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Tensile Force of Locked Coil Ropes with Broken Profile Wires

Résistance à la traction de câbles clos présentant des ruptures de fils

Zugkraft von verschlossenen Seilen mit gebrochenen Profildrähten

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SUMMARY

The tests were carried out with five differently locked ropes. Adjacent wires of the same cross-section were severed in turn. The re-establishing of the tensile force in a severed wire was observed. Among others, the following statements could be made: The re-establishing of the tensile force in a broken wire remains more or less similar. The practically full tensile force is reached at a distance of 1.5 to 2.5 lay lengths. If an adjacent wire breaks in the same cross-section of the rope, the re-establishing length of both wires is double.

RÉSUMÉ

On a fait des essais sur cinq différents câbles clos. Des fils voisins de la même section du câble ont été perforés l'un après l'autre. On a observé la recroissance de la force de traction dans un fil perforé. Entre autre, les constatations suivantes ont pu être faites: La recroissance de la force de traction dans un fil cassé reste à peu près la même. La force de traction pratiquement complète est atteinte après 1,5 à 2,5 pas de câblage. Si un fil voisin dans la même section du câble est cassé, la longueur de recroissance dans les fils est double.

ZUSAMMENFASSUNG

An fünf verschiedenen, verschlossenen Seilen wurden Versuche durchgeführt, indem man benachbarte Drähte im selben Querschnitt nacheinander durchtrennte. Dabei beobachtete man den Wiederaufbau der Zugkraft im durchtrennten Draht. Es konnten u.a. die folgenden Feststellungen gemacht werden: Die Zunahme der Zugkraft erfolgt in einem gebrochenen Einzeldraht jedesmal etwa gleich. Die praktisch volle Zugkraft wird nach 1,5 bis 2,5 Schlaglängen erreicht. Bricht ein Nachbardraht im selben Querschnitt des Seiles, so verdoppelt sich die Aufbauänge in beiden Drähten.



1. PROBLEM

Wire breaks only mean a local weakening of a rope. As a result of the friction with the adjacent wires, the tensile force in the broken wire re-establishes itself, which means that at a certain distance the wire has again reached its full carrying force. This distance is called the critical length (l_{cr}).

The aim of the present investigation was to collect data regarding the regularity of this force re-establishing also in cases where several adjacent wires are broken. This should make it possible to use the number and distribution of the wire breaks as well as the design data of the structure in order to calculate the weakening of the rope. This is, of course, an important but not the only criteria for the evaluation of the further usability. The chronological increase of the wire breaks [1], the reason of the wire breaks, the danger of springing out of the wires from the cover layer [2], the deformations of the rope, etc., must also be considered.

Theoretical considerations, for example [3], imply that the tensile force in the broken wire (S_g) increases with the distance from the break spot (l) after

$$S_g = k_1 (e^{\mu k_2 l} - 1)$$

while k_1 and k_2 are constants which depend on the construction data and μ is the coefficient of the friction acting between the wires.

When determining the constants and the coefficients of friction, however, one meets with difficulties and therefore depends on measurements.

2. ROPES TESTED

The tests were carried out on the five ropes mentioned in Table 1.

In order to assess the degree of prestressing (elastic deformation) displayed by the shaped wires the ropes to be tested were marked out into sections measuring about five lay lengths and taken apart. The stress-relieved wires were then measured as to rope diameter, length of lay and distortion. The results of these measurements are listed in Table 2.

Rope no.	1	2	3	4	5
Diameter d (mm)	29.0	39.5	32.5	33.0	23.0
Construction	1+5+7+ +13+18 Z	1+6+12+ +18+21 Z	1+6+12+ +18+24+ +25 Z	(3+3) +9+ +15+21+ +21 Z	1+4+8+ +14+23 Z
Length of lay of outer layer λ (mm)	255	333	272	265	235
Effect. breaking force (kN)	760	1560	1010	≈1050	522

Table 1 Main data of ropes used for tests

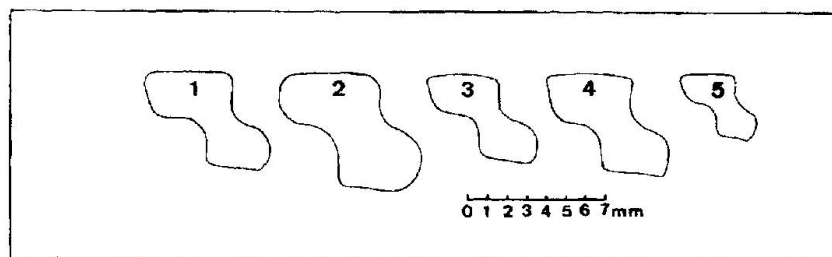


Fig.1 Type and size of shaped wires used in the five tested ropes

Rope no.	1	2	3	4	5
$(\Delta\lambda/\lambda) \cdot 100$	+1.0	+1.8	+2.1	+1.9	+1.9
$(\Delta d/d) \cdot 100$	-7...-14	-11...-14	-6...-15	-10...-14	-7...-17
φ/λ	≈ 0	untwist 22.2°	untwist 8.1°	untwist 19.2°	untwist 8.7°

Table 2 Degree of elastic deformation (prestressing) of Z-wires after removal from unloaded ropes
(λ = lay length, d = rope diam., φ = angle of distortion)

3. METHODS OF MEASUREMENT APPLIED

In the tensioned ropes adjacent wires of the same cross-section of the rope were severed one after the other by means of a carbide tipped drill. During this process the behaviour of the tensile force in the severed wire was observed.

Two different methods were applied in determinating the tensile force of the single wires, namely:

3.1 Strain gauges (rope 1)

Strain gauges were glued on the outer surface of the shaped wires in their longitudinal direction. Circuit wiring and information processing took place in the usual way. The calibration was carried out as follows:

The rope with ends held in cast sockets was put into a tensile testing machine. After ten variations of the rope tensile force between 2 and 40 % of the breaking strength the different measuring bridges were set up and the amplifications were adjusted in such a way that the signals during the change of the rope tensile force were of an equal size for all the measuring bridges. This method is based on the assumption that, in case of central loading of the rope, shaped wire which are intact show the same stress and its change on all the spots but that the single measuring chains (strain gauge, amplifier, galvanometer) show deviations from one to the other.



3.2 Measuring of the wire displacement (ropes 2, 3, 4 and 5)

If sharply defined markings (hairlines) situated across the rope axis are placed on the surface of the rope, the displacement (V) of the broken wire can be read from them with an accuracy of $1/10$ mm.



Fig.2 The displacement of a broken wire can be determined by means of the markings. The picture shows the displacement of two adjacent broken wires at a distance of one lay length from the break spot (test 3, phase b). Attention should be paid to the fact that the displacement of the two wires was of equal size although they had broken one after the other.

Considering the difference of the wire displacement of two adjacent markings (a and b), the contraction of the wire on the stretch in question is

$$\varepsilon = V_a - V_b$$

which is proportional to the decrease of the tensile force in the wire. This means neglecting as a second order effect the fact that, as a result of the wire breaks, the distance between the markings on the intact wires also changes. The calibration is carried out by determining the distances between markings as a function of the tensile force.

Such markings are, of course, also suited for the display of wire breaks which occur in not observable spots on the cover layer of locked coil ropes. This applies, for example, to cast sockets and supporting shoes [4].

4. TESTS CARRIED OUT

The tests were carried out in detail as follows:

Rope no.1

Test 1A: The strain gauges were situated at the following distance from the wire break spot:

- Wire no. "n": 0.1, 0.5, 1, 2, 10, 20 lay lengths
- Wire no. "n + 1": 0.1 lay length
- Wire no. "n + 9": 180° opposite the break spot of the wire "n".

Between the cast sockets the rope measured 30 lay lengths. The break spot was at a distance of 8 lay lengths from the cast socket.

After the calibration described under 3.1 the rope was, step by step:

- a) unloaded $S = 0$
- b) loaded $S = 0.4 \cdot S_B$ (100 %)

- c) unloaded ($S = 0.02 \cdot S_B$); wire "n" spot-drilled at spot "0": tensile force increased till $S = 0.4 \cdot S_B$; the spot-drilled wire "n" broke at $S = 0.17 \cdot S_B$.
- d), e) and f) unloaded once ($S = 0.02 \cdot S_B$) and again loaded with $S = 0.4 \cdot S_B$
- g) unloaded till $S = 0.02 \cdot S_B$; subsequently moved (knocked with a hammer, subjected to the passage of a cross load): tensile force increased to $S = 0.4 \cdot S_B$
- h) twice unloaded and loaded (according to d)

The results are shown in Fig.3 and 4.

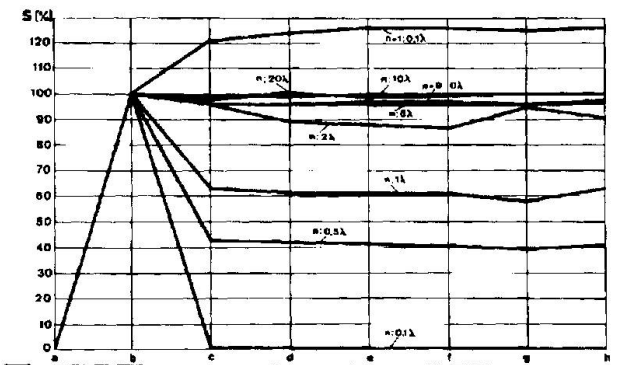


Fig.3 The tensile force in the wires "n"; "n + 1" and "n + 9" during the phases of test 1A. The length indication (λ) gives the distance in lay lengths between the measuring point and the break spot of the wire "n".

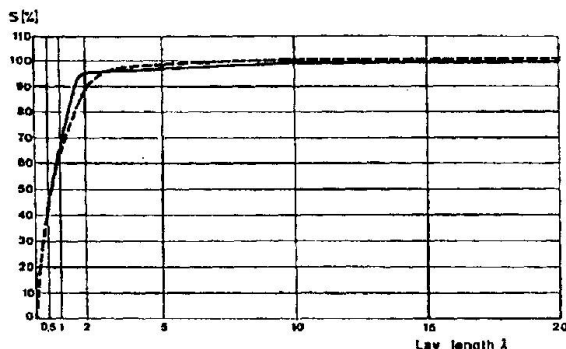


Fig.4 Behaviour of the tensile force in wire "n" after the breaking of the wire (phase c, full line) and after six repeated pulsating loads of the rope (phase h, broken line). It is remarkable that the pulsating load has changed the force behaviour only negligibly.

Test 1B: Like test 1A, but with a concentration of the measuring points near the break spot. The strain gauges were situated:

- on wire "n" at: 0.1, 0.25, 0.5, 0.75, 1.0, 1.5, 2.0, 3.0, 5.0, 8.0 lay lengths
- on wire "n + 9": 180° opposite the break spot of wire "n"

After calibration, step by step,

- a) the rope was unloaded $S = 0$ and loaded by $S = 0.4 \cdot S_B$ (100 %);
- b) the wire "n" was severed at the spot "0";
- c) the rope tensile force was lowered to $S = 0.02 \cdot S_B$ and again increased to $S = 0.4 \cdot S_B$;
- d) the wire "n + 1" was severed at the spot "0";
- e) the wire "n + 2" was severed at the spot "0";
- f) the wire "n + 3" was severed at the spot "0".

The tensile force behaviour of the wires up to phase d was about equal to that in test 1A. Subsequently it became apparent that in such cases where several adjacent wires are broken measuring the tensile force by strain gauge is not possible any more. Besides the tensile force, bending and torsion of the wire also change. The strains caused in this process cannot be separated by strain gauge.

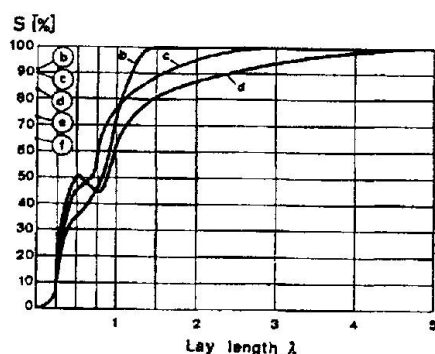


Fig. 5 Test 1B, behaviour of the tensile force in wire "n" after the phases b, c and d. It shows that the tensile force in the wire itself following the break of the adjacent wire is fully re-established after 5 lay lengths. In the break plane the circles are indicating the tensile force in wire "n + 9" (opposite the break spot) after the corresponding test phases.

Test 1C: Like test 1A, but the tensile force was measured on both sides of the break spot. The strain gauges were fixed accordingly:

- On wire "n" on both sides of the break spot at: 0.1, 0.5, 1.0, 2.0 and 4.0 lay lengths.
- On wire "n + 9": 180° opposite the break spot of wire "n".

After calibration, step by step,

- a) the rope was unloaded $S = 0$ and loaded with $S = 0.4 \cdot S_B$ (100 %);
- b) the wire "n" was severed at the spot "0";
- c) the wire "n + 1" was severed at the spot "0". In this process, wire "n-1" which was damaged during the cutting off of wire "n" also broke.
- d) the wire "n + 2" was severed on the spot "0";
- e) the rope tensile force lowered six times to $S = 0.02 \cdot S_B$ and again increased to $S = 0.4 \cdot S_B$. This produced practically no tensile force change in the broken wires.

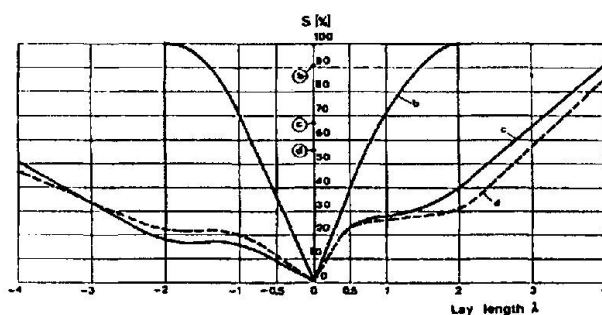


Fig. 6: Test 1C. The tensile force in the cut-off wire "n" is proceeding symmetrically on the left and right side of the break spot. When totally three or four adjacent wires have been cut off (phase c and d), there is no symmetry any more. The circles on the break plane are indicating the tensile force in wire "n + 9" (opposite the break spot) after the corresponding test phases.

Rope no. 2

The cross hairlines according to chapter 3.2 were placed on both sides of the designated break spots at distances of 0.1, 1.0, 2.0, 3.0, 4.0 and 5.0 lay lengths.

Free rope length approx. 800 m.

Rope tensile force = $0.24 \cdot S_B = \text{const.}$

After calibration, step by step,

- a) the wire "n" was severed;
- b) the break spot was subjected to the passage of a carriage with six soft-lined rollers (diameter 80 mm; load 3.0 kN/roller);
- c) the wire "n + 1" was severed and the break spots filled with lead;
- d) the break spots were subjected to four passages of a carriage as mentioned under b);
- e) the break spot was passed over with an engaged track rope brake (see Fig. 8).

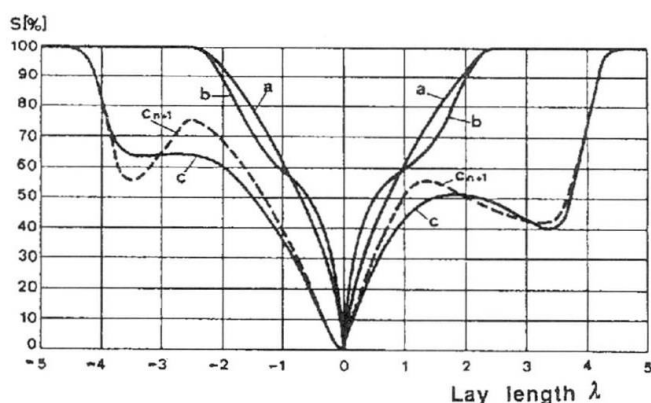


Fig. 7: Rope no.2. Re-establishing of the tensile force in wire "n" on both sides of the break spot: a) after the break of wire "n"; b) after the passage of the rope with rollers and c) after the break of the adjacent wire. The tensile force behaviour in the wire "n + 1" which broke in phase c (broken line) differs only negligibly from that of wire "n".



Fig. 8: The minimal gap between the wires and the lead filling shows that the stress of the two adjacent broken wires has not been relieved because of the passage of loaded rollers (d) and because of a track rope braking (e). Data of the braking: Shoe lining material = multicomponent bronze; shoe length 260 mm; shoe pressure 90 kN.

Rope no.3

The cross hairlines according to chapter 3.2 were placed on both sides of the designated break spot at distances of 0.1, 1.0, 2.0, 3.0, 4.0, 5.0, 6.0 and 7.0 lay lengths.

Free rope length approx. 800 m.

Rope tensile force = $0.30 \cdot S_B = \text{const.}$

After calibration, step by step,

- the wire "n" was severed;
- the wire "n + 1" was severed;
- the break spot was subjected to two passages of the carriage, as described under test 2, point b;
- the wire "n - 1" was severed.

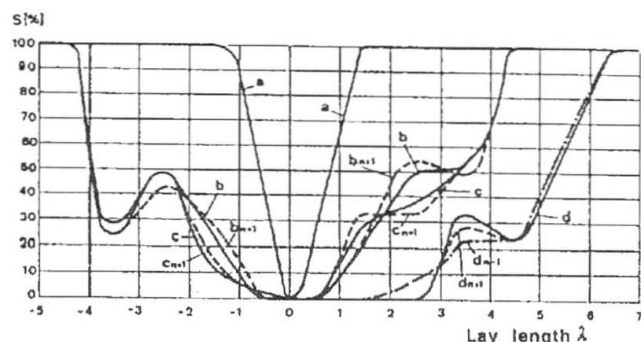


Fig. 9: Rope no.3. Re-establishing of the tensile force in the broken wires with increasing distance from the break spot during the different phases. Again the tensile force behaviour in the adjacent broken wires differs only negligibly from that of wire "n".



Rope no.4

Measuring method and markings like rope no.3.
Free rope length approx. 800 m.
Rope tensile force = $0.29 \cdot S_B = \text{const.}$

After calibration, step by step,

- a) the wire "n" was severed;
- b) the wire "n + 1" was severed;
- c) the wire "n + 2" was severed.

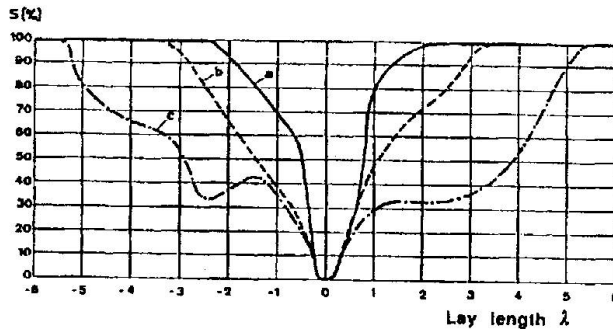


Fig.10: Rope no.4. Re-establishing of the tensile force in wire "n" with increasing distance from the break spot after the cutting off of wire "n" (a), wire "n + 1" (b) and wire "n + 2" (c).

Rope no.5

Cross hairlines according to chapter 3.2 at 0.1 and after each lay length.
Free rope length approx. 32 lay lengths.
Rope tensile force = $0.29 \cdot S_B = \text{const.}$

- a) wire "n" severed
- b) wire "n + 1" severed

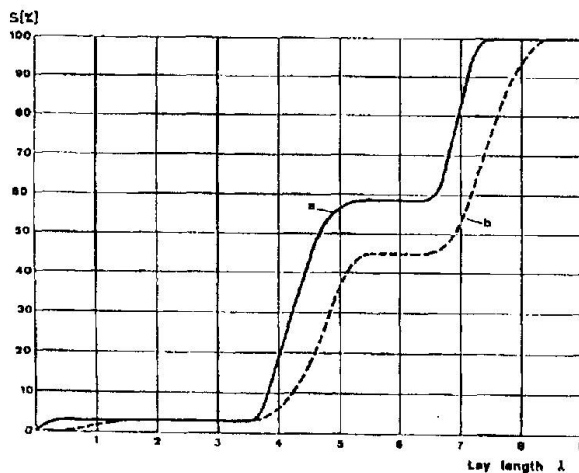


Fig.11: Rope no.5. Re-establishing of the tensile force in the broken wire "n" after its cutting off and after the break of the adjacent wire (b). The fact that the tensile force is only re-established after 8 lay lengths is due to the irregular and loose twisting of the cover layer. From the unloaded rope even a single broken Z-wire could be easily removed.

5. OBSERVATIONS AND CONCLUSIONS

In view of the limited number of findings no generally valid rules can be formulated. However, within the test conditions the following statements may be made:

- In a broken single wire the re-establishing of the tensile force occurs more or less in the same way each time if the cover layer has been firmly twisted. Half of the initial tensile force is reached at a

distance of 0.5 to 0.8, the practically full tensile force after 1.5 to 2.5 lay lengths.

- If the cover layer is loose, as it was the case with rope 5, the critical length can amount to a multiple of the above value.
- If an adjacent wire breaks in the same cross-section of the rope,
 - the re-establishing behaviour of the tensile force in both broken wires is the same.
 - the critical length is doubled and its scattering also increases. Again after exclusion of rope no.5 half of the tensile force was reached after 1 to 4, the full tensile force after 3.5 to 5 lay lengths.
- A rope with wire breaks behaves similarly to a notched homogenous tension bar:
 - In the wire lying near the break spot, the tensile force is increased superproportionally to the decrease of the cross-section.
 - The tensile force is decreased in the wire lying opposite the break spot.

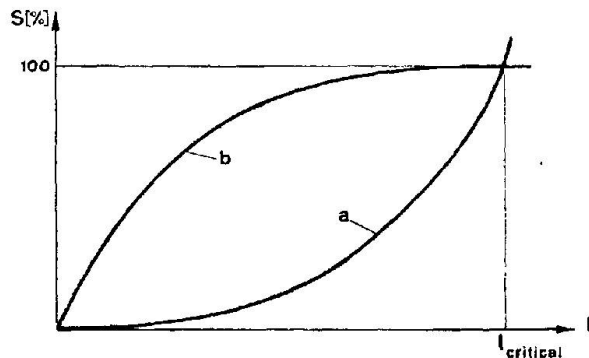


Fig.12: Qualitative behaviour of the re-establishing of tensile force in the broken wire:

- a) expected, neglecting the internal rigidity of the wire;
- b) measured.

- The re-establishing behaviour of the tensile force (S) does not follow, as expected, an exponential curve (a) but rather a saturation curve (b) (Fig.12). This indicates that the re-establishing in the broken wire is not primarily caused by the friction between the wire and the core of the rope (which is due to its spiral-shaped wrapping) but rather by the friction with the adjacent wires caused by the change of form (torsion and bending) which occurred due to the break of the not ideally preformed wire. This means that the internal rigidity of the wire should not be neglected during the theoretical analysis of the problem.

This change of wire form (torsion and bending) is also the reason why the tensile force cannot be measured with strain gauges near the break spot.

- The pulsating bending and tensile stress of the rope but also the track rope braking do not change the tensile force distribution along the broken wire in a significant way. This means that no important increase of the critical length has to be expected during operation.

Practical experience seems to confirm these observations. Gaps of wire breaks have not or have only minimally changed during nine years in the case of five other track ropes in operation. In a double fix anchored track rope where the range of stress amounts to 20 % of the base tensile force a gap grew during these nine years from 20 to 23 mm. These observations should, however, be continued and extended to other ropes.



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