WIRE ROPE
TECHNOLOGY AACHEN

Are you safe?

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Content

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The following paper discusses safety aspects of machines designed on the basis of fatigue criteria as opposed to designs based on a safety factor. A few wire rope related examples, both historical and recent, illustrate how unsafe conditions develop and how they could possibly be avoided.

If you look up the word safety in a dictionary, you might find the following definition: Safety is the absence of danger.

When engineers started to quantify different levels of safety, they were confronted with a difficult question: How do you measure the absence of danger?

The first engineering attempt was to define a safety factor. This factor was supposed to express by how much stronger a given structure was compared to the forces it was subjected to. If the safety factor was e. g. 4, the structure could theoretically support forces up to 4 times as high as the maximum forces it would ever be subjected to.

The story of the safety factor is a story of trial and error. Nobody really knew what the optimum level for the 'absence of danger' was. Long periods without accidents encouraged the engineers to lower the safety factors because obviously they were 'overdesigning' the structures and were therefore wasting material and money.

Sudden failures of structures, on the other hand, would tell the engineers that obviously they had to increase the „absenceof danger“ by raising the safety factors to account for unknown stresses or stress concentrations.

The safety factor became known as the „factor of ignorance“.

1. A historical example (1): The safety factor of bridges

In 1847, the Dee bridge in the UK, designed by the famous engineer Robert Stephenson, collapsed under the weight of a railway train only eight months after its completion. A jury analyzed the failure and found that the safety factor had been as low as 1,6. The jury decided that the safety factor for future bridges built in the UK should not be less than 6.

John Roebling, the designer of the East River Suspension Bridge, today better known as the Brooklyn Bridge (Fig. 1), was not only one of the leading bridge builders of his time, he was also the first manufacturer of wire rope on the American continent.

Based on his experience with both wire ropes and bridges Roebling agreed that every enduring structure should initially be put in place six times stronger than needed to carry the highest expected load.The extra strength was anticipated as a buffer for deterioration due to corrosion or fatigue, for shock loads and many other unpredictable influences.

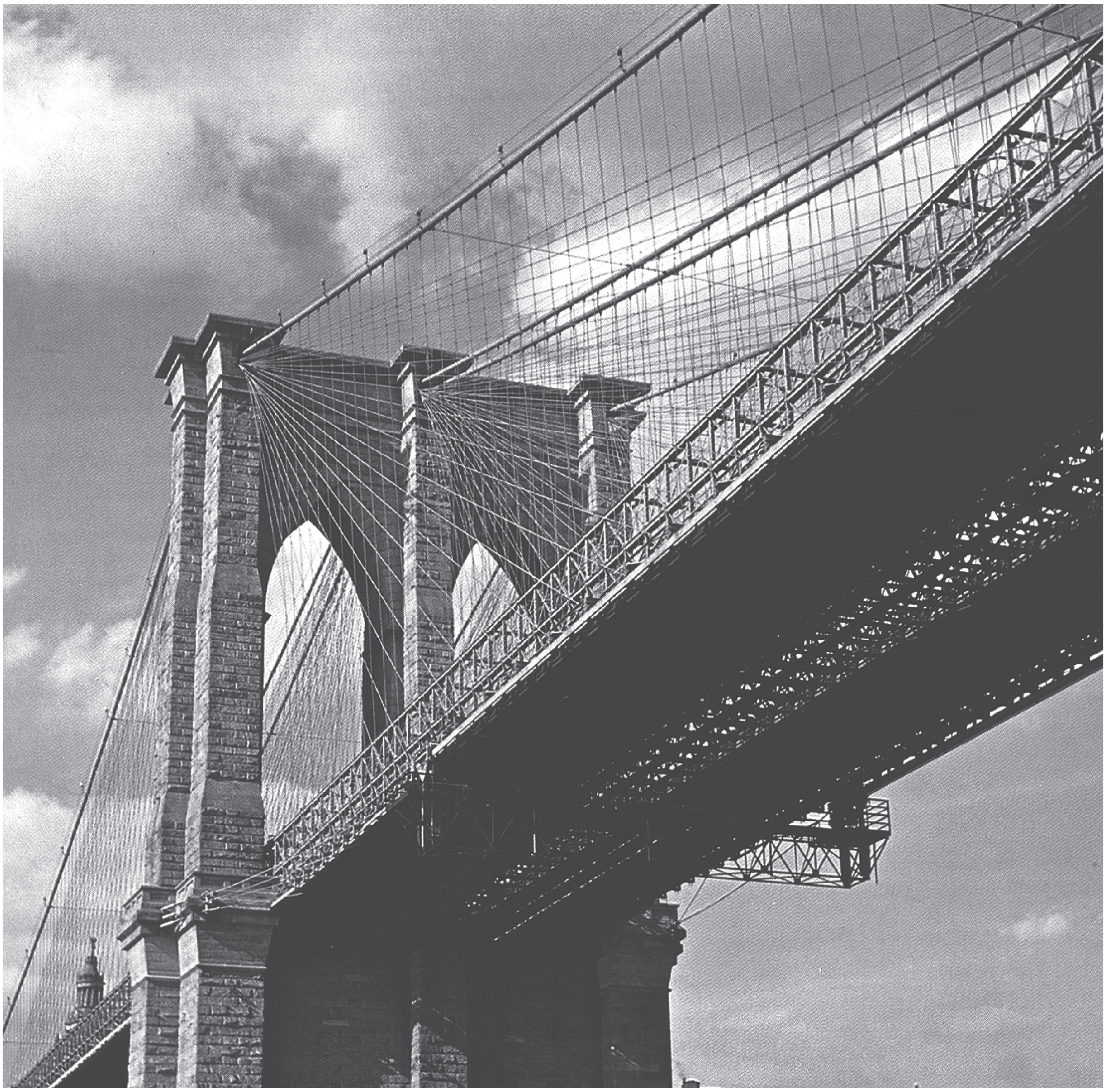

Fig. 1: The Brooklyn Bridge

Consequently, the suspension ropes of the Brooklyn Bridge were also designed with a safety factor of 6. During the time the bridge was being built, John Roebling died, and his son Washington Roebling continued his work. After the stone towers were completed in 1877, the main cables were spun in place. Wire by wire was pulled over the pylons so that it could adopt its natural catenary, and then it was bundled with the other wires. This procedure, invented by John Roebling, allowed the wires inside the bend to be shorter and the wires outside the bend to be longer than those in the center, guaranteeing a uniform stress distribution over the cable cross section.

Before installation, every steel wire was tested by an independent observer, and wires with insufficient strength were rejected. In 1878, Washington Roebling noticed that the pile of rejected wire, which should be slightly growing each week, had actually almost disappeared. He started a secret investigation and found that all the rejected wires had been worked into the main cables anyway!

He did some calculations, taking into account the reduced strength of the rejected wires, and found that by slightly redesigning the cables and adding extra wires, he could still maintain a safety factor of 5. He decided not to mention the problem to anybody and to finish the bridge with a reduced safety factor of 5.

But while the bridge was still under construction, the bridge owners, who were completely unaware of the reduced strength of the main cables, decided to modify the bridge deck and to include railway tracks! Their calculations showed that this would reduce the safety factor of the ropes to about 5, but they concluded that the bridge would still be strong enough. Washington Roebling, however, was the only one to know that the safety factor was already down to 5 and that the additional weights would actually reduce the safety factor down to only 4!

Roebling decided the bridge was still „safe“ and modified it as requested. Time has proved him correct: Heavy railroad trains crossed the bridge for more than 50 years, and after more than 120 years of heavy daily traffic the main cables of the Brooklyn Bridge are still in place.

1.1. The safety factor of ropes and cranes

A crane or a reeving system designed with a high safety factor is not necessarily ‘safer’ than one with a lower safety factor. The contrary might even be true.

The concept of a ‘safety’ factor applied to ropes and cranes reveals a complete misunderstanding of the failure mechanisms that actually take place in every structure which is stressed above its fatigue limit.

As discussed above, the safety factor is based on the highest possible stress level that might possibly occur. But it is not the stress level itself that makes structures fail but the continuous *change* in stress level. We call that failure mechanism *fatigue*.

1.2. Tension-tension fatigue

Let us suppose we subject a steel wire rope to a load of 50% of its breaking strength. The safety factor is only 2, but if the line pull does not change and if the rope does not travel over sheaves, it could theoretically support the load for an unlimited time.

Let us now subject the same rope to a line pull which continuously changes between 2% and 10% of the rope’s breaking strength. We now have a very high safety factor of 10 (5 times higher than in the previous example). But now the changes in line pull will continuously cause changes in the stress level of the rope wires, which in turn will cause relative motions between the rope elements. These mechanisms will cause wire fatigue and material abrasion, which in turn will reduce the strength of the rope. So in spite of its high safety factor this rope will only have a limited lifetime.

1.3. Bending fatigue

Let us now subject the rope to a *constant* line pull of 10% of the rope's breaking strength, but let it run back and forth over a sheave with a diameter of 16 times the nominal rope diameter (D/d = 16). We have a very high safety factor of 10 again, but now the bending stresses and the sheave contact pressures will add to the stresses caused by the line pull. The changes between the straight and the bent condition will create severe changes in the stress level of the rope wires and cause great relative motions between the rope elements. These mechanisms again will cause wire fatigue and material abrasion, which in turn will reduce the strength of the rope. So in spite of its constant line pull this rope will only have a limited lifetime.

Let us now double the rope diameter. This will increase the safety factor from 10 to 40. Is our reeving system safer now? And will our rope last longer? No.

By doubling the rope diameter, we will automatically decrease the D/d- ratio from 16 to 8, thereby severely increasing our bending stresses (the fluctuating part of our stresses). In spite of the higher safety factor our rope will therefore deteriorate much faster than before.

A higher safety factor will not make the reeving system safer. It might in some cases postpone the rope failure to a later date, but in other cases it might even accelerate it.

It is very important to understand that if we have changes in line pull or if the rope is running over sheaves, it will fail. Therefore wire ropes must be inspected at regular intervals in order to be discarded before an unsafe condition occurs.

Every wire rope will fail if it is not taken out of service in time.

We should stop using the word 'safety' in context with machine elements which we know will inevitably fail if we keep using them. It is much safer to call the old safety factor the 'design factor'.

Sometimes we cause failure by trying to make things safer. Galileo Galilei [1] reports an early example:

2. A historical example (2): The marble column

Marble columns often had to lay on the ground for long periods of time before being erected. If they remained in contact with the floor, they would discolour on one side. So they were normally laid on two supports (Fig. 2). Sometimes, a column would break in the middle under its own weight.

Fig. 2: Column with 2 supports

Fig. 3: Column with 3 supports

Galilei reports: „A large marble column was laid out so that its two ends rested each upon a piece of beam; a little later it occured to a mechanic that, in order to be doubly sure of its not breaking in the middle by its own weight, it would be wise to lay a third support midway; this seemed to all an excellent idea.“

The column broke in the middle shortly afterwards, but not *in spite of* the third support but *because of* the third support. Under the weight of the column, the supports would be pressed into the ground at different rates, based on the hardness of the ground. If the middle support would give the most, it would be of no value. If one of the outer supports would give more than the others, it would almost certainly lead to the failure (Fig. 3).

There are similar examples from the wire rope world:

3. A modern case study (1): The second aluminium clamp

In a great opera house engineers were very concerned that the ends of the small diameter steel wire ropes operating the scenery above the performers were only secured by one aluminium clamp (Fig. 4). They decided to secure the ends of all ropes operating above the stage using two clamps (Fig. 5), assuming that this would double the safety of the end connections. A few months later one of these end connections failed. It did not fail *in spite of* the second clamp, but *because of* the second clamp.

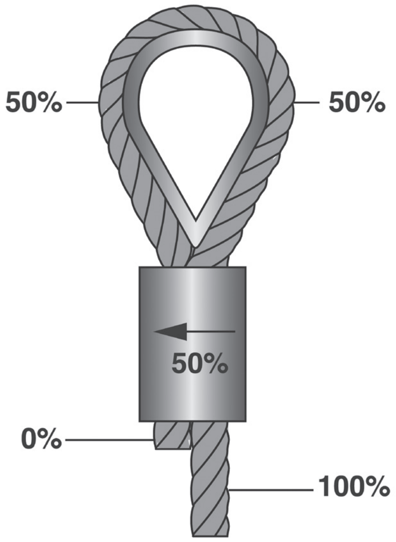

Fig. 4: End connection with one clamp

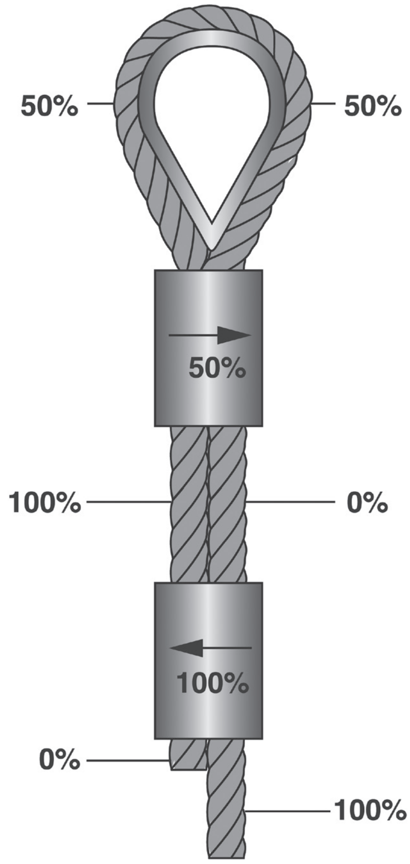

Fig. 5: End connection with two clamps

In the clamp zone, the ‘live’ rope line usually transfers 50% of the line pull to the dead line (Fig. 4). If a second clamp is fitted in the vicinity of the first, it might happen that - due to uncontrollable movement in the section between the clamps during the pressing procedure - the ‘live’ load line is slightly longer than the ‘dead’ line. As a consequence, one of the clamps must now transfer not only 50%, but100% of the line pull (Fig. 5). When the line pull is high, the clamp cannot withstand these stresses. It will break, transferring the full load onto the other clamp as a shock load. This will make the second clamp fail as well.

If you *increase* the number of clamps you *decrease* the level of safety.

4. A modern case study (2): The rope socks

Rope socks or ‘Chinese fingers’ are made of braided wires or strands and are used to install electrical cables or steel wire ropes (Fig. 6). One day the author was present when a hoist rope was installed on an offshore crane. The rope sock was pulled over the rope end, and the fitters started to secure the sock by a greater number of wire seizings (Fig. 7 right).

Fig. 6: Installing a wire rope using a sock (incorrect method)

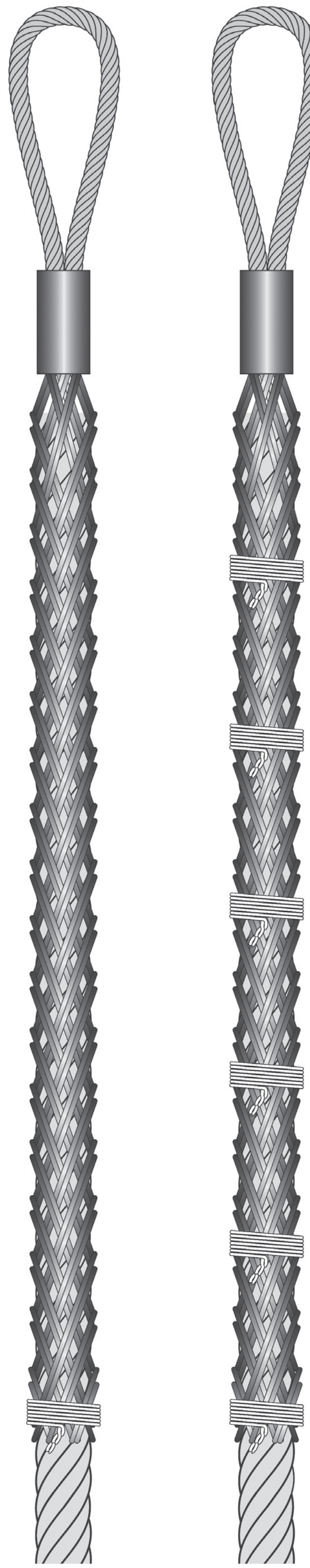

Fig. 7: Correct (left) and incorrect (right) number of seizings

The author stopped them and said there should only be one seizing, and that should be at the sock end. He was told to stay away: it had been done like this for 20 years, and it would be done like this for another 20 years.

It wouldn't: When the rope was pulled 80m up the boom, the connection failed and the rope fell down, luckily not hurting anybody. 40m of rope had been damaged and had to be cut off.

What had the fitters done wrong? A rope sock must be secured by only one seizing at the end (Fig. 7 left). Under load, the sock will get longer and thinner, there by gripping the rope the harder the more it was pulled at. If, however, the sock is secured by a greater number of seizings along its length, the seizings will prevent it from getting longer and thereby prevent it from getting thinner and from gripping the rope.
So when the rope was installed, it was only held by the last seizing. The higher the rope was pulled, the heavier the load on the seizing would get, and finally the seizing would break. Then the full load would be transferred to the second last seizing, which in turn would fail. Within a second this mechanism would repeat itself until all seizings were broken, and the rope would fall down.

If you *increase* the number of seizings you *decrease* the level of safety.

Seemingly logical decisions can cause a disaster:

5. A modern case study (3): The shortened rope length

A 400t ladle crane in a steel mill had a lifting height of 40m. It could lift the ladle basket from 10m below to 30m above the floor level. The hoist ropes had always achieved a service life of about 15 months.

After a few years of operation, the 10m hole in the ground had to make way for a road and was therefore filled and paved. After a few months, the production supervisor realized that the crane could no longer lower the block below ground level and would therefore no longer require two sets of ropes for a lifting height of 40m but for 30m only. His superior agreed, and the next set of ropes was ordered correspondingly shorter.

After 10 months of service the ropes failed, causing a damage of half a million dollars. The reason: internal fatigue in an unexpected area.
The crane had been designed so that in the highest position of the block the fleet angles between the wire ropes coming off the drum and the first sheaves were 0° (Fig. 8). In the lowest block position, the fleet angles achieved the maximum permissible value of 4°.

After the modification, however, a few wraps of rope were missing on the drums. Therefore in every position of the block the ropes had greater fleet angles than before.

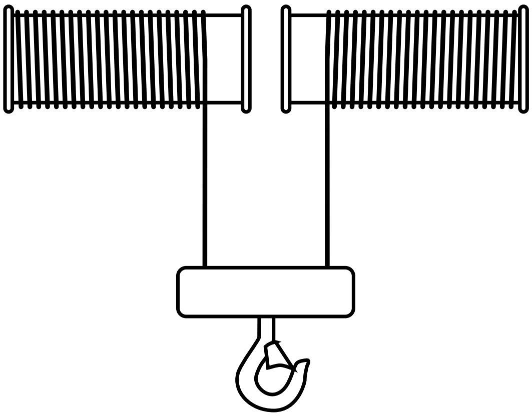

Fig. 8: Original reeving system

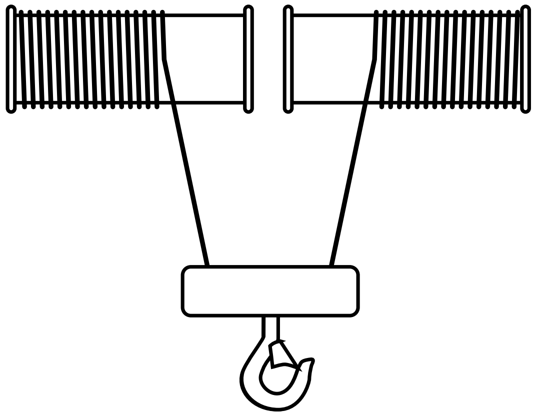

Fig. 9: Modified reeving system

The fleet angles were now 2,56° in the highest (Fig. 9) and more than the permissible 4° in the lowest block position.

Because the permissible fleet angle of 4° was exceeded in the lowest position, the crane would no longer have been allowed to operate. But what really caused the failure was the considerable fleet angle of 2,56° in the highest block positions: The twist caused by the fleet angle of 4° in the low position was taken up by relatively long rope lengths, whereas the twist caused by the fleet angle of 2,56° in the highest position had to be absorbed by very short rope sections. These sections were severely unlayed, overloading the rope cores and finally leading to a rope break without any warning.

Undoubtedly the shortening of the rope caused the failure. But what did the crane user do wrong? Changing the rope lengths changes important design parameters of the system (e. g. the fleet angles) and may therefore not be done by the crane user alone.

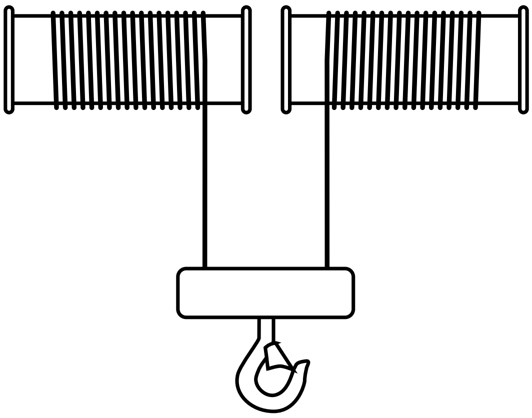

Fig. 10: How the reeving system should have been modified

He should therefore have consulted the crane designer. The crane designer would have moved the fixed point on the drum in order to keep the same fleet angles (Fig. 10).

Wire ropes will inevitably fail if we do not discard them in time. Therefore we must regularly inspect them. But we must do it in the right places (Fig. 11).

Fig. 11: Thorough rope inspection (in the wrong location)

6. A modern case study (4): Wire rope inspection at the equalizer sheave

Fig. 12 shows the reeving system of a twin drum overhead crane. The mid sheave is called the equalizer sheave. It is meant to compensate differences in rope length or line pull which might occur between the two sides of the reeving system.
During lifting and lowering of the block, the two travelling sheaves will make a few revolutions. The equalizer sheave in the middle, however, will normally not rotate at all. Many standards acknowledge this fact by allowing the equalizer sheaves to have a smaller diameter than the other sheaves in the reeving system.

In the past, accidents have happened because wire ropes have failed right at the equalizer sheaves. Why? Let us take a look at the number of bending cycles different sections of the wire rope will undergo during a typical crane operation:
During the lifting operation, section ‘A’ of the wire rope will travel over 1 sheave (= 1 bending cycle) and onto the drum (=1/2 bending cycle). Then the crane will transport its load to a different location and lower it back to the ground. During the lowering operation, section ‘A’ of the wire rope will leave the drum (= 1/2 bending cycle) and travel over 1 sheave again (= 1 bending cycle). In total, section ‘A’ will have done 3 bending cycles.

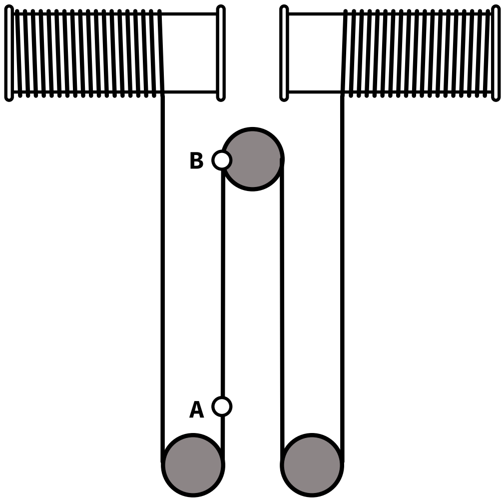

Fig. 12: Twin drum overhead crane with an equalizer sheave

Let us now take a look at section ‘B’ close to the equalizer sheave: During lifting, section ‘B’ will not be subjected to any bending. It will stay right in front of the sheave. But during the transport of the load through the building, the load will swing under the crane bridge, constantly creating length differences between the two sides of the reeving system.

Therefore, a short length of wire rope willcontinuously travel on and off the equalizer sheave, subjecting section ‘B’ to e.g. 30 bending cycles.

Section ‘B’ is the most stressed rope zone in this particular reeving system. It will be subjected to 10 times as many bending cycles as section ‘A’, and even over a reduced diameter! But often it is the only section of rope which will not be inspected, on the one hand because it is not accessible, on the other hand because in theory ‘it does not work’.

Only reeving systems with a great number of running sheaves are ‘safe’ with respect to fatigue at the equalizer sheave because they will have other, more accessible areas subjected to even greater fatigue.

Sometimes an accident happens because there was nothing we could have learnt the lesson from. The accident simply happens because nothing similar has ever happened before:

7. A historical example (3): The Tacoma Narrows Bridge

The Tacoma Narrows Bridge was opened for traffic on July 1st, 1940. It was built to the engineering standards of the time, but it collapsed after only four months of service on November 7, 1940.

Fig. 13: The Tacoma Narrows bridge collapse

The bridge collapse was not caused by an overload. It was caused by a relatively inoffensive wind which lifted the bridge girder and made it swing in a torsional eigenmode, an effect never observed on bridges before (Fig. 13). And if you have not seen the film about the bridge collapse, you will not believe that such a large bridge can swing as much as this one did.

8. A modern case study (5): The Cavalese accident

In February 1998, an American military aircraft hit the 51mm ropes of a ski lift in Cavalese, Italy. Experts would have predicted any aircraft hitting a steel wire rope with a breaking strength of more than 200t would have been destroyed. The wire rope, on the other hand, would have been given a great chance of survival. The opposite happened: the aircraft severed the track rope and even cut the haulage rope in two locations 1,5m apart from each other, but returned to its airbase almost undamaged.

It was later found that the high speed of the aircraft had caused an impact force to propagate through the rope cross section in two nearby locations, breaking the rope wire by wire, thereby not allowing the wires to 'bundle' their forces and stop the aircraft.

After a few hundred years of engineering our failure statistics should be better than they are. But failures keep happening. The examples above showed a certain lack of understanding of the mechanisms that finally led to failure, but also that sometimes things happen which we haven't foreseen.

We should learn the engineering lessons taught by these accidents, and we should understand their moral: that we should never be complacent about safety.

The author would like to thank Dr. Isabel Ridge, for proofreading the paper and making helpful suggestions.

9. Roland's rules for crane ropes and reeving systems

9.1. Crane Design

- Use the largest sheave diameters possible
- Use the smallest rope diameters possible
- Minimise the number of sheaves
- Avoid reverse bends
- Use the right groove diameters (nominal rope diameter + 6%)
- Keep the fleet angles low
- Use sheaves with groove angles 45° and greater
- Have a heavy block with a low center of gravity
- For block stability, have a reeving system with a large base
- Avoid uneven numbers of rope falls
- Avoid rollers
- Avoid equalizer sheaves, use equalizer beams or equalizer drums, if possible
- Avoid multi- layer spooling where possible

9.2. Rope Selection

- Use the right ropes (not the cheapest, but the safest)
- Don't use standardized ropes
- Don't use ropes with fibre core
- Prefer 8- strand ropes to 6- strand ropes
- Use ropes with plastic infill, if you can
- Use rotation resistant ropes only if necessary
- Rotation resistant ropes should have 14 outer strands or more
- Use galvanized ropes
- For multi- layer spooling, use Lang's lay ropes
- For multi- layer spooling, use ropes with compacted outer strands
- For fatigue resistance, use ropes with thinner outer wires
- For abrasion resistance, use ropes with thicker outer wires
- For right hand drums or reevings, use left hand ropes
- For left hand drums or reevings, use right hand ropes

9.3. Rope Storage

- Store your ropes in clean and dry places
- Ropes stored outside must be protected against rain and moisture

9.4. Rope Installation

- Avoid twisting the rope during installation
- Before cutting ropes, make proper seizings
- Overwind- overwind or underwind- underwind
- Avoid any transfer of twist from the old rope to the new rope
- Install ropes spooling in multi-layer under tension

9.5. Crane Operation

- Avoid dynamic loads (easier said than done)
- Don't slew while you are lifting or don't lift while you are slewing
- Don't modify anything without consulting the crane designer

9.6. Rope Inspection

- Inspect your wire ropes frequently
- Inspect your wire ropes in the right places:
    - in the most fatigued zones,
    - at load pick- up points,
    - at the equalizer sheaves
    - on the drum
- Inspect the rope end connections
- Measure the grooves of sheaves and drums
- Use NDT if you can
- Keep an inspection log book

9.7. Rope Maintenance

- Remove broken wires
- Relubricate your ropes at regular intervals
- Use a pressure lubricator if you can
- Use a cut and slip procedure if you can

9.8. General

- Keep learning and improving
- Don't ever feel safe

10. References

[1] Galileo Galilei, 1638, Dialogues Concerning Two New Sciences, Translated by H. Crew and A. de Salvio, 1914.

[2] Henry Petrosky, Design Paradigms, Cambridge University Press 1994, ISBN 0-521-46108-1 hardback, ISBN 0-521-46649-0 paperback.

[3] Donald Sayenga, Sling Design Factors Discussion, Slingmakers

[4] Gabor Oplatka et al., Why was it the rope that broke and not the wing? OIPEEC bulletin 76, 1998, pp 21-24

Roland Verreet, Handling, Installation and Maintenance of Steel Wire Ropes

Roland Verreet and William Lindsay, Wire Rope Inspection and Examination

Roland Verreet, Wire Rope End Connections

Roland Verreet, The Rotation Characteristics of Steel Wire Ropes

Roland Verreet, Calculating the Service Life of Running Steel Wire Rope

Roland Verreet, Analysis of the Bending Cycle Distribution of 1-to 8- part Electric Hoists

Roland Verreet, Wire Ropes for Offshore Cranes, Problems and Solutions, Offshore Crane Conference, Kristiansand, 1998

Roland Verreet & Isabel Ridge, Wire Rope Forensics

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