



Mooring line performance in warm climate and dynamic conditions

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The maritime sector is progressing as fast as ever. New regulatory requirements, higher safety standards, cost pressure, and larger vessels are just some of the challenges operators are facing today. The combination of larger vessels, exposed terminals and rapid climate change means that mooring lines are increasingly subjected to extreme conditions both in terms of load and temperature.

Summary

- DSM and Samson Rope Technologies have co-developed a model to predict rope temperature in any condition where a rope is subjected to dynamic loading conditions.
- Based on first principles, the model has been validated with experimental data and has shown to give accurate predictions in a wide range of conditions.
- Combining the temperature model with DSM's Performance Model, the lifetime of a mooring line can be predicted more accurately than ever before.
- Even in challenging conditions with severe loading and high load amplitudes, rope temperatures stay well below Dyneema® SK78's continuous safe use limit of 70 °C.
- In a typical case study, the lifetime for a mooring line with SK78 on an LNG vessel traveling back and forth between Middle-East and Northern Europe is calculated to be in excess of 15 years based on 480 mooring hours per year.
- In the same case study, calculations for an equivalent rope with generic HMPE yield lifetimes between 5-8 years.

Introduction

The use of HMPE mooring lines has matured over the past years. Early failures because of human error, suboptimal rope constructions, or total system designs have been reduced considerably. Nowadays, the operational lifetime is therefore very much determined by adequate maintenance and the specific characteristics of the type of HMPE fiber. Mooring lines with Dyneema® are used across the globe, in tropical environments and cold weather, in benign mooring conditions, and increasingly at exposed terminals. With global temperatures rising and ship sizes increasing, it is becoming more and more important to determine the (fatigue) loading conditions and their impact on rope residual life.

In this document, we present a co-development by DSM and Samson Rope Technologies: a tool to predict lifetime of mooring lines with Dyneema® SK78 subjected to tension-tension fatigue in any environmental temperature.

The tool

The tool is based on numerical modeling combined with real life data and evidence generated⁽¹⁾ in test facilities (Figure 1). Rope temperature can be calculated depending on rope construction, loading conditions, and environmental conditions (Figure 2).

Based on first principles modeling, heat buildup is calculated caused by hysteresis and internal sliding of rope yarns, depending on material characteristics like a viscoelastic constitutive model⁽²⁾ and coefficient of friction. The heat buildup is in competition with heat loss to the environment via conduction through the rope, and convection and radiation to the environment, calculated using energy balance equations^(3,4). These depend on the surrounding medium (air/water) and wind or water flow.

The higher the rope temperature becomes, the more heat is lost to the environment. Consequently, the rope usually reaches a steady state temperature at which heat generated by loading is in equilibrium with heat loss to the environment. Steady state temperature increases with higher loads, higher loading frequencies, and larger rope diameter. Conversely, low environmental temperature, high wind speed, or higher braiding pitch lead to lower steady state temperatures.

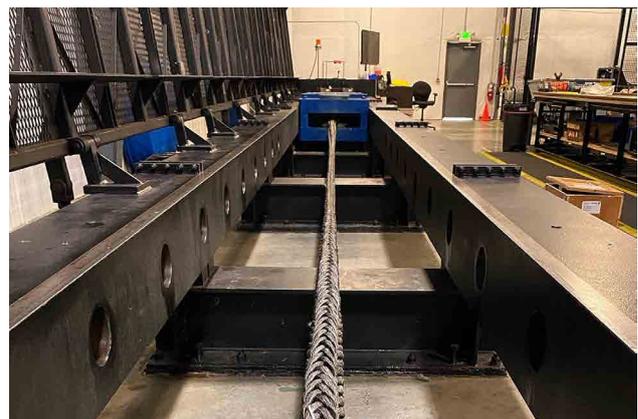
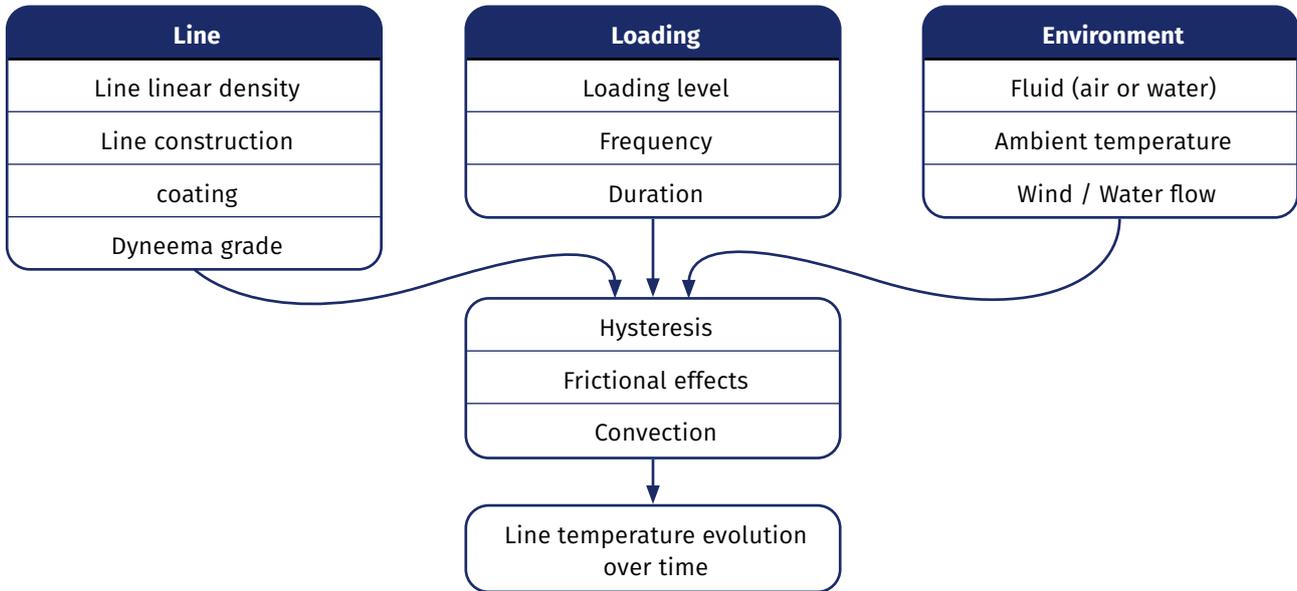


Figure 1: Testing equipment at Samson

All results presented in this white paper have been obtained with the same physical parameters, with different scenarios being represented by difference in input parameters (shown in Figure 2). The physical parameters were obtained as much as possible from literature and independent characterization measurements. Two additional parameters were required to fine-tune heat transfer and heat generated by hysteresis, which we determined from the experiments on 5 mm ropes and subsequently used to calculate all other data points, including the results for the 21 and 42 mm diameter ropes.

Figure 2: Mooring line temperature model developed by DSM and Samson



Insights into rope temperature

The resulting tool has proven to be reliable in a wide range of conditions. Also, it gives insight into temperature distribution over the cross-section of a rope: in the first example presented in this white paper, a 42 mm diameter rope made with Dyneema® SK78 is modelled in a mild (benign) mooring condition. Ambient temperature is 15 °C with a calm wind. The rope is cycled between 1% (approximating slack) and 20% of its designed break load with a period of 12 seconds. In Figure 3, the temperature distribution resulting from tension fatigue from center to core of the 42 mm rope with SK78 at steady state is shown. The core heats up 11°C with respect to ambient temperature whereas the surface temperature heats up 8°C. The 3° difference between core and surface means that temperature measured on the outside of the rope is a decent predictor of the core temperature.

Moreover, we have investigated the time needed for a rope to reach elevated temperatures in demanding conditions. See, for example, Figure 4: the simulations show that for a 42mm diameter rope with Dyneema®

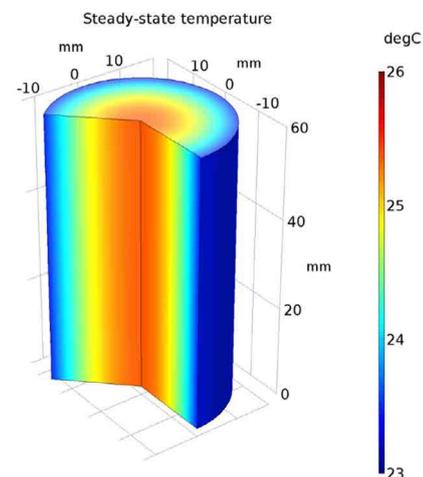


Figure 3: Depiction of temperature distribution throughout a 42mm rope with Dyneema® SK78. The rope is cycled between slack and 20% MBL with a period of 12 seconds and a wind speed of 1 m/s (1 Bft) at environmental temperature of 15°C. Note that after bedding in, the diameter is reduced from 42 to 36 mm.

SK78 in an ambient temperature of 15 °C, it takes approximately 1.5 hours for the rope to reach a maximum core temperature of 26 °C. This is the steady state temperature, meaning that, if ambient conditions do not change, heat generation inside the rope and heat loss to the environment are in equilibrium. For a 28 mm

diameter rope, the time to reach steady state is approximately 45 minutes. For the same loading conditions (stress, amplitude, frequency) it is observed that the bigger the rope diameter, the higher the eventual temperature rise and the longer it takes to reach a steady state temperature.

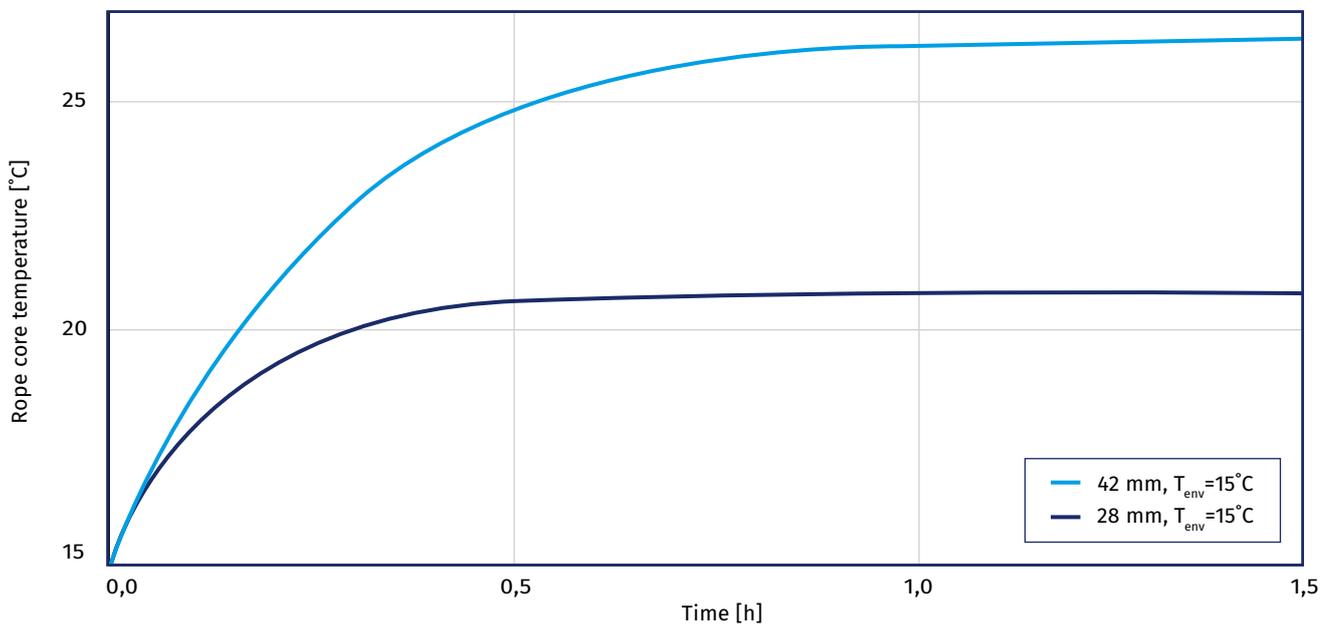


Figure 4: Evolution of rope core temperature in time for a 28 and 42 mm rope with SK78. In steady state conditions, it takes approximately 1.5 hours for the core temperature to reach a steady state. The rope is cycled between slack and 20% MBL with a period of 12 seconds and a wind speed of 1 m/s (1 Bft) at a 15°C ambient temperature.

A reliable tool

Extensive validation on full size rope testing has shown that the temperature tool is more than sufficiently accurate for the purpose, as is demonstrated by the maximum difference between measured and predicted data points being 3°C over a wide range of conditions (see Figure 6). It is important to note that for all the calculations shown, the same parameter set for the model was used. As mentioned in the above, the model is based on first principles and the only adjustments required on heat transfer coefficient and intrinsic

hysteresis was determined based on experiments with 5 mm ropes. All predictions for 21 and 42 mm ropes were ab initio predictions.

The calculations are very close to measured temperatures for a wide range of conditions, performed in state-of-the-art facilities at Samson Rope Technologies in the US, the DSM Materials Science Center in The Netherlands, and IFREMER in France. See for example Figure 5 and Figure 6, where experiments and predictions are compared. In Figure 5, the impact of rope diameter on temperature is clearly visible. The higher the diameter, the more heat is generated compared to the available surface area to cool the rope, and as a result the temperature in similar conditions is higher compared to thinner ropes. Moreover, the excellent match between the predictions from the newly developed tool and experimental data is visible.

Practical use cases

Having a model for rope temperature in place, we can now predict the lifetime of mooring lines in various conditions by combining the temperature model with the well-established Performance Model from DSM^(6,7,8). As an example, we have considered a mooring line on an LNG carrier that travels back and forth between the Middle East and Northern Europe, taking 8 round trips per year, mooring for 30 hours at each location (see Figure 7). Typical conditions for temperature, wind speed, and loads are given in Table 1. In this example the vessel encounters a storm condition during a mooring in Northern Europe every year. At the other end of the journey, in the Middle East, the vessel encounters a long swell condition once per year.

In Table 1, corresponding calculated rope temperatures are presented for these conditions. Combining the calculated temperature with DSM's proprietary Performance Model, we have calculated a cumulative lifetime for such a mooring line. Due to the superior fatigue lifetime of ropes with Dyneema® SK78 compared to generic HMPE types, it is the longest lasting choice in challenging conditions.

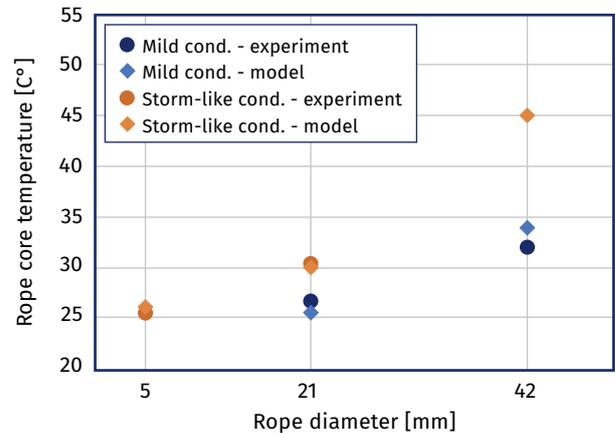


Figure 5: Rope core temperature. The load was cycled between zero (slack) and either 27% ("mild conditions") or 40% ("storm-like conditions") of maximum break load with a period of approximately 10 seconds.

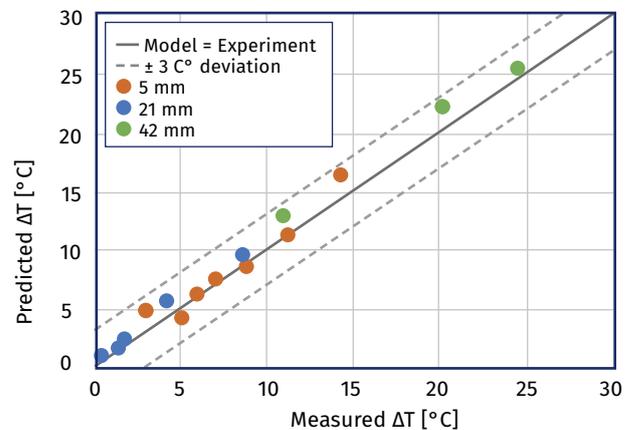


Figure 6: Comparison between measured temperature increase and predictions from the tool for a wide range of conditions in terms of rope diameter, load level and frequency, and environmental conditions like ambient temperature and wind speed (see Fig 2). ΔT denotes the difference between rope core temperature and environmental temperature.

	Exposed port in Northern Europe		Port in Middle East	
	Benign Conditions	Storm	Normal Conditions	Long Swell
Rope diameter	42 mm			
Coating	PUR coating			
Ambient temp	15 °C		31 °C (day), 22 °C (night)	
Wind speed	0 m/s (BF 0)	10 m/s (BF 5)	0 m/s (BF 0)	0 m/s (BF 0)
Pre-load (% of rope break strength)	15% BL	25% BL	15% BL	25% BL
Load amplitude	5% BL	20% BL	5% BL	10% BL
Period	12 sec	12 sec	12 sec	20 sec
Calculated line temperature (core)	23 °C	42 °C	40 °C (day) 30 °C (night)	51 °C (day) 41 °C (night)
Time to steady state	90 min	45 min	90 min	110 min
Dyneema® SK78 lifetime¹	15.9 years			
Generic HMPE 1 lifetime¹	5-6 years			
Generic HMPE 2 lifetime¹	7-8 years			
Occurrence	7 moorings per year, 30 hours at a time	1 mooring per year	7 moorings per year, 30 hours at a time	1 mooring per year

Table 1: Lifetime predictions in various conditions for 42 mm HMPE mooring lines, 31°C and 22°C are the average year long day and night temperatures, respectively

¹ Based on combination of calculations with DSM's Performance Model (6,7,8) and accelerated creep measurements.

Ongoing developments

With a reliable tool for predicting fatigue lifetime in place, DSM and Samson Rope Technologies are continuing to work on predictive models and products to enable safer mooring operations. One of these developments is a tool that models a mooring line in contact with an external surface like a fairlead, which in some circumstances can lead to an increased surface temperature state.

A preview of this model is presented in Figure 7. A 42mm diameter mooring line is modeled which is in contact



Figure 7: Case study for LNG carrier traveling back and forth between Middle-East and Northern Europe.

with a rectangular metal block representing a fairlead with high temperature (60°C) as it has been warmed up by the sun. The model shows that a part of the outer surface of the rope rises in temperature at the location where it is in direct contact with the metal surface. It also shows that the effect is local as the temperature increase disappears only centimeters away from the hot surface, because the high thermal conductivity of Dyneema® SK78⁽⁵⁾ quickly conducts the heat away from the source. Consequently, the impact of the fairlead is confined to a small section in the rope roughly 5 mm thick. Hence, the majority of load bearing fibers are not subjected to any elevated temperature, an observation that is in qualitative agreement with measurements published in earlier work ⁽¹⁰⁾.

In this context, it is additionally important to note that mooring lines made with Dyneema® SK78 can be used safely at temperatures of 70°C^(10,11) as Dyneema® SK78 fibers affected by high temperatures regain their original properties after cooling down. There is no permanent effect of core temperatures of 70°C. Even exceeding this temperature for a short time is not an issue as Dyneema® under load only starts to melt at 145°C⁽⁹⁾. As a next step, the external surface model will be combined with the fatigue load model presented in this white paper.

The number one choice for mooring

Performance of mooring lines relies on the right fiber choice, rope coating and construction, mooring design, and service and maintenance package. In case a vessel operator faces an extreme environment, whether it be hot climates, diverse loading conditions, or a combination of both, the tools presented in this white paper can provide confidence in mooring lines made with Dyneema® SK78 and provide recommendations to increase the safety of mooring.

Thanks to the combination of tension fatigue and creep performance, abrasion resistance, high and low temperature performance, and reduced environmental

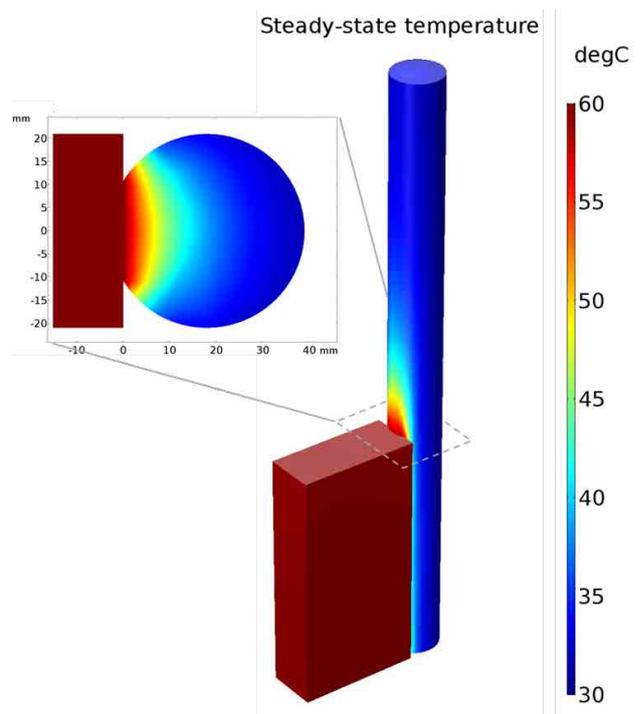


Figure 7: Plot for a 42mm mooring line in contact with a metal block at 60 °C. Ambient temperature: 30 °C. The rope reaches almost the same temperature as the block locally, but due to the high thermal conductivity of Dyneema SK78®, the majority of the cross section is unaffected.

impact, Dyneema® SK78 is the **number one fiber choice for vessel mooring lines.**

Alongside our premium fiber rope partners, DSM remains at the heart of developing mooring safety and operational excellence. Selecting the right fiber is a critical step in choosing the right mooring lines. Equally important is the selection of the right mooring line design, complemented with maintenance and servicing packages. Samson has a proven history of providing mooring solutions with Dyneema® SK78, proprietary coatings, and optimized constructions specifically designed for different vessel types. By going through a thorough mooring line selection process, operators can

be sure not only of durable, strong, and safe mooring lines at the time of installation, but also the tools and maintenance packages to keep them performing, year after year.

In this paper, we have demonstrated that lines with SK78 perform excellently under standard and severe mooring conditions, both with elevated temperatures and increased load amplitude. No fiber from other manufacturers shows a similar lifetime performance under standard and aggravated conditions.

DSM offers a wide portfolio of Dyneema® fibers suited for multiple heavy industry applications in maritime, offshore and heavy lifting – including Dyneema® SK78 and DM20. To find out more about our portfolio of fiber solutions, please **get in touch** with one of our experts today.

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