Estimation of the loss of cross-section of wire ropes

Basics of signal analysis in wire rope testing

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The estimation of the loss of cross-section of a wire rope is one of the essential procedures to measure the damage of a rope. The value is widely accepted as an indicator of the general condition of a wire rope. Most discard criteria are based on this value.

Nevertheless, the international standards do not provide rules how to calculate the loss of cross-section. Instead of an exact formula a general formulation is used, for example "The loss of cross-section has to be calculated taking into account wire breaks, wear and corrosion".

This paper presents some methods to calculate the loss of cross-section for stranded ropes and track ropes, taking into account wire breaks and wear.

Basics of the calculation

Wire ropes have some unique physical properties that need to be explained in advance. Ropes are built of wound wires. If a rope is streched the wound wires and strands build up a radial compression force. This force couples the wires by means of friction. The coupling forces within rope and strands hold the wires in position and prevent the complete unloading of a broken wire. The broken wire is unloaded only over a short distance in the vicinity of the break position[1].

This unique feature of wire ropes makes them fault tolerance: A broken wire will only influence a small region of the rope around the position of the wire break. This behaviour must be taken into account when calculating the loss of cross-section of a wire rope. International standards usually give so called reference lengths for the calculation of the loss of cross-section. For example the EN 12927-1 defines three reference lengths for stranded ropes, 6 times rope diameter, 40 times rope diameter and 500 times

[1]A broken wire in a stranded rope is able to carry its full load in maximum 7 lay lengths away from the position of the breakage due to the coupling (friction) forces. In many cases the recovery occurs already after only 3 lay lengths away from the position of the breakage!

rope diameter and corresponding discard criteria. As mentioned above, no formulas for the calculation of these loss values are provided.

An estimation of the loss of cross-section needs to take into account wire breaks, wear, and corrosion. However, this subject is not trivial, because the state-of-the-art testing methods do not cover all aspects of a possible damage of wire ropes.

The loss of cross-section due to wire breaks

The calculation of the loss of cross-section due to wire breaks seems to be straight forward: Count all wire breaks within a reference length and multiply it by the cross-section of the wires, and get the result. The result should usually be stated as per cent of the nominal cross-section of a rope.

But already at this state some problems arise: Neither all the wires of a rope have the same cross section, nor the magneto-inductive test with local default sensors allows to identify which wire in the cross-section is actually broken. It is, therefore, often necessary to make some assumptions about the wire cross-section used to determine the loss of cross-section of a wire rope.

The above discussed assumption is coupled with other aspects of the analysis of wire rope testing data. One of these aspects we call the focus of a wire rope test. Depending on testing instrument, sensor properties and rope properties, the size of typical indications in the test signal may vary in a wide range. A tester must decide, which indications he will take into account and which indications he will neglect. An analysis focus on large wires needs different assumptions for the calculation of the loss of cross-section than an analysis focus on small wires. Multiple wire breaks at the same position may complicate the problem further more.

A second aspect of the analysis of test signals is the probability of detection of faults. The probability of detection depends on the condition of the rope. Unfortunately, it diminishes with increasing number of wire breaks. General rules cannot be derived, because of its dependence of the testing equipment and the rope design. We expect the probability of detection to be in the region of 90 to 95 % in the case of a Seale 6 x 19 stranded rope near the discard criteria.

A third aspect of the analysis is the quality of the test signals. Wear and corrosion may strongly influence the signal quality and may prevent to detect "small" indications. A noisy signal, therefore, may influence the calculation of the loss of cross-section.

A conservative approach

One possible solution to the limits of magneto-inductive testing is to use always the largest wire for the calculation of the loss of cross-section. This calculation over-estimates the actual loss of cross-section under most conditions.

Advantages. This conservative approach over-estimates the loss of cross-section under most conditions and is, therefore, on the save side.

Disadvantages. Depending on the rope design, this approach produces extremely conservative results, for example in the case of a 6 x 29 Filler Wire stranded rope. This construction features an extremely large king wire of 1.5 % cross section. Another disadvantage is its inconsistence regarding rope designs. The largest wire of a 6 x 17 Seale rope has a cross-section of approximately 1.5 %, the largest wire of a 6 x 19 rope has a cross-section of 1.6 % to 1.7 %. This leads to the strange result that less wire breaks are allowed for a 6 x 19 rope than for a 6 x 17 rope. There are other rope designs that show similar inconsistencies.

A popular approach

Most wire rope tester use the cross-section of the outer wires of a strand to calculate loss of cross-section for stranded ropes. With very few exceptions, the cross-section of the outer wires of a strand gets smaller with increasing number of wires of a rope. This method may under estimate the actual loss of cross-section under some circumstances (for example 6 x 29 Filler Wire ropes).

Advantages. Consistent results for most rope designs.

Disadvantages. The most important disadvantage of this approach is that it may under estimate the loss of cross-section under some circumstances.

Track ropes (locked coil ropes)

Locked coil ropes widely used for track ropes need special treatment. Locked coil ropes are designed as an open spiral rope covered by one or more layers of Z-shaped wires[2]. In general the cross-section of the Z-shaped wires are significantly larger than the cross-section of the round kernel wires. And because of the strong friction (coupling) forces between the inner layers of a spiral rope, wire breaks in the inner layers of a track rope tend to open very slowly. This leeds to the problem, that faults of the outer layer show huge indications while faults of the inner layers may produce very small indications.

A consistent analysis of the faults of a track rope must take into account both type of faults. This fact enforces testers to assume a loss of cross-section for each indication[3]. A reasonable approach may be to assume the cross-section of the outer most wire of the spiral core for all "small" indications and the cross-section of Z-shaped wires to all "larger" indications. Nevertheless, this approach cannot be proved and it may be completely wrong under some rare circumstances. We recommend careful visual controls and radiography in the case of any uncertainty.

Internal wear

All wire ropes tend to develop a significant wear during life time. The wear is directly coupled with the internal friction between the wires of the rope. The estimation of the reduction of cross-section due to wear is, therefore, not a simple, straight forward procedure, because the distribution and the size of wear is not visible. And the magneto-inductive rope test does not detect internal wear under all possible conditions.

In some special cases it is, however, possible to estimate internal wear on the basis of rope diameter, lay length and rope design. The estimation is limited to stranded ropes and it takes only into account wear due to friction between the strands of the rope. Internal wear of the strands is neglected. For parallel stranded ropes this is usually not a problem, because the contacts between the strands are point type contacts and the contacts within a strand are line type contacts with significantly less wear than point type contacts.

The calculation is based on the fact, that diameter, lay length and construction of a rope are not independent. For each stranded rope there is a distinct diameter, where the strands touch each other and begin to produce wear at the intersection points (Figure 1, “6 x 7 rope with touching strands”). Stranded ropes, however, do not behave like rigid bodies, and the strands may deform or change orientation with respect to each other. If the rope diameter diminishes further, the strands will not produce a considerable wear, until they are completely locked (Figure 2, “6 x 7 rope with internal wear”).

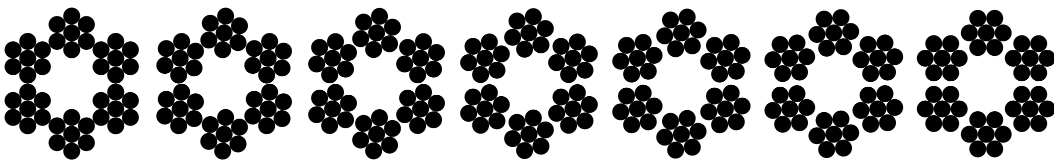

Figure 1. 6 x 7 rope with touching strands

[2]Older track ropes may contain mixed layers of round wires and I-shaped wires.
[3]This assumption may base on additional controls, for instance a visual control.

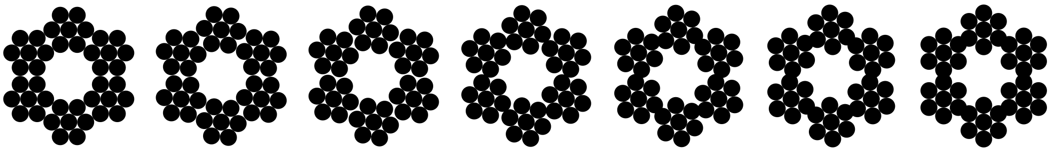

Figure 2. 6 x 7 rope with internal wear

The calculation of the loss of cross-section is, therefore, reduced to the calculation of cross-section of the outer wires of the strands and it may be calculated with the following formula[4]:

$$\beta_{rope} = \arctan\left[\frac{\pi\cdot\left(\hat{D}_{rope}-D_{strand}\right)}{\lambda_{rope}}\right]$$

$$\epsilon = \left[\frac{\pi\left(\hat{D}_{rope}-D_{strand}\right)}{\lambda_{rope}}\right]^2$$

$$t_{upper} = \frac{D_{strand}}{2} - \frac{\left(\hat{D}_{rope}-D_{strand}\right)}{2}\left[1-\frac{3}{8}\cdot\epsilon+\frac{15}{128}\cdot\epsilon^2+\frac{45}{1024}\cdot\epsilon^3\right]$$

$$t_{lower} = \frac{\left(D_{strand}-D_{wire}\right)\cdot\cos\left(\frac{\pi}{N_{wires}}\right)+D_{wire}}{2} - \frac{\left(D_{rope}-D_{strand}\right)}{2}\left[1-\frac{3}{8}\cdot\epsilon+\frac{15}{128}\cdot\epsilon^2+\frac{45}{1024}\cdot\epsilon^3\right]$$

$$\Omega = 2\cdot\arccos\left(1-\frac{2\cdot t}{D_{wire}}\right)$$

$$\Delta = \frac{3\cdot N_{wires}\cdot D_{wire}^2\cdot\left[\Omega-\sin\left(\Omega\right)\right]}{4\cdot A}$$

Equation 1. Upper and lower limit of internal wear of stranded ropes.

The formula gives a lower and an upper limit of internal wear of stranded ropes with six strands[5], based on the two configurations shown in Figure 2, “6 x 7 rope with internal wear” (lower limit) and Figure 1, “6 x 7 rope with touching strands” (upper limit). As mentioned above, it does not make much sense to invest great efforts in so called "exact"calculations, because strands may deform before producing considerable wear.

The calculation strongly depends on the strand diameter. This diameter must be calculated from the wire diameter, and, of course, the strand design. The calculation of the diameter of the strands is outside of the scope of this paper. Please refer to literature or existing programs for more information. Because of the strong dependence, measured strand diameters are generally not suitable as an input parameter of the calculation.

For more information about the above equations and their practical application refer to Example B.1, “Comparison of different rope designs”. The internal wear of track ropes (locked coil ropes) cannot be estimated using the reduction of the diameter of the rope.

External wear

External wear of stranded ropes is a delicate subject for estimation. Because stranded ropes tend to change their diameter with use, the loss of cross-section due to external wear cannot be measured directly. The change of diameter does not directly correlate with the loss of cross-section.

[4]The formula has been derived with the help of asymptotic methods. The depth of the notches is given in the form of a Taylor series, which can be evaluated numerically. Only a few elements are necessary for accurate approximations.
[5]Other values for the number of strands significantly complicate the formulas.

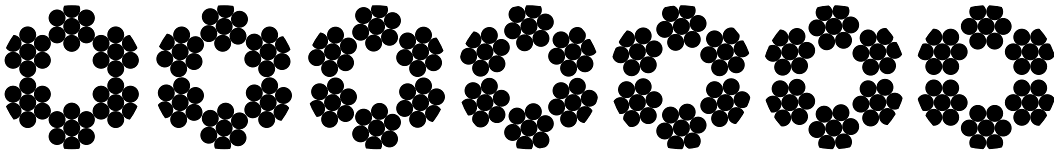

Figure 3. 6 x 7 rope with external wear

There are two possible solutions to this problem:

1. If possible, take a wire out of the strand and measure its reduced diameter. This allows to estimate a overall loss of cross-section.

2. There is a possibility to calculate the reduction of the cross-section of a wire by measuring the length of the cut surface produced by external wear (see Figure 4, “Definition of the length *b*.”). The loss of cross-section of one wire may be calculated as follows:

$$\beta_{strand} = \arctan\left[\frac{\pi \cdot \left(D_{strand} - D_{wire}\right)}{L_{strand}}\right]$$

$$\Omega_1 = \arcsin\left[\frac{b \cdot \sin\left(\beta_{strand}\right)}{D_{strand}}\right]$$

$$\Omega_2 = \arcsin\left[\frac{b \cdot \sin\left(\beta_{strand}\right)}{D_{rope} \cdot \cos\left(\beta_{rope}\right)}\right]$$

$$t_{external} = \frac{D_{strand}}{2} \cdot \left[1 - \cos\left(\Omega_1\right)\right] - \frac{D_{rope}}{2} \cdot \left[1 - \cos\left(\Omega_2\right)\right]$$

$$\hat{D}_{rope} = D_{rope} + 2 \cdot t_{external}$$

Equation 2. External wear

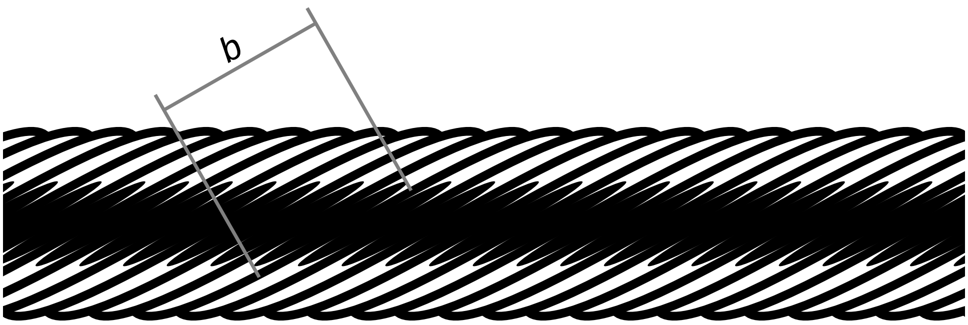

Figure 4. Definition of the length *b*.

The calculation is very sensitive to the length *b*. In addition our experience show that it is very difficult to measure *b* with reasonable accuracy[6]. We, therefore, recommend method 1 in critical situations.

To estimate the overall loss of cross-section, the loss of cross-section of a wire has to be multiplied by the number of wires showing wear within the desired length.

External wear is often combined with internal wear (Figure 5, “6 x 7 rope with external and internal wear”). Because internal and external wear occur on the same wire, they are not additive. The loss of cross-section due to external or internal wear is the larger of the two values.

[6]Only fresh cut surfaces can be used to measure *b*.

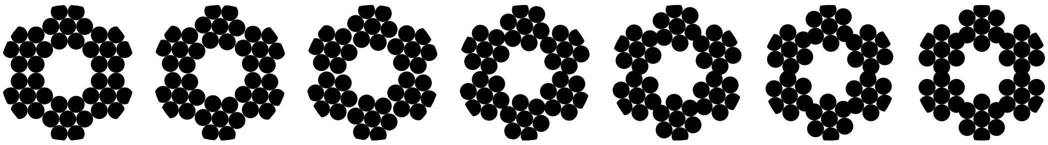

Figure 5. 6 x 7 rope with external and internal wear

Please refer to Example B.2, “Combined internal and external wear” for more information about the calculation mechanism and its practical application.

Calculating the external wear of track ropes is in general much simpler. The external wear can be estimated by measuring the diameter of the rope and comparing it to an undisturbed position. Do not forget to estimate the loss on per wire basis and then multiply it by the number of wires affected within the reference length.

Conclusions

The aim of this paper is to demonstrate several methods to estimate the loss of cross-section of wire ropes in general. This is not a trivial task and, it is definitely not a straight forward task. Different testers may use different approaches and the results may, therefore, differ slightly. Especially the task of estimating wear is difficult. It is not possible to see the type of internal wear and it is generally not possible to measure values used for direct calculation.

The above discussed methods to estimate wear avoid parameters that are not available to wire rope testers and, therefore, may be applied with reasonable effort. The disadvantage is their accuracy: The methods give only bounds as a result.

However, we have found several stranded ropes with measured diameter below the theoretical "strand-touching" diameter that show no signs of significant wear. On the other hand all ropes with calculated lower bound significantly greater than zero show clear signs of internal wear[7]. The two bounds may be too far away from each other to be used as a strict criteria for discarding ropes, but together with other information[8] available during a state-of-the-art test they may play an important role in an overall judgement. But in the case of any uncertainty there is no way around opening a rope and taking out a wire of a strand for direct inspection[9].

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A. Symbols and their Definitions

D_{rope}	The measured diameter of the rope.
D_{strand}	The nominal (calculated) strand diameter.
D_{wire}	The diameter of the outer wires of a strand (nominal value).
$N_{strands}$	The number of strand of the wire rope.
N_{wires}	The number of outer wires in one strand.
λ_{rope}	The measured lay length of a rope.
λ_{strand}	The nominal lay length of a strand.
b	The length of the cut surface visible on the outer wires in the case of external wear.
β_{rope}	The winding angle of the strands of a rope. Helper variable to simplify equations.
β_{strand}	The winding angle of the outer wires of a strand. Helper variable to simplify equations.
ε	A "small" variable.
Ω	Helper variable to simplify equations.
t_{upper}	The (hypothetical) depth of the notches in the wires produced by internal wear, calculated with respect to touching strands. The actual depth of notches will probably be smaller.
t_{lower}	The hypothetical depth of the notches in the wires produced by internal wear, calculated with respect to completely locked rope. The actual depth of notches will probably be greater.
$t_{external}$	The measured or calculated depth of external wear on outer wires.
t	A placeholder. Should be replaced with t_{upper}, t_{lower} or $t_{external}$.
A	The nominal cross-section of the rope.
Δ	The loss of cross-section.

B. Numerical examples

Example B.1. Comparison of different rope designs

This example contains a demonstration of the sensitivity of the estimation of the loss of cross-section due to internal wear. The upper and lower limit of the loss of cross-section have been calculated for a typical 30 mm stranded rope with respect to rope diameter and rope design.

Construction	Limit	29.5 mm	29.0 mm	28.5 mm	28.0 mm	27.5 mm	27.0 mm	26.5 mm
6 x 7 Standard	Δ_U	0.43%	1.91%	3.94%	6.39%	9.16%	12.21%	15.48%
	Δ_L	0 %	0 %	0 %	0 %	0.68%	2.33%	4.51%
6 x 17 Seale	Δ_U	0.49%	2.20%	4.54%	7.33%	10.48%	13.92%	17.59%
	Δ_L	0 %	0 %	0.12%	1.53%	3.70%	6.39%	9.46%
6 x 19 Seale	Δ_U	0.53%	2.33%	4.81%	7.77%	11.09%	14.70%	18.54%
	Δ_L	0 %	0 %	0.64%	2.54%	5.09%	8.11%	11.49%
6 x 25 Filler Wire	Δ_U	0.61%	2.70%	5.55%	8.91%	12.66%	16.70%	20.93%
	Δ_L	0 %	0.38%	2.33%	5.09%	8.40%	12.12%	16.14%

The above values should not be applied to real ropes, because the values for the loss of cross-section depend strongly on the strand diameter and the lay length of the rope. Nevertheless, some tendencies may be observed. The loss of cross section increases with the number of outer wires of a strand and the difference between the upper limit and the lower limit decreases with increasing number of outer wires.

Example B.2. Combined internal and external wear

This example demonstrates the effect of combined internal and external wear for a typical 6 x 19 Seale stranded rope with 30 mm Diameter.

b	Limit	29.5 mm	29.0 mm	28.5 mm	28.0 mm	27.5 mm	27.0 mm	26.5 mm
0 mm	Δ_U	0.53%	2.33%	4.81%	7.77%	11.09%	14.70%	18.54%
	Δ_L	0 %	0 %	0.64%	2.54%	5.09%	8.11%	11.49%
5 mm	Δ_U	0.34%	2.01%	4.41%	7.31%	10.58%	14.16%	17.98%
	Δ_L	0.23%	0.22%	0.44%	2.21%	4.68%	7.65%	10.99%
10 mm	Δ_U	1.85%	1.83%	3.23%	5.93%	9.06%	12.52%	16.25%
	Δ_L	1.85%	1.83%	1.81%	1.79%	3.49%	6.26%	9.46%
15 mm	Δ_U	-	6.47%	6.40%	6.33%	6.47%	9.69%	13.24%
	Δ_L	-	6.47%	6.40%	6.33%	6.25%	6.17%	6.87%
20 mm	Δ_U	-	-	16.27%	16.11%	15.93%	15.75%	15.57%
	Δ_L	-	-	16.27%	16.11%	15.93%	15.75%	15.57%
25 mm	Δ_U	-	-	-	-	34.43%	34.11%	33.77%
	Δ_L	-	-	-	-	34.43%	34.11%	33.77%

The above values should not be applied to real ropes, because the values for the loss of cross-section depend strongly on construction parameters as for example strand diameter, rope and strand lay length.

The values in the above table are - on the first view - astonishing. The loss of cross-section diminishes with increasing value of *b*. This effect is easy to explain. A rope with external wear and the same diameter as a cable without external wear has significantly less internal wear. Because internal wear and external wear both affect all outer wires, but at different positions, they are not additive. Only the larger of both values should be taken into account. As long as internal wear dominates, the loss of cross-section will diminish with increasing *b*, as soon as external wear dominates, the loss of cross-section will increase.