AWRF Meeting Spring 2012
Atlanta, Georgia

April 22nd to 25th, 2012

AWRF Est. 1976

Universität Stuttgart

IFT – Rope Technology
University of Stuttgart

Test laboratory

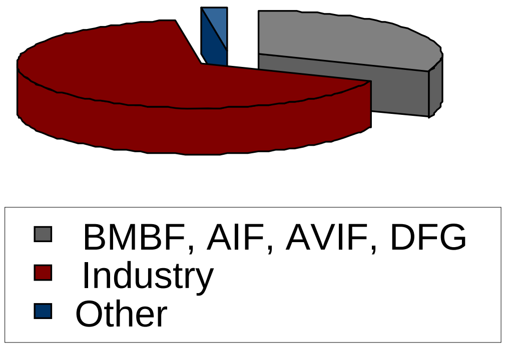
IFT was founded in 1927

Fields of research:

- **Materials handling**
- **Logistics**
- **Rope technology**
  - **15 employees**
  - **10 student research assistants**

Third-party funds 2010:

1.8 Mio. €



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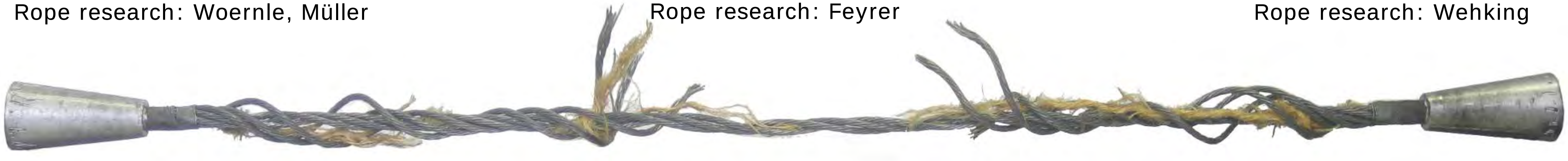
History of rope research at IFT

1927-1977
Rope research: Woernle, Müller

1977-1996
Rope research: Feyrer

since 1996
Rope research: Wehking



1927
Foundation of IFT by Woernle; start of bending tests

1931
Start of tests for magnetic inductive rope testing

1937
Separable solenoid for magnetic inductive rope testing (patent Woernle, Müller)

1968
DIN 15020*, VDI 2358: standard and code for design of rope drives

1980
Statistical analysis of bending tests

1983
Analysis of the increase of wire breaks

1987
Method for lifetime calculation of running wire ropes (Feyrer Formula)

1997
Lifetime calculation for wire ropes under fluctuating tension

1999
High resolution magnetic rope testing

2000
Multi-layer spooling of crane ropes, swaged terminals, fleet angle

2002
Research on compacted ropes

2004
Groove profiles; stainless steel ropes

2006
Finite element calculation; new working field Offshore rope technology

2008
Research of running fibre ropes

2010
Lifetime calculation for tension-tension-torsion wire ropes

*national and international standards, e.g. German industry standard (DIN) or European standard (EN)

Rope test lab today

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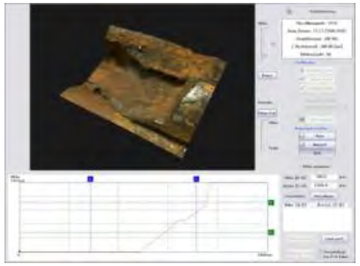
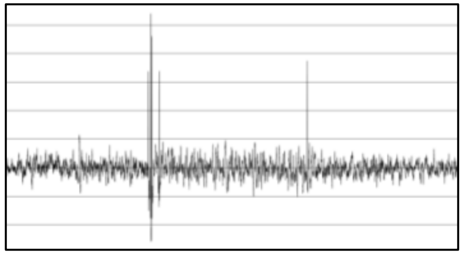
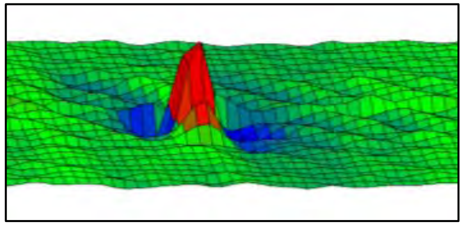
Destructive testing

- bending fatigue tests
- tension tests
- tension- tension tests
- traction tests
- tests with fleet angle
- tests of ropes in multilayer spooling
- long- term tests
- measuring of elongation
- measuring of twist and torsion
- microscopy/ fraktography
- Wire quality determination



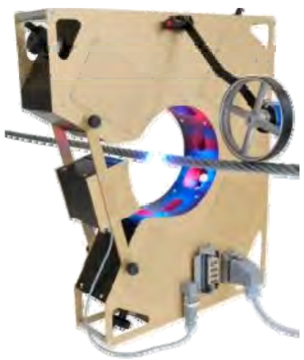
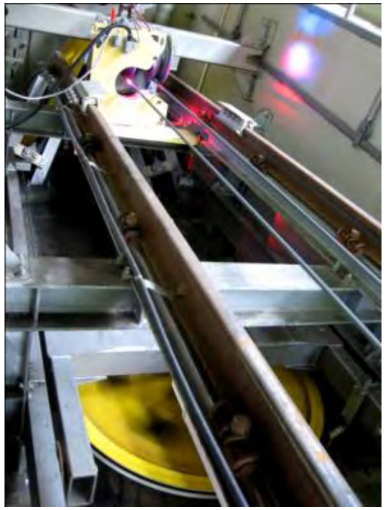
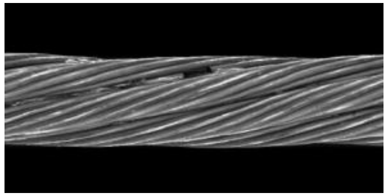
Non-Destructive testing



IFT is testing over 180 ropeways every year all over the world and develops and markets own rope testing devices like:

- **magnetic rope testing**
- **high resolution magnetic testing**
- **automated visual rope testing**
- **ultra sonic sound testing**
- **each testing is completey monitored by state of the art hard- and software**


Examples & References

cranes

storage systems

Examples & References

Offshore

elevators

ropeways

Expert Opinion on Damages and Rope Drives

Running ropes under high tension can break (Picture 1), if the rope is insufficiently maintained or if the rope reached its end of lifetime. Therefore lifetime calculations have to be done to secure an safe use.
Suspension ropes (Picture 2) are highly stressed due to cyclic loads at loading and unloading of goods. If not inspected properly ropes can break eventually.

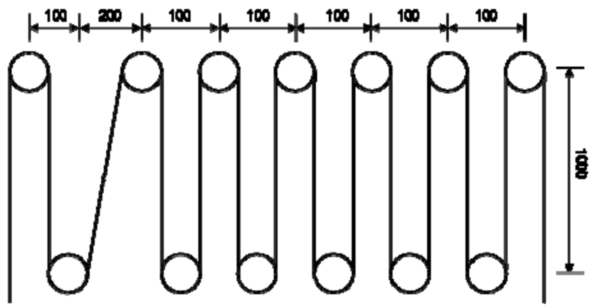
Picture 1: Hook block after rope break

Picture 2: Crawler crane after breakage of the suspension rope

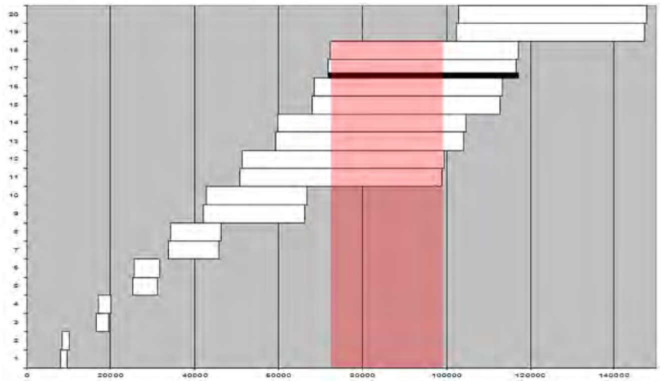
Expert Opinion on Damages and Rope Drives

Picture 1: **Reeving of an mobile crane**

Based on the empirical lifetime formula for running ropes developed by the IFT, staff members analyze rope driven applications regularly. For such a analysis the most used rope zone has to be determined (Picture 3). For the determination the technical data of the rope drive (Picture 2, as an principle example of the rope drive seen in Picture 1) has to be investigated. With the knowledge of the most used rope zone a calculation of the rope lifetime can be done.



Picture 2: Example for a sketch of the rope drive seen in Picture 1 (sheaves tilted)



Picture 3: Example for a sketch to calculate the most used rope zone

Expert Opinion on Damages and Rope Drives

- Analytical Methods to Forecast the Endurance of Ropes -

Number of bending cycles at break

- The Lifetime of wire ropes can be described with the number of bending cycles at break N.
- In bending tests the number of bending cycles at break is determined in reference of significant parameters. The main parameters are:

  1) The diameter ratio of sheave to rope D/d
  2) The construction of the rope (kind of core, making of the rope, wire tensile strength, etc.)
  3) Greasing of the rope
  4) The specific rope force S/d^2

- The experimental determined number of bending cycles at break are described in a double logarithmic chart through a straight
- The mathematical description of the straights is done with a multiple regression. Into the regression the main parameters are integrated.

$$\lg N = a_0 + a_1 \lg \frac{S \cdot d_0^2}{d^2 \cdot S_0} + a_2 \lg \frac{D}{d} + a_3 \lg \frac{S \cdot d_0^2}{d^2 \cdot S_0} \cdot \lg \frac{D}{d}$$

N ..... number of bending cycles at break
S ..... rope force
d ..... diameter of the rope
D ..... diameter of the sheave
$a_{0,1,2,3}$ coefficient of regression

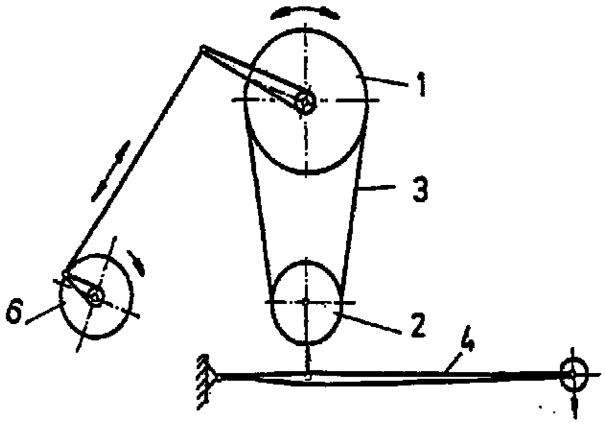
Source: Feyrer, K.: Drahtseile. Bemessung, Betrieb, Sicherheit. Berlin, Heidelberg: Springer Verlag 1994: ISBN 3-540-57861-7. S.228-229

Expert opinion on damages and rope drives

- Analytical Methods to Forecast the Endurance of Ropes -

Table 1: Factors b_i for the calculation of the medial number of bending cycles N until breakage of the rope respectively the number of bending cycles N_{10} at which, with a secureness of 95%, at most of the ropes are broken

Rope		b_0 for $\bar{N}$		b_0 for N_{10}		b_1	b_2	b_4	b_5	
		sZ	zZ	sZ	zZ				$\bar{N}$	N_{10}
Standard 6x19	FC	-0.760	--	-1.225	--	0.875	6.480	-1.850		
		--	-0.609	--	-1.019	0.562	6.430	-1.628		
Seale 8x19	FC	-1.900	-1.677	-2.166	-1.943	1.280	8.562	-2.625		
Filler+Warr.8x19	FC	-1.679	-1.456	-1.945	-1.722	1.280	8.562	-2.625		
Warr.Seale 8x36	FC	0.858	0.966	0.592	0.700	0.096	7.078	-1.920		
Seale 8x19	WC	-1.723	-1.663	-2.018	-1.958	1.290	8.149	-2.440	1.2	1.9
Filler+Warr.8x19	WC	-1.635	-1.575	-1.930	-1.870	1.290	8.149	-2.440		
Warr.Seale 8x36	WC	1.327	1.381	1.032	1.086	0.029	6.241	-1.613		
Spiral-round stranded rope	low torsional	-2.492		-2.724		1.566	9.084	-2.811		
	torsion free	-1.014		-1.461		1.351	7.652	-2.485		



Configuration of rope sheaves for simple bending of ropes

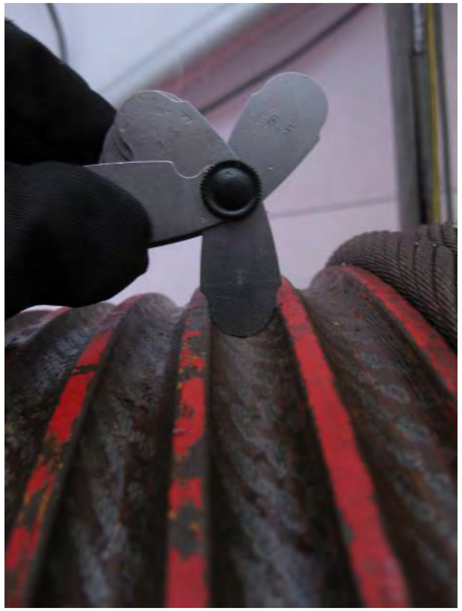
1 drive pulley
2 test sheave
3 rope
4 load crank
5 jockey pulley
6 drive train

According to: Feyrer, K.: Bauteile von Fördermitteln. Studienblätter zur Vorlesung. Institut für Fördertechnik, Universität Stuttgart, 1983, S. B5

Expert Opinion on Damages and Rope Drives

IFT, as an independent testing institute, deals with incidents when the expected service life of the rope is not reached or when damages on parts of the rope drive appear. The members of the department of rope technology investigate such incidents on the site, but also at the institute itself. When the rope drive is inspected, several measurements are done, like the determination of the sheaves and the position to each other.

Picture 1: Inspection of an elevator



Picture 2: Measurement of the groove radius of a rope drum

Picture 3: Inspection of a damaged rope at IFT

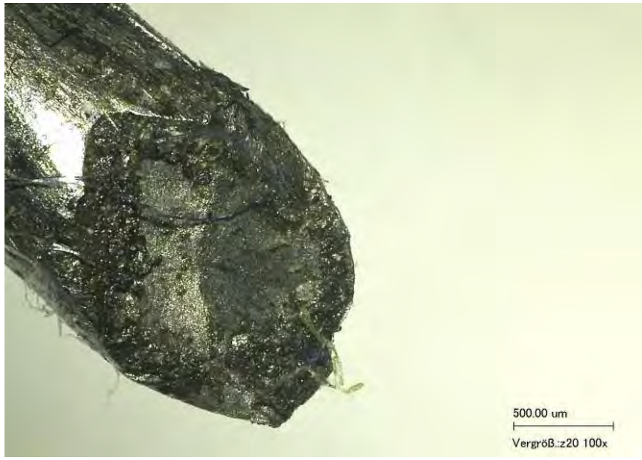
Expert Opinion on Damages and Rope Drives

- Wire Breaks under the Microscope -

Picture 1: Diagonal wire breaks caused by torsion

Picture 2: Wire break caused by reduction of diameter of the wire

Picture 3: Wire break due to bending of the rope on a sheave



Picture 4: Diagonal wire break

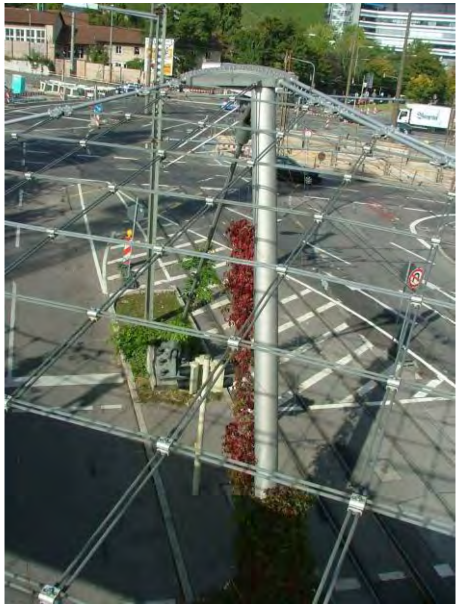
Picture 5: Cup-and-Cone fracture of wires caused by overloading

End Terminations with Fittings

Picture 1: Swaged terminal with clevis end

Picture 2: Killesberg-Tower, Stuttgart

Picture 3: Swaged Terminal on a bridge

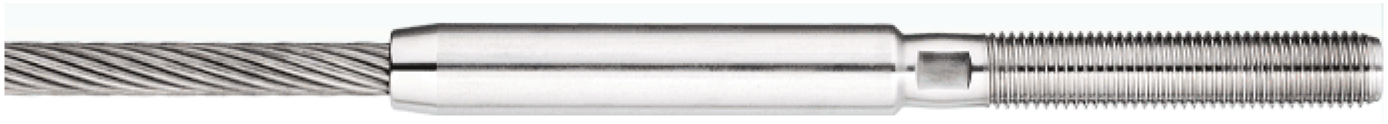


Picture 4: Rope net at Löwentorbridge, Stuttgart

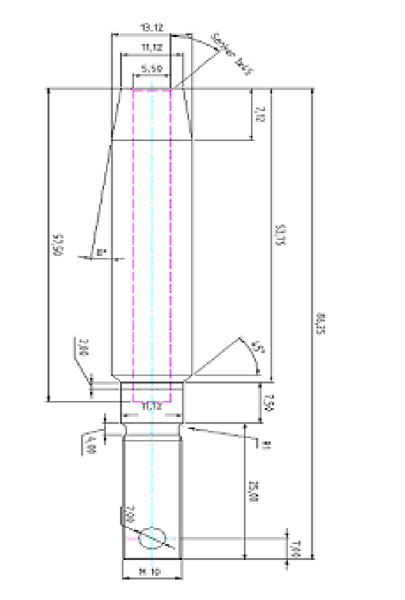
End Terminations with Fittings

- Motivation -

Swaged terminals are used to realize end connections for architectural projects but also in elevators or cranes. To evaluate the lifetime of swaged terminals made of steel under a stress cycle a research project was started at IFT. The results of the research project lead to a new CEN standardization, which was not available up to then.

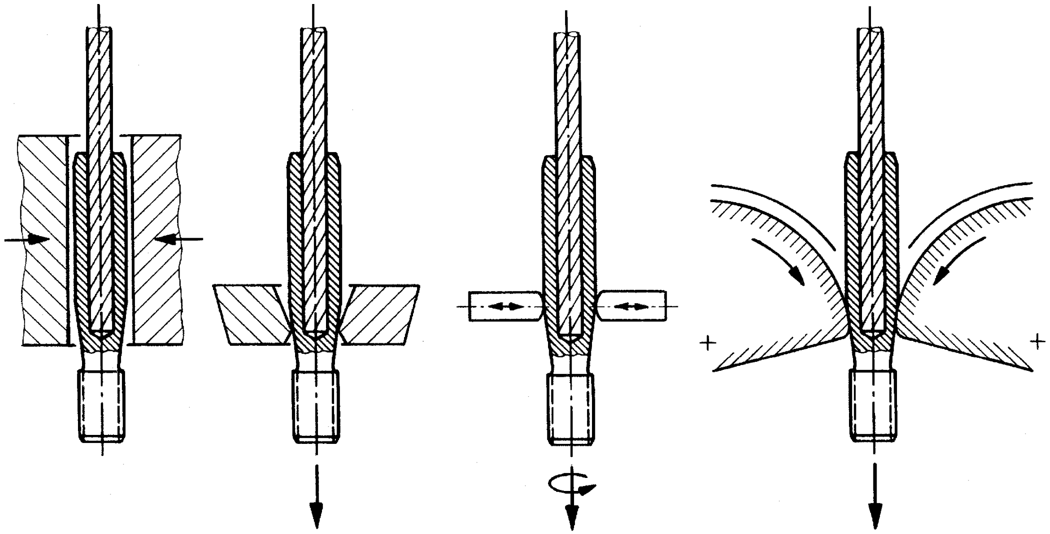


Parameters of the jackets	
d_{rope}	5 up to 30 mm
d_i	$1{,}1{*}d_{Seil}$
L_{ges}	$1{,}18{*}\ D_{w.min}$
$L_{rolling}$	$17{,}25{*}d_{Rope}$
L_{insert}	$10{,}75{*}d_{Rope}$
$D_{w.min}$	$D_{min} = d * \sqrt{\frac{f * R_{0,Seil}}{R_{0,Bolzen}} + 1}$

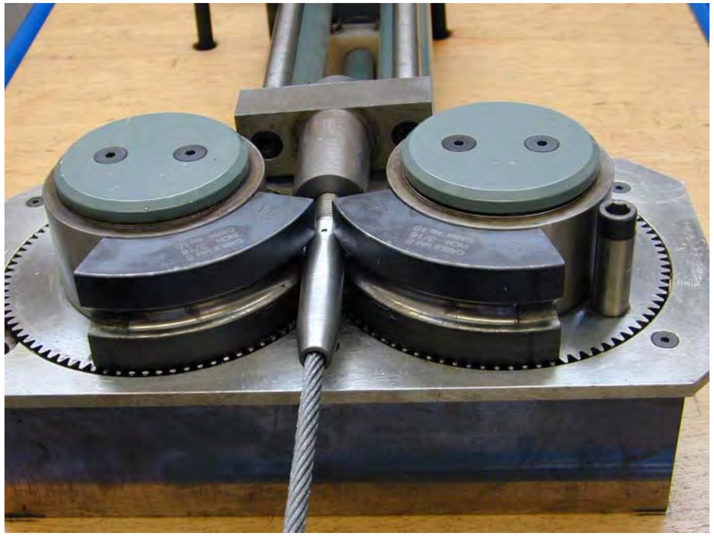


End Terminations with Fittings

- Manufacturing Process -



Picture 1: Manufacturing techniques for swaged terminals (from left: Pressing, Drawing, Hammering, Rolling)



Picture 2: Rolling machine at IFT, used in the project

End Terminations with Fittings

As swaged terminal in the tension-tension test swaged external threads were used (Picture 1).

A systematic test program with different rope constructions and materials was done (Table 1). Round strand ropes and open spiral ropes made of carbon and stainless steel were tested in conjunction with bolts made of S355J2G3 and stainless steel. Up to 5 diameters of the ropes were tested with nominal strength of up to 2160 N/mm² at the carbon steel ropes. The variations were done to calculate a lifetime formula.

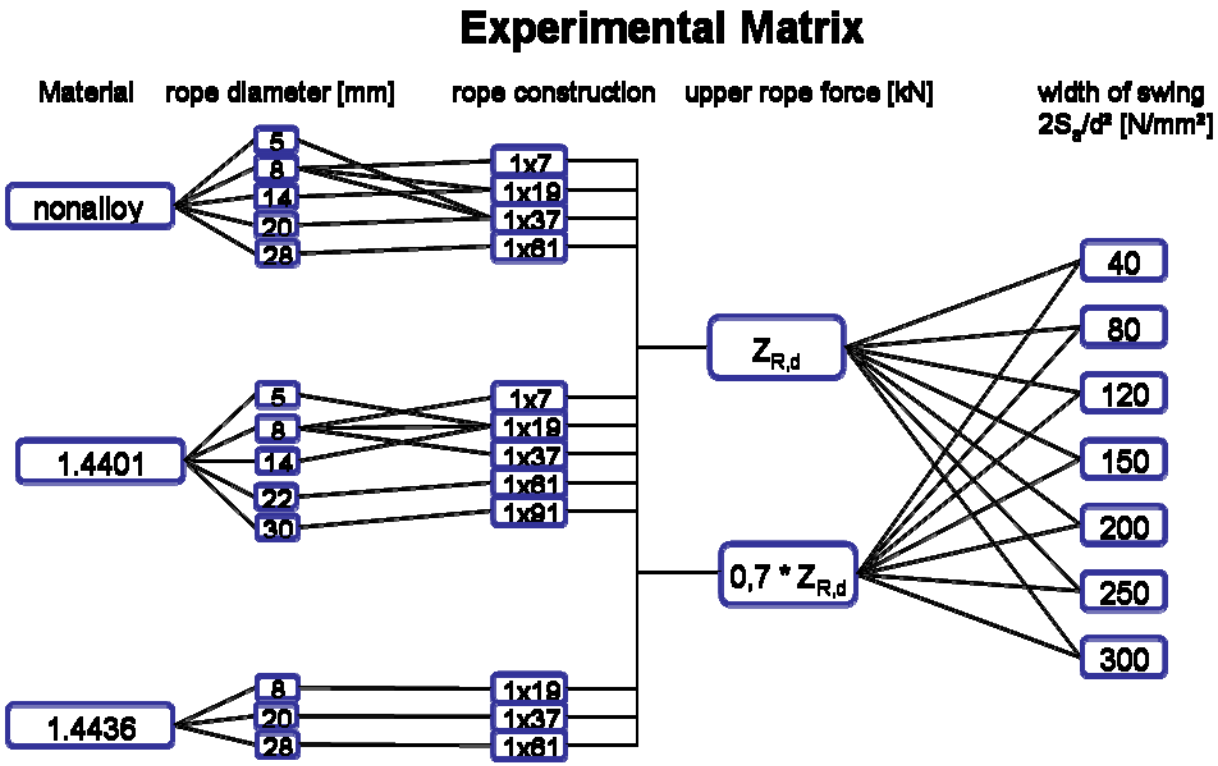
Picture 1: In the research project used swaged external threads

Table 1: Overview of the rope constructions and materials used in the research project

Rope construction	Round strand rope with steel- and fiber core		Open spiral rope (1x19, 1x37, 1x61)		
Rope material	Carbon steel	Stainless steel 1.4401	Carbon steel		Stainless steel 1.4401
Bolt material	S355J2G3	Stainless steel 1.4401	S355J2G3		Stainless steel 1.4401
Nominal rope diameter d [mm]	Up to 24		Up to 24	Up to 14	Up to 24
Nominal strength of the wire R_0 [N/mm²]	Up to 2160	Up to 1570	Up to 1570	Up to 1770	Up to 1570
Relative pressing length l_0/d	6		10		
Level of pressing D_0/D	1,16 to 1,20		1,18 to 1,22		

End Terminations with Fittings

- Test Program -



Picture 1: Tension-Tension test machine 75 kN at IFT

End Terminations with Fittings

- Results of the research project -

The systematic tests led to the following equation, which describes the average number of stress cycles:

$$lg\overline{N} = a_0 + a_1 lg \frac{2S_a \cdot d_0^2}{d^2 \cdot S_0} + a_2 \frac{S_u \cdot d_0^2}{d^2 \cdot S_0} + a_3 \left(\frac{S_u \cdot d_0^2}{d^2 \cdot S_0} \right)^2 + a_4 lg \frac{d}{d_0} + a_5 \frac{1}{lg \frac{R_m}{R_0}} + a_6 lg z$$

Based on the research results it can be stated that the endurance limit of the open spiral strands, arranged according to ascending influence, depends on guaranteed ultimate tensile strength, rope diameter, rope construction and wire material.

End terminations with Fittings
- Examples of performance charts -

In summary it can be stated that the more wires a rope consists of, the greater the lifetime und tension-tension load it will achieve, as seen in Diagram 1. Also in Diagram 1 (diamond symbols) it can be seen that the greater the amplitude of the tension-tension load the higher the lifetime of the rope.

Also it can be stated that wire ropes made of carbon steel have a greater lifetime under tension-tension load than wire ropes made of stainless steel, as shown in Diagram 2.

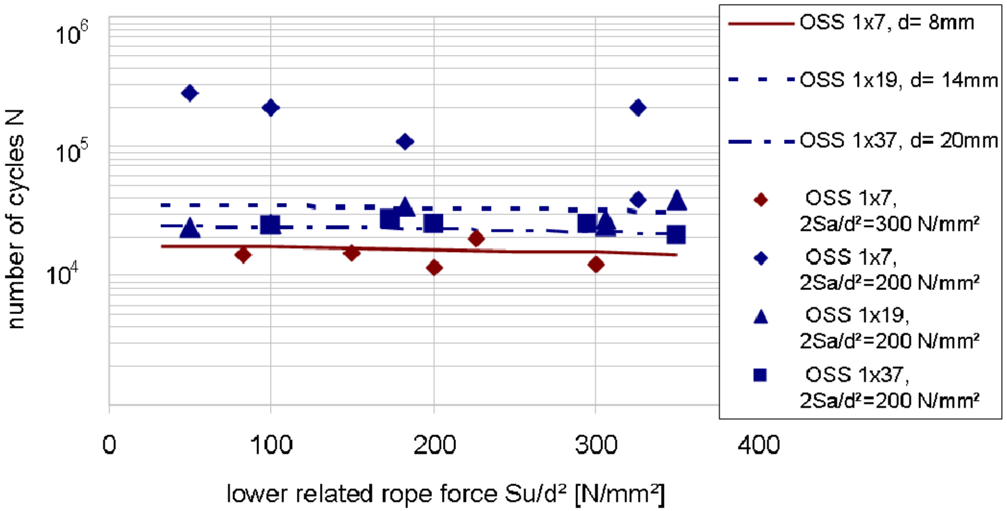


Diagram 1: Overall regression for the rope constructions 1x7, 1x19, 1x37

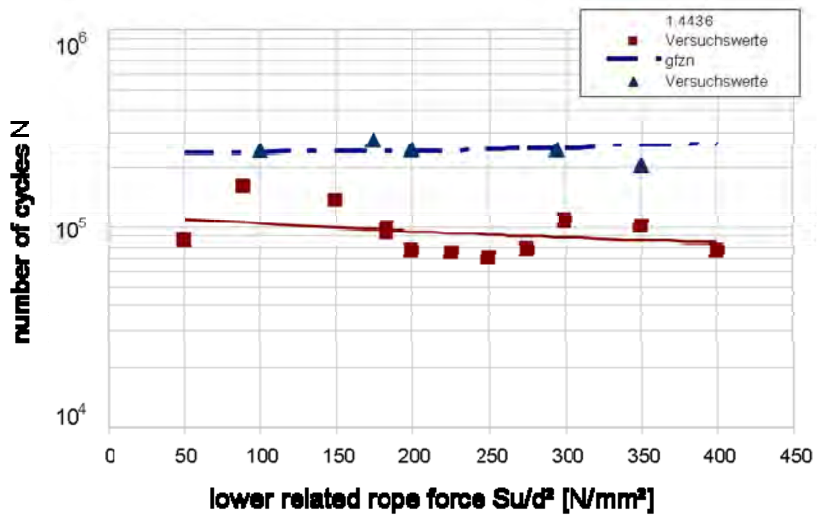


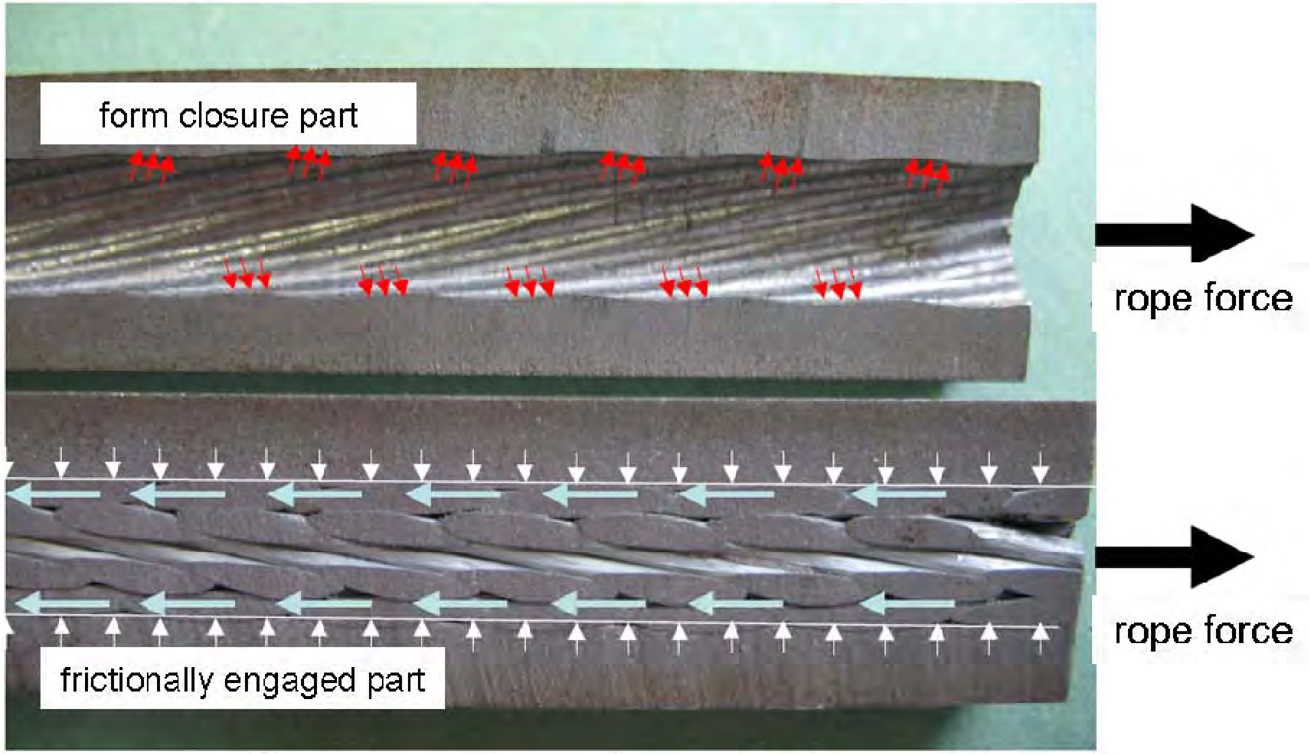
Diagram 2: Comparison between wire ropes made of carbon and stainless steel

End Terminations with Fittings

- Investigations on the active principle of load transmission in swaged terminals -

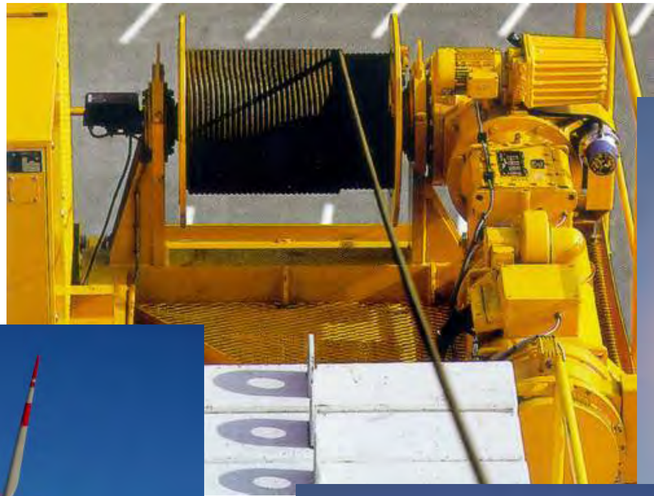
Based on the research work the active principle of form closure and friction take effect in a swaged terminal when a force is applied.

Not only friction is active, like believed before these examinations, but also form closure.



Picture 1: Illustration of the active principles in a swaged terminal

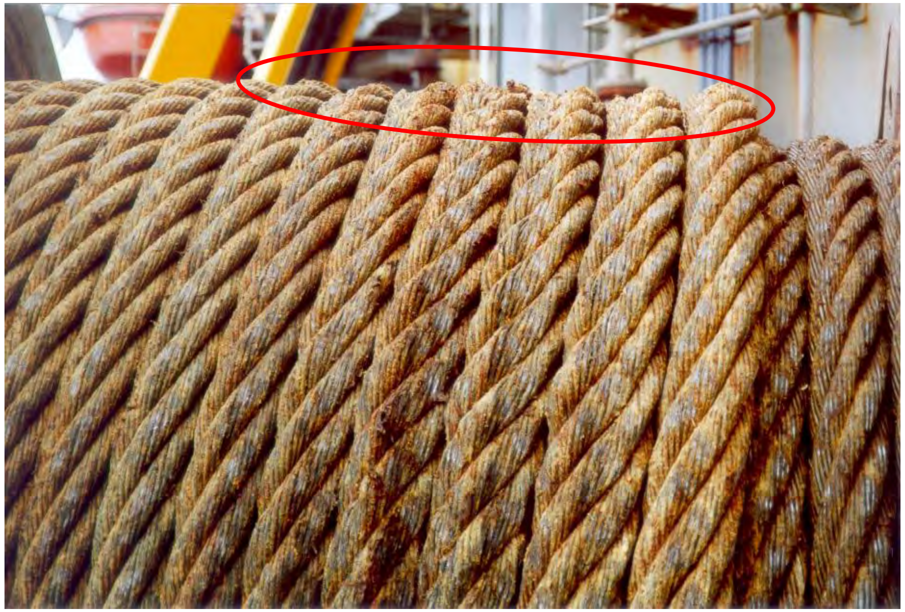
Hoisting Ropes in Multi-layer Spooling



Hoisting Ropes in Multi-layer Spooling

- Problems with Multi-layer Spooling -

Picture 1: Spooling failure



Picture 2: Imprint of rope lines into the subjacent layer of rope

Picture 3: Cutting in of a rope line into the subjacent layer of rope

Hoisting Ropes in Multi-layer Spooling

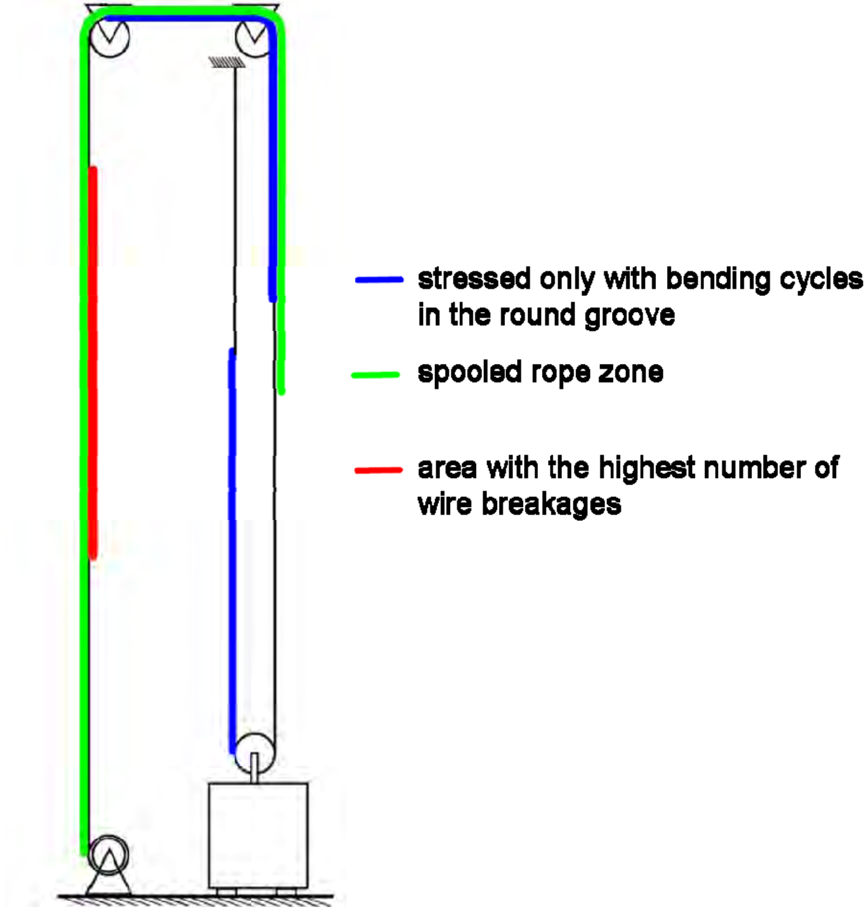
- Research projects on multi-layer spooling and on capstan winches done at IFT:
  - Multi-layer spooling of non-rotating wire ropes with Lebus-System
    - Lifetime formula of Dr. Weiskopf

$$\lg N = a_0 + a_1 \lg \frac{S}{d^2} + a_2 \lg \frac{D}{d} + a_3 \lg \frac{D}{d} \cdot \lg \frac{S}{d^2} + a_4 \lg F_V + a_5 \lg Z_L$$

    - Understanding of the damaging mechanisms within multi-layer spooling
  - Multi-layer spooling of wire ropes in connection with a capstan winch
    - Enhancement of rope lifetime

Hoisting Ropes in Multi-layer Spooling

- Multi-layer Test Stand at IFT -



Picture 1: Principle of the multi-layer test stand at IFT

Picture 2: Drums of the multi-layer test stand at IFT, the right drum is the according one to the one displayed in Picture 1

Hoisting ropes in multi-layer spooling

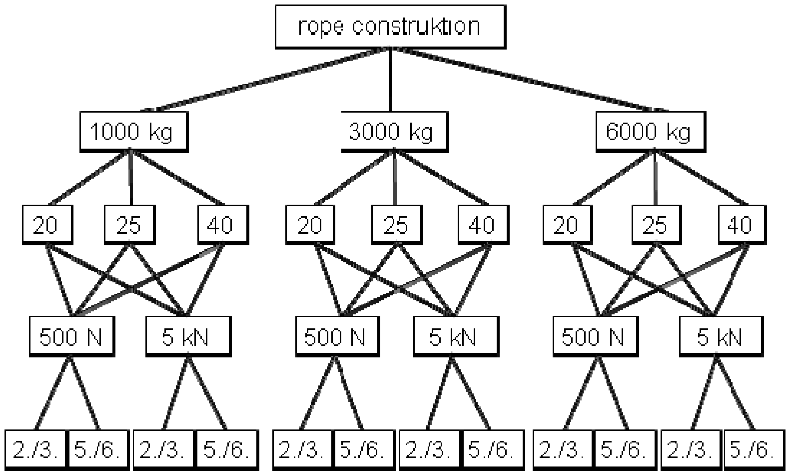
- Experimental matrix and used ropes of the research project -

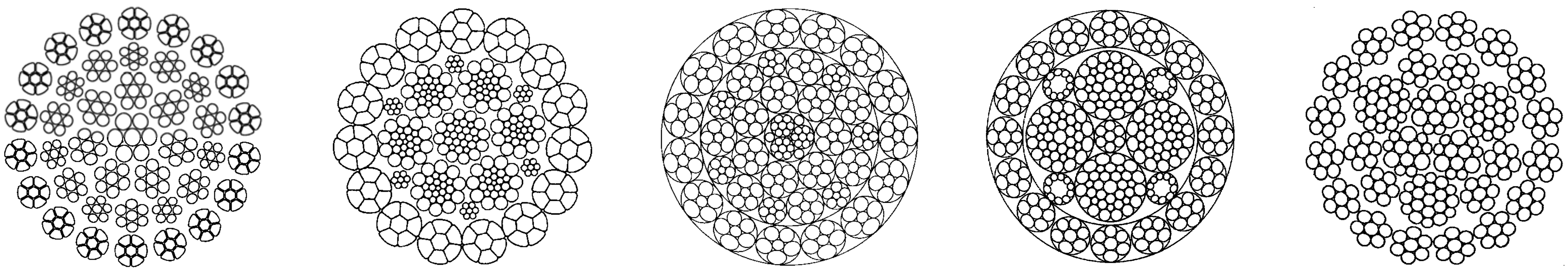
Parameters of the tests

Chosen from a list of 18 influencing factors of main deteriorations in multi-layer spooling

- **Applied load**
- **Ratio of Drum to rope diameter D/d**
- **Pretension at installation of the rope**
- **Layer change**

experimental matrix



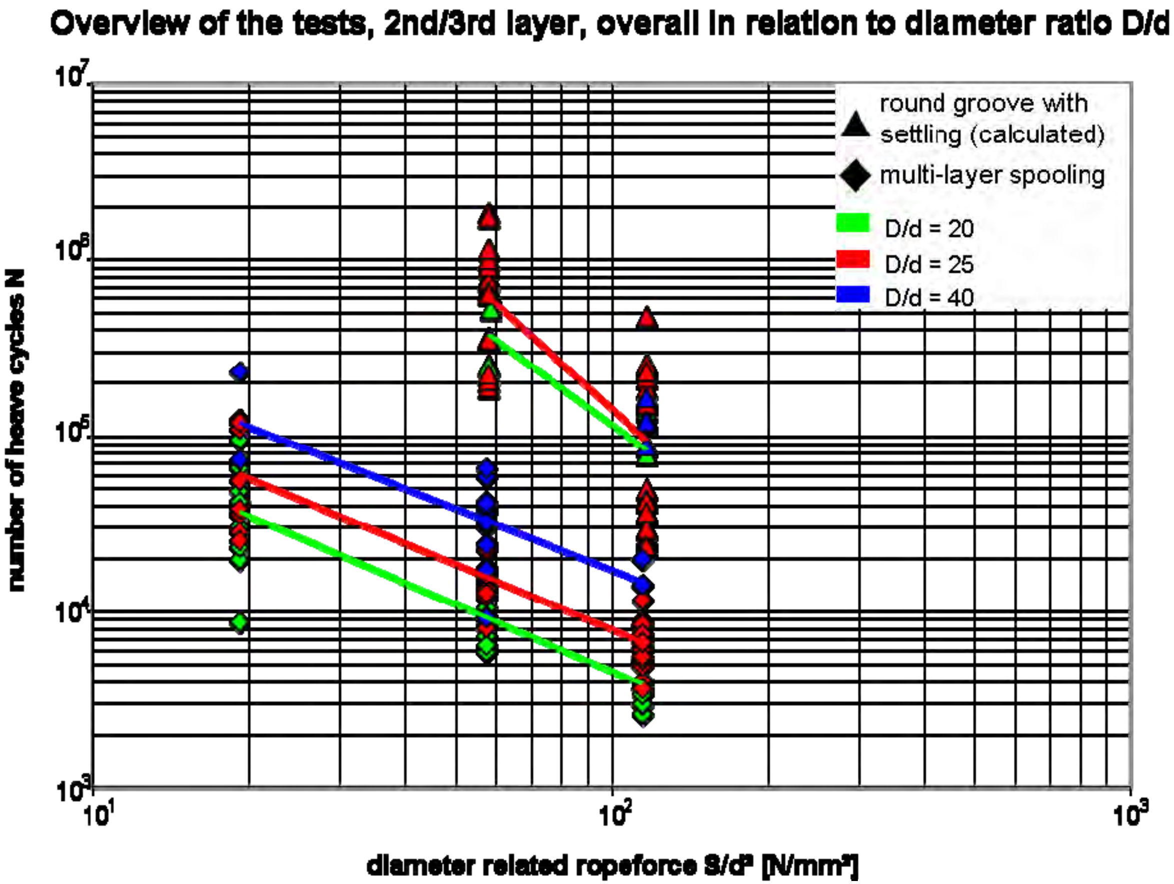


Pictures: In the research project used non-rotating ropes

Hoisting ropes in multi-layer spooling

- Overview of the results of the research project -

Results of the project showed that multi-layer spooling decrease the lifetime of a rope down to 2 to 8% in comparison to the lifetime in a standard bending test.



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Hoisting Ropes in Multi-layer Spooling
- Outcome of the Research Project -

A lifetime formula for ropes in multi-layer spooling was stated:

$$\lg N = a_0 + a_1 \lg \frac{S}{d^2} + a_2 \lg \frac{D}{d} + a_3 \lg \frac{D}{d} \cdot \lg \frac{S}{d^2} + a_4 \lg F_V + a_5 \lg Z_L$$

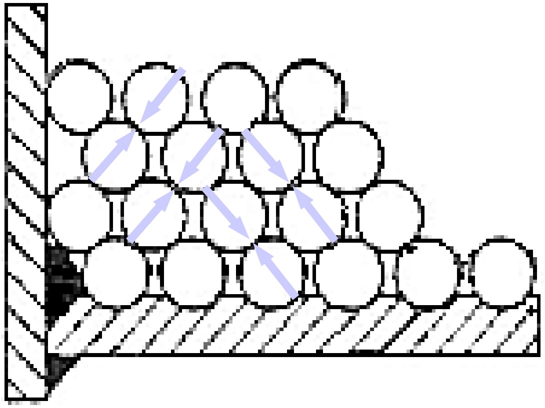
Picture 1: Typical rope damage in multi-layer spooling

Picture 2: Wire breaks on 1st layer

Picture 3: Broken strands at the end of a test

Hoisting Ropes in Multi-layer Spooling

- Pretension at the Installation of the Rope -



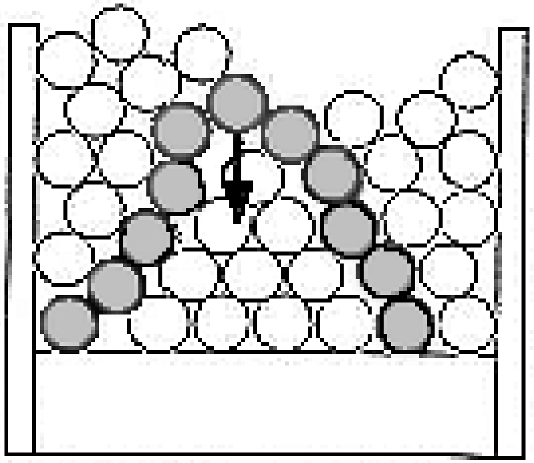
Picture 1: Spooling pyramid when pretension is sufficient

In multi-layer spooling the rope lines have direct contact to each other.

Problems with to little pretension:
- spooling pyramid is not stable and can collapse
- spooling failures and cutting in of a rope line into the subjacent layer can occur

To determine the needed rope pretension comprehensive tests were done at IFT

Picture 2 and 3: Spooling failure when spooling with insufficient pretension

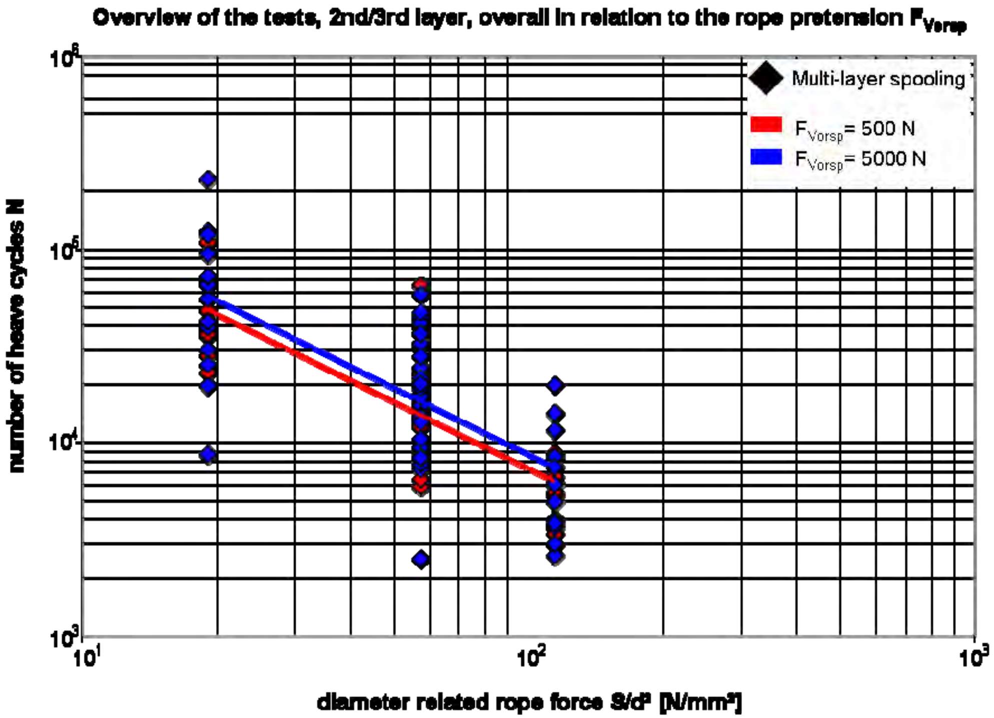


Picture 4: Spooling pyramid when pretension is insufficient

Hoisting Ropes in Multi-layer Spooling

- Pretension at the Installation of the Rope -

Additional tests were done in which the pretension with which the rope was spooled on the drum during installation was varied. The result was, that the pretension has an great influence on the lifetime of the rope. Improvements of about 30% can be achieved with an sufficient pretension. Also like stated before the spooling pyramid is more stable with a higher pretension.



Picture 1: Lifetime of ropes under different pretension forces in multi-layer spooling

Rope Drives with Plastic Sheaves
- Enhancement of the Rope Lifetime -

The lifetime of ropes in rope drives with plastic sheaves is higher than the lifetime in a rope drive with steel or casted sheaves. The rope surface is preserved and on the cones of the strands and wires are no high stressed zones. The improvement of lifetime is about 2. The medial improvement on the lifetime can be calculated with following equation:

$$f_k = \left(\frac{N_K}{N_{GG/St}}\right)_{50} = 8{,}37 * N_{GG/St}^{-0{,}124} \approx 0{,}75 + 0{,}36 * \frac{S/d^2}{D/d} - 0{,}023 * \left(\frac{S/d^2}{D/d}\right)^2$$

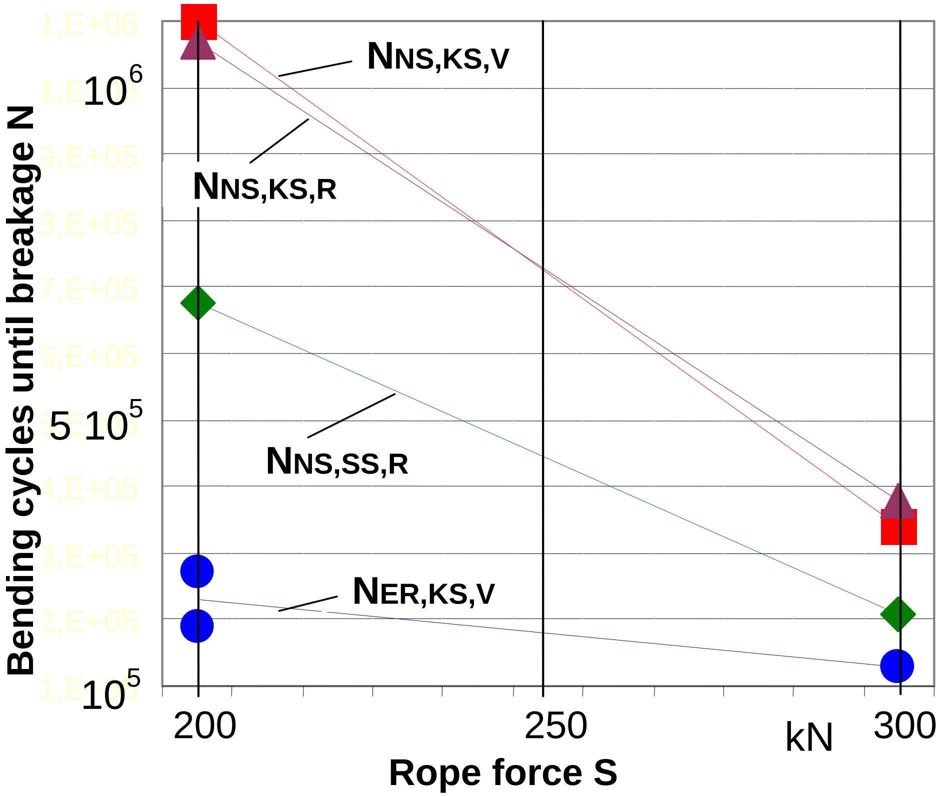
Also plastic sheaves weigh less than sheaves made of steel. That is why plastic sheaves are preferred in mobile cranes.

Picture 1: Plastic sheaves used in the multi-layer test stand at IFT

Rope Drives with Plastic Sheaves

- Enhancement of the Rope Lifetime -

Tests at IFT were done in which stainless steel ropes and steel ropes were tested on plastic sheaves and calculation were done in which the rope lifetime of the steel rope on plastic sheaves and on steel sheaves were identified. In the diagram on the right the results can be seen.



$N_{ER,KS,V}$ (Blue line): Bending cycles until breakage of a stainless steel rope on a plastic sheave (Test)
$N_{NS,KS,V}$ (Red line): Bending cycles until breakage of a steel rope on a plastic sheave (Test)
$N_{NS,SS,R}$ (Green line): Bending cycles until breakage of a steel rope on a steel sheave (Calculation)
$N_{NS,KS,R}$ (Brown line): Bending cycles until breakage of a steel rope on a plastic sheave (Calculation)

Rope Drives with Plastic Sheaves

- Cutting in of the Groove -

Plastic sheaves are made mostly of Polyamide 6 which is not as hard as steel or cast iron. A rope will bury itself into the groove of a plastic sheave cut a tooth profile in it as seen in Picture 1. If the drum and the first sheave in a rope drive are not in line, the rope will run on the sheave under an deflection angle. The groove of the plastic sheave will run in and cause severe damages on the flanks as seen in Picture 2.

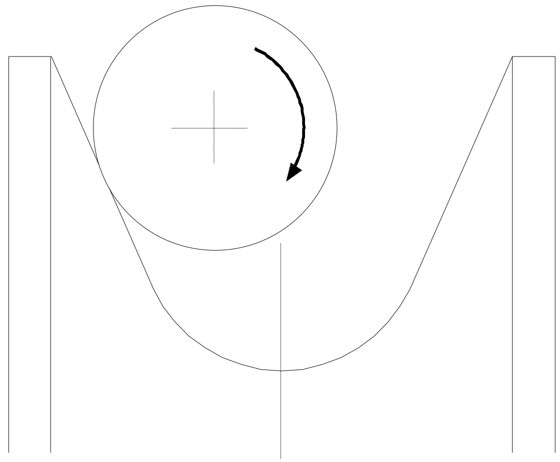
Picture 1: Discarded sheave from the multi-layer test stand at IFT with tooth profile

Picture 2: Discarded sheave from the multi-layer test stand at IFT with run in groove

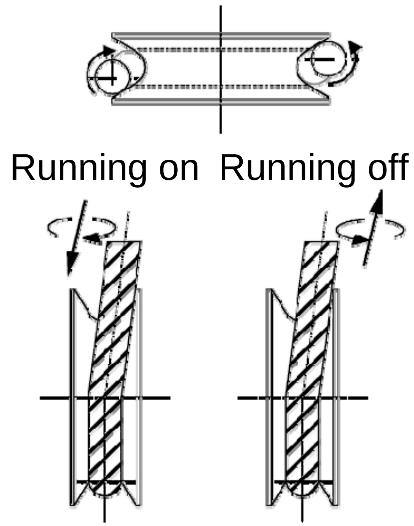
Rope Drives with Plastic Sheaves

- Twisting of the Rope caused by deflection -

Due to the high friction coefficient between the plastic rope and the wire rope, the tendency to twisting the rope at deflection is very high. Caused by this twisting the lifetime of the rope is reduced as the doctor thesis of Dr. Schönherr at IFT for steel sheaves showed. The rope is rolling down the flank when it hits the sheave under an deflection angle as seen in Picture 1. The rope is untwisted and closed at running on the sheave and running off the sheave as seen on Picture 2.



Picture 1: Rope is rolling down the flank when it hits the sheave at an deflection angle



Picture 2: Twisting of a rope at Overriding and Expiration

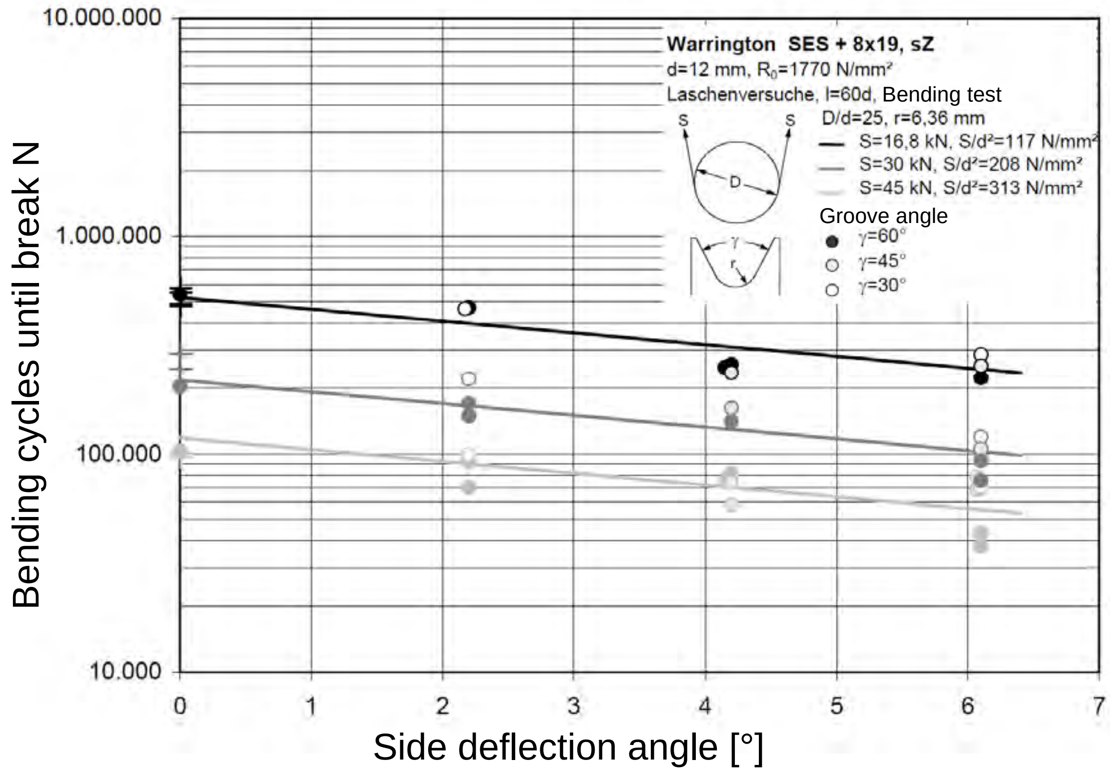
Rope Drives with Plastic Sheaves

- Twisting of the Rope caused by deflection -

The higher the deflection angle the more severe is the reduction of rope lifetime. As seen in the diagram on the right for a sheave made of steel. With a plastic sheave the damage will be higher.

These damaging mechanism can lead to baskets and loops in the rope which will reduce the lifetime of the rope additionally.

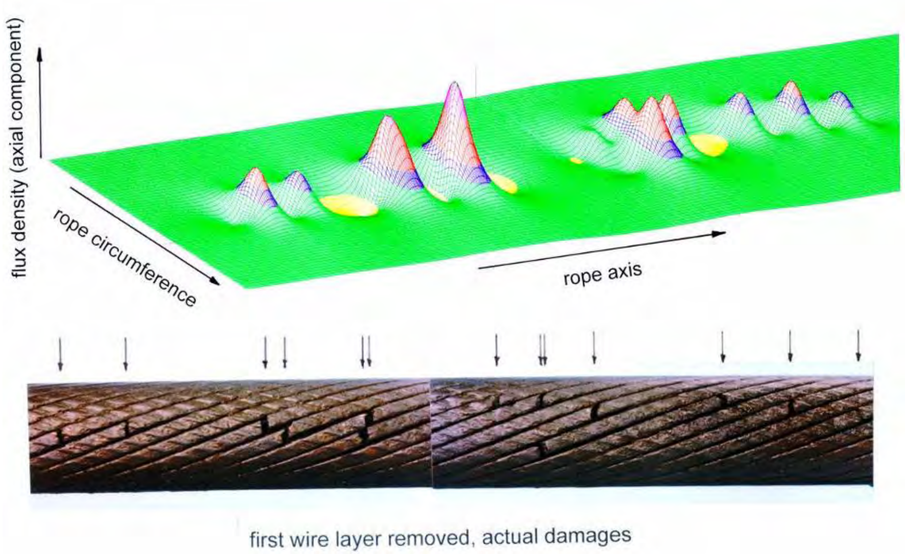
Research on the subject of deflection angle at plastic sheaves has not been done yet.



Rope Drives with Plastic Sheaves

- Inner Wire Breaks -

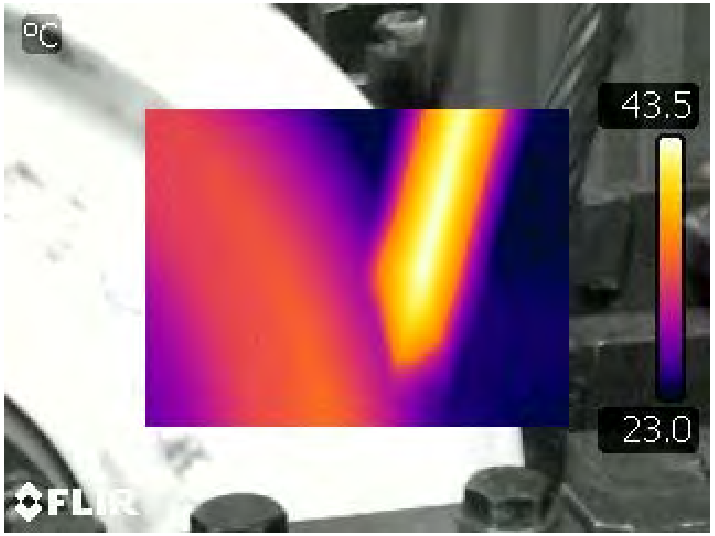
Because of the smooth groove of plastic sheaves the development of outer wire breaks in the rope is less likely to happen even with ropes in ordinary lay. Wire breaks will occur in the inside of the rope at the contact points of the strands. The possibility that no outer wire breaks will occur during the lifetime of the rope is high. Magnetic inductive testing, like displayed in Picture 1,and careful operation of the rope is very crucial. If the rope is not sufficiently inspected the rope can break without further notice. Even the core of the rope can be damaged so much, that it will break.



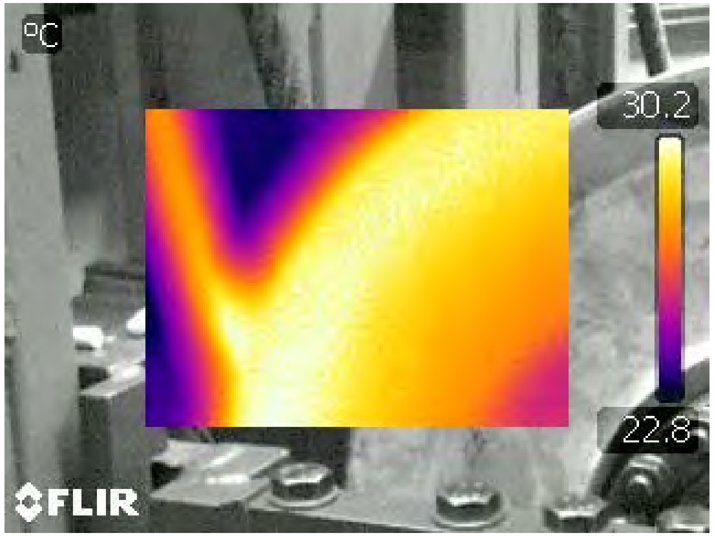
Picture 1: Above: Magnetic high resolution testing of a rope
Below: According rope with inner wire breaks, first wire layer removed

Rope Drives with Plastic Sheaves
- Heating up of Plastic Sheaves -

The heat conduction of plastic is less than the heat conduction of steel, thus ropes on plastic sheaves will heat up much more, see Picture 1, than ropes on steel sheaves, see Picture 2. This especially is a problem in applications with high number of bending cycles with short distances and with high rope forces. Steel sheaves will transport the heat much better away from the rope in the surrounding parts of machinery than sheaves made of plastic. This can have an great influence on the rope lifetime if the rope is heating up to much and the lubricant is getting to fluid and is leaving the inner of the rope.



Picture 1: Heat image of a plastic sheave in a bending test at IFT



Picture 2: Heat image of a steel sheave in a bending test at IFT

Thank you for your attention!

Questions?