Influence of the positioning of plastic sheaves and steel sheaves on rope life and service life: Insights from extended bending fatigue analysis.

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Summary

This study provides a comprehensive analysis of how the material composition and sheave arrangement affect the lifetime and safety of wire ropes. Using a special bending fatigue testing machine, the research evaluates the effect of different configurations of plastic and steel sheaves on rope durability.

The results indicate that the lifetime of wire ropes decreases significantly as the proportion of steel sheaves increases. Importantly, the study finds that, depending on the rope design, the presence of at least one steel sheave, in some cases at least two steel sheaves is critical in reliably signalling the imminent end of a rope's service life.

The research highlights the dual role of steel sheaves: while accelerating the wire breaks of the rope, they are essential in providing a timely indication of the need for rope replacement. This balance between durability and safety is critical to the design of reeving systems, providing essential guidance for improving both operational efficiency and safety protocols in industries that rely heavily on complex reeving configurations.

Keywords: rope life, service life, rope discard, wire ropes, steel sheaves, pulleys, plastic sheaves

1 Introduction

In the dynamic field of modern rope technologies, particularly within reeving systems, the use of lightweight materials such as plastic sheaves have increasingly been favoured for their notable cost and weight benefits. However, the need to integrate steel sheaves remains [1], serving a dual purpose of facilitating early detection of wire breaks and so the end of service life.

Previous research has highlighted that the inclusion of at least one steel sheave is crucial for enhancing safety by providing clear indicators for necessary rope replacement [2,3]:
The previous study investigated the effect of different configurations of plastic and steel sheaves on rope life and service life. Various sheave configurations were tested in a series of bending fatigue tests using an 8xK26WS - EPIWRC rope construction. These tests highlighted specific correlations between the service life achieved by each configuration and the time to reach rope´s discard state depending on these configurations.
It has been observed that the lifetime of the rope decreases by $\approx$17.50% for every additional 20% steel sheave in the reeving system. It has also been observed that the more steel sheaves are introduced into the system, the greater the safety margin between the service life and the failure of the rope if the steel sheaves are arranged consecutive.

In particular, the strategic placement of even a single steel sheave within the reeving system proved to be crucial in signalling when a rope was nearing the end of its service life. However, the underlying mechanisms driving this phenomenon remained elusive.

This study extends previous work by performing a comprehensive bending fatigue analysis to further investigate the effect of sheave materials and their positioning on service life and overall lifetime.
New experimental data is presented to evaluate the fatigue performance of different sheave configurations. The results show how specific configurations affect the bending fatigue behaviour of ropes and provide deeper insights into the optimum sheave positioning and the number of sheaves required for reliable end of service life detection.

2 Research Methodology & Experimental Design

In the study, an advanced machine concept was employed to test ropes under bending fatigue, markedly different from conventional testing methods. As it can be seen in **Figure 1**, at the core of this machine is a system comprising five sheaves, which can consist of varied materials. Unlike traditional testing machines that run the rope over a single sheave, this approach creates more realistic test conditions, especially regarding the influence of positioning different sheave materials in the reeving system

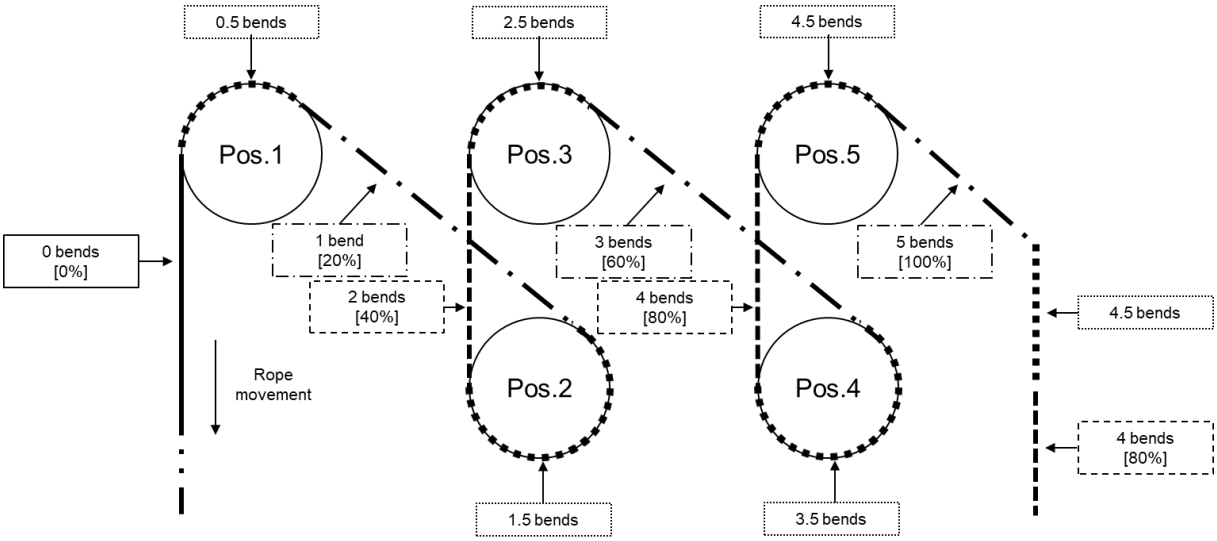


Figure 1: Bending Fatigue Test – Sheave Arrangement

This specialized bending fatigue machine allows for the testing of ropes in controlled conditions, with a focus on the most heavily stressed section of the rope. In this area, the rope is subjected to 10 bending cycles per machine cycles (100%), while adjacent areas experience decreasing bending cycles (80%, 60%, 40%, 20%), showed in **Figure 2**.

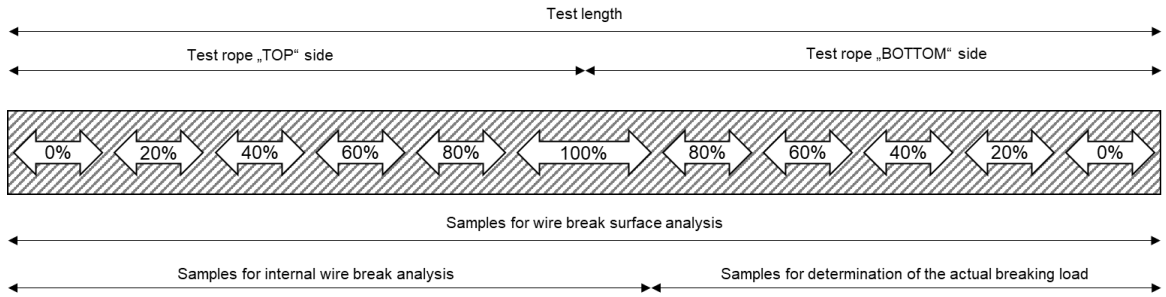


Figure 2: Bending Fatigue Test – Evaluation Scheme

Furthermore, the design allows for continuous measurement of various rope properties and a detailed analysis of both, external and internal rope damage as well as the actual breaking forces of the ropes at various stages of their lifecycle. A detailed description of the concept can be found in [4].

The specific test parameters, test sheaves used, and the rope construction that was investigated are shown in the tables below (**Table 1**,**Table 2**,**Table 3**):

Table 1: Rope construction & properties

	Rope 1	**Rope 2**
Construction	8 x K26WS EPIWRC	8 x K26WS EPIWRC
Rope diameter d	16 mm	16 mm
Lay direction	RHOL	RHOL
Surface	Galvanized	Galvanized
Nom. wire strength R_0	1960 N/mm^2	1960 N/mm^2
Rope Category Number (RCN)	09	09
Discard criteria ISO 4309		
Number of visible wire breaks on reference length of 6d	9	9
Number of visible wire breaks on reference length of 30d	18	18

Table 2: Sheave construction & properties

	Steel	**Plastic**
Material composition	42CrMo4	PA66
Hardness	53[1]	160/125[2]
D/d ratio	20	20
r/d ratio	0.53	0.53
Opening angle	60°	60°

Table 3: Test parameter

Safety Factor SF	8.33
Rope velocity v	1,15 m/s

To validate the hypothesis presented in the previous study [2,3], the former test series was extended to include configurations with three and four consecutive steel sheaves (configurations (4) and (5) in **Figure 3**).

In addition, configurations (1) to (7) were retested using the same rope construction, but sourced from a different manufacturer.

This approach was specifically designed to investigate the effect of sheave material and arrangement on the service life and lifetime of wire ropes.

Figure 3 shows all the configurations tested in this study.

[1] HRC

[2] $H_{358/30}$ according to ISO 2039-1

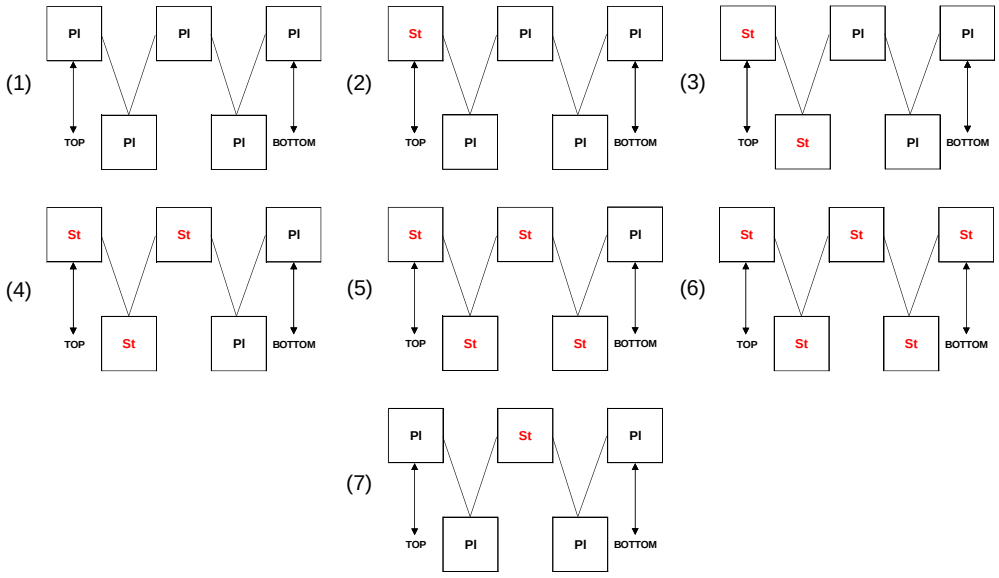
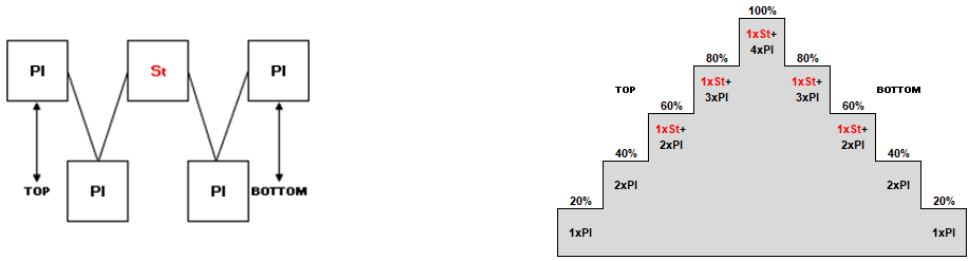


Figure 3: Bending Fatigue Test – Sheave Arrangement (1) – (7)

The general evaluation scheme is illustrated in **Figure 4** using the test configuration (7). This method makes it possible to associate the rope sections from the bending fatigue test and the identified wire breaks on the rope surface with a percentage of steel and plastic sheaves. This allows general statements to be made about the service life and lifetime of ropes in different reeving systems.



Number of St.[3]	% St.[3]	Number of Pl.[4]	% Pl.[4]	Lifetime	Sheave Order
0	0%	2	100%	20% -	Pl Pl
0	0%	4	100%	40% -	Pl-Pl Pl-Pl
2	33,33%	4	66,67%	60% -	Pl-Pl-St St-Pl-Pl
2	25%	6	75%	80% -	Pl-Pl-St-Pl Pl-St-Pl-Pl
2	20%	8	80%	100%-100%	Pl-Pl-St-Pl-Pl-Pl-Pl-St-Pl-Pl
2	25%	6	75%	- 80%	Pl-Pl-St-Pl Pl-St-Pl-Pl
2	33,33%	4	66,67%	- 60%	Pl-Pl-St St-Pl-Pl
0	0%	4	100%	- 40%	Pl-Pl Pl-Pl
0	0%	2	100%	- 20%	Pl Pl

Figure 4: Bending Fatigue Test – Evaluation Scheme

[3] St. = Steel Sheaves

[4] Pl. = Plastic Sheaves

3 Results

The approach described in the previous section was designed to ensure an accurate and reliable evaluation.

To this end, the rope was fatigued in the chosen sheave arrangement until either failure of an outer strand was detected or a significant increase in elongation occurred within a pre-defined period, indicating failure of the rope core.

On completion of the tests, a careful assessment of the wire breaks occurred, was made. This assessment was based on the examination of individual sections shown in **Figure 4** and was conducted in accordance with the guidelines of ISO 4309 [5].

The bending fatigue results from the different test configurations are presented in **Table 4**:

Table 4: Bending fatigue test results

Sheave Order		Lifetime N [-]	Discard N_{A30d}		Test Nr.	Rope Nr.
Pl-Pl-Pl-Pl-Pl	Pl-Pl-Pl-Pl-Pl	632290	619644	100%	2[5]	1
Pl-Pl-Pl-Pl-Pl	Pl-Pl-Pl-Pl-Pl	524502	514102	100%	10	2
St-Pl-Pl-Pl-Pl	Pl-Pl-Pl-Pl-St	511000	112420	22%	3[5]	1
St-Pl-Pl-Pl-Pl	Pl-Pl-Pl-Pl-St	379463	379463	100%	11	2
St-St-Pl-Pl-Pl	Pl-Pl-Pl-St-St	411500	102875	25%	4[5]	1
St-St-Pl-Pl-Pl	Pl-Pl-Pl-St-St	335697	99998	30%	12	2
St-St-St-Pl-Pl	Pl-Pl-St-St-St	328960	105267	32%	7	1
St-St-St-Pl-Pl	Pl-Pl-St-St-St	258974	98987	31%	13	2
St-St-St-St-Pl	Pl-St-St-St-St	275350	110140	40%	8	1
St-St-St-St-Pl	Pl-St-St-St-St	194410	105156	43%	14	2
St-St-St-St-St	St-St-St-St-St	242590	127164	52%	1[5]	1
St-St-St-St-St	St-St-St-St-St	149840	92582	62%	9	2
Pl-Pl-St-Pl-Pl	Pl-Pl-St-Pl-Pl	433750	433750	100%	5[5]	1
Pl-Pl-St-Pl-Pl	Pl-Pl-St-Pl-Pl	414930	402482	97%	6[5]	1
Pl-Pl-St-Pl-Pl	Pl-Pl-St-Pl-Pl	333520	333520	100%	15	2

[5] Tests conducted in the previous study

3.1 Consideration as a 5-Sheave-Reeving-System

In the following section, each test arrangement is considered as a dependent system, equipped with the same number of sheaves and materials as described in the previous chapters.

Figure 5 shows the influence of the number of steel sheaves to discard and failure of **Rope 1** based on the data of **Table 4**.

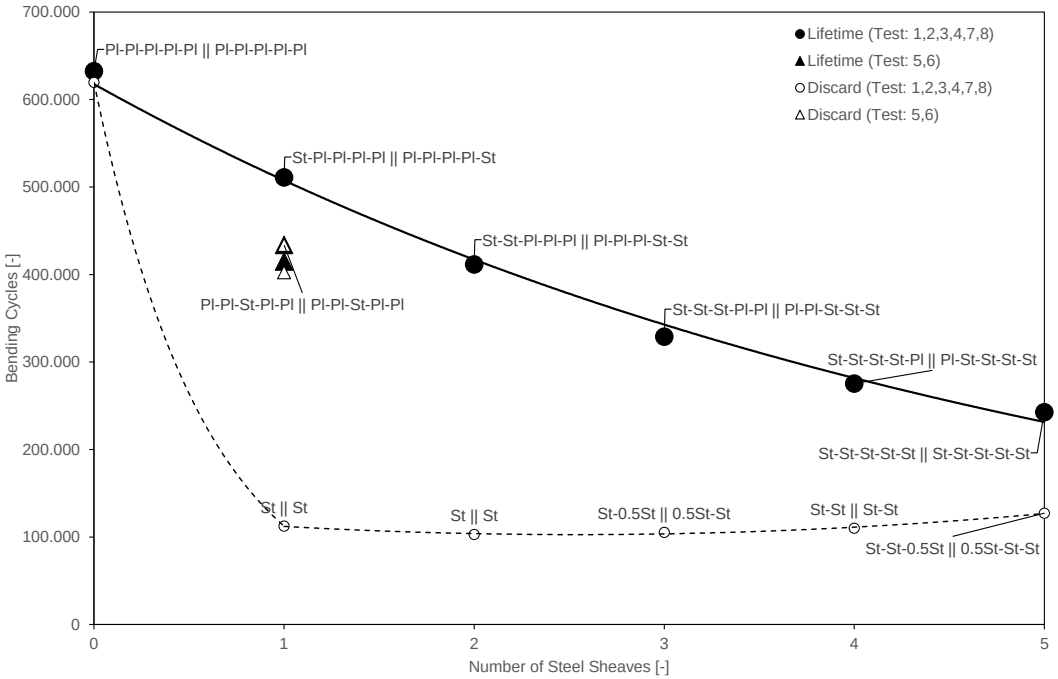


Figure 5: Lifetime and Discard depending on the Number of Steel Sheaves (Rope 1)

Figure 6 shows the influence of the number of steel sheaves to discard and failure of **Rope 2** based on the data of **Table 4**.

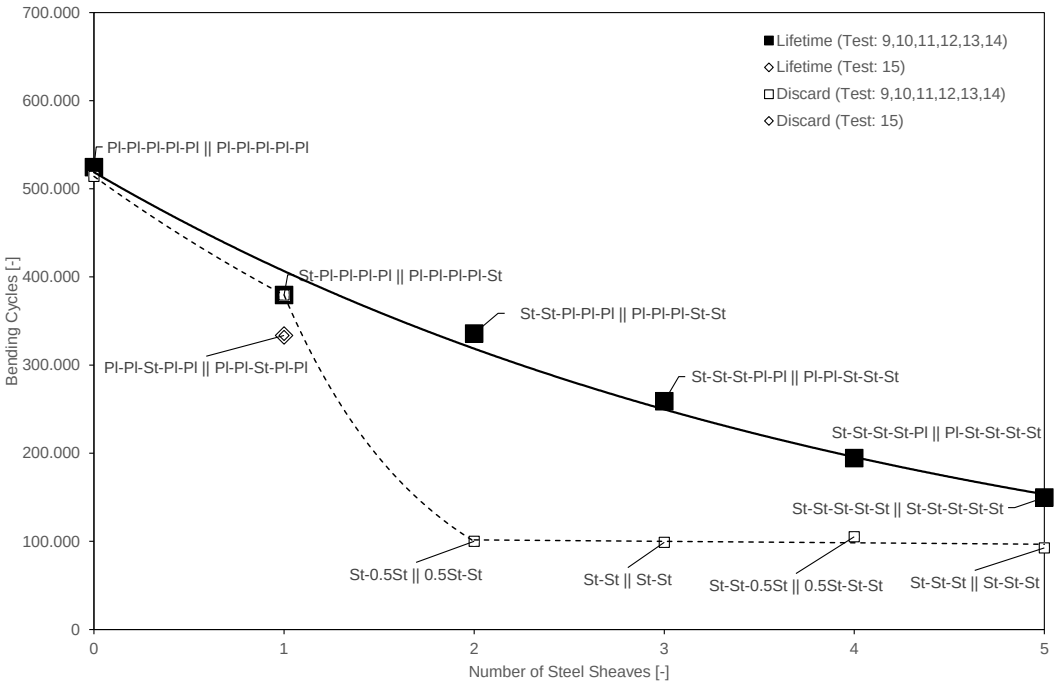


Figure 6: Lifetime and Discard depending on the Number of Steel Sheaves (Rope 2)

The following **conclusions** can be drawn from these data for Test **Rope 1**:

- The rope lifetime on **plastic sheaves only**, is increased by a factor of 2.61 compared to steel sheaves only, and the service life is increased by a factor of 5.40.
- If the **steel sheaves are arranged consecutive**,
    - the rope life will be reduced continuously as the number of steel sheaves increases.
    - for all tested configurations, the end of service life is reliably indicated on a steel sheave with sufficient residual lifetime, **if at least one steel sheave is installed in the reeving system**.
- If there is **no steel sheave** in the system, the service life of the rope ends short before end of rope life.
- If only **one sheave is positioned in the centre** of the arrangement, the lifetime is reduced to 83% compared to the lifetime with the sheave at the first position. The service life increases by a factor of 3.72 without having enough residual life.

The following **conclusions** can be drawn from these data for Test **Rope 2**:

- The rope lifetime on **plastic sheaves only** is increased by a factor of 3.50 compared to steel sheaves only, and the service life is increased by a factor of 5.55.
- If the **steel sheaves are arranged consecutive**,
    - the rope life will be reduced continuously as the number of steel sheaves increases.
    - for all tested configurations, the end of service life is reliably indicated on a steel sheave with sufficient residual lifetime, **if at least two steel sheave is installed in the reeving system**.
- If there is **no or only one steel sheave** in the system, the service life of the rope ends short before end of rope life.
- If only **one sheave is positioned in the centre** of the arrangement, the lifetime and the service life are reduced to 88% of the tests with the sheave at the first position. In both arrangements, there is no residual lifetime available.

It can be concluded that in both test series the position of the steel sheave has an influence on the service life and lifetime of the rope, especially when the sheave is placed in the middle of the reeving system.

Furthermore, it can be concluded that the rope type affects the minimum number of steel sheaves required within a reeving system, to ensure the detection of rope´s end of service life.

A possible conclusion for this dependency could be that ropes with lower residual lifetime, in steel sheave only reeving systems, require multiple steel sheaves to ensure safe and timely discard indication. However, this behaviour could also be due to the general scatter in fatigue tests.

3.2 Consideration as a General-Sheave-Reeving-System

In the following section, each test arrangement is considered as an independent system, equipped with a percentage amount of plastic and steel sheaves.

Figure 7 shows the influence of the percentage of steel sheaves to discard and failure of **Rope 1** based on the data of **Table 4**.

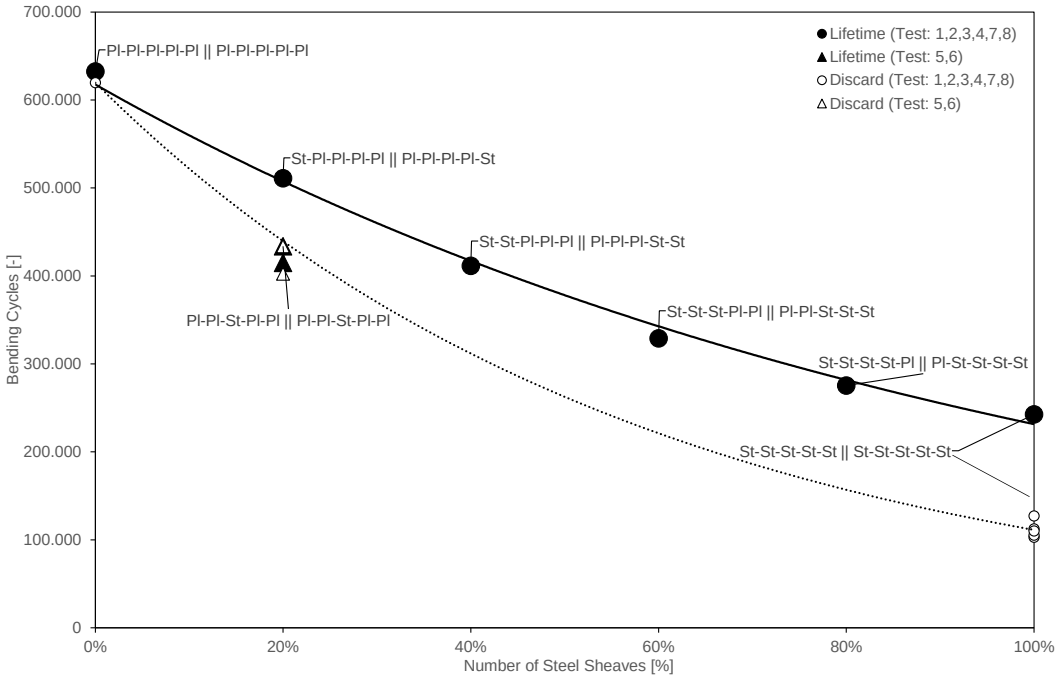


Figure 7: Lifetime and Discard depending on the Percentage of Steel Sheaves (Rope 1)

Figure 8 shows the influence of the percentage of steel sheaves to discard and failure of **Rope 2** based on the data of **Table 4**.

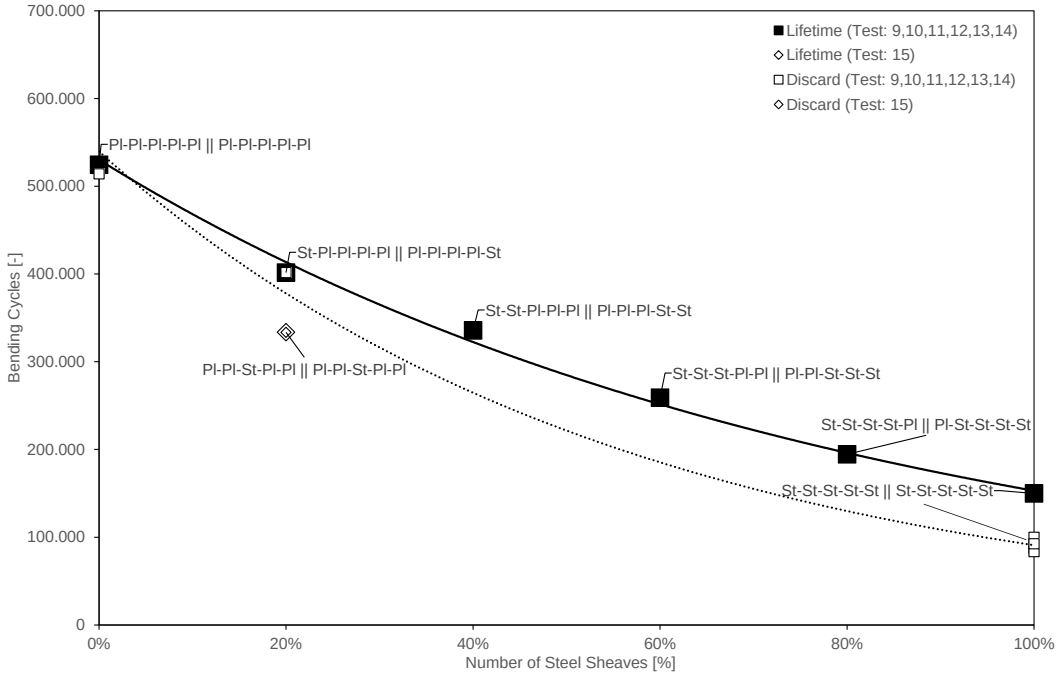


Figure 8: Lifetime and Discard depending on the Percentage of Steel Sheaves (Rope 2)

Several **conclusions** can be made from these data:

- As the number of steel sheaves increases, the lifetime of the rope decreases, if the steel sheaves are arranged consecutively.
- As the percentage of steel sheaves in the system increases, the service life of the rope decreases.
- Correlations can be found between the individual reached lifetime and the time to discard of the rope in dependence of different sheave arrangements.
- **Even a single steel sheave / two steel sheaves** in the system, correctly placed, can make the rope operation considerably safer by increasing the residual lifetime.

For **Rope 1**, it can be noted that the lifetime of the rope **decreases by ≈17.82%** for every additional 20% of steel sheave in the system Therefore, if the steel sheaves are arranged consecutive, the following relationship emerges:

$$Reduction\ factor\ rope\ life = e^{-0.981 * \frac{number\ of\ steel\ sheaves}{total\ number\ of\ sheaves}} \quad (1)$$

It can be also noted that the residual lifetime of the rope increases proportional for every additional 20% of steel sheave in the system. Therefore, if the steel sheaves are arranged consecutive the following relationship emerges:

$$Residual\ life = N * \left(1 - \left(1{,}00 * e^{-0.736 * \frac{number\ of\ steel\ sheaves}{total\ number\ of\ sheaves}}\right)\right) \quad (2)$$

For **Rope 2**, it can be noted that the lifetime of the rope **decreases by ≈22.01%** for every additional 20% of steel sheave in the system Therefore, if the steel sheaves are arranged consecutive, the following relationship emerges:

$$Reduction\ factor\ rope\ life = e^{-1.243 * \frac{number\ of\ steel\ sheaves}{total\ number\ of\ sheaves}} \quad (3)$$

It can be also noted that the residual lifetime of the rope increases proportional for every additional 20% of steel sheave in the system. Therefore, if the steel sheaves are arranged consecutive, the following relationship emerges:

$$Residual\ life = N * \left(1 - \left(1{,}01 * e^{-0.441 * \frac{number\ of\ steel\ sheaves}{total\ number\ of\ sheaves}}\right)\right) \quad (4)$$

The authors' assumption from the previous test series that the service life of **Rope 1** is reduced by approximately 17.50% for each additional sheave in the system can therefore be confirmed.

The positional dependence of the sheave, which can be seen from the results for **Rope 1** and **Rope 2**, can also be confirmed (see **Figure 7**, **Figure 8**).

There is also a difference in the reduction in rope life between **Rope 1** and **Rope 2**. This is probably due to the general behaviour of the different ropes during cyclic bending fatigue tests, as known from tests with different forces or D/d-ratios.[6].

3.2.1 Wire break distribution

Figure 9 shows the wire break distribution from the individual sections of the **Rope 1** on the data of **Table 4**.

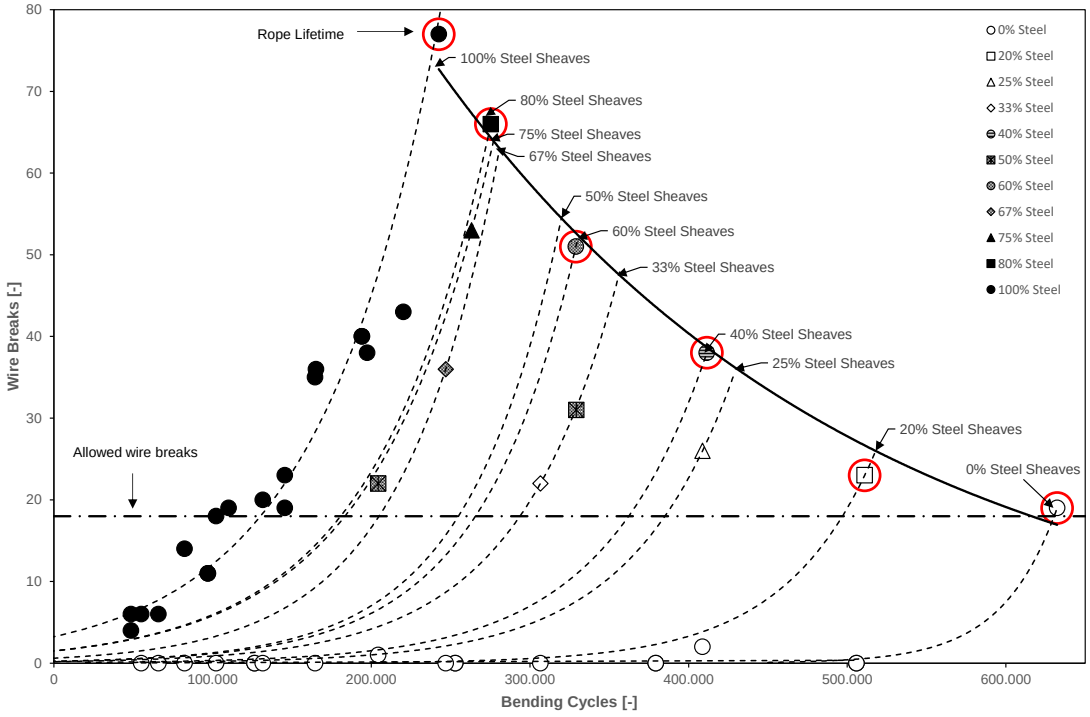


Figure 9: Wire Break Distribution (Rope 1)

Figure 10 shows the wire break distribution from the individual sections of the second tested rope based on the data of **Table 4**.

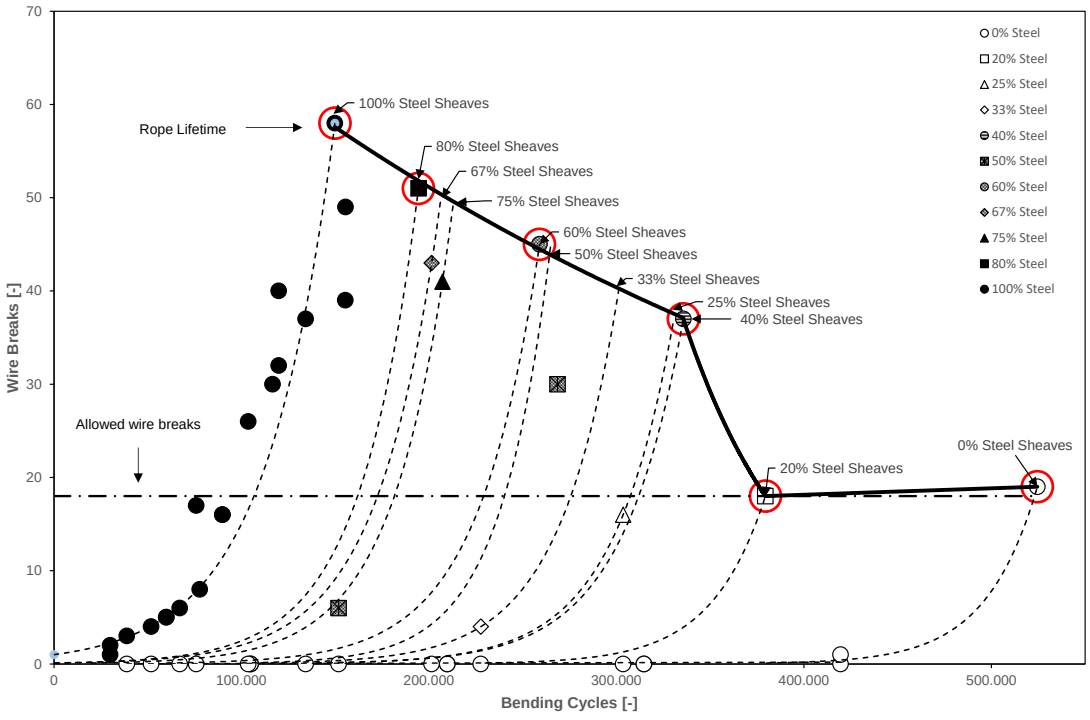


Figure 10: Wire Break Distribution (Rope 2)

For both ropes, the wire break distribution of different steel sheave proportions in a reeving system were determined using an exponential approach for the wire break distribution of the all-steel sheave configuration, as known from the literature [6].

As can be seen out of the two figures, there are some inconsistencies in the order to the distribution of total rope life and service life achieved. This approach represents a first attempt to represent the wire break distribution and the service life of the rope under the influence of different sheave materials and arrangements.

The authors are aware that this estimation is very limited due to the small amount of data available. Furthermore, the authors assume that for a combination of plastic and steel sheaves, the wire break distribution will only be subject to a limited exponential relationship.

4 Conclusions

The interaction between sheave materials—specifically plastic and steel—and their arrangement in a reeving system, significantly influences the lifetime, service life, and reliability of wire ropes. Results from extensive bending fatigue tests show that the presence and positioning of steel sheaves has a significant impact on the wire break and fatigue behavior of wire ropes, determining both their lifetime and the safety indications for rope replacement.

This study validates the previously established relationship between sheave material composition and wire rope service life [2,3,7]. Through systematic bending fatigue tests across a range of steel-plastic sheave configurations, clear trends regarding the impact of sheave materials and their arrangements on rope durability, discard indication reliability, and residual lifetime were identified.

The results indicate that the lifetime of wire ropes decreases significantly as the proportion of steel sheaves increases. Importantly, the study reveals that the presence of at least one steel sheave, in some cases depending on the rope design, at least two steel sheaves are critical in reliably signaling the imminent end of a rope's service life.

However, the strategic placement of steel sheaves within the system is critical to ensure reliable detection of the impending end of service life.

In addition, the evolution of wire breaks was estimated to assess the service life and wire break distribution of certain configurations. Further validation testing is necessary to refine the accuracy of this model and applicability across a broader range of configurations.

Overall, these insights underscore the importance of carefully selecting sheave configurations tailored to specific rope characteristics and application requirements. By understanding these boundary conditions, operators and system designers can optimize reeving systems to reliably detect discard conditions, thus minimizing risks and enhancing rope failure safety in accordance with ISO 4309 standards.

5 Acknowledgements

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7 Authors' Introductions



Mr. Marco Elig received his Bachelor of Engineering degree in Mechanical Engineering from the University of Applied Science Kaiserslautern in 2015, followed by a Master of Engineering degree in the same field in 2023.

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