

# WIRE ROPE

## TECHNOLOGY AACHEN



**What we can learn  
from wire rope failures**



# **What we can learn from wire rope failures: Predictable and unpredictable rope failures**

by Dipl.-Ing. Roland Verreet

## **Content**

1. Predictable rope failures .....	4
2. Unpredictable (catastrophic) rope failures.....	13
3. Summary .....	24
4. References .....	24

© 2005, 2014, 2018 Ingenieurbüro für Drahtseiltechnik Wire Rope Technology Aachen GmbH

Cartoons: Rolf Bunse

Layout and typesetting: Benedikt Dolzer, Aachen

Reproduction, in whole or in part, only with written permission of the author.

## **1. Predictable rope failures**

If no corrosion, excessive heat, mechanical or chemical damage is involved, the rope is going to fail in the zone which has been subjected to the greatest amount of fatigue and abrasion. For many applications this means that the most likely zone where a rope failure is going to occur can be predicted.

### **1.1. Where is the rope most likely going to fail?**

The fatigue distribution along the rope length depends both on the design and the mode of operation of the reeving system.

Figure 1 shows the bending fatigue distribution per lifting cycle (1×lifting, 1 × lowering) of four different 4-part overhead cranes which always lift loads from the ground to 25%, 50%, 75% and 100% of the maximum lifting height, respectively.

If the rope of the second crane will not be taken out of service in time, it will one day fail at about 40 to 46 m away from the wedge socket.

If the rope of the fourth crane will not be taken out of service in time, it will one day fail at about 8 and 24 m away from the wedge socket (on the so-called “dead” fall).

### **1.2. You can hear the rope failure coming**

If the discard state is not detected or ignored by the rope user, the wire rope will fail one day in the most deteriorated zone, but not without having announced its coming failure by a great number of individual wire failures first.

Videos taken during lifts which ended in a rope failure often show that the rope had announced its coming breakage by a great number of individual wire failures, often within seconds from each other, continuing for as much as ten minutes. If the machine operator had understood the warning signals, in many cases he would have had plenty of time to stop the lift.

### **1.3. Wire rope inspection**

Steel wire rope inspections must be carried out at regular intervals in order to be able to discard the rope before it reaches an unsafe state. And still many accidents happen, either because the rope was inspected at the wrong locations or because the rope had failed from the inside out.



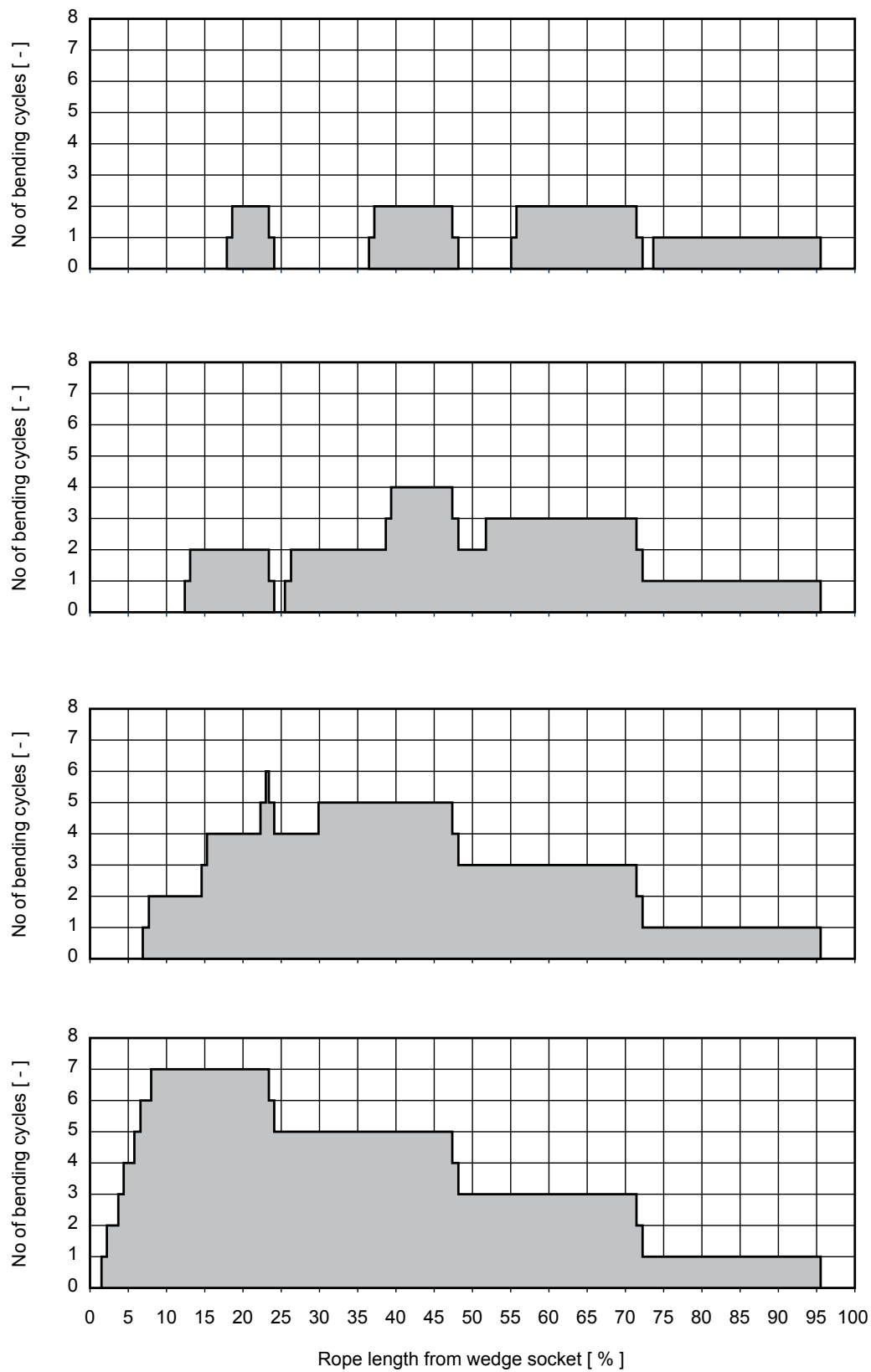


Fig. 1: The bending fatigue distribution per lifting cycle (1 × lifting, 1 × lowering) of four different 4- part overhead cranes.

### **1.3.1. Inspecting at the wrong location (1): Repetitive motion**

Reeving systems which repeat the same operation over and over again are critical with respect to the rope inspection. If, e.g., the rope of the first crane shown in Fig. 1 is always inspected at 10m and 30m away from the wedge socket (because these rope sections are maybe more accessible than others), an increasing rope deterioration at 20 m, 40 m and 60 m will never be detected. Then one day the rope will fail, e.g. at 20 m, without the inspector having detected one single wire break before.

### **1.3.2. Inspecting at the wrong location (2): The "dead" fall**

In a multi part reeving systems many, if not most, rope failures occur on the so-called "dead" fall. The rope falls further away from the wedge socket travel faster than the "dead" fall. But if the block is typically travelling to great lifting heights, the slow "dead" turn is going to see the greatest amount of fatigue.

This alone would not be a major problem. The rope deterioration could be detected during a proper rope inspection. But most rope inspectors think that the slowly travelling "dead" fall will not be subjected to a great amount of fatigue. They will therefore preferably spend their time inspecting the "fast" falls where (as the fourth crane in Fig. 1 shows) much less fatigue damage is accumulated.

***"Dead" fall means: death is waiting here.***

### **1.3.3. Inspecting at the wrong location (3): The equalizer sheave**

The two points of entry into the equalizer sheave in overhead cranes are the single most critical locations for a steel wire rope failure on cranes. Fig. 2 shows a schematic drawing of a twin drum crane with such an equalizer sheave.

During a typical lift, these two sections at the equalizer sheave will not be subjected to a bending cycle. That is why crane designers think they should be allowed to make the equalizer sheaves smaller than the other sheaves in the reeving system.

During the crane travel between lifting the load and lowering it again, however, the load will swing under the crane bridge. This load swing will force the critical sections to continuously enter and leave the equalizer sheave and thereby subject them to great number of bending cycles.

During the same load swing, also other rope sections located at points of entry into the other sheaves of the crane will be subjected to the same number of bending cycles. Because of the ever changing lifting height, however, different rope sections will be affected every time whereas it will always be the same sections at the equalizer sheave.

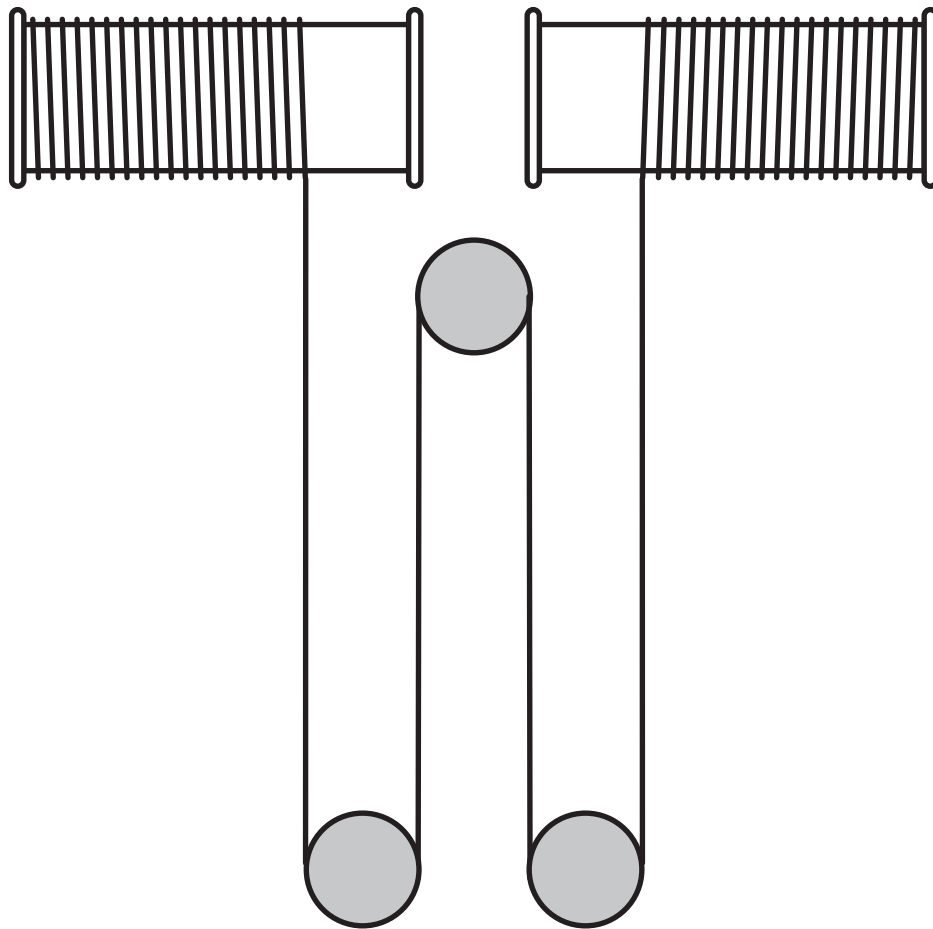


Fig. 2: Schematic drawing of a twin drum crane with an equalizer sheave (the middle, smaller sheave).

The fact that the equalizer sheave is often smaller in diameter than the other sheaves in the reeving system increases the amount of fatigue damage in this area, and the fact that the equalizer sheave is often the least accessible sheave makes the detection of a coming rope failure in this location even more unlikely.

#### **1.4. Internal wire breaks (1): Tension- tension fatigue**

Ropes subjected to a great amount of tension- tension fatigue and comparably little or no bending fatigue have a tendency to fail from the inside out.

Fig. 3 shows 14 of the 49 wires of a simple rope design ( $7 \times 7$ ). In such a rope one

centre wire is straight, 12 wires form helix and 36 wires form a helix around a helix. If this rope was lengthened by, e.g. 1 cm, the straight centre wire would have to get 1 cm longer whereas all other wires would adapt to the new length by partly stretching and by partly simply changing their angle. The helixes would normally stretch more than the double helixes.

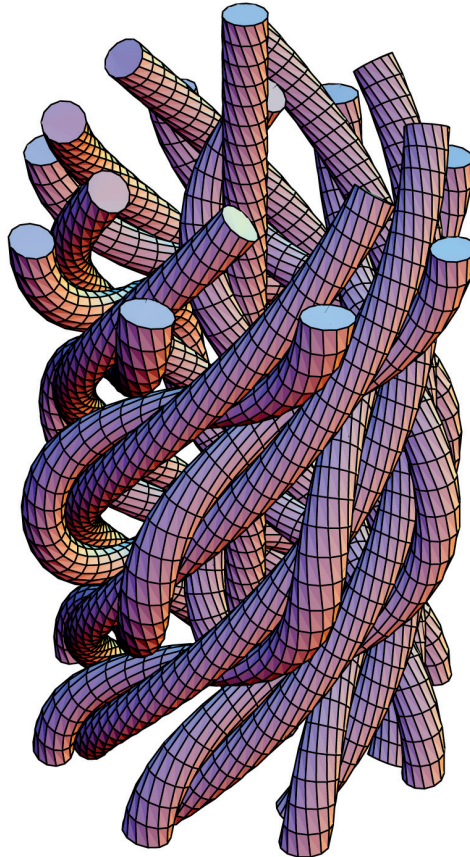


Fig. 3: 14 of the 49 wires of a simple rope design ( $7 \times 7$ ).

In a typical wire rope the load-elongation chart (Fig. 4) is characterized by a non-linear zone where the shorter elements carry the greatest amount of the rope load (0% of the minimum breaking strength to about 11%), a linear zone where all rope elements share the load (about 11% of the minimum braking strength to about 55%) and another non-linear zone where more and more rope elements yield (about 55% of the minimum breaking strength until the rope failure).

If the rope is subjected to tension-tension loads lower than about 11% of its minimum breaking strength it will be most likely to fail from the inside out.

This means that especially in “very safe” installations (operating with relatively low line pulls or high “safety factors”) the rope inspector will not have any chance to detect an increasing rope deterioration.

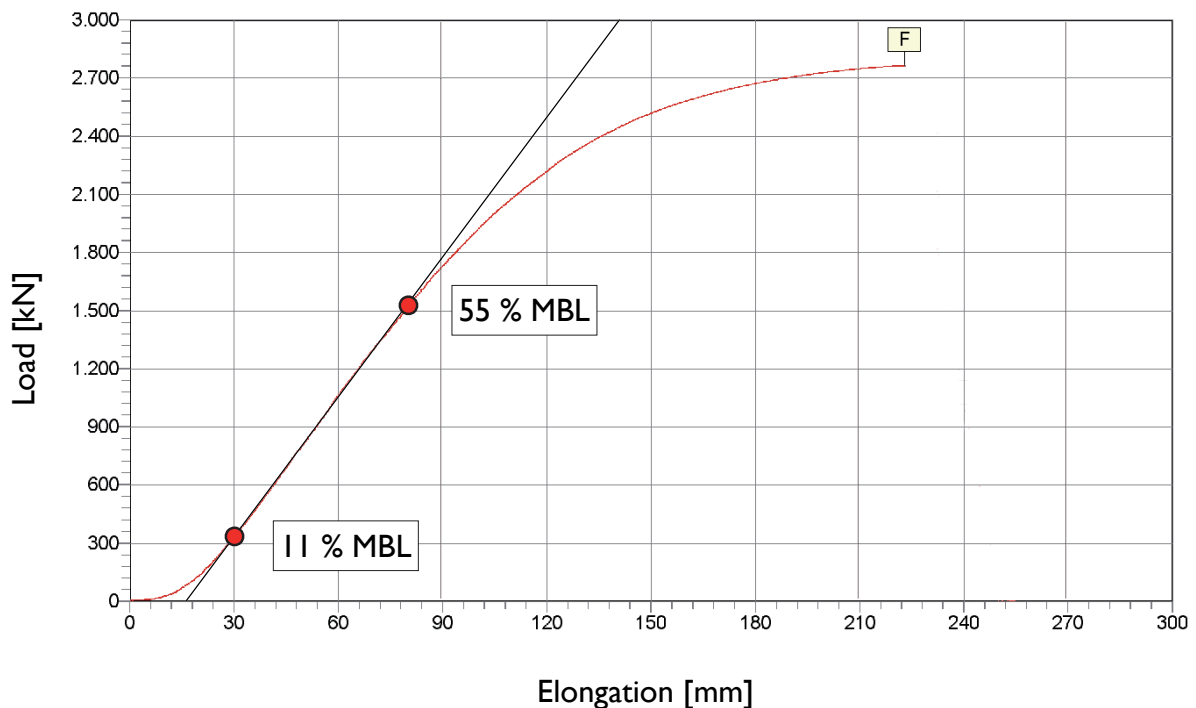


Fig. 4: Typical wire rope load-elongation chart.

### 1.5. Internal wire breaks (2): Rope twist

Very often a coming rope failure is not detected because the wire rope fails from the inside out.

A steel wire rope is normally designed in a way that the core and the outer strands share the load in proportion to their metallic cross sectional area. Twisting the rope (during production, during installation, by the machine or by the self weight of the rope), however, can lead to a load shift which will overload the core.

This effect is even more pronounced in rotation resistant ropes. Because in these ropes the IWRC is closed in the opposite direction of the outer layer, a rope twist in the lengthening sense of the outer layer will shorten the IWRC and lead to a load transfer to the core. Therefore a load shift between the outer strands and the rope core (IWRC) is more likely to occur in rotation resistant ropes.

The great number of rope failures with (especially rotation resistant) ropes having  $\pm 12$  outer strands indicates that the number of outer strands of the rope has a great influence on whether this load shift will lead to wire rope failure or not.

With increasing number of outer strands, the share of the outer strands on the cross section of the rope will decrease and the share of the core will increase (Fig. 5).

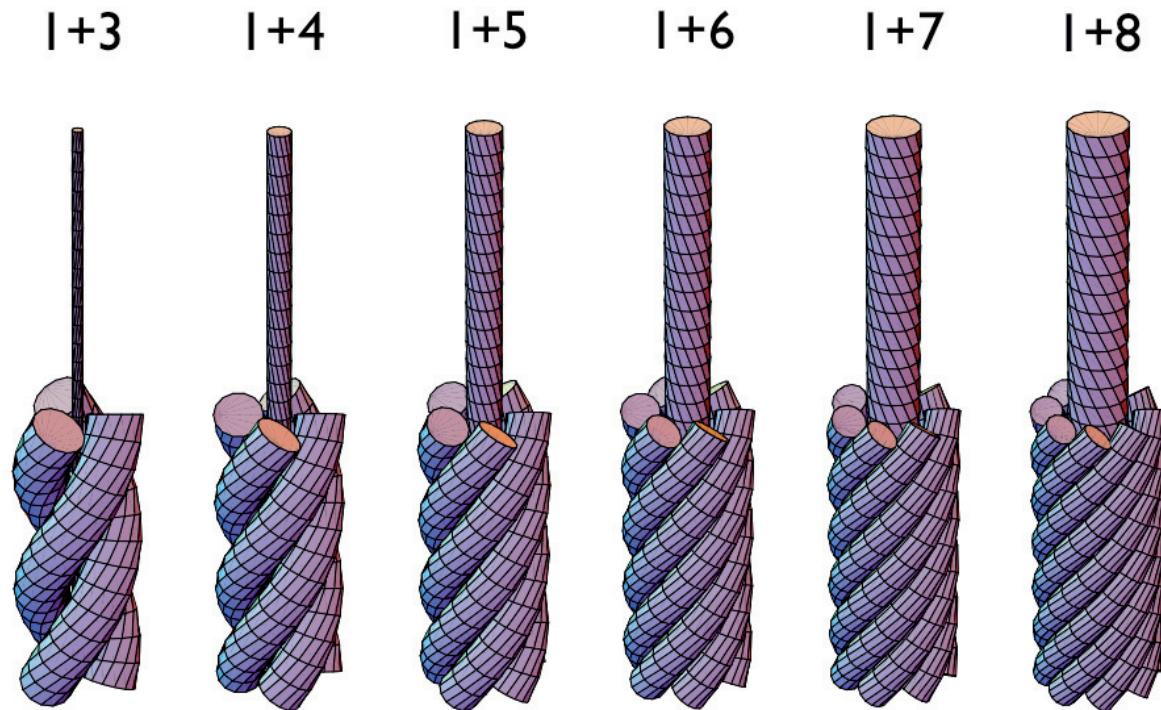


Fig. 5: Relationship between the number of outer strands and the size of the core in a rope.

Fig. 6 shows the percentage of the metallic rope cross section represented by the core of the rope.

Let us now suppose the rope is operating with a design factor of 4. This means the rope cross section will be subjected to a line pull representing 25% of the breaking strength of the rope.

#### **1.5.1. The 4 strand rope**

If due to twist the outer strands of a 4 strand rope would be unloaded and the core (which represents 4% of the cross section of the rope) would have to hold the full load, it would immediately fail. But nothing serious would happen: the rope force will now be transferred to the outer strands, and these remaining 96% of the rope cross section will safely hold the load.



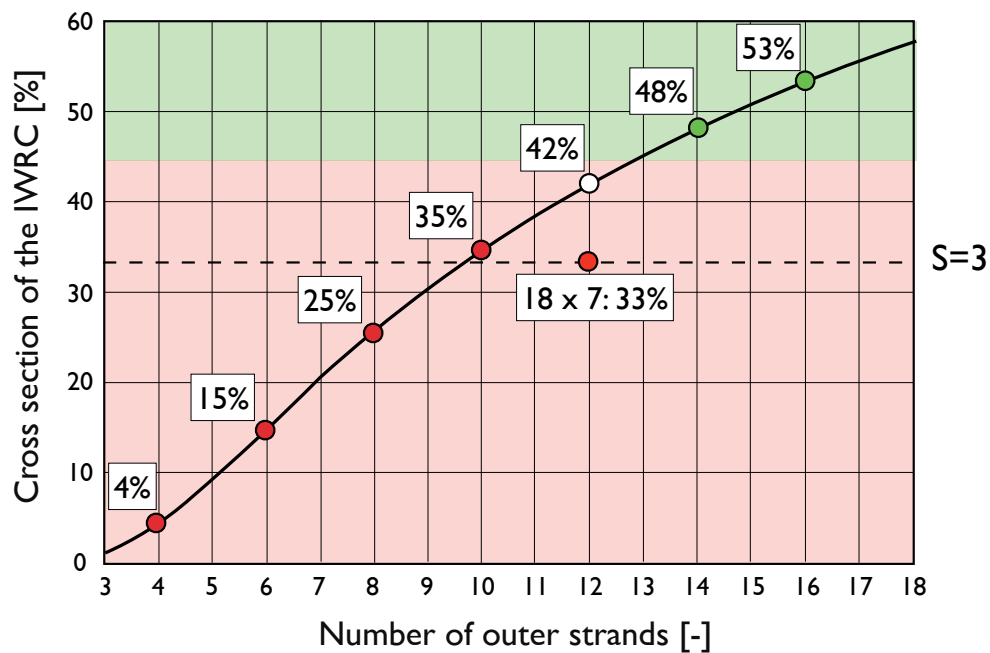


Fig. 6: Percentage of the metallic rope cross section represented by the core of the rope.

### 1.5.2. The 18 strand rope

If due to twist the outer strands of an 18 strand rope would be unloaded and the core (which represents 55% of the cross section of the rope) would have to hold the full load, the core would be twice as strong as the applied load and therefore it would not fail. The outer strands would become loose and over time form a birdcage, but that would not lead to a fatality.

### 1.5.3. And in between: the 12 strand rope

In a typical 12 strand rope the core contains between 33 and 40% of the metallic cross section of the rope. If due to twist the outer strands of such a 12 strand rope would be unloaded and the core would have to hold the full load, the core would only be slightly stronger than the applied force and therefore would in the beginning be able to hold the load. It would, however, stretch enough to prevent the formation of a birdcage as an indicator for the unsafe state. And it would deteriorate very rapidly. Once the IWRC fails the outer strands would be subjected to the full load as an impact load and fail as well.

We can make the same reasoning of paragraphs 1.5.1 to 1.5.3 for a case where the design factor is 3, which is the minimum allowed for cranes. This design factor  $S=3$  is also shown in Figure 6. The green dots are safe in the event of a birdcage formation: even with a load of 33% of the MBL, the IWRC representing 48% or 53% of the rope cross section will not break. The 12-strand rope with 42% might break due to the extra impact load. But the 12-strand rope with only 33% of the cross section in the IWRC certainly will. As will all the other ropes with red dots.

Twisting a rope around its own axis in the opening sense will lengthen the outer layer and the IWRC to a different degree. The length difference thus created will lead to a load transfer between the layers.

### 1.6. Corrosion

Corrosion, and especially internal corrosion, is a frequent cause for wire rope failure.

One of the most expensive rope accidents ever happened because a wire rope had corroded internally (Fig. 7). The ungalvanized rope had been manufactured with only little lubrication and then worked as a hoist rope on an offshore platform for several years.

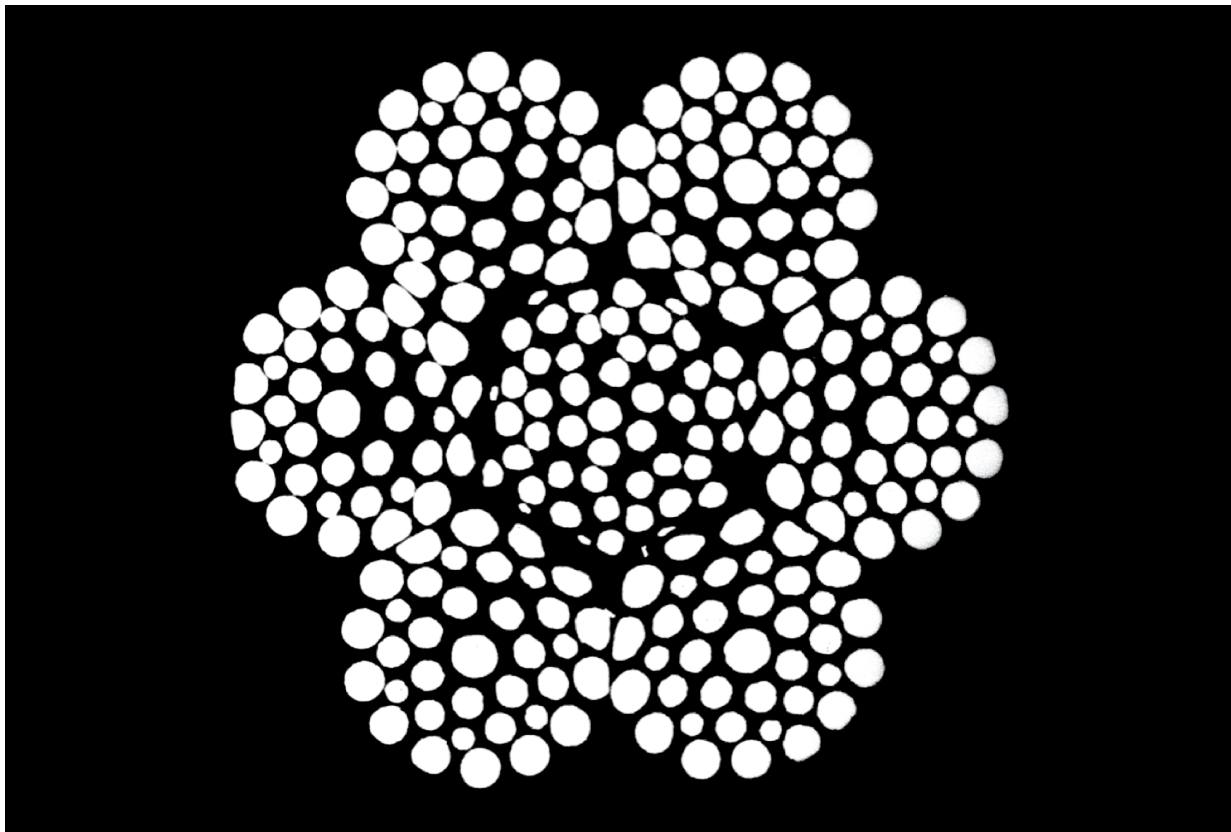


Fig. 7: This rope shows severe abrasion and corrosion inside while the outside looks good.

In order to protect the rope from the corrosive environment, the rope was relubricated externally. The lubricant, however, did not penetrate inside the rope. Therefore corrosion and abrasion could destroy the rope internally, while the outer coating prevented the rope inspector from seeing the problem.

Finally, the rope failed during a heavy lift, creating a great amount of damage.

## **2. Unpredictable (catastrophic) rope failures**

Unlike the predictable rope failures which tend to occur at the end of a normal life of a steel wire rope, the catastrophic failures can happen at more or less any moment in the rope life.

### **2.1. A rope “jumping the sheave”**

Probably the most frequent single cause for a catastrophic rope failure is a rope “jumping the sheave”. The wording for this kind of failure is not well chosen because the rope does not actually jump out of the sheave: it fails to get *into* the sheave. Various causes can lead to such a failure.

#### **2.1.1. Cause 1: Excessive fleet angles**

The greater the fleet angle under which a steel wire rope enters a sheave the more likely it is that the rope will fail to get into the sheave. This is one of the reasons why fleet angles are limited in reeving systems.

#### **2.1.2. Cause 2: Too small groove angles**

On the other hand, the smaller the groove angle of the sheave the more likely it is that the rope will fail to get *into* the sheave.

In the USA, a rope “jumping the sheave” is more likely than in other countries because of the US Standard requiring a groove angle of 30°.

The German Standard 15061 asks for a minimum groove angle of 45°, and British Standard 6570 requires 52°. In these countries a rope “jumping the sheave” is much less likely. Based on new insights, the newest version of ISO Standard 4308 specifically allows for groove angles up to 60°.

Fig. 8 shows groove angles of 30° (USA), 45° (Germany) and 60° (ISO).

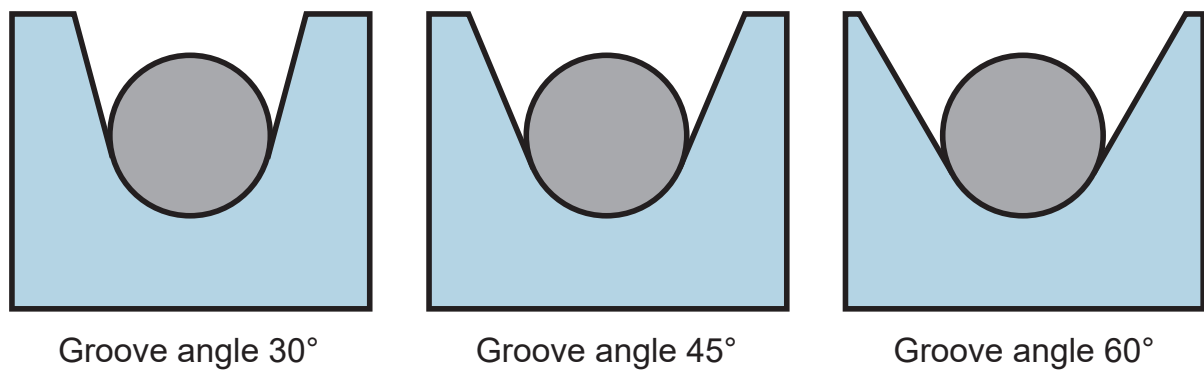


Fig. 8: Groove angles of 30° (USA), 45° (Germany) and 60° (ISO).

### 2.1.3. Too wide groove radii relative to the rope diameter

Over the last years, the author has analyzed many accidents caused by ropes which had “jumped the sheave”. In retrospect he found that in most cases the groove diameter in the sheave was much greater than the rope diameter (Fig. 9 right).

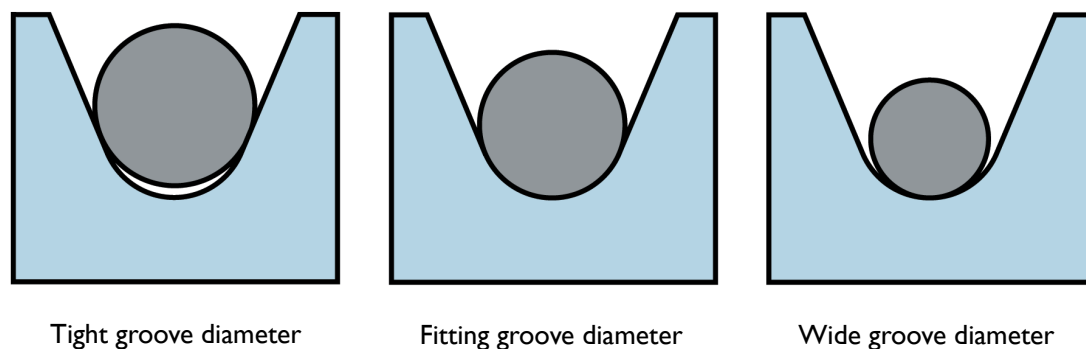


Fig. 9: Schematic diagram showing different size ropes sitting in a groove (of the same diameter in each case).

He also found that ropes spooling onto single layer drums with too big groove radii had a tendency to jump over the rim of the grooves into the neighbouring groove (which is the same as “jumping the sheave” except for the fact that this does not immediately cause a rope failure).

Fig. 10 shows a typical outer wire break surface from a rope which had “jumped the sheave” (scanning electron microscope photograph by the author).



Fig. 10: Typical outer wire break surface from a rope which had “jumped the sheave” (scanning electron microscope photograph by the author).

The fact that the groove had been too wide for the rope increased the bearing pressure on the fewer outer wires in contact with the groove. Therefore a fatigue break was initiated at the bottom of the break surface.

The (lentil- shaped) fatigue area then propagated further into the wire cross section until a much bigger residual break surface was created by the catastrophic event. Because the rope was not held firm to the left and to the right after entering the sheave (as it would have been in a tight or well-fitting groove), any rope vibrations or oscillations outside the sheave could cause the rope to roll back and forth in the wide groove and gain momentum for the “final jump” (Fig. 11).

At the bottom of the break surface in Fig. 10 the flattened band along the break was caused by the rope rolling back and forth to the sides in the wide groove.



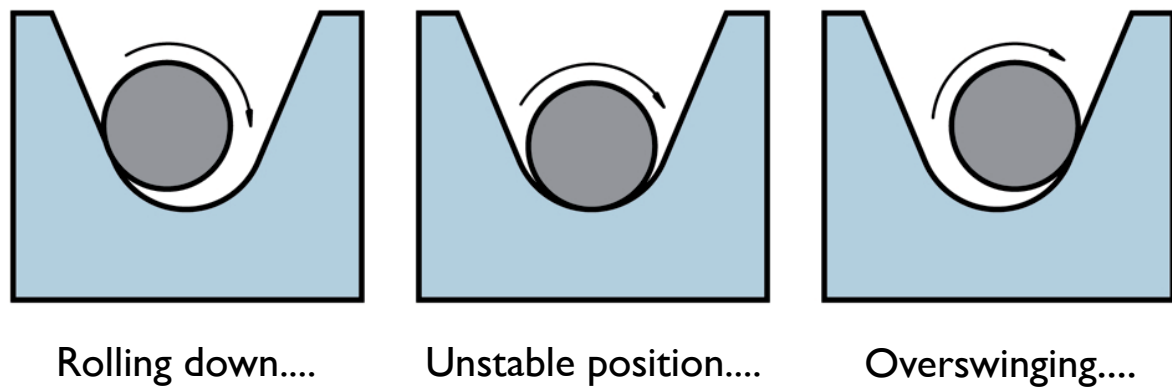


Fig. 11: Schematic diagram showing how rope vibrations or oscillations outside the sheave could cause the rope to roll back and forth in a wide groove and gain momentum for the “final jump”.

## 2.2. Lightning strike

During the construction of a 300 ft (100 m) radio tower workers were lifted every day to the top of the tower in a man basket. One morning the hoist rope failed and five workers were killed.



Fig. 12: Individual rope wires welded together as a result of lightning strike discharge through the rope.



A rope analysis showed that at the location of the break and in two additional locations along the rope individual rope wires were welded together (Fig. 12).

The accident was reconstructed as follows:

The reeving system of the lift consisted of the man basket, a rope of 9.5 mm diameter, one sheave which was attached to the tower using a nylon sling, and a drum. Fig. 13a shows the man lift in operation.

When the man lift was not working, the hoist rope was slack and leaning against the lattice structure of the tower.

One night a lightning struck the tower. Because the tower was insulated from the ground, the electricity travelled along the wire rope and the drum (which was the only connection the ground), fusing wires together at the points of contact between the rope and the tower (Fig. 13b).

When the man lift was used again the next morning, nobody was aware of the three rope sections damaged by the lightning strike (Fig. 13c).

When during the first lift one of the damaged sections was bent around the winch, the hoist rope failed.

A thorough inspection of the whole length of rope performed that very morning would probably have revealed the damage, but the odds were clearly against this.

If a rope is struck by lightning, the wire structure will recrystallize (Fig. 14) and the wire will lose about 2/3 of its tensile strength. That is not the main problem, however. If neighbouring wires are fused together, the rope becomes very stiff and the wires will break instantaneously when the rope is bent around a sheave or drum.

A steel wire rope can operate in a very hot environment (Fig. 15) provided it can conduct the heat it is subjected to to cooler areas of the crane. In Germany, e.g., about 80% of all ladle cranes even operate with steel wire ropes with a plastic layer between the outer strands and the IWRC.

If, on the other hand, the ropes stand in the heat for only a minute too long, the wire material anneals and the rope becomes dangerous (Fig. 16).

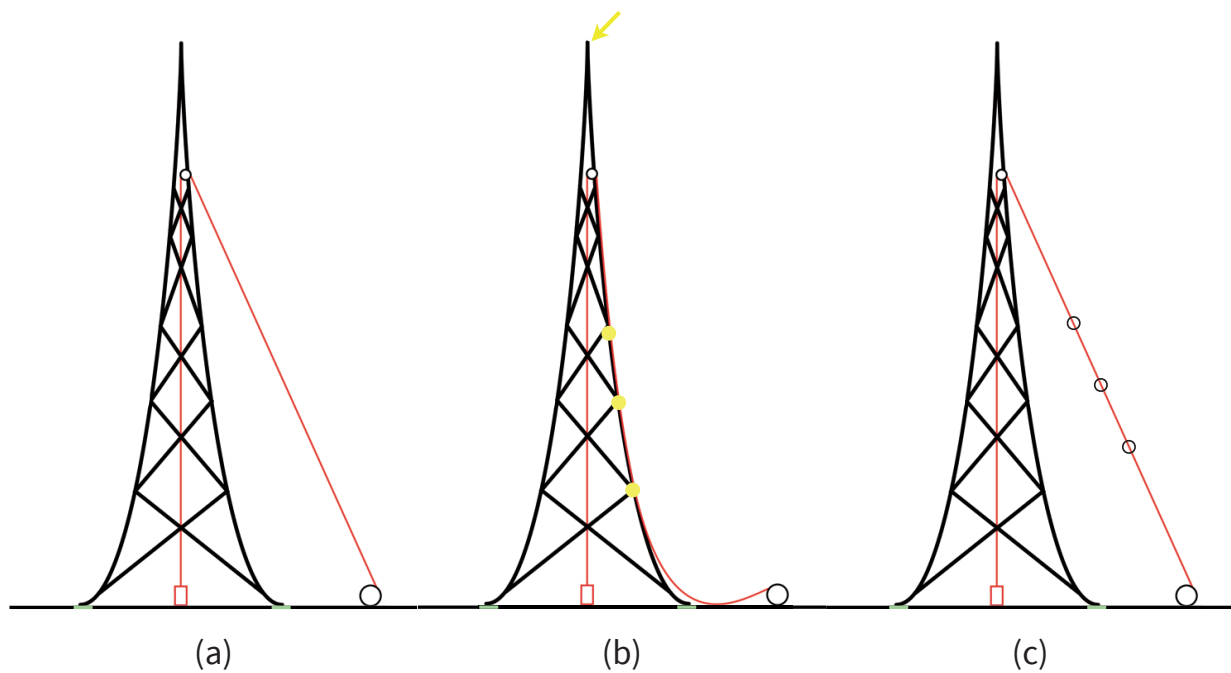


Fig. 13: Sequence of events leading to the damage of a man riding basket hoist rope on a radio tower.

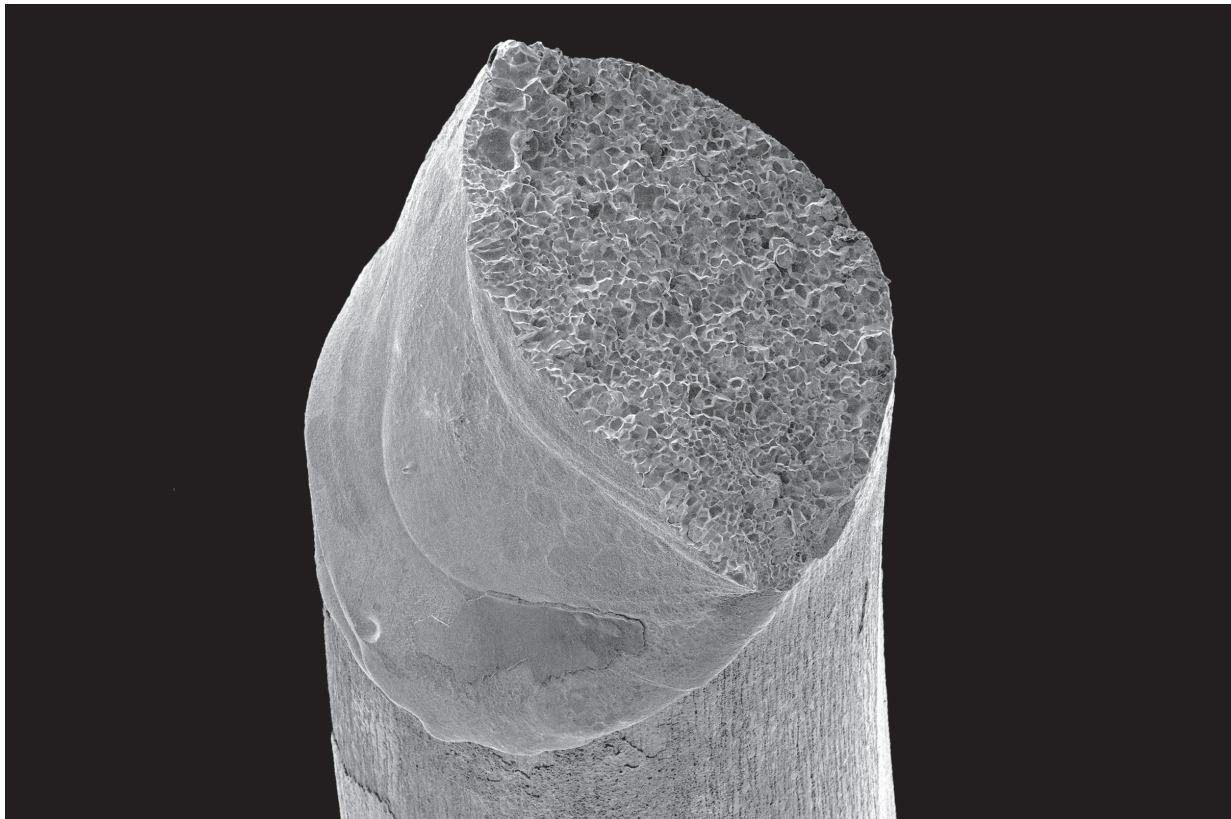


Fig. 14: Recrystallized wire micro-structure caused when the rope was struck by lightning.



Fig. 15: A steel wire rope operating in a ladle crane in a steel mill.



Fig. 16: A wire rope in which the wires have become too hot and annealed.



### 2.3. Hydrogen embrittlement

The stainless steel fall protection ropes to which workers can attach their safety harnesses when walking over a crane girder are normally installed with a relatively moderate pretension. Therefore it came as a great surprise that one day one of these ropes failed without being additionally loaded.

A microscopic analysis of the rope wires revealed a great number of cracks in the vicinity of the point of failure. Along its length every crack had split up in two cracks which a little bit further had split up again (Fig. 17).

A scanning electron microscopic analysis showed that at every forking point the wire surface had split off as if the material was very brittle (Fig. 18).

Also at the break ends the wires showed a topography typical for a brittle material and very unusual for a ductile rope wire (Fig. 19).

When asked about a possible exposure of the fall protection rope to chemicals a worker remembered that a pipe transporting hydrogen peroxide had burst near the location of the rope's break. The pipe had been repaired, but nobody had worried about the rope. Hydrogen had diffused into the steel and caused hydrogen embrittlement.

Finally the moderate pretension of the rope was sufficient to break it.

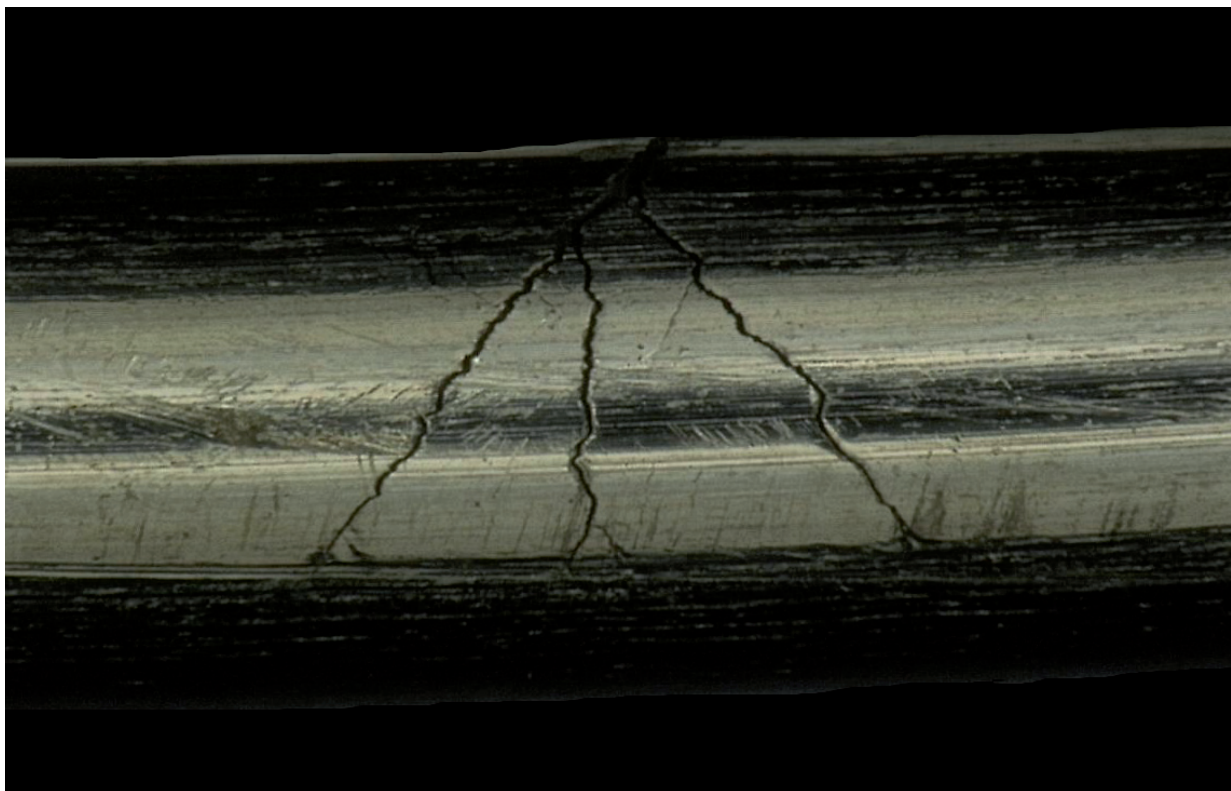


Fig. 17: Cracks in a stainless steel wire in the vicinity of the rope failure.



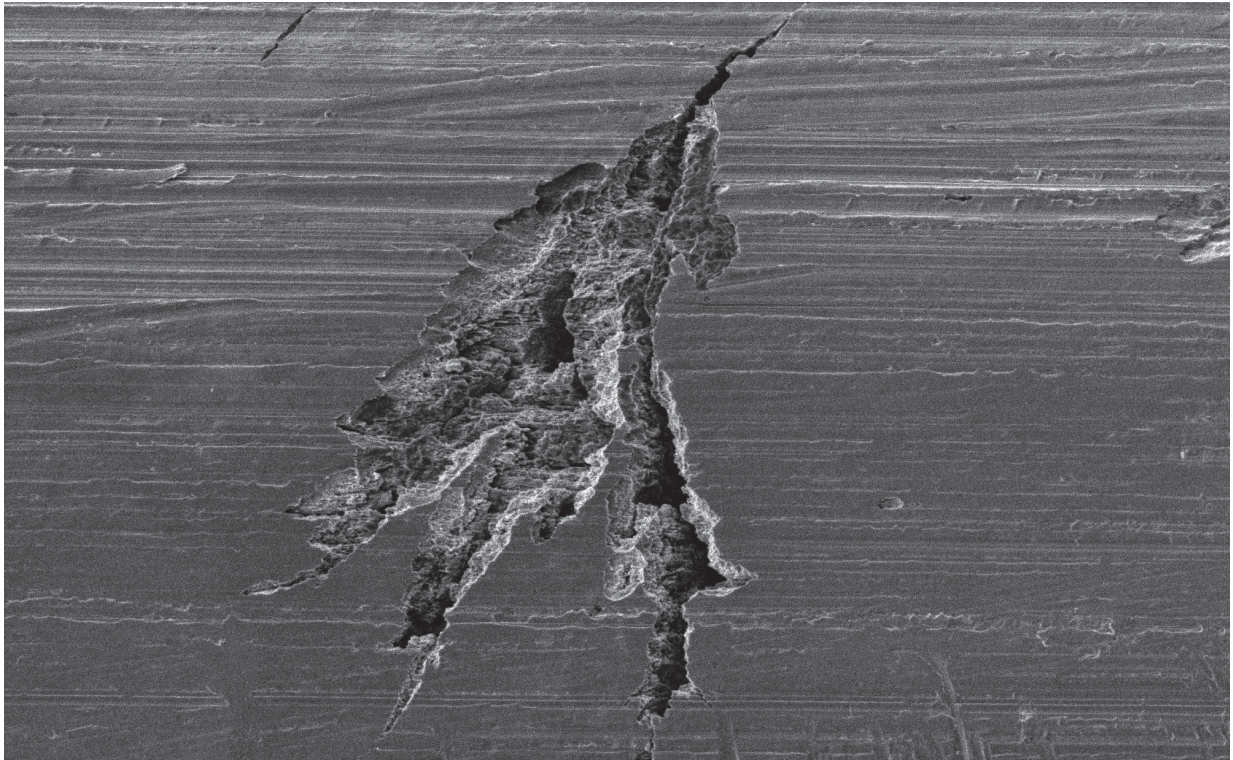


Fig. 18: SEM photograph showing apparent material brittleness at every forking point on the wire surface where material had split off.

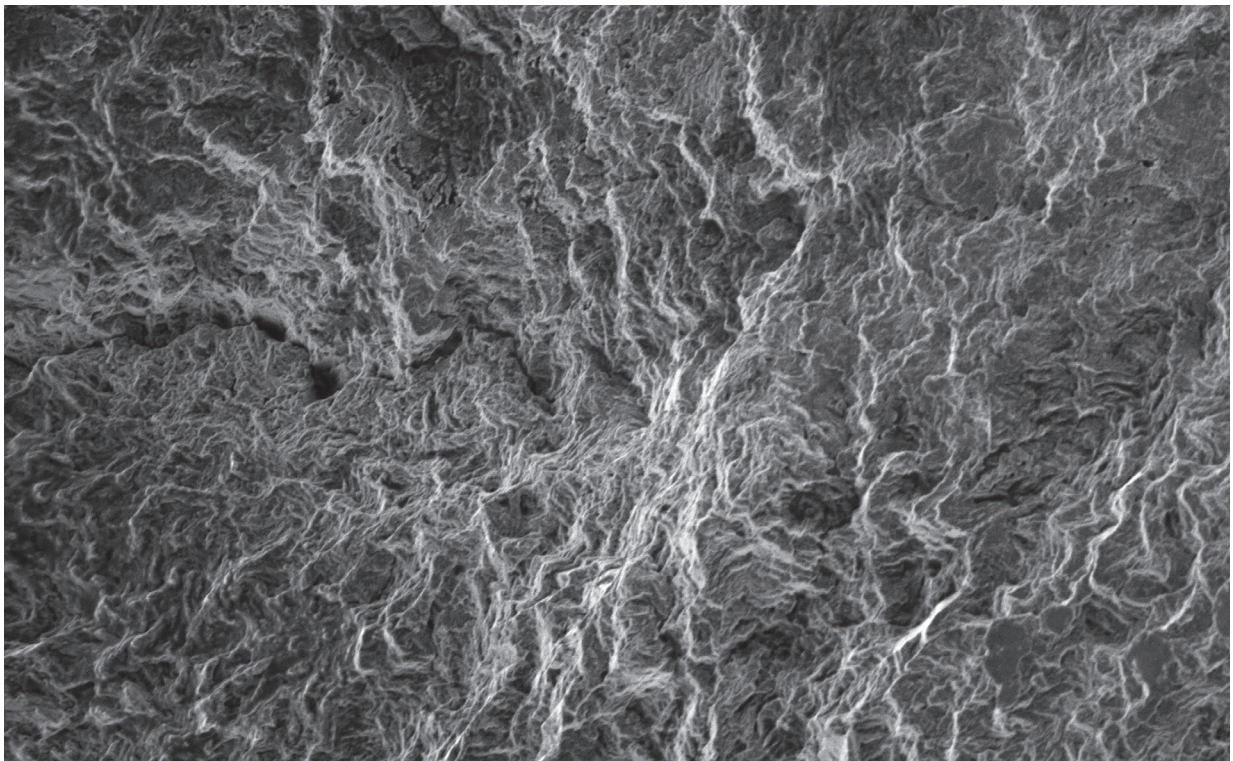


Fig. 19: Wire break fracture surface showing a topography typical for a brittle material and very unusual for a ductile rope wire.



## 2.4. Kinks

A steel wire rope can be twisted during installation (Fig. 20), or twist can be induced by the machine or the mode of operation of the crane.

A consequence of this might be a twisting rope block.

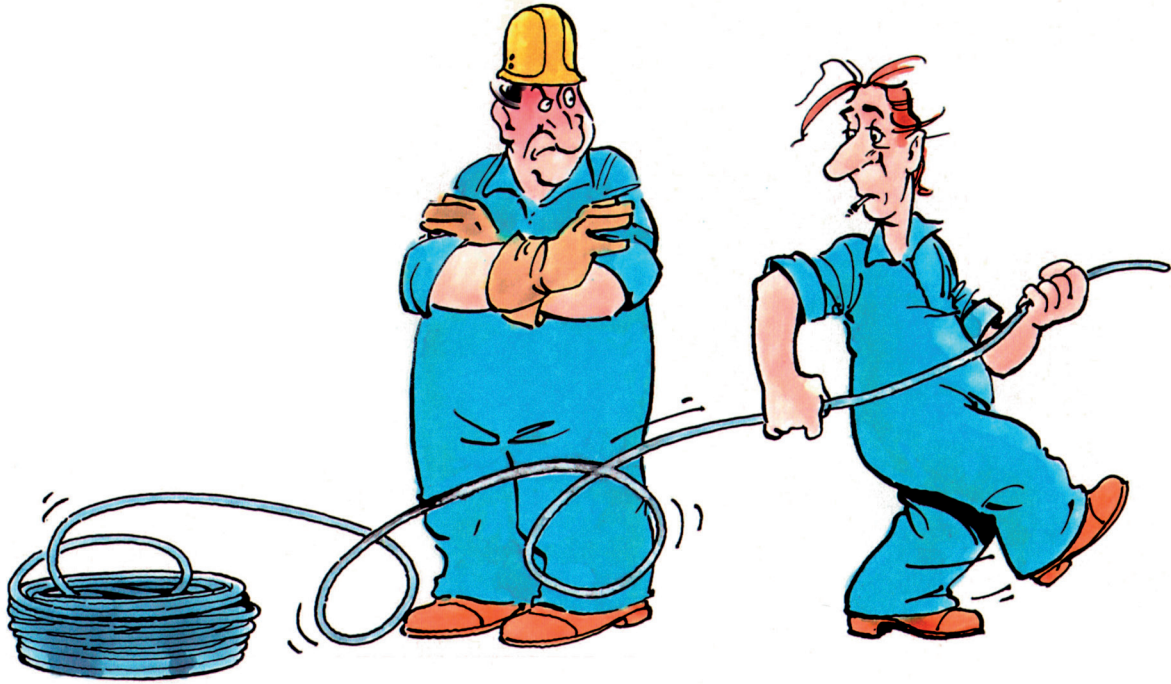


Fig. 20: Inducing twist in a wire rope during installation.

But very often a steel wire rope operates in a twisted condition without the operator ever getting to know about this fact. As long as the rope stays under tension, it might perform well. But if only once the tension is released below a critical value, a kink will form (Fig. 21).

If subsequently the kink is pulled tight, the rope might fail catastrophically. In deep shaft mines, the hoist rope section just above the conveyance is loaded by weight of the skip. The same rope 2000 m higher is loaded by the weight of the skip plus the weight of 2000 m of rope. The low load at the bottom of the shaft creates a low rope moment in one direction, the much higher load at the top will create a much higher moment in the opposite direction. As a consequence, the top section of the rope will unlay in the opening sense, while the bottom part of the rope will be twisted in the closing sense.





Fig. 21: A kink in a wire rope which is apparent at low tension.

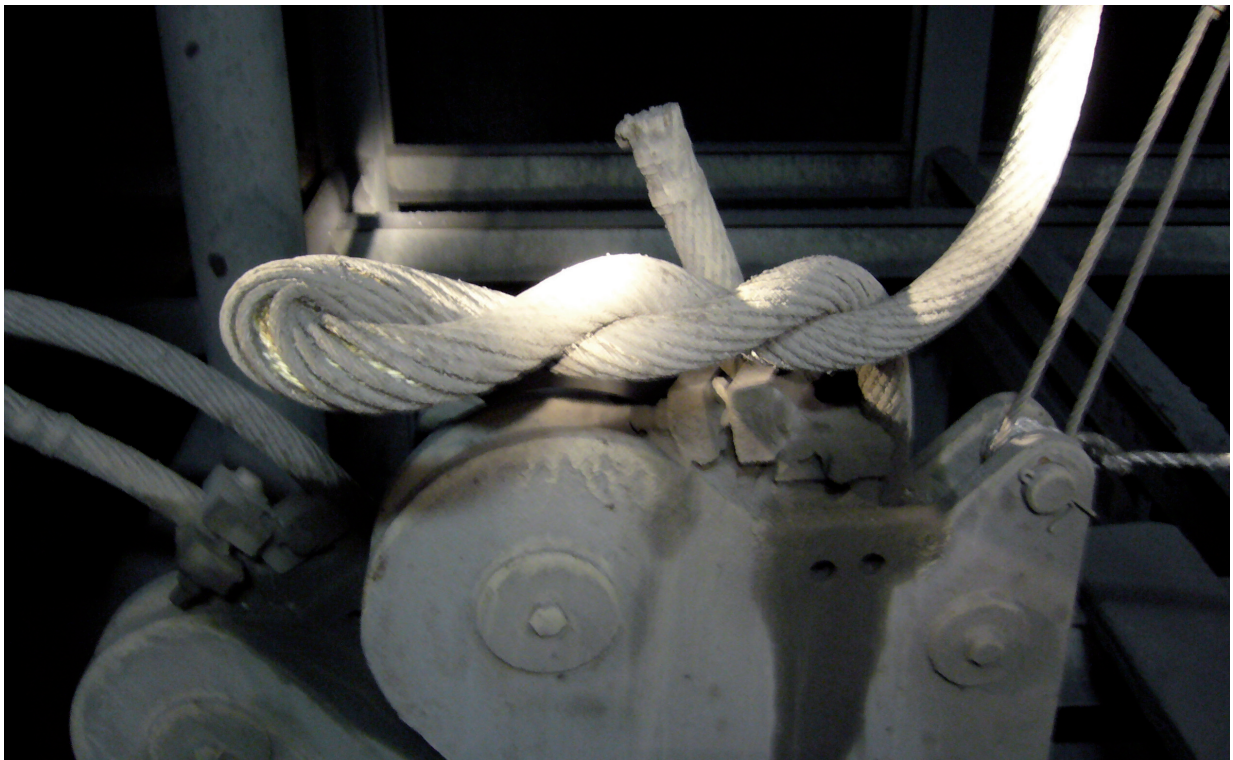


Fig. 22: A kink has formed above the conveyance of a deep shaft mine when the rope became slack.

This twisted state of the rope does not present a real problem during the operation of the shaft (although the fatigue life of the rope will be reduced). If, however, during an upward motion of the skip an emergency break occurs, the hoisting drum will stop turning while the skip continues its upward motion. As a consequence, the rope section just above the skip might become slack (Fig. 22) and, because of its twisted state, form a kink.

When the skip loses momentum and falls back, the rope might fail.

Ropes with variable lay lengths avoid the problems described here by producing the same rope moment under the low load above the skip as under the high load 2000 m higher. Therefore these ropes will not have to twist to find a state of equilibrium, and as a consequence work in a non-twisted condition. This improves the fatigue life while at the same time reducing the risk of a kink formation in a slack rope condition.

### **3. Summary**

Steel wire ropes are highly loaded machine elements. A rope failure can have disastrous consequences.

Some accidents are predictable and bound to happen, if no corrective measures are taken. Others catch us by surprise.

This is why we have to keep studying accidents involving steel wire ropes and teach about the lessons learned.

Education is a key element in making the use of ropes safer.

### **4. References**

BS 6570 (1986): The selection care and maintenance of steel wire ropes. British Standards Institution, London.

DIN 15061 (1977): Hebezeuge; Rillenprofile für Seilrollen (Lifting appliances; groove profiles for wire rope sheaves). Deutsches Institut für Normung e.V.

ISO 4308-1 (2003): Cranes and lifting appliances - Selection of wire ropes. Part 1: General, International Standards Organisation.

Verreet, R. (2001): Steel wire ropes with variable lay lengths for mining applications. OIPEEC Bulletin 81 - 2001, pages 63-70.



**Wire Rope Technology Aachen**

Dipl.-Ing. Roland Verreet

Grünenthaler Str. 40a • 52072 Aachen • Germany

Phone: +49 241- 173147 • Fax: +49 241- 12982

Mail: [R.Verreet@t-online.de](mailto:R.Verreet@t-online.de)

[www.ropetechnology.com](http://www.ropetechnology.com)