Analysis of fatigue mechanism in locked coil wire ropes by means of fractography

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Summary

A fracture area in a locked coil wire rope can deliver important information which can be used for the selection of a corrective measure. Besides the knowledge in interpretation of fractographic and metallographic findings, a careful performance of the failure analysis is needed in order to obtain the maximal information.
Based on the results of failure analyses full-scale fatigue tests were performed to simulate deterioration of the flexed and overrolled rope areas. Fractographic and metallographical investigations revealed the mechanism of crack nucleation and propagation. Typical findings are described and corrective measures are recommended.

Keywords

Locked coil wire ropes, crack initiation, crack propagation, fretting fatigue, abrasive wear, Hertzian pressure, lubrication, mechanical (impact) damage, fractography, metallography, white etching areas, adiabatic shear bands

Introduction

In aerial tramways the track ropes used are deflected over a roller chain in the lower terminal station. Fatigue damage within the lower flexed rope area determines the life time of the whole rope. For this reason a spare length of rope is stored in the upper terminal, wound over a drum. When the damage within the flexed, lower area reached the state demanding descharge, part of the rope is cut away and shift. Thus the spare rope, stored in the upper station, is a part of the loaded track and is overrolled in service. Damage due to inappropriate mounting and service within this area can become critical.

Over recent years, during regular nondestructive testing (Lüthi, Blaser) as well as during visual inspections numerous wire breaks and surface impact damage were found. Based on the results of failure analyses a program for simulated fatigue tests was set up which examined fatigue behaviour of the ropes (Kopanakis, 1991). The aim of the experiments was to clarify the fatigue behaviour in both critical parts of the ropes: within the critical flexed area in the lower part as well as the influence of artificially introduced impact damage in the upper part (Hellwig, Vaclavik).

It is obvious, that the fatigue loading spectrum within the flexed area, as well as within the overrolled area, is very complex and consists of tensional, bending, torsional, and compressive components. In addition there is the influence of corrosion, abrasion and adhesion. The numerical solutions for the determination of the dominant mechanism caused by such multi-componental loading in a single wire are still not satisfactory, and hence a theoretical approach is almost impossible. Since the fracture surface and its near area is a detailed record of the damage history, an attempt has been undertaken to determine the significant loading components by means of a fractographic and metallographic approach.

Material and tests

The fatigue experiments were conducted in the Institute of Lightweight Structures and Ropeways of the Swiss Federal Institute of Technology, Zürich (Kopanakis, Vaclavik).

a) Service deterioration of the flexed area over the roller chain

The specimens were taken from a 50.7mm diameter, 1 1/2 locked coil rope of 1+6+(6+6)+12+19+25+14 I +14 O +30 Z construction and minimum breaking load of 2 640 kN (Fig 1). The rope specimen was bent over the roller chain and tensioned by the hydraulic cylinder. The saddle, which slides under the fixed roller chain simulates the movement actually taking place in practice during the compensating movement of the counterweight. The data of the tests conducted are described in detail in Kopanakis, 1991. A completed test numbered approx. 600'000 bending load cycles and lasted about three months. The propagation of the fatigue breaks in single wires was followed by means of γ-ray examinations applied regularly during the test. After 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 surrounding of the breaks. The area of the first cracks as revealed by the γ-ray examination were always of prime interest.

b) Influence of predamaged surface on the fatigue life under overrolling

On the surface of the locked coil rope with 23mm diameter of 1+6+12+17 Z construction and minimum breaking load of 535 kN well defined forms of damage were introduced. The damage consisted of indententions which were made by impact using a hammer (fast loading), a roller (slow loading) and a file (removing of material). Their orientation was transverse to the rope's longitudinal axis. The impact indentations were introduced under tension (153 kN) and in an unloaded rope. The impact damage which was made on the pulley side of the rope was overrolled during the fatigue test and the indentations on the opposite side were never in contact with the pulley. In addition to these specimens, a restored rope was tested. The restoration consisted iof removing the displaced material around an impact zone by grinding with a wheel. Another approach was the regular relubrication of the zone which suffered the impact.

The rope specimen (length: 4'400mm) was loaded with a constant tensioning force.The middle part of the rope over a length of 610mm was overrolled with a pulley. In this way forced bending was introduced.

Results

a) Flexed area over the roller chain

The fatigue damage started in the 2nd layer.After the 1st layer was dismantled it was established that the sites with the breaks showed lack of lubricant locally.

In all ropes investigated the cracks and breaks within the second layer were clustered together (s. Fig.2). Two configurations dominated: either in a circumferential direction (around the cross-section) or in a helical direction (along the contact line of the superimposed wire of the first layer).

With few exceptions, the breaks appeared within the intensive wear zones. Typical for the 1 1/2x locked coil wire ropes were crack origins in the "I" wires on the surface facing the first layer, whereas the "O" wires showed crack origins mostly on the interface with the adjacent "I" wire (Fig. 4). The contact zones between "I" and "O" wires showed the typical structure of fluctuating compressive loading (s. Fig. 5). The hammered-like surface topography can be attributed to contact fretting with small lateral amplitude. On the other hand the contact areas with the "I" wires and "Z" wires e.g. between the 1st and 2nd layer showed distinct wear traces as typical feature of abrasive wear, as revealed in Fig. 6.

A detailed metallographic investigation was carried out on numerous longitudinal sections which were taken both from the prime fracture regions and neighbouring contact areas. An examination of these sections revealed formation of white etching areas in the subsurface region prior to fatigue cracks. Within the contact zones of the "O" wires the formation of white etching areas predominantly appeared along the shear planes as shown in Fig.7. The crack origin sites in the "I" and "Z" wires from the second layer showed a severely worn surface as a result of frictional wear which was also accompanied by the creation of white etching areas. The typically rounded shape of the layer of white etching areas in an "I" wire is shown in Fig. 8.

A further aim of the fractographic investigation was the evaluation of the fracture features, such as beach marks, steps, and shearlips. In the case of "O" profile wires, the results indicated the direction and the mode of loading (Woodtli,1975, 1995). Based on the curvature of the beach marks on the fracture surface it was found, that bending and torsion were definitely the driving forces behind crack propagation.

The first layer of these ropes suffered fatigue cracks with origins on the rope surface and not, as presupposed, on the interface with the second layer. Since the fatigue cracks in the first layer are a consequence of the breaks in the second layer they are of less importance for these experiments.

b) Overrolled rope with mechanical damage

The indentations made by a file did not influence the service life of the wires significantly. On contrary, the indentations made by hammer or roller caused a severe reduction of the fatigue life. Some wires showed only 30% of the original service life. No significant differences could be observed between indentations made by a hammer and those made by a roller. Nevertheless, the reduction of fatigue life was more profound with indentation made on an unloaded rope. Of great importance was the location of the indentation with respect to the pulley: the indentation towards the pulley side suffered r fatigue damage earlier than that on the opposite side.

The fractographic investigation of the fatigue fractures in the Z-wires showed, that the crack initiation took place predominantly sideways to the damaged zones at the contact with the neighbouring wire in the same layer. In these zones displaced material from the indentation was pressed against the neighbouring wire. In some wires the crack initiation took place at the interface with the wire from the second layer which was altered by the impact. As Fig. 9 reveals, there was always a remarkable fretting scar which was promoted by the material displacement caused by the plastic flow near the indentation area. The indentations made by a file did not cause any material displacement by plastic flow. Therefore no reduction of service life was caused by the these indentations.

To avoid the intensive fretting in the vicinity of the damaged zones, the displaced material was totally removed by grinding prior to the fatigue test. Since the thickness of the grinding disc was greater than the space between the wires, the restored wires suffered a reduction in cross-section. Such reduction in combination with local notch (grinding slot) caused a reduction in fatigue life. A deeper grinding slot led to a reduced service life due to early crack initiation by enhanced local stress.

Another palliative approach was the use of regular local relubrication within the area, where the lubricant was squeezed out. This measure was very succesfull since the initiation of fatigue was significantly delayed.

Discussion

Based on the microscopic features as revealed by the fractography and metallography, it can be said that the dominating damage mechanism in all wires is the fretting. Within the areas where fretting took place, fatigue cracks were initiated. Thus the deterioration of the locked coil wire ropes is caused by **fretting fatigue**.

Fretting fatigue occurs when a pair of structural elements are in contact and cyclic stress and relative displacement are forced along the surface. Under the fretting conditions the fatigue strength decrease, as shown by following empirical formula (Nishioka, Hirakawa):

$$\sigma_{ff} = \sigma_n - 2\mu P \{1-\exp\frac{s}{k})\}$$

where σ_{ff} and σ_n are fatigue life under fretting fatigue and normal fatigue life
μ is the friction coefficient
P is the max. contact pressure
s is the slip amplitude
k is a constant for the material.

Considering all parameters, only the coefficient of friction and maximal contact pressure could be effectivelly controlled in the locked coil wire ropes. All above findings correspond well with this consideration. The relubrication showed a significant life improvement also in critical zones of indentations, which simulated local damages due to impact.

The influence of maximal contact pressure is a highly significant aspect of fretting fatigue in tested ropes. The results presented clearly show that the geometrical irregularities in the rope construction lead to slight displacemnt of single wires which create cluster concentration of crack nuclei. In this way the helical distribution of crack clusters beneath one wire was created. On the one hand, these displacements are caused by local deviation of the tolerances with respect to the cross-section or lay length which originated during production, and on the other hand they are a consequence of the wire breaks and the relaxation of the elastic internal stresses in the rope caused by displacement and re-alignment of the rope structure (Kopanakis, 1993).

On the microscopic level two relevant fretting mechanism were identified. Severely worn surface-areas with traces of sliding are typical of **friction wear.** The microstructure of the metallographic sections shows cold worked areas with local, irregularly distributed white etching areas. Such microscopic changes strongly influence the local mechanical properties and are responsible for the nucleation of fatigue cracks. This mode of damage was primarily found at the interface of the second and first layers of "I" wires. This frictional wear is a result of mainly axial relative motion of the superimposed layer during the bending of the ropes under tension. The intensity of this wear damage was locally enhanced due to the helical misfit of single wires (described above), which caused reduction of the contact area.

On the other hand, the fatigue nucleation in the "O" wires shows typical features of **fluctuating compression** loading with small lateral displacements. The hammered-like surface and transformation of the microstructure along slip planes into white etching areas in sub-surface zones (adiabatic shear bands) are typical for oscillating Hertzian stress with high vertical compressive component.

Regarding the 1st layer of the upper part of the rope, the indentations made by a file did not cause any material displacement by a plastic flow. Therefore no reduction of service life was caused by this damage. This reveals clearly that the reduction of the wire cross section as well as the local notch effect is negligible compared to the influence of fretting fatigue.

Conclusions

- - Deterioration of service life in locked coil wire ropes is caused by fretting fatigue.

- - The crack initiation period can be retarded by reduction of coefficient of friction through relubrication and through reduction of Hertzian stresses either by improved construction or adjustment when in service.

- - Unfavourable effect of impact damage in outer wires could be overcome by regular relubrication.

- - The propagation of fatigue cracks can be decelerated by reducing the local bending stress.

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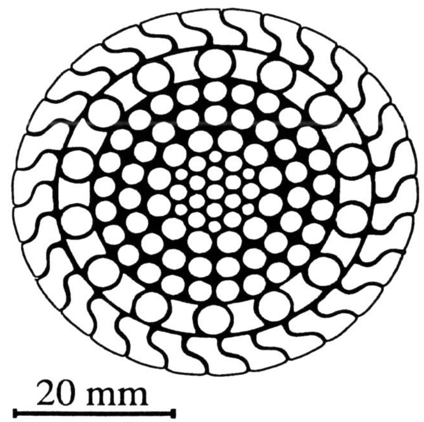

Fig. 1 Cross section of the 1 1/2 locked coil wire rope.

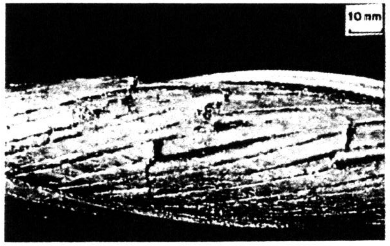

Fig 2. Partly dismantled rope. View of the second layer with clustered cracks.

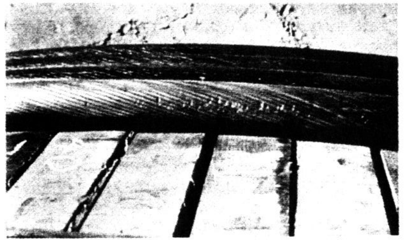

Fig 3. Damage due to hammering on the surface of the locked coil wire rope.

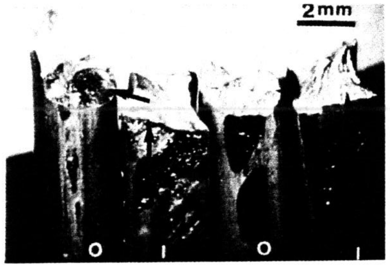

Fig. 4 Breaks in the 2nd layer. Arrows indicate crack origins.

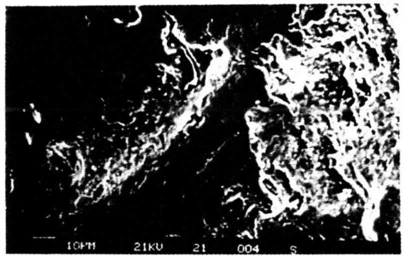

Fig.5 "O"-wire. Microscopic surface structure typical for fluctuating compressive loading.

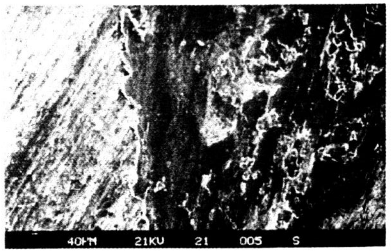

Fig. 6 "I"-wire. Microscopic surface structure typical for abrasive wear.

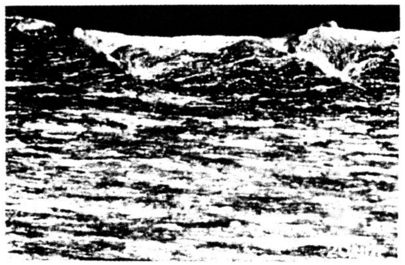

Fig. 7 "O"-wire: White etching areas, adiabatic shear bands. Longitudinal section.

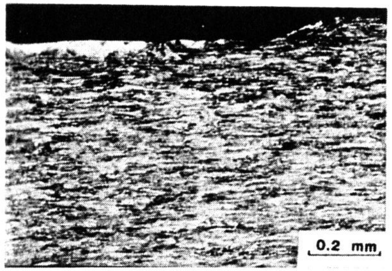

Fig. 8 "I"-wire: White etching areas within abrasive scar. Longitudinal section.

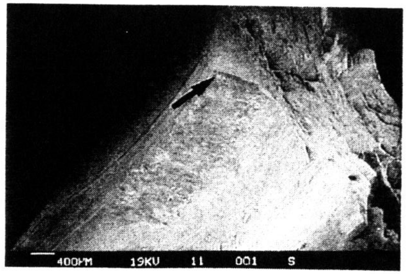

Fig. 9 SEM-micrograph of a broken wire with fretting scar at the side of the indentation. Crack origin at fretting scar (arrowed).