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# DEVELOPMENT OF HMPE FIBER FOR DEEPWATER PERMANENT MOORING APPLICATIONS

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## Abstract

For a number of years, the creep performance of standard High Modulus Polyethylene (HMPE) fiber types has limited their use in synthetic offshore mooring systems. In 2003, a low creep HMPE fiber was introduced and qualified for semi-permanent MODU moorings. This paper reports on a new High Modulus Polyethylene fiber type with significantly improved creep properties compared to any other HMPE fiber type, which, for the first time, allows its use in permanent offshore mooring systems, for example for deepwater FPSO moorings. Results on fiber and rope creep experiments and stiffness measurements are reported. Laboratory testing shows that ropes made with the new fiber type retain the properties characteristic of HMPE such as high static strength, high fatigue resistance and stiffness, and illustrate that stiffness properties determined on HMPE fiber or rope are dependent on the applied load and temperature.

## 1. Introduction

With oil and gas field exploration going deeper and further offshore, mooring system designers are faced with engineering mooring systems that balance the demands of maximum platform offsets, wind and wave peak loads, and long-term high tensions in loop currents.

Polyester ropes are commonly used for deepwater moorings. Beyond 2,000m water depth, however, the high stretch of the polyester rope becomes a problem as the longer mooring lines allow greater horizontal offsets. A 2,000m polyester line may have 40m elongation, while a 3,000m line would allow 60m elongation under the same environmental conditions, creating greater horizontal offsets which may exceed the limits of risers. Using High Modulus Polyethylene with similar break load these offsets would be only 12m for a 3,000m line.

In addition, High Modulus Polyethylene is now widely considered to be the most suitable material for these longer deepwater mooring line lengths. The fibers are characterized by high strength and high modulus, producing lighter and smaller diameter high stiffness ropes, providing both technical and operational advantages over traditional polyester mooring lines. A stiffer HMPE mooring system is potentially more riser friendly than polyester. HMPE ropes typically have an extension at break of 2%-2.5% for a worked rope.

During station-keeping, wave movements impose cyclic loadings on mooring lines, causing fluctuating fiber elongation. The mooring lines are subject to tension-tension fatigue loads. HMPE fiber ropes have shown a longer fatigue life compared to polyester ropes for the same rope construction and are not vulnerable to axial compression fatigue compared to aramid fiber [1], [2].

However, the high stiffness of HMPE can also be a limiting factor. In high storm and hurricane risk areas the

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mooring system needs stretch to maintain storm survivability. Hybrid mooring lines combining HMPE rope segments with polyester rope segments provide the stiffness needed to handle maximum loads during station-keeping in storm, while ensuring sufficient elasticity to damp peak loads induced by waves [3], [4], [6].

The pretension is responsible for the long-term loading of the mooring lines. HMPE fibers are sensitive to these long-term static loads, and will irreversibly elongate proportionally with time. This phenomenon is known as creep. Excessive creep causes an increased offset of the moored vessel. The degree of creep is dependent on HMPE type, operating temperature, mean load and loading time.

All HMPE fiber types perform differently; in general the fibers from DSM Dyneema combine the greatest tensile strength and modulus with the highest creep resistance. Recent fiber developments have been aimed at significantly reducing the creep rate (% elongation / time unit), as well as developing a model to accurately predict creep rate and creep elongation, and thus providing better estimates of creep lifetime for grades offered by DSM Dyneema.

In 2003 the SK78 fiber grade, a low creep HMPE, was introduced for semi-permanent Mobile Operating Drilling Unit (MODU) moorings. Petrobras - Petróleo Brasileiro SA has recently placed an order for a set of SK78 mooring ropes with 630 tonne minimum breaking load (MBL) for deepwater MODU projects offshore Brazil.

Table 1. Main properties of some DSM Dyneema HMPE fiber types

| | **General** | **Reduced creep** | **Further reduced creep** |
|---|---|---|---|
| Dyneema® fiber | SK75 | SK78 | DM20 |
| Titer | 1740 dtex | 1740 dtex | 1740 dtex |
| Tenacity | 35 cN/dtex | 35 cN/dtex | 31 cN/dtex |
| Modulus | 1160 cN/dtex | 1160 cN/dtex | 920 cN/dtex |
| Elongation at break | 3.5% | 3.5% | 3.6% |
| Typical use | Work ropes | MODU mooring | Permanent mooring |

Further research on creep rate reduction has resulted in the development of the DM20 fiber grade, especially designed for deepwater permanent mooring. Table 1 lists the main properties for the different HMPE fiber types.

Extensive testing has been performed on the DM20 fiber type to determine its properties and behavior in permanent offshore mooring systems, covering:

- strength properties: break strengths in subrope constructions,
- stiffness properties: dynamic yarn stiffness and static yarn stiffness, and rope stiffness,
- creep properties: fiber creep rate and creep lifetime experiments for creep model development, and rope creep rate tests to verify this creep model,
- lifetime related properties: yarn-on-yarn abrasion performance, fatigue life on rope samples, UV resistance and thermal aging on fibers in reference to the SK78 fiber type that has been accepted by the industry for deepwater MODU moorings.

## 2. Creep

### 2.1. Creep Estimation in Offshore Loading Condition

The tendency of HMPE offshore mooring ropes to creep has to be addressed in the design of permanent moorings. A high creep rate poses a potential failure risk via creep rupture.It also necessitates rope re-tensioning, and a reduction in the quasi-static rope stiffness over long storm duration.

For permanent mooring systems, a creep elongation of 0.5% in 25 years on the total mooring line is considered as acceptable. Creep failure safety factors are proposed by several industry guidelines [5]; for example a safety factor of 5-8 for long-term moorings as recommended by DNV [7].

A model describing the creep properties has been derived from the fiber creep experiments, and used to estimate creep for offshore mooring lines under realistic loading conditions. It illustrates the major improvement of DM20 over other HMPE fiber types (Table 2).

## 2.2. Fiber Creep versus Rope Creep Data

In comparing fiber and rope creep data on a relative load basis, a fiber / rope break strength conversion factor, or realization factor, must be taken into account. This factor is dependent upon rope construction, rope manufacturer, and the type of fiber used.

$$RF = \frac{YBL/w}{MBL/W} \tag{1}$$

Where: RF = Realization factor (-)
YBL = Yarn break load (kN)
w = Yarn weight (g/m)
MBL = Rope minimum break load (kN)
W = Rope weight (g/m)

Creep test results of a fiber under 20% fiber break strength (resulting in a stress level of 684 MPa) are not directly comparable to creep of a rope under 20% rope break strength (resulting in a stress level of 270 MPa) and, as such, no conclusions on the rope creep performance can be drawn (see Table 3).

nstead, comparing fiber and rope creep data based on comparable stress levels (e.g. MPa or kN/(g/m)) gives a direct correlation, without the need for realization factors.

Table 2. Creep model expectations for HMPE fiber types

| | **SK75** | | **SK78** | | **DM20** | |
|---|---|---|---|---|---|---|
| **Rope strength (typical)** | 630 t | | | | | |
| **Rope weight (excluding cover)** | 4.2 kg/m | | | | 4.4 kg/m (estimated) | |
| | **Estimated creep elongation** | **Creep failure safety factor** | **Estimated creep elongation** | **Creep failure safety factor** | **Estimated creep elongation** | **Creep failure safety factor** |
| **MODU mooring condition (5 years of 20%BL at 16°C)** | 6.6% | Can not be met | 1.7 % | Can be met | 0 % | Can be met |
| **Permanent mooring condition (25 years of 20%BL at 16°C)** | Failure | | failure | | < 0.3 % | Can be met |

Table 3. Relation between rope break strength and yarn break strength
for a typical rope out of SK78 fiber

| **Rope break strength (MBL)** | 630 mt | **Yarn break load (YBL)** | 0.611 kN | |
|---|---|---|---|---|
| **Rope weight (W)** | 4.5 kg/m | **Yarn weight (g/m)** | 0.174 g/m | |
| **Creep load** | 20% MBL | **Creep load** | 20% YBL | 8% YBL |
| **Stress level** | 270 MPa | **Stress level** | 684 MPa | 270 MPa |

When the stress level corresponding to the relative load level on the full size rope is determined, creep experiments at this level can be performed on fiber, rope yarn or subrope, resulting in comparable creep data.

Note: It is advisable to consult the fiber manufacturer when defining the load levels and duration of the verification tests on HMPE ropes, in order to achieve results within acceptable time frames.

**2.3. DM20 Fiber Creep Characterization**

Following the method described by Vlasblom and Bosman [8] a number of creep rate and creep rupture experiments have been performed on DM20 fiber at temperatures ranging from 30°C to 70°C and load levels from 300 MPa to 1700 MPa. This is comparable to load levels above 20% break load for a typical offshore mooring rope.

At room temperature, DM20 fiber loaded at 10% fiber break strength shows a creep rate of 0.03% per year; while SK78 showed a creep rate of 2% per year, and SK75 a creep rate of 10% per year. Like the other HMPE fibers, a temperature increase of 20°C increased the creep rate by approximately a factor of 10.

For comparative testing, accelerated creep tests are performed at elevated temperatures to provide results in an acceptable time frame. Fig. 1 shows a creep elongation over time on DM20 fiber, SK78 fiber and SK75 fiber at 70°C and 300 MPa stress level, which is comparable to 20% break load of a mooring rope. The experiment on DM20 fiber was continued over 100 days without any signs of imminent creep failure.

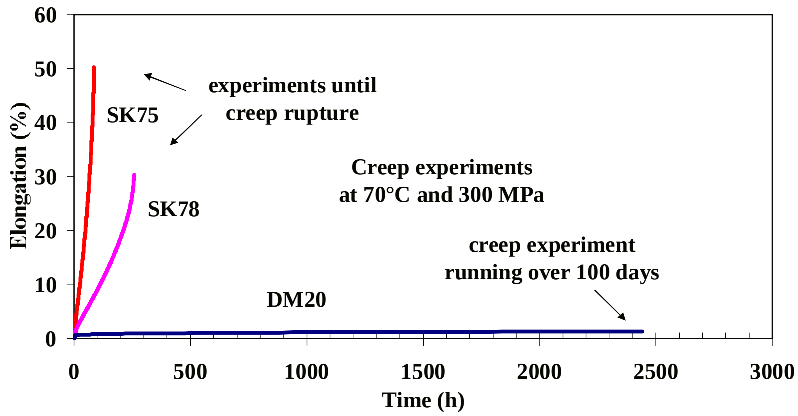


Figure 1. Measured creep elongation as a function of time
at a 70°C, 300 MPa fiber creep experiment

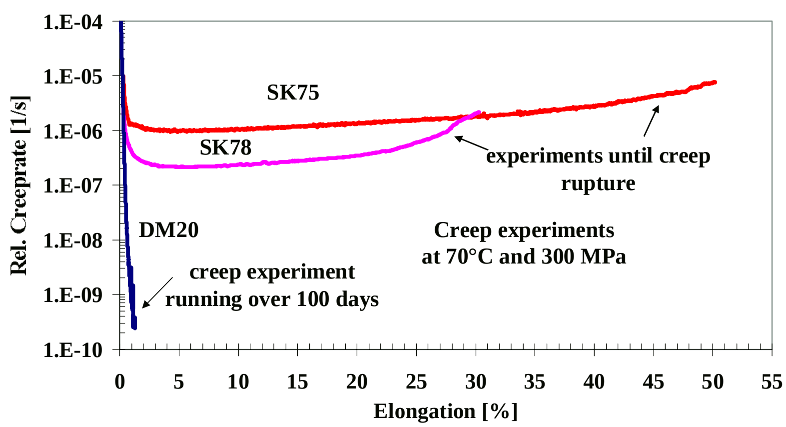


Figure 2. Measured logarithmic creep rate as a function of elongation
at a 70°C, 300 MPa fiber creep experiment

The same data is shown in Fig. 2 as logarithmic creep rate over elongation, illustrating the significant reduction in creep rate and low elongations experienced by DM20.

Fiber creep rate experiments indicate that, under normal offshore mooring rope loading conditions, the creep rate of DM20 fiber is 50 times lower than that of SK78. As with SK75 and SK78, the start of creep failure of DM20 depends upon the applied load and temperature. The HMPE's raw material feedstock, production methods, strength and modulus all have a bearing on the fiber's resistance to creep failure.

Under the same load levels, DM20 will reach the start of creep failures after much longer time than SK78; see Fig. 3, and with lower elongations. This suggests that the discard criterion of 10% permanent elongation recommended for general HMPE types and SK78 in industry guidelines and standards needs to be lowered for DM20.

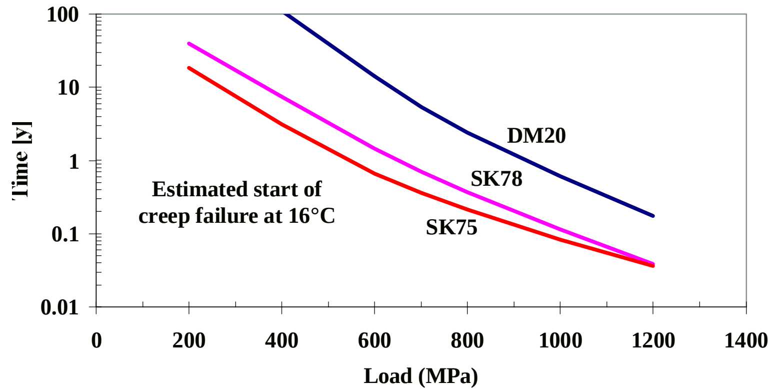


Figure 3. Estimated times at start of creep failure of DM20 fiber versus other HMPE fiber types at 16°C

## 2.4. DM20 Rope Creep Characterization

Lankhorst Ropes manufactured 8 strand braided subropes in 29mm diameter with 657 kN average break strength (spliced end termination) to verify the very low creep properties of DM20 mooring ropes.

On a 1000 kN capacity test frame at IFREMER, a creep test was performed, at 30°C and 290 kN (45% BL) over 30 days, by measuring the extension of the central part of the sample using a 500 mm elongation wire displacement transducer clamped to the rope [9].

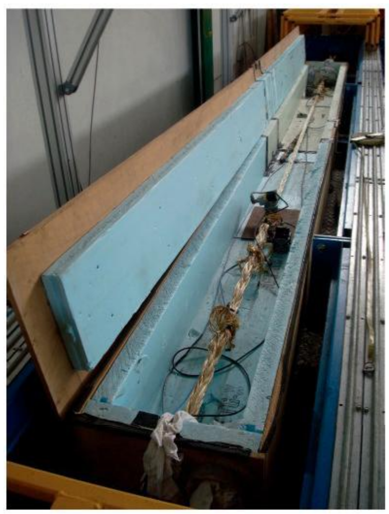

Figure 4. Interior of temperature chamber at Ifremer

The central part of the 8 meter eye-to-eye rope sample was heated by air heaters to 30°C. To record the temperature, a probe was inserted in a 1-meter length of HMPE braided rope of the same size and placed in the centre of the chamber next to the sample (Fig. 4).

The sample was subjected to 5 bedding-in cycles to 290 kN, and then held at a constant load of 290 kN at 30°C for 30 days. Fig. 5 shows the elongation of the central part of the rope for the duration of the creep test. As reference, the result of an identical test performed in 2003 on a rope made of SK78 is shown in the same figure [10]. While the rope made with SK78 reached creep failure at 30% elongation, the rope with DM20 showed only a small amount of creep.

After 30 days, the load on the rope made of DM20 was removed and the strain recorded during recovery for a further 68 hours at a load of 5.8 kN (1% nominal break load). A permanent strain of around 1.5% was recorded.

At the end of the recovery test the sample was completely unloaded, a new bed-in cycle was applied, and the rope ramped up to failure at 839 kN at a rate of 120 kN/minute.

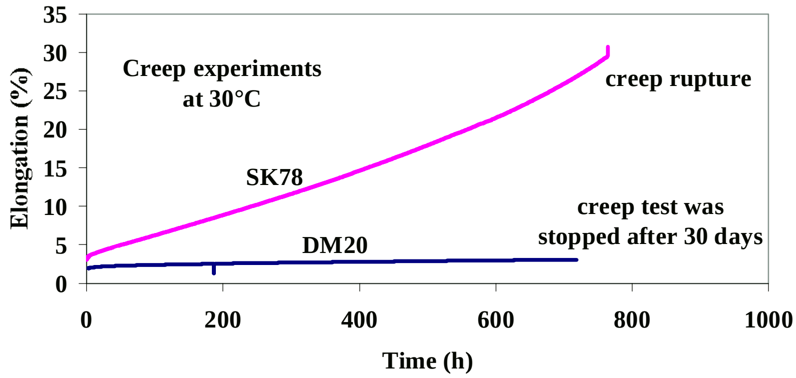


Figure 5. Creep elongation of 29 mm rope with DM20 and SK78 at 30°C

## 3. Stiffness

### 3.1. Stiffness measurements

To verify the offsets under heavy load conditions, the creep of fibers has to be taken into account. Del Vecchio and Monteiro [11] have stated that equivalent secant stiffness, incorporating creep of the most tensioned and most slack lines for storm durations of 24 to 72 hours, are relevant to a mooring analysis and have shown how yarn results can be used to produce estimates of rope properties. The equivalent secant yarn stiffness testing involves preliminary cycling followed by the actual stiffness cycling measurement. From this the creep of the yarn is estimated based on changes in elongation at pre-defined steps for periods up to 72 hours.

Stiffness measurements have been performed on DM20 fiber type in relation to the SK78 fiber, covering:

- Yarn stiffness based on Yarn Break Load
- Rope stiffness
- Yarn stiffness based on typical rope realization factor
- Yarn stiffness based on typical rope realization factor at 4°C

### 3.2. Yarn stiffness based on Yarn Break Load

Following this test procedure, measurements were performed on DM20 fiber and SK78 fiber to determine the quasi-static stiffness for wind- and leeward mooring lines (Fig. 6, Fig. 7 and Table 4). After an initial pre-loading (10-30%YBL), windward is defined from the delta elongation between 20%YBL (Yarn Breaking Load) and 45%YBL over 24 hours (incorporating creep) and leeward is defined from the delta elongation between 20%YBL and 5%YBL over 24 hours (incorporating creep recovery).

The stiffness values were calculated according to equation 2.

$$Stiffness = \frac{\Delta F / YBL}{\Delta L / L_i} \qquad (2)$$

Where:
$\Delta$F = force gradient from 20% to 45% considering high load creep and from 20% to 5% considering low load creep recovery;
$\Delta$L = elongation of the yarn correspondent to $\Delta$F;
YBL = Yarn Breaking Load, and,
$L_i$ = Sample Gauge Length at the beginning of the test.

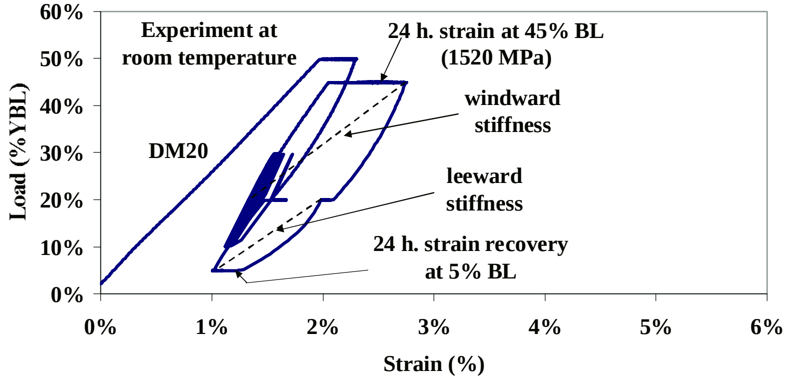


Figure 6. Load – strain results measured on DM20 fiber at room temperature, based on Yarn Break Load

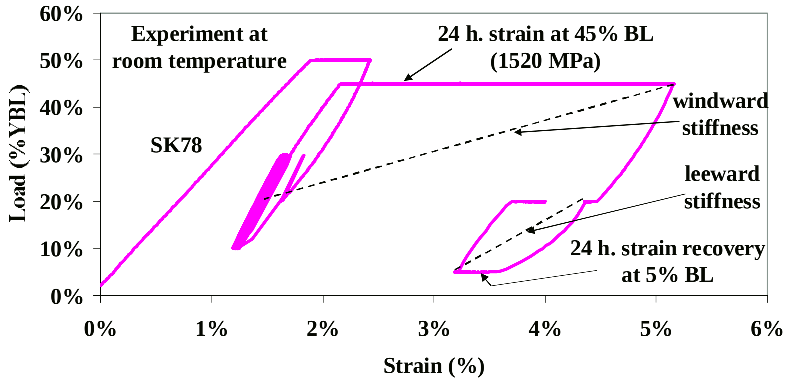


Figure 7. Load – strain results measured on SK78 fiber at room temperature, based on Yarn Break Load

Table 4. Equivalent secant stiffness and dynamic stiffness of SK78 and DM20 fiber at room temperature, based on yarn break load

| **Yarn stiffness based on Yarn Break Load** | **SK78 fiber** | **DM20 fiber** |
|---|---|---|
| Windward 24h. | 6.8 x YBL | 17.9 x YBL |
| Leeward 24h. | 13.0 x YBL | 15.5 x YBL |
| Dynamic stiffness (10-30%YBL) | 43.7 x YBL | 44.6 x YBL |

### 3.3. Rope Stiffness Measurements

HMPE is a visco-elastic material and its stiffness characteristics will vary dependent on load intensity, duration of loading and number of cycles. During early loading cycles, the bedding-in of the rope will result in some initial elongation. The equivalent secant stiffness and dynamic stiffness of DM20 in a rope construction was measured on the 52 mm diameter Gama98® rope construction subrope of 1843 kN average break strength (spliced end termination), produced by Lankhorst Ropes, and compared with data derived on a full size MODU rope made from SK78 (Table 5). Fig. 8 shows the result of the stiffness test. For a more visual representation, only the start point and the end point of each load step have been plotted.

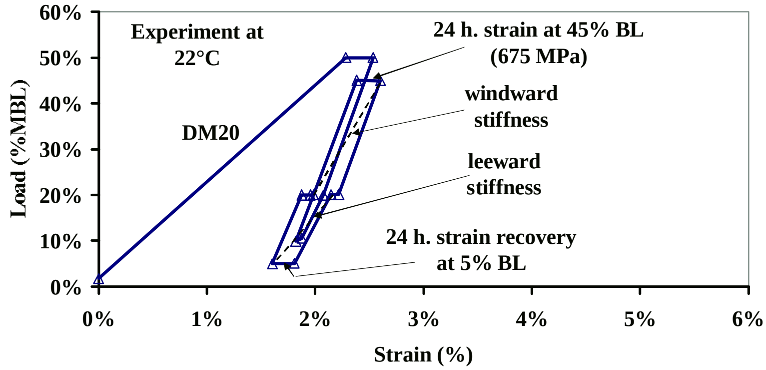


Figure 8. Load – strain results measured on 52 mm diameter subrope with DM20 fiber at 22°C [12]

Table 5. Equivalent secant stiffness and dynamic stiffness of subrope with SK78 and DM20 fiber at 22°C [12]

| **Rope stiffness** | **Rope with SK78 fiber** | **Rope with DM20 fiber** |
|---|---|---|
| Windward 24h. | | 40.3 x MBL |
| Leeward 24h. | | 27.8 x MBL |
| Dynamic stiffness (10-30%YBL) | 60 x MBL | 60 x MBL |

### 3.4. Yarn Stiffness Based on Typical Rope Realization Factor

Comparing table 4 and table 5 shows that although tested at same temperatures, the equivalent secant stiffness values of the yarn experiments based on the yarn break load are much lower than the values derived from the rope experiment.

When stiffness data is to be determined on a yarn, the load should be selected such that it is comparable to the load on the rope application. This means that for comparing fiber and rope stiffness data on a relative load basis, the fiber / rope break strength conversion factor, or realization factor (see equation 1), must be taken into account. Fig. 9, Fig. 10, Fig. 11 and Table 6 show the load – strain results of the same fibers based on a realization factor that is typical for offshore mooring rope applications.

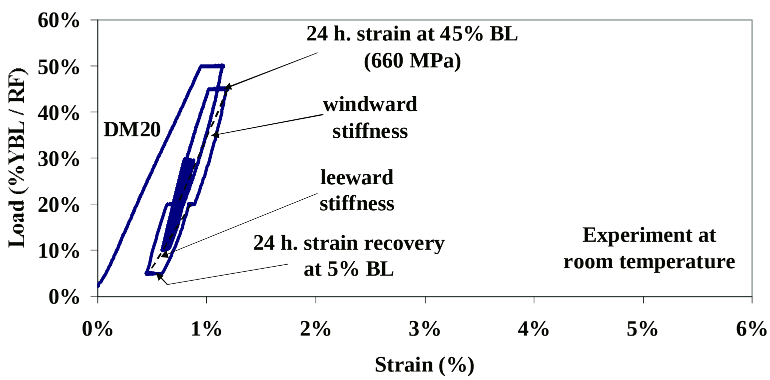


Figure 9. Load – strain results on DM20 fiber at room temperature, based on typical rope application realization factor

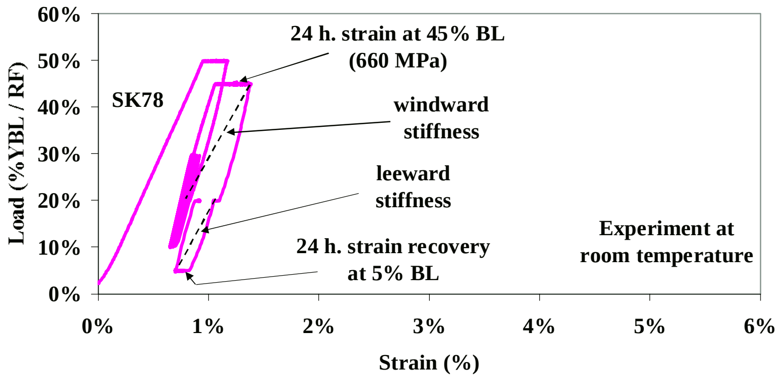


Figure 10. Load – strain results on SK78 fiber at room temperature, based on typical rope application realization factor

Table 6. Equivalent secant stiffness and dynamic stiffness of SK78 and DM20 fiber at room temperature, based on typical rope application realization factor

| Yarn stiffness based on rope realization factor | SK78 fiber (x YBL / RF) | DM20 fiber (x YBL / RF) |
|---|---|---|
| Windward 24h. | 39.9 | 52.5 |
| Leeward 24h. | 43.3 | 38.9 |
| Dynamic stiffness (10-30%YBL / RF) | 101.6 | 96.6 |

### 3.5. Yarn Stiffness Based on Typical Rope Realization Factor at 4°C

The degree of creep is, besides load and HMPE fiber type, dependent upon the operating temperature. This means that for comparing fiber and rope secant stiffness data, the temperature and load should be selected such that it is comparable to the temperature and load on the rope application. Fig. 11, Fig. 12 and Table 7 show the load – strain results of the same fibers based on a realization factor that is typical for offshore mooring rope applications measured at a temperature of 4°C.

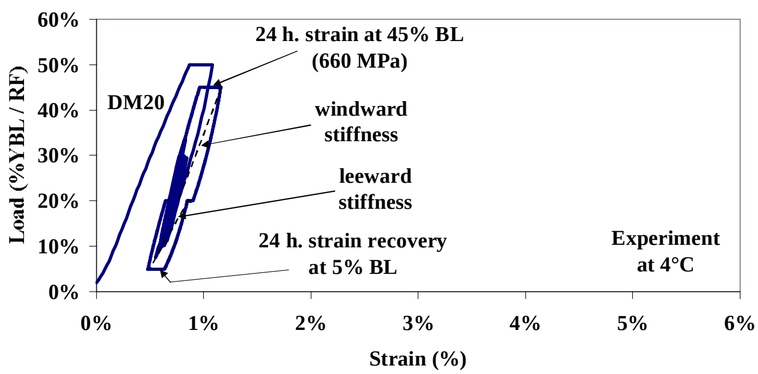


Figure 11. Load – strain results on DM20 fiber at 4°C, based on typical rope application realization factor

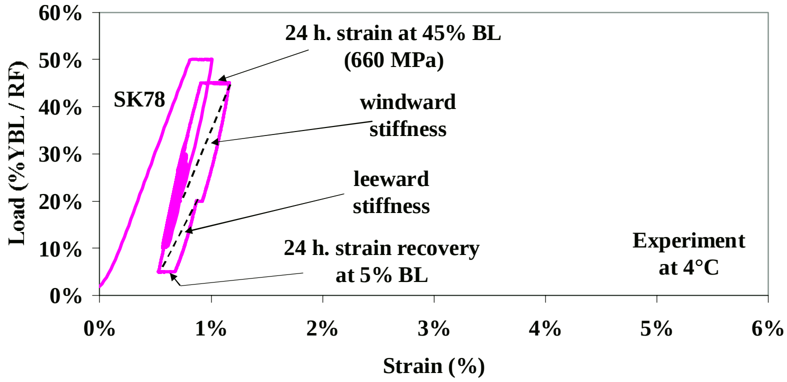


Figure 12. Load – strain results on SK78 fiber at 4°C, based on typical rope application realization factor

Table 7. Equivalent secant stiffness and dynamic stiffness of SK78 and DM20 fiber at 4°C, based on typical rope application realization factor

| **Yarn stiffness based on rope realization factor** | **SK78 fiber (x YBL / RF)** | **DM20 fiber (x YBL / RF)** |
|---|---|---|
| Windward 24h. | 48.8 | 52.1 |
| Leeward 24h. | 44.4 | 40.8 |
| Dynamic stiffness (10-30%YBL / RF) | 109.6 | 110.2 |

### 3.6. Discussion

The results shown in Table VI and Table VII seem to indicate that the windward stiffness and leeward stiffness of SK78 and DM20 fiber are very similar. However since the equivalent secant stiffness test combines stiffness and creep elongation in one test, the fiber creep properties should be reflected in the outcome.

Besides the already mentioned applied load and environmental temperature, the creep elongation is also a function of the exposure time. The small difference in windward and leeward stiffness of the two fibers, as shown in Table VI and Table VII, is an indication that the duration of the constant load was too short for the fibers to reach the plateau creep rate of creep regime I as discussed by Vlasblom and Bosman [8].

For representative tests, the fiber or rope should have been stabilized, or brought in creep regime II, by either a longer or higher pre-loading phase or a pre-loading phase at an elevated temperature. The pre-loading phase should be tuned to each fiber type, dependent upon the creep sensitivity. In doing so, it is expected that the equivalent secant stiffness of DM20 fiber will be close to the dynamic stiffness value, since creep elongation will be minimal.

In summary, the fiber and rope stiffness measurements have illustrated that:

- Secant stiffness of DM20 is higher than SK78 when measured on fiber or rope level,
- Dynamic stiffness of DM20 is in line with SK78 at rope level.
- Preferably stiffness values are to be determined on (sub)rope level.
- As creep is a function of temperature and time, secant stiffness is a function of temperature and time as well.

## 4 Abrasion and Fatigue Resistance

The DM20 fiber was tested for several more properties, including UV resistance, yarn on yarn abrasion resistance [5] and bending and tension fatigue resistance. DNV performed the fatigue resistance tests in its Høvik facility on a 34mm subrope construction manufactured by Lankhorst Ropes. The non fatigued subrope was break tested at Lankhorst at 90 tons.

DNV conducted cyclic loading tests according to ISO/TS 14909/1/section B.5.2. After cyclic loading tests the rope was pulled to failure at the DNV Bergen facility. The total number of cycles is 10.000 with load ranging from 5 to 50% of rope break strength. After cyclic loading a break test was conducted and resulted in a break strength of 1039 kN [13], being 118% of the break strength of the non cycled rope and confirming the good fatigue resistance of the subrope made with DM20 fiber.

Figure 13. Test setup at DNV Høvik

## 5. Conclusions

High Modulus Polyethylene is widely considered to be the most suitable material for longer, ultra deepwater mooring lines beyond 2,000m. The fibers are characterized by high strength and high modulus, producing lighter and smaller diameter high stiffness ropes, compared with polyester mooring lines for the same MBL. However HMPE's creep performance has prevented its use in long-term deepwater moorings. Systematic improvements in creep performance by DSM Dyneema have led first to the development of SK78 fiber for semi-permanent MODU moorings, and now DM20 fiber for offshore permanent production moorings.

The long-term creep properties of DM20 match industry requirements for the duration of permanent moorings.

As requested by various industry guidelines and standards, a creep estimation model based on fiber data has been developed for DM20 to demonstrate the fiber's ability to meet creep performance requirements, and thus limit the need for full size rope testing. The fiber creep rate properties were confirmed by creep tests on subropes.

Because of its extreme low creep elongations, the discard criterion of 10% permanent elongation - suggested in industry guidelines and standards for general HMPE types and MODU grade SK78 - needs to be re-considered for DM20.

DM20 fiber shows comparable physical and environmental properties as SK78 grade. Its excellent tension fatigue resistance has been confirmed by a test conducted by DNV.

Dynamic stiffness of DM20 equals SK78, while secant stiffness of DM20 is higher than SK78, confirming the reduced creep of this new fiber. It is advised to determine stiffness values on (sub)rope level.

In order for measurements at fiber level to be predictive for the rope level, the temperature and load level on the fiber should be selected such that they are comparable to the temperature and stress level in the rope in service.

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