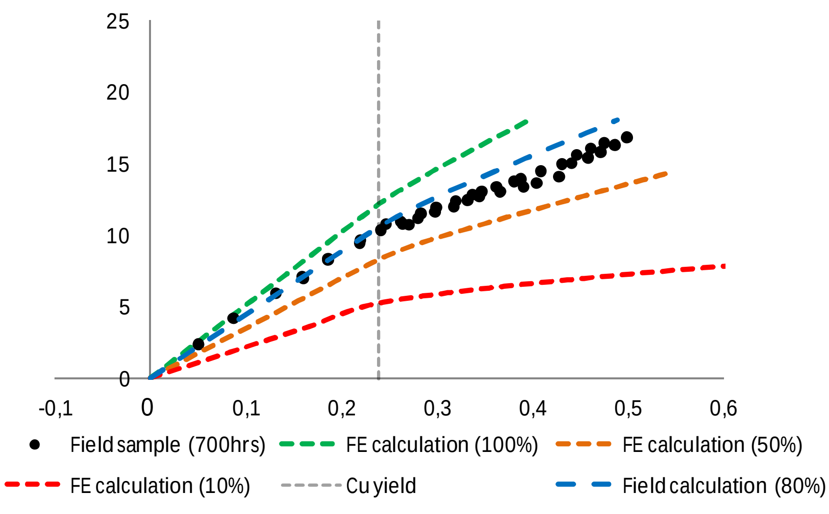
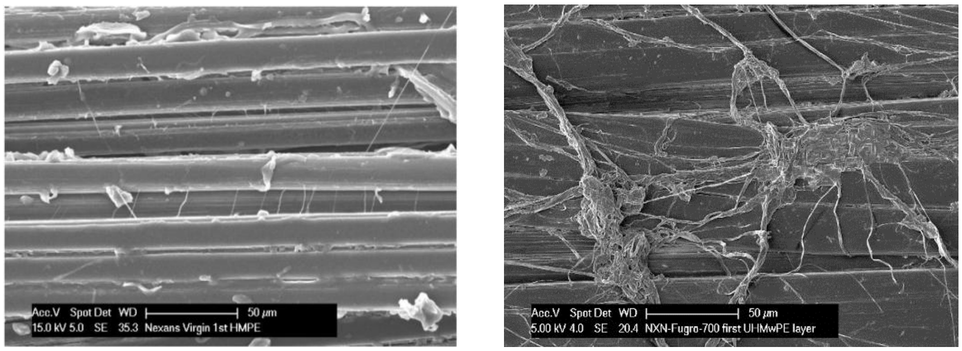


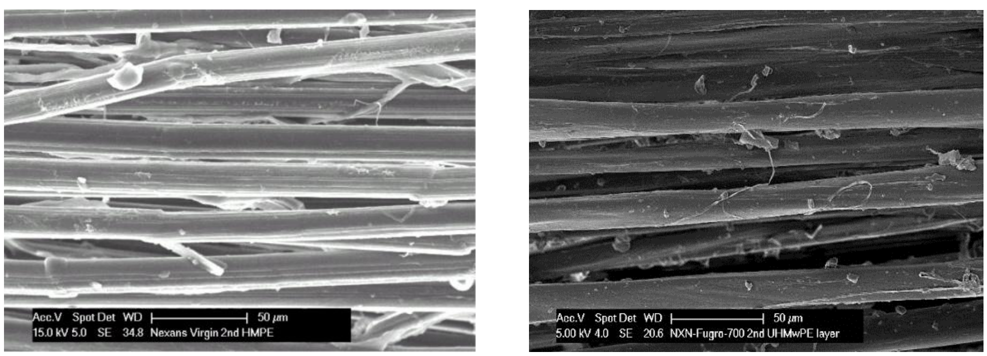
Figure 4. Axial stiffness measurement of field-tested improved ROV tether cable.

Knowing that the number of re-terminations typically done with the conventional ROV tether cable within the first 700 hours in operation can be up to 10 due to loss of functionality, these results show an significant improvement.

Figure 5 depicts the SEM images of the inner and outer layer of the strength member within the virgin improved ROV tether cable as well as the specimen of this improved ROV tether cable. Figure 5 shows a very interesting feature. Outer filaments in the inner yarn layer seem to be 'fused' during loading due to the radial pressure forces the filaments are exposed to. The fused yarns create a shield on the interface between the inner and outer layer of the strength member, which restricts layer-to-layer abrasion to a minimum. Also a low level of fibrillation can be seen. This figure also shows some 'fusion' as well, but hardly any fibrillation, of the outer filaments in the outer layer compared to the virgin. Misalignment and compression failures of filaments cannot be detected.



(A) *Inner* layer in virgin improved ROV tether cable specimen *(left)* and field tested specimen *(right).*



(B) *Outer* layer in virgin improved ROV tether cable specimen *(left)* and field tested specimen *(right).*

Figure 5. SEM images of bending optimized UHMWPE fibers probed from *(A) inner* layer and *(B) outer* layer of both virgin *(left)* and bend fatigue loaded *(right)* improved tether cable specimen.

5. Discussion

As oil and gas exploration moves to 2,000m water depth and more, the requirements to the ROV tether cables are continuously increasing. To meet these requirements the key challenge is to improve the bending fatigue performance of the conventional ROV tether cable, of which the strength member is commonly made with aramid fibers. Both the reduction of internal friction and reduction of the compression sensitivity of these multi-filament high-performance fibers are key parameters in optimizing the design towards longer service life.

Several tests, incl. field tests, and material analyses have shown that the use of bending optimized UHMWPE fiber has a positive influence on the service life of the improved ROV tether cable. The axial stiffness was only slightly compromised without affecting the functionality, whereas the outer diameter and break strength were not compromised at all. The use of UHMWPE fiber did also result in a reduction of the linear weight of the ROV tether cable in water by 60% (Table 2).

The improved bending performance of the ROV tether cable can be harvested in different ways in normal operations, depending on the operator's strategy, by means of a prolonged service life on existing systems or similar mechanical lifetime on smaller systems. Furthermore, the substitution of aramid fibers by bending optimized UHMWPE fibers can lead to more flexibility in the design of tether cables. E.g. due to the durability one can consider using less strength members, thereby reducing the overall outer diameter. Another opportunity is using the reduction in specific weight to carry more Cu conductors thereby reducing voltage drop and achieving longer excursion lengths. This can be considered case by case depending on the individual operator's requirements.

By invoking the similarity principle (for design, manufacturing, and material selection) the performance of the improved tether cable is believed to hold true for all Nexans standard ROV tethers in the range 20-45mm outer diameter. The performance of this improved tether cable design will be continuously monitored during more subsea operations.

6. Conclusions

In Nexans' ENABLE® ROV tether cable traditional aramid fiber has been substituted by a bending optimized Dyneema® (SK78 XBO) fiber. A combination of Finite Element Modeling, material analyses, mechanical testing and field testing (by Fugro Subsea Services) have shown that this substitution improves the service life significantly. This next generation of Nexans' ROV tether cables enables longer operational time between re-termination of the ROV end and longer operational time between replacements of tethers.

Furthermore, other required parameters, such as the axial stiffness and break strength of the ROV tether cable, were not affected, while the linear weight in water of the improved ROV tether cable was reduced significantly. Given all results, the bending optimized Dyneema® fiber has become the preferred material for the strength member in Nexans' ENABLE® ROV tether cable. Also its compatibility with Nexans' design and manufacturing philosophy as well as the given space and weight constraints in today's TMS's supports this preference.

7. Acknowledgements

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