
# Enhancing Engineered Lifting Reliability with Fatigue Performance Modelling

## A case study featuring Lanko®Force HL Slings made with Dyneema® SK78 fiber

Authors: Marc Eijssen[1], Pedro de Jager[2], Martin Vlasblom[1], Binay Patel[1], Marcel Van der Molen[2]
[1] *Avient* [2] *Lankhorst Ropes*

Selecting the right rigging components out of a broad spectrum of offers is more important than ever. And increasingly, getting the most out of rigging assets can help to meet project demands and budgets without compromising on safety and productivity. Therefore, successful rigging selection needs to be focused around designing for both application loads and sling lifetime.

## Introduction

A core principle of the rigging industry is that "all lifts require a lifting plan." Whether the lift is a general-purpose, repetitive lifting operation or a complex engineering project, a lifting plan is essential for ensuring operational success while prioritizing the safety of crew and physical assets. The most intricate lifting plans are dedicated to engineered lifts which encompass either onshore or offshore non-routine lifting operations of robust assets. Engineering, Procurement, Construction & Installation (EPCI) project teams are already conducting engineered lifting operations using slings with breaking loads of approximately 3,000 - 5,500 mt. And these figures are expected to scale to nearly 10,000 – 15,000 mt within the next decade.

As project teams are confronted with ever larger load requirements their lifting plans must also transform to adequately assess and mitigate the risks involved in these demanding lifting operations. Project resources including people, budget and rigging hardware are not unlimited. Rigging hardware, for example, is commonly limited to strict dimensional requirements which can favor the use of slings at nominal design factors that are much lower than those prescribed for general-purpose lifts. On the other side of the coin are operational conditions, particularly the dynamic loading of assets due to interactions with winds and waves during the lifting operation. Therefore merely conducting a breaking test prior to the lifting operation does not provide adequate data on how the sling will perform. Scaling to ever higher nominal design factors to mitigate these dynamic loading conditions is not practical since synthetic sling suppliers face manufacturing equipment limitations for reaching ever increasing rated capacities. This again, favors the use of slings with lower nominal design factors.

Both Avient Protective Materials and Lankhorst Ropes, for example, have each developed engineering resources to aid project teams in the formation of customized lifting plans. At the fiber level, Avient Protective Materials has developed a DNV-certified fatigue performance model[1] to assess the utility of Dyneema® fibers for specific engineered lifting conditions. This modeling can be paired with sling level performance through, for example, full-scale testing that Lankhorst Ropes has conducted as part of their Heavy Lift Development Program[2,3].

In this whitepaper, we'll demonstrate how fatigue performance modeling can support the assessment of a sling's lifetime design factor and the development of safe and reliable engineered lifting plans. We have modeled the fatigue lifetime of Lanko®Force Heavy Lifting slings made with Dyneema® SK78 fiber during a real-world subsea lifting operation with data provided by TechnipFMC. And to prove the accuracy of our predictive modeling, we have conducted full-scale testing of the sling under the same loading conditions through accelerated testing at Lankhorst Ropes. The predicted fatigue lifetime was found to be safely before the measured fatigue lifetime. Therefore, we are confident fatigue performance modeling can help enhance the reliability of engineered lifting operations by delivering predictive data to project teams well before the actual lifting operation is performed.

# Overview of Subsea Lifting Scenario

Lankhorst Ropes deliberately chose a subsea lifting scenario since these types of offshore lifts involve variable dynamic loading induced by both winds and waves. Subsea lifting scenarios are routinely simulated in dynamic analysis software such as Orcina's OrcaFlex suite or Principia's Diadore™ suite. However, Lankhorst Ropes elected to utilize actual dynamic loadings experienced from a subsea lifting operation conducted by TechnipFMC.

The dynamic loadings provided by TechnipFMC were recorded during an actual subsea operation. Figure 1 shows the typical phases of a subsea lifting operation and the resultant load variations at each phase. This subsea lift is best characterized as a "ship-to-seabed" scenario where the intended load starts off on a ship, is lifted into the air, lowered to and through the splash zone and then travels down the water column, and ends its journey by being positioned on the seabed. Table 1 provides the specific load variations and cycle characteristics for each phase of the "ship-to-seabed" operation performed by TechnipFMC. Overall, the largest mean load and load amplitudes are experienced when the load is passing through the splash zone and during the initial lowering (Phases 2 & 3). In this particular example, the subsea lift takes approximately 27 minutes to complete.

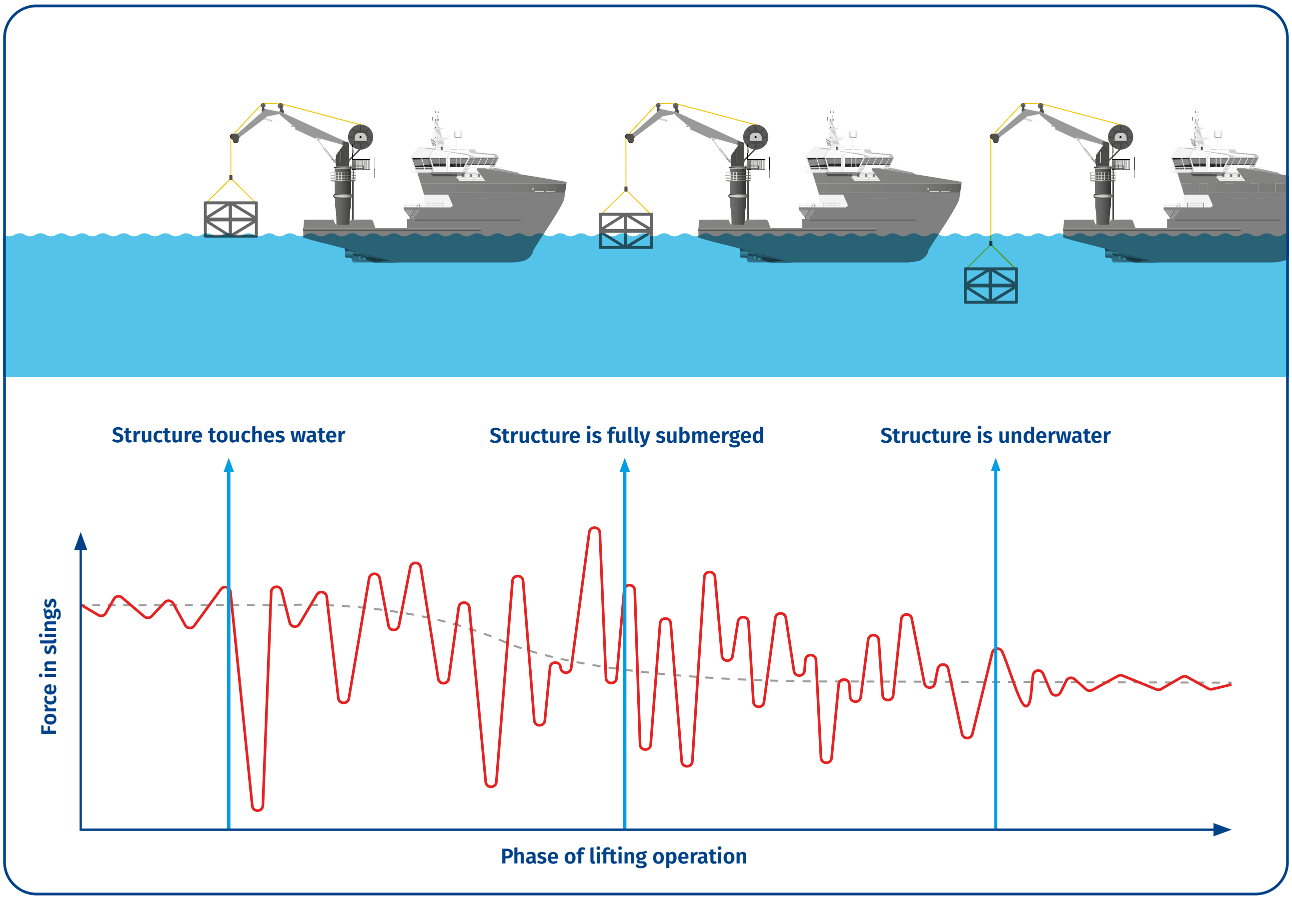


*Figure 1: Overview of a typical subsea "ship-to-seabed" lifting operation.*

| "Ship-to-Seabed" Lifting Operation | | | Measured Fluctuations | | |
|---|---|---|---|---|---|
| **Phase** | **Description** | **Duration (minutes)** | **Number of Cycles** | **Load (%MBL)** | **Cycle time (seconds)** |
| 1 | **Lifting in air** | 2.24 | 1 | 2 – 27 | 134.3 |
| 2 | **Passing the splash zone** | 2.7 | 30 | 25 – 36 | 5.4 |
| 3 | **Lowering** (without active heave compensation) | 8.78 | 65 | 23 – 30 | 8.1 |
| 4 | **Lowering** (with active heave compensation) | 3.83 | 115 | 25 - 29 | 2.0 |
| 5 | **Pre-landing** | 0.15 | 1 | 6 – 27 | 8.8 |
| 6 | **Load positioning** | 2.94 | 1<br>40 | 6 – 16<br>16 - 20 | 8.4<br>4.2 |
| 7 | **Landing and recovery** | 0.29 | 1<br>1 | 12<br>8 | 5.1<br>12.1 |
| 8 | | 1.88 | 1<br>1 | 9<br>5 | 108.6<br>3.9 |
| 9 | | 2.04 | 1<br>1 | 5<br>3 | 120<br>2,2 |
| 10 | | 2.04 | 1<br>1 | 3<br>2 | 120.1<br>2.3 |

*Table 1: Dynamic fluctuations experienced during a subsea "ship-to-seabed" lifting operation based on actual data collected by TechnipFMC.*

## Fit-For-Purpose Sling Construction

Lankhorst Ropes has developed a dedicated offering for heavy lifting applications under the brand name Lanko®Force HL[2,3]. For this full-scale testing applying the "ship-to-seabed" lifting conditions (as summarized in Table 1), the following fit-for-purpose sling (shown in Figure 2) was constructed in accordance with DNV-ST-N001:

| | |
|---|---|
| **Sling Construction** | Lanko®Force HL (12x3, eye-and-eye) |
| **Load Bearing Core Material** | Dyneema® SK78 |
| **Minimum Breaking Strength** | 2,000+ kN |
| **Sling Diameter** | 52 mm |
| **Load Design Factor** | 2.79 - 4.30* |

*Based on the range of load fluctuations experienced during the most severe dynamic loads (Phase 2 and 3).

*Table 2: Overview of the fit-for-purpose sling construction designed and manufactured by Lankhorst Ropes.*

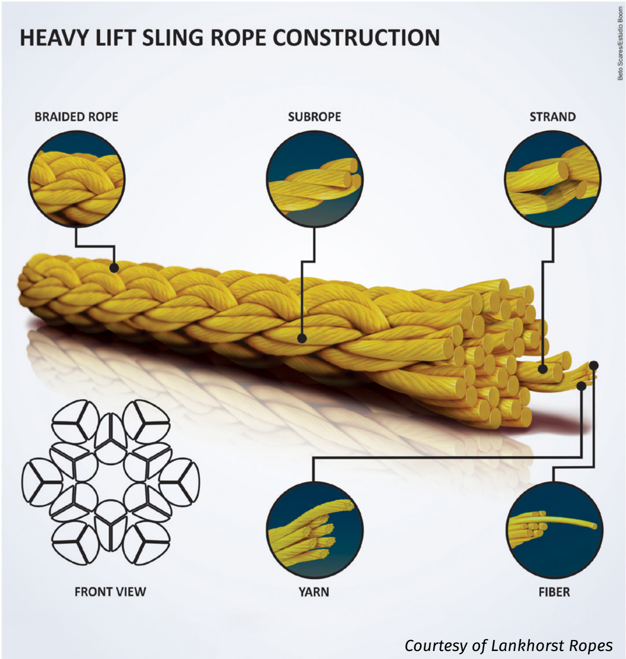


*Figure 2: A schematic of the Lanko®Force HL sling with a 12x3 made with Dyneema® SK78 fiber.*

To fully ensure fit-for-purpose and reliable sling design for any lift in accordance with standards such as DNV-ST-N001 it is critical to consider the statistical likelihood of failure under severe dynamic conditions. This approach accounts for the sling design load (the maximum calculated dynamic axial load in the sling during the operation) and the intended design strength of the sling (the sling's capacity). The sling design load is determined by allowances, loads and load factors covering uncertainties related to the payload and rigging design as well as operational conditions, such as dynamic loading induced by winds and waves. As depicted in Figure 3, the sling's capacity and the intended design load are most accurately described by a Gaussian distribution. The intention of fit-for-purpose and reliable sling design is to minimize the overlap between these distributions since overlaps increase the risk of overloading. The nominal design factor encompasses these uncertainties related to sling performance including those related to the performance of the load-bearing fibers.

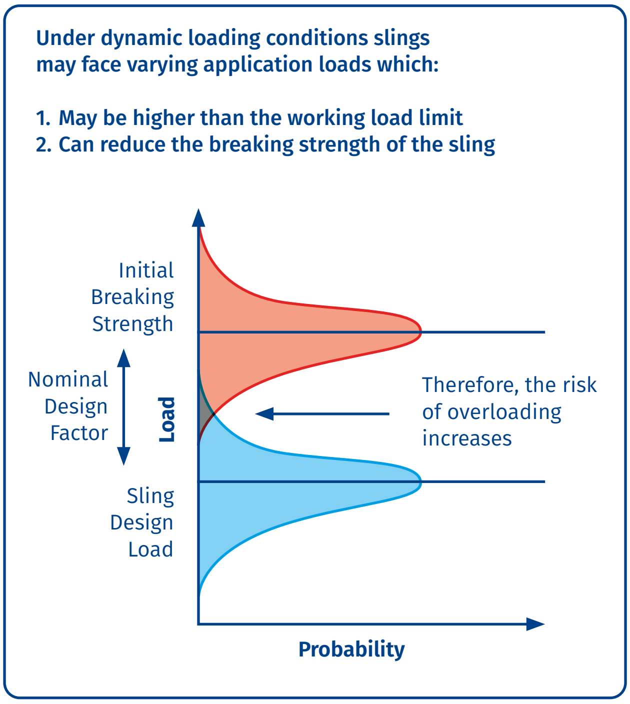


*Figure 3: The impact of dynamic loading conditions on reliable sling design.*

For typical offshore engineered lifting operations, a nominal design factor range of 2.79-3.79 is used. The loading conditions as mentioned in Table 1 reflect these design factors. The product of the nominal design factor and the design load, also referred to as "safe working load" or "working load limit", is the minimum initial breaking strength of the sling. DNV, a premier classification society for offshore applications, recommends that design assessments should be based on 2.5% quantile[4] calculations which ensure that for 97.5% of cases the actual load and capacity distributions will not overlap. Average values (representing the 50% quantile of a distribution) are not recommended since the risk of an actual load overlapping with a capacity distribution is 50% i.e., half of all cases may overload.

To assess if the intended nominal design factor range of 2.79-3.79 is sufficient for this specific subsea lift it is critical to assess the fatigue lifetime of the as-constructed sling. Merely conducting a breaking test prior to the lifting operation does not provide adequate data on how the sling will perform during the intended lifting operation and thereafter. However, assessing the fatigue lifetime of the as-constructed sling under the anticipated environmental conditions provides an accurate gauge for the reliability of the intended sling design.

# Assessing Sling Lifetime

## Modeling Fatigue Performance

Avient Protective Materials has developed a fatigue performance model which predicts the anticipated time to failure for load-bearing components, such as slings, under variable dynamic loading conditions. The model has been used for more than 20 years to aid in the design of load-bearing applications in a range of industries including, but not limited to, offshore energy, maritime, and construction. The core equations for the fatigue performance model are certified by DNV for the purpose of providing design data for load-bearing applications with Dyneema® fibers[1]. The model accounts for the "4T's" – time, tension, temperature, and type of fiber grade – which collectively influence the fatigue performance of Dyneema® fibers.

The output of the fatigue performance model is only as strong as the inputs provided for the modeling analysis. From our perspective, close collaboration between all members of the value chain is critical to realizing operational success for engineered lifting operations. Figure 4 provides an overview of the inputs for the fatigue performance model gathered from the full value chain.

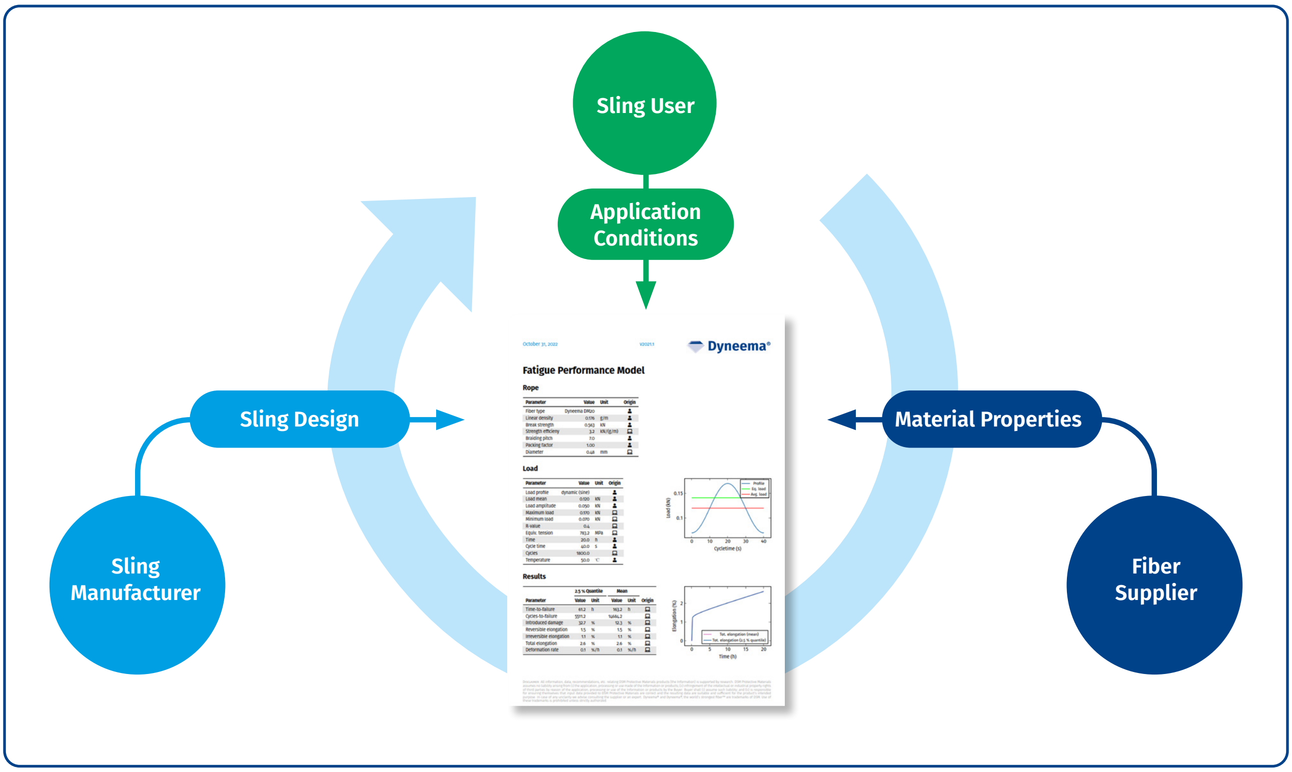


*Figure 4: Illustration of the valuable inputs from each part of the value chain for Avient's Dyneema® fatigue performance model.*

### Full-Scale Fatigue Testing until Failure

The real-world dynamic loading data provided by TechnipFMC presented a tremendous opportunity to prove the accuracy of predicting the performance of slings made with Dyneema® SK78, such as, Lanko®Force HL slings using Avient Protective Materials' Dyneema® Fatigue Performance Model. Full-scale testing of the intended sling construction was conducted at Lankhorst Ropes utilizing the data provided by TechnipFMC. Figure 5 shows the full-scale test set up at Lankhorst Ropes testing facility in The Netherlands. At the top right in Figure 5 a large oven chamber is shown encompassing the Lanko®Force HL sling made with Dyneema® SK78 fiber. The oven chamber is utilized to accelerate the fatigue testing by subjecting the sling to an elevated temperature until failure. In previous studies[5], Avient Protective Materials has demonstrated that fatigue lifetime obtained at elevated temperatures can accurately be scaled to lower temperatures such as those directly applicable for the intended real-world application. Thermocouples placed inside the portion of the sling within the oven chamber revealed that the sling reached a temperature of 62°C during testing.


*Figure 5: Full-scale fatigue testing set up at Lankhorst Ropes*

## Results

### Predicted vs. Measured Sling Fatigue Lifetime

Utilizing the dynamic loading data provided by TechnipFMC, the sling construction and elevated temperature (62°C) data from Lankhorst Ropes and fiber-specific data from Avient Protective Materials, a predicted time-to-failure of 32 hours was calculated by Avient's Dyneema® Fatigue Performance Model[1]. The predicted time-to-failure calculation is based on the DNV recommended 2.5% quantile, 95% confidence interval of the anticipated distribution in the sling's time-to-failure. For context, the predicted time-to-failure of 32 hours represents performing at least 71 full lifting operations at the referenced dynamic loading conditions.

An additional output of the fatigue performance model is the introduced damage on the sling due to each phase of the subsea lifting operation. As shown in Figure 6, most of the damage introduced into the sling during a subsea lifting operation is generated due to passing through the

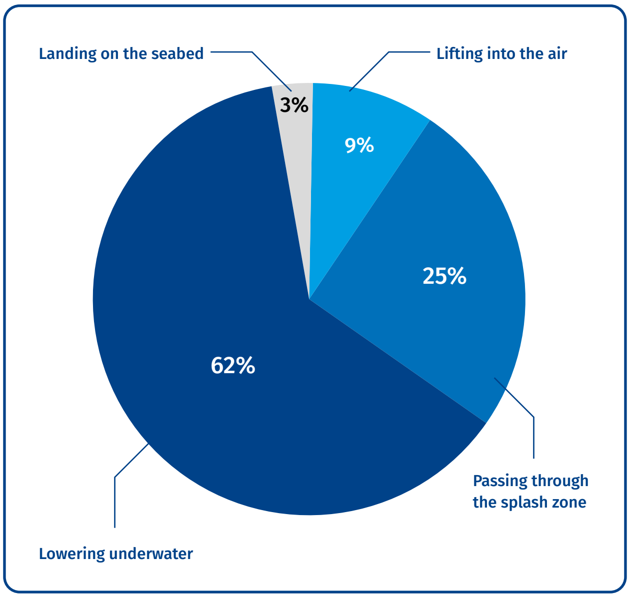


*Figure 6: Introduced damage at each stage of the subsea lifting operation as predicted by Avient's Fatigue Performance Model.*

splash zone (Phase 2) and lowering of the load when fully submerged (Phase 3). During lift planning and risk assessment, project teams can leverage data such as the introduced damage at each phase to pinpoint critical portions of an intended lifting operation and to ensure that the intended sling design is fit for the intended application.

The full-scale testing at Lankhorst Ropes was conducted to complete failure which was achieved after 54 hours of continuous testing. The measured time-to-failure represents at least 120 lifting operations at the referenced dynamic loading conditions.

As shown in Table 3, since the predicted time-to-failure (at 2.5% quantile, 95% confidence interval) was below the measured time-to-failure, Avient's Dyneema® Fatigue Performance Model is well suited to provide project teams with upfront knowledge on how an intended sling design will respond to anticipated environmental conditions.

It is imperative to mention that for both predicted and measured time-to-failure values an adequate lifetime design factor must be applied to further mitigate against uncertainties faced in the field. As shown in Figure 7, similar to prescribing nominal design factors to sling capacity and design loads under dynamic loading conditions (Figure 3), a lifetime design factor can be applied to predicted time-to-failure values to establish a useful service life for a sling. DNV specifies the safety level, or annual probability of failure, by means of Safety Classes[6,7]. Lifetime design factors on time-to-failure can range from 3-10 depending on the applicable Safety Class.

| | Prediction by Avient's Fatigue Performance Model | Full-Scale Fatigue Testing by Lankhorst Ropes |
|---|---|---|
| **"Ship-to-Seabed" Operation** | Same as described in Table 1 | |
| **Sling Construction** | Same as described in Table 2 | |
| **Environmental Temperature** | 62 °C | |
| **Time to Failure*** | 32** hours | 54 hours |

* Assuming continuous lifting operation
** 2.5% quantile, 95% confidence interval

*Table 3: Predicted versus measured deformation of the Lanko®Force HL sling made with Dyneema® SK78 based on fatigue performance modeling and full-scale testing.*

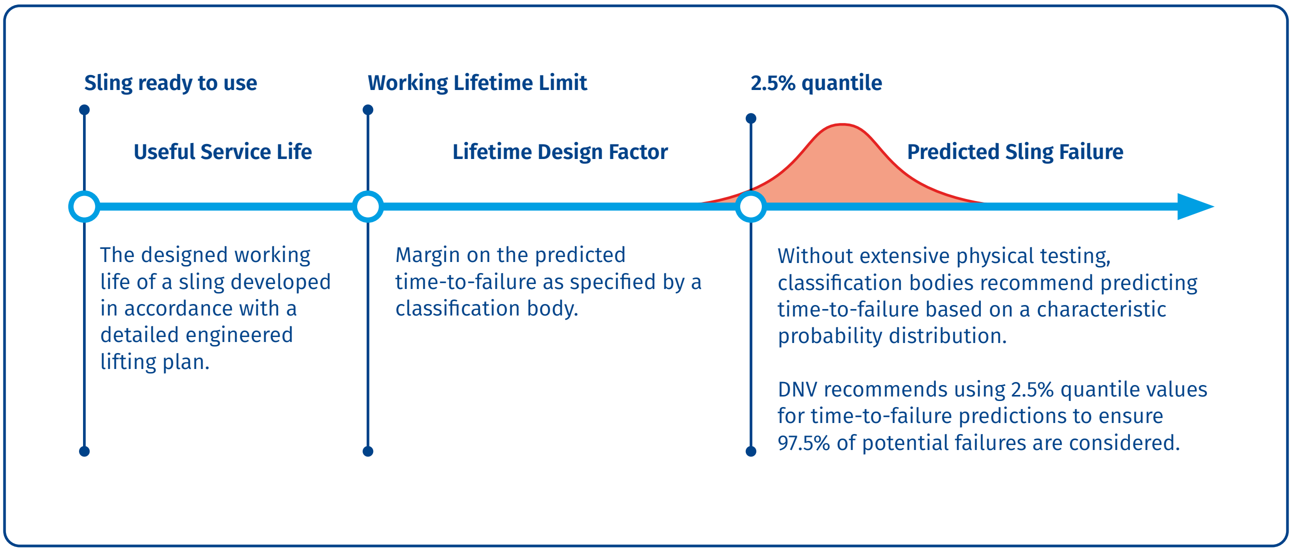


*Figure 7: The application of design factors to reliably establish realistic service life criteria from time-to-failure values.*

## Case Study

### Predicted Sling Lifetime at Application Temperatures in the US Gulf of Mexico

Table 4 summarizes the use of a Lanko®Force HL sling made with Dyneema® SK78 fiber under the same dynamic loading conditions provided by TechnipFMC, while assuming that the lifting operation is performed in the Gulf of Mexico during the month of August where water temperatures in the splash zone can reach 32°C.

If a classification society, such as DNV, rates the intended lifting operation as "Consequence Class 2" then the fatigue performance model predicts that at least 530 lifting operations may be performed during the useful service life of the sling at the referenced dynamic loading conditions. Getting the most service life of a sling requires quality manufacturing prior to delivery and meticulous maintenance and inspections after delivery. Furthermore, other potential failure mechanisms beyond fatigue performance must be adequately mitigated.

| Case Study | "Ship-to-Seabed" Lifting Operation in US Gulf of Mexico |
|---|---|
| Sling Construction | Lanko®Force HL (12x3, eye-and-eye) |
| Load Bearing Core Material | Dyneema® SK78 |
| Minimum Breaking Strength | 2000+ kN |
| Sling Diameter | 52 mm |
| Application Loads | Same as Table 1 |
| Application Temperature | 32 °C |
| Predicted Time to Failure* (2.5% quantile, 95% confidence interval) *: assuming continuous lifting operation | 3.3 months |
| Predicted Number of Lifting Operations to Failure | 5300 |
| Lifetime design factor* *: Assuming DNV Consequence Class 2 | 10:1 |
| Sling Design Lifetime (number of lifting operations) | 530 |

*Table 4: Predicted sling lifetime if the same "ship-to-seabed" lifting operation was performed in offshore Gulf of Mexico during the month of August.*

## Conclusion

### Optimizing your next engineered lifting plan

Environmental conditions and loading requirements vary from project to project. Avient's Dyneema® Fatigue Performance Model can help you assess and mitigate project risks. In this whitepaper, we have provided an example of how to leverage the fatigue performance model for conducting subsea "ship-to-seabed" lifting operations.

The model can also be utilized for:

- Cutting overall project costs by optimizing design factors
- Reducing the need for (or quantity of) full-scale physical testing
- Evaluating the lifetime of used slings for repurposing and re-use
- Supporting project certification such as via DNV-OS-E303
- Supporting Technology Qualification according to DNV-SE-0160

The full-scale testing referenced in this whitepaper was also utilized by Lankhorst Ropes to qualify their Lanko®Force HL sling technology for engineered lifting operations according to DNV-SE-0160. The engineering data generated from the qualification can support sling design and optimization. Examples of the data include D/d effects and rope flattening at bearing points.

Avient Protective Materials and our premium sling manufacturing partners, such as Lankhorst Ropes, are committed to providing EPCI project teams with tangible data that they can leverage to plan and perform engineered lifting operations safely, reliably, and cost-effectively. We invite you to connect with us to learn more about how our products and services can support your next engineered lifting project.

## Acknowledgements

The authors would like to thank TechnipFMC for contributing the realistic subsea “ship-to-seabed” dynamic loading scenario referenced throughout this whitepaper.


## References


1 Statement of Qualified Technology, DSM Dyneema Performance Model – core equations, Certificate no. 2019-3232, December 12, 2019

2 Statement of Qualified Technology, Lanko®Force HL lifting slings, Certificate no. 2019-3072-1, December 9, 2019

3 Realistic testing and development of high-performance synthetic fibre rope slings, Lankhorst Ropes, ODN 0968, OIPEEC Conference, The Hague, 2019

4 Design, testing and analysis of offshore fibre ropes, DNVGL-RP-E305, September 2015

5 Fundamental understanding of HMPE mooring rope endurance, Vlasblom, Bosman, Gualdi and Plaia, ODN 0967, OIPEEC Conference 2019

6 Composite Components, Offshore Standard DNV-OS-C501, Det Norske Veritas AS, November 2013

7 Qualification of innovative floating substructures for 10MW wind turbines and water depths greater than 50m, Deliverable D7.1 Review of FOWT guidelines and design practice, Gujer, P. and Kretschmer, M., 1-XA7H9F, LIFES50+ consortium, 31 August 2015