Fatigue and Failure of a Flexed Locked Coil Wire Rope

Fatigue et défaillance de câbles clos soumis à une flexion forcée

Ermüdung und Versagen von verschlossenen Seilen unter erzwungener Wechselbiegung

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SUMMARY
Investigations are currently being carried out on locked coil ropes both in service and in a specially contructed full-scale fatigue testing machine in order to examine the fatigue behaviour of a locked coil rope flexed at a roller chain. This paper describes the results of a part of this investigation.

RÉSUMÉ
Des essais de fatigue sont effectués pour étudier, dans la pratique ainsi qu'à l'aide d'un dispositif spécialemenet construit pour les essais en vraie grandeur, le comportement de câbles clos porteurs passant en flexion sur une chaîne à rouleaux. Ce travail décrit les résultats d'une partie de ces essais.

ZUSAMMENFASSUNG
Es werden Untersuchungen von verschlossenen Tragseilen in der Praxis und in einer speziell dafür konstruierten Prüfmaschine im Maßstab 1:1 durchgeführt, um das Ermüdungsverhalten von verschlossenen Seilen an Rollenketten zu ermitteln. Die vorliegende Arbeit beschreibt die Ergebnisse eines Teiles dieser Untersuchungen.

1. INTRODUCTION

In order to compensate potential load variations of the track rope of a reversible aerial tramway, due to fluctuating ambiance temperature, cabin load and cabin position, a counterweight can be used. In most aerial tramways the track rope is directly deflected to the counterweight over a roller chain. The compensating movement of the counterweight causes a motion of the rope and the roller chain over the deflection saddle.

Over recent years, during regular nondestructive testing, a number of track ropes have been found to have an unexpected degree of damage within the areas subject to alternate stretching and bending at the roller chain.

The calculation of the multicomponental loading of a single wire in a bended steel wire rope is still not satisfactory, which makes a theoretical approach almost impossible. Therefore the Institute of Lightweight Structures and Ropeways of the Swiss Federal Institute of Technology Zurich started carrying out investigations of locked coil track ropes both in service and in a specially constructed full-scale fatigue testing machine in order to answer the following questions:

- how the damage nucleates and develops within the flexed area of the rope;
- whether there is a visible or acoustic indication, reliably warning of a critical amount of damage;
- to what extent the results of Gamma Ray Examination applied in this area are reliable, as well as
- how the fatigue behaviour of the track rope over roller chain is influenced by
  * the rope itself (design & construction, lubrication)
  * the ropeway installation (geometrical parameters of the deflection saddle and roller chain, number and length of the spans)
  * the ropeway operation (trip frequency, cabin load).

2. EXPERIMENTAL PART

2.1 Test equipment (Fig. 1a & 2))

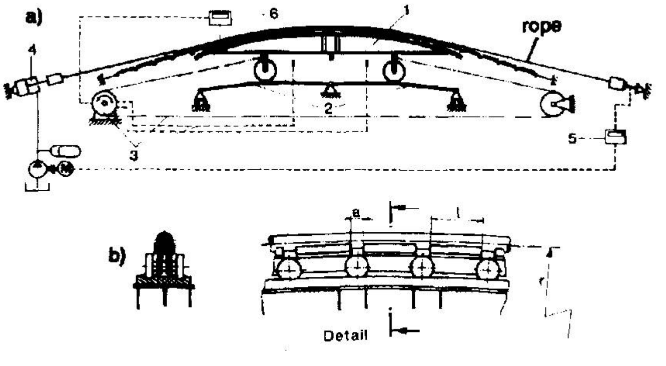

Fig. 1: Layout of the roller chain testing machine.

The testing machine consists of the following parts:

1. Saddle and roller chain (fabricated by the Swiss Ropeways Industry) fixed on a carriage
2. Track (of the carriage)
3. Drive system
4. Tensioning cylinder
5. Automatic control of the tensile force
6. Automatic control of the carriage velocity, influenced by rope temperature.

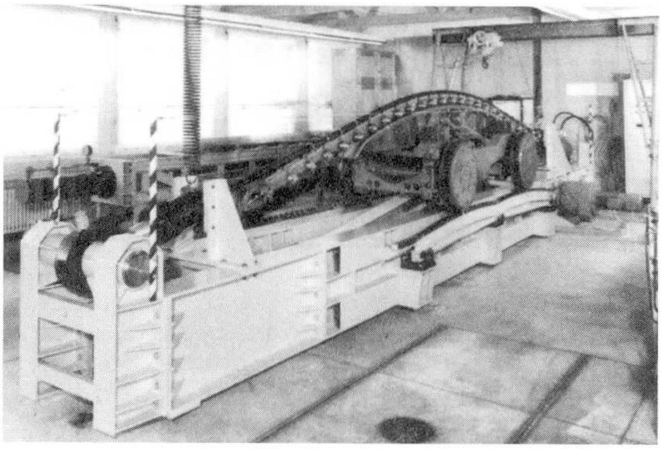

Fig. 2: View of the roller chain testing machine.

It has been designed to test ropes up to a diameter of 55 mm, reproducing the actual stress condition of a locked coil track rope flexed at a roller chain of a reversible tramway.

The rope specimen is bent over the roller chain and tensioned by the hydraulic cylinder. The shape of the carriage tracks has been calculated to invert the movement actually taking place in practice. Thus it is not the roller chain and the rope which roll over the saddle but the saddle which slides under the fixed roller chain and rope.

For the application of additional lubricant, drip oil lubrication was used.

In order to perform the necessary regular NDT it is ensured that the rope can be totally clear of the roller chain along each flexed area under the regular service load.

2.2 Tests

The fatigue tests were conducted using specimens taken from two different ropes:

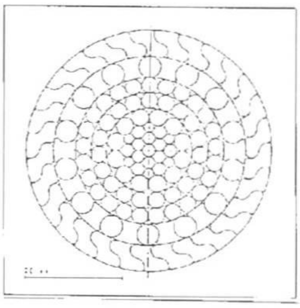

Fig. 3: Rope R_1

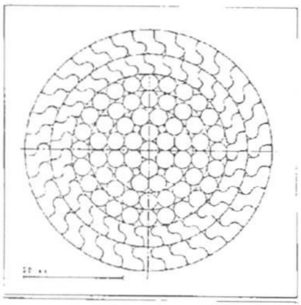

Fig. 4: Rope R_2

R_1: 50.7 mm diameter, 1 1/2 x locked coil rope of 1+6+(6+6)+12+19+25+14I+14x0+30xZ construction and minimum breaking load of 2640 kN (Fig. 3).

R_2: 50 mm diameter, 2 x locked coil rope of 1+(6+6)+12+18+24+31Z+34Z construction and minimum breaking load of 2590 kN (Fig. 4).

The rope specimens have been manufactured with three different initial lubricants (L1, L2 & L3).

Two different saddle/roller chain sets have been tested:

RK_1: radius = 5500 mm (r_1/d = 108.5), link length = 185 mm, link distance = 40 mm, link form = curved ($r_{link} = r_{saddle}$), link lining = Polydur

RK_2: radius = 5000 mm (r_2/d=98.5), link length = 360 mm, link distance = 45 mm, link form = curved ($r_{link} = r_{saddle}$), link lining = Polyacetate

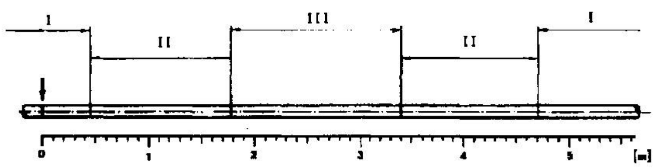

Fig. 5: Areas of the rope specimen
I: constantly stretched area (0 bc)
II: flexed area (n bc)
III: constantly bent area (1 bc)

The length of the flexed area adjusted for the tests comes to 1200 mm (~ 3 x the lay length of the outer layer) and the length of the constantly bent area to 1600 mm (~ 4 x the lay length of the outer layer) (Fig. 5).

A completed test numbered 600'000 bending cycles (bc) and lasted about three months. The frequency of bending cycles chosen ensured that the temperature of the rope surface never exceeded 40°C during the tests.

The development of the number of wire breaks was followed by means of Gamma Ray Examination applied regularly during test life. In order to keep close to practice, the chosen NDT methods as well as the equipment required were those used on tramways for regular examinations. Thus an Ir^{192} source was used throughout all the experiments. After the end of each test the rope specimen was carefully dismantled and the damage found was registered.

Although the reproducibility of wire rope fatigue tests is mostly not high even when using one and the same rope, the tests mentioned here show that in this particular case of locally high resultant stress a high degree of consistancy is possible (Fig. 6).

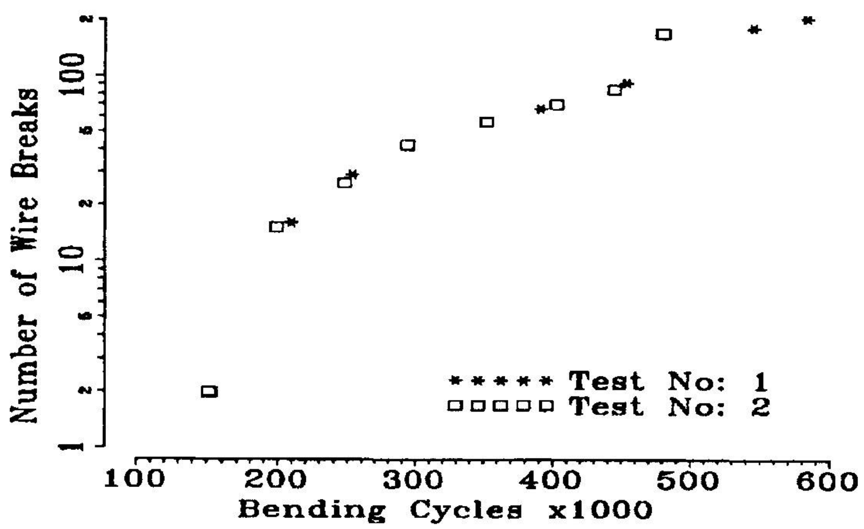

Fig. 6: The development of the number of wire breaks as a function of bending cycles, an example of the good reproducibility.

The plots in figures 6, 10, 11, 12 and 13 show the development of the number of wire breaks as a function of bending cycles. The number of wire breaks is plotted with a logarithmic scale on the Y axis, and the number of cycles is plotted with linear scale on the X axis. The straight lines drawn are an exponential approximation.

During the dismantling of the rope the relative position of the wires in the rope was registered in order to enable reconstruction of the local configuration in the surroundings of the breaks.

The areas of the first cracks as revealed by the Gamma Ray Examination were always of prime interest.

3. RESULTS OF THE TESTS

The first observation to be made is that the damage first starts and propagates in the second layer. The first wire breaks start in the "lower part" (i.e. at the rope side contacting the roller chain links) or/and in the "upper part" of the rope (i.e. the opposite rope side) (Fig. 1b).

Audible crackle emissions starting during an early stage of a test were always very soon followed by the first wire breaks occurring, as well as by a high amount of total damage at the end of a test.

However, the fact that during other tests no crackle emissions could be heard did not mean that no wire breaks occurred later. In those cases the damage started later without reaching a high amount, and the lubricant condition found after terminating the test was constantly better.

After the first breaks have occurred, more wire breaks follow almost in the same cross section. They first remain in the same layer, and they propagate ringwise.

Visible helical distortion - generated during service life - always indicated a concentration of wire breaks within the same area in the second layer.

Wire breaks in the first layer always followed previous advanced damage (i.e. all wires having multiple breaks) within this area in the second layer.

After terminating the test, the rope specimens were dismantled. The found state of the second layer described below was constantly repeated throughout the tests.

Fig. 7: A 60 mm long piece of O-wire (d = 4.5 mm) taken from the second layer, broken five times.

Almost all the wires of the second layer were found to have multiple breaks (Fig. 7), as well as several cracks next to the existing breaks (Fig. 8). An extreme local lack of lubrication within the contact areas of two wires of different layers (Fig. 9), and traces of frictional wear within these areas characterized the damage.

The amount of the fretting corrosion found depended on the quality and quantity of the lubricant used, i.e. in cases of a better lubricant - for this particular application - there was hardly any fretting corrosion to be found, which also resulted in a life improvement.

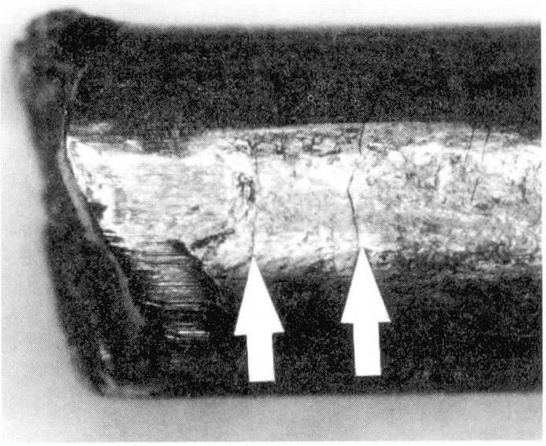

Fig. 8: A piece of an O-wire taken from the second layer with a fatigue break at the left. The arrows indicate the cracks nucleated next to the fatigue break.

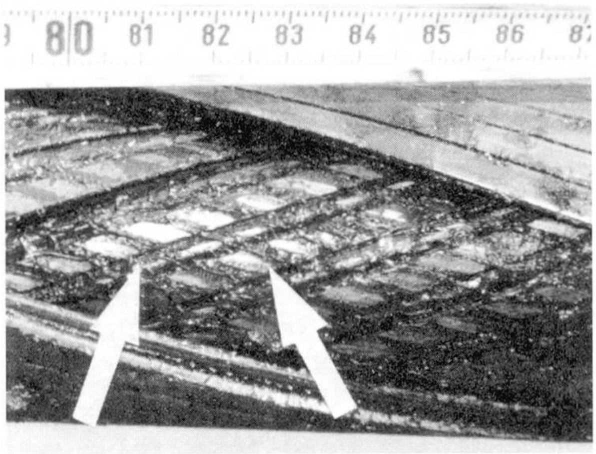

Fig. 9: Picture of the second layer after partly removing the first layer. The arrows indicate the contact areas with the wires of the first layer with visible local lack of lubrication.

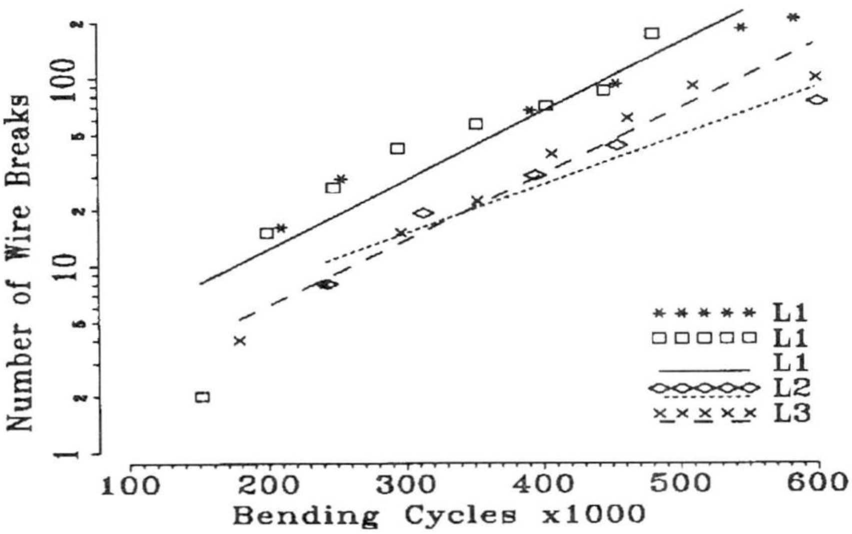

Fig. 10: The development of the number of wire breaks as a function of bending cycles; comparison between three initial lubricants.

Fig. 10 shows the comparison between three initial lubricants. The lubricants L2 and L3 have the same main component, being totally different to L1.

The influence of service relubrication depends on the compatibility with the initial lubricant, as well as on the ability to penetrate at least to the second layer of the locked coil wire rope.

An example is shown in Fig. 11. In this case a life increase of about 40 % has been achieved. Fig. 12 shows that if there is no compatibility between initial and service relubrication no significant improvement can be expected.

The above results show that the choice of the initial lubricant, as well as the application of a proper service relubricant, has significant influence on the fatigue behaviour of the rope under these resultant stress conditions.

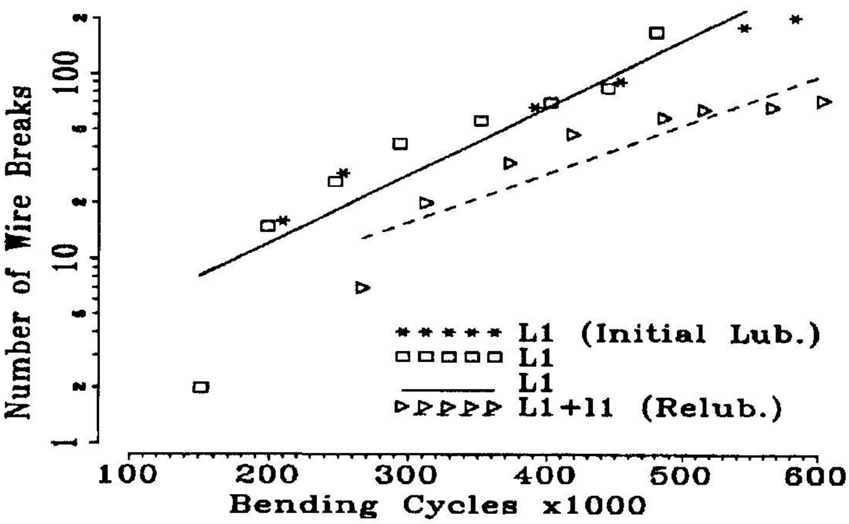

Fig. 11: The development of the number of wire breaks as a function of bending cycles; influence of service relubrication using a relubricant compatible with the initial lubricant.

The life increase due to the lubricant found here has led to the start of a detailed investigation of the influence of this parameter on fatigue behaviour.

The life expectance of the rope construction R_2 (2 x locked coil) was, for this particular application and the ropes tested, almost 80% longer than that of R_1 (1 1/2 x locked coil) (Fig.13).

All the above findings correspond well to the results of the metallographic examinations carried out by the Swiss Federal Laboratories for Materials Testing and Research, according to which, with the exception of some single wires, all the origins of the first cracks were situated within the intensive wear zones (Fig.14), mainly caused by high local pressure. On the other hand the crack propagation is caused by combined bending and torsion and secondarily by tension.

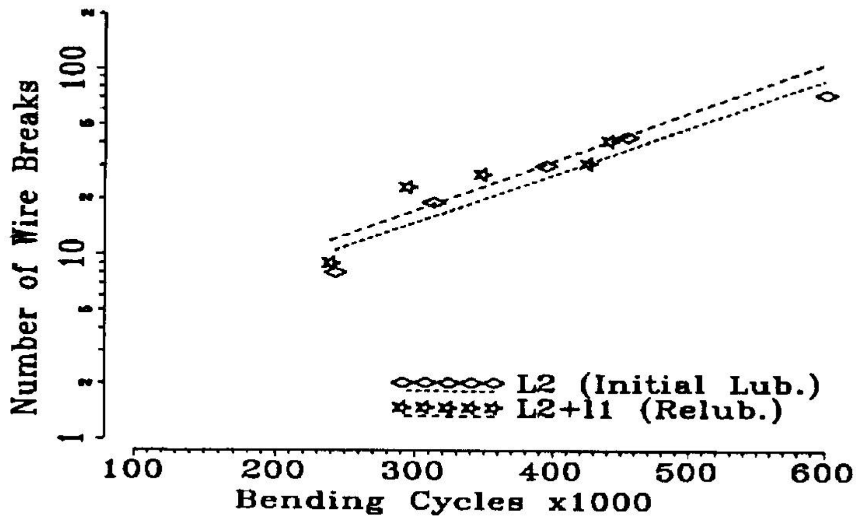

Fig. 12: The development of the number of wire breaks as a function of bending cycles; influence of service relubrication using a relubricant incompatible with the initial lubricant.

Finally the correspondence between the diagnosed (by NDT) sum of wire breaks and the actual figure has been found to be satisfactory. Even in cases of considerable damage, 80% of the wire breaks have been identified. However, the existence of

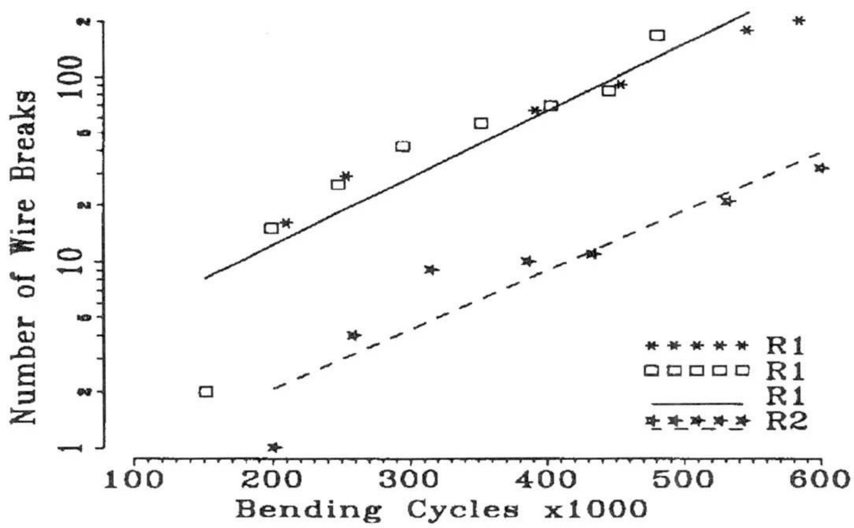

Fig. 13: The development of the number of wire breaks as a function of bending cycles; influence of the rope design and construction.

numerous multiple wire breaks makes the correlation between the diagnosed number of wire breaks and the actual cross section loss practically impossible.

4. CONCLUSIONS

From this part of the investigations the following conclusions can be drawn:

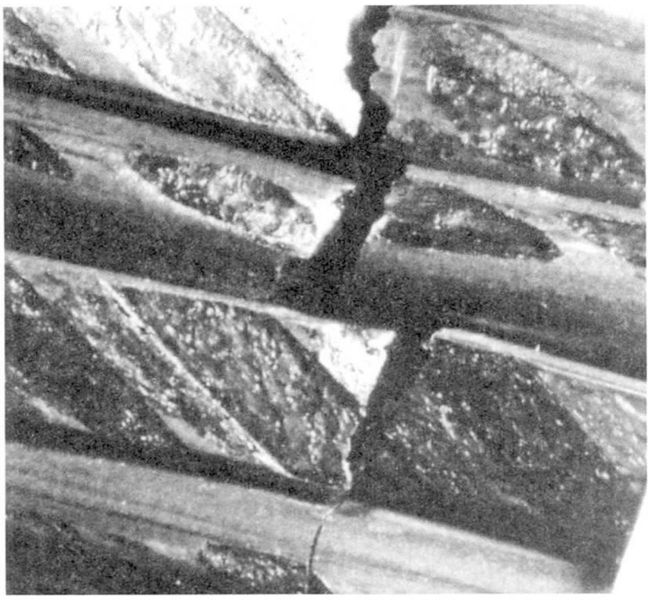

Fig. 14: Almost all the origins of the first cracks were situated within the intensive wear zones.

- The damage starts and first remains in the second layer. When this layer has reached a significant amount of damage, a visible damage in the first layer follows.

- Audible crackle emission indicates approaching damage, and visible helical distortion of the rope surface indicates existing wire breaks.

- The crack initiation in the second layer is a result either of friction wear combined with high pressure or of fretting.

- Improvement of the rope construction and lubrication results in a significant life improvement.

- If the application of Gamma Ray Examination is possible, satisfactory results can be expected for the diagnosed number and location of the wire breaks which occurred.

5. ACKNOWLEDGEMENTS

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6. BIBLIOGRAPHY

CHAPLIN, C.R./ TANTRUM, N.R.H.: The Influence of Wire Break Distribution on Strength. OIPEEC Round Table Conference, Glasgow, June 1985.

CZITARY, E.: Seilschwebebahnen. Springer Verlag, 1962.

KOPANAKIS, G.: -Zum Verhalten von Seilen an Rollenketten Internationale Seilbahn-Rundschau, 1 (1990) -On the Behaviour of Ropes on Roller Chains International Aerial Lift Revue, 1 (1991).

KOPANAKIS,G.: Fatigue Behaviour of Locked Coil Ropes over Roller Chains. OIPEEC Technical Meeting "Safety, Acceptance and Discard of Ropes, Nantes, October 1991.

LEIDER, M.: Die Bestimmung der Zusatzspannungen bei der Biegung von Drahtseilen und ihr Einfluss auf die Seillebensdauer. Diss. TH-Karlsruhe, 1975.

LUETHY, Th./ BLASER, E.: Radiographic Examination of Steel Wire Ropes. OIPEEC Round Table Conference, Zurich, September 1989.

OPLATKA, G.: Nachschmierung von Drahtseilen. Draht 8 (1985).

WOODTLI-Folprecht, J./ FICHTER, R.: Fraktographie von Brüchen an Seildrähten aus Stahl.
- Draht 5 (1975)
- Il Filo Metallico 3 (1976)
- Alambre 1 (1976)
- Le Tréfilé 2 (1976)

WOODTLI, J. / KOPANAKIS, G.: Fractographical Evaluation of Fatigue Damage in Locked Coil Ropes. Fourth International Conference on Structural Failure, Product Liability and Technical Insurance, Vienna (A), July, 1992.