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Failure analysis of a ropeway accident focussing on the wire rope's fracture load under lateral pressure

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Abstract

The bi-cable reversible aerial ropeway had been built as a winch system exclusively for goods transport. During upwards transport the winch was brusquely stopped by the operator. This caused the winch rope to slack and eventually to fracture at the moment of the jerky stretching by the backward rolling carriage. The brakeless carriage sped downhill along the track rope and finally crashed into the lower station leading to the unfortunate death of the farmer sitting unlawfully in the carriage. The steel wire rope ($\varnothing 6$ mm, type 6 x 7-FC) showed no indication of the typical failure mechanism of moving ropes, i.e. fretting fatigue. The single wires were broken in almost the same cross section showing a mixture of conical and shear fractures. This unusual fracture pattern could have been either the consequence of a local pre-damage or of an excessive lateral pressure and bending at the cross point of two windings on the winch. The latter alternative was evaluated by a test setup, allowing continuous increase of the deflection angle β until fracture of the rope.

As a rule of thumb for $\beta < 25^\circ$, the deflection angle in degree is numerically roughly equal to the caused load capacity reduction of the rope in percentage, e.g. a deflection angle of 10° reduces the load capacity by approximately 10%. Based on this empiric relationship, along with the calculated critical back-roll velocity of the carriage, it could be proven that the jerkily stretched rope could have fractured without being necessarily pre-damaged.

The quantified susceptibility of the rope's ultimate load to lateral pressure at sharp bending can also support future investigations of similar failure cases and risk analyses.

Highlights

- The failure analysis of a fatal ropeway accident is presented.
- The failure mechanism of the winch rope was not typical: fast fracture but not fretting fatigue.
- The residual fracture load of the wire rope under lateral pressure due to sharp bending was quantified experimentally.
- For the investigated rope type, the deflection angle in degree and the resulting load capacity reduction in percentage are roughly equal numerically.
- The dynamic load peak in the jerkily stretched rope was calculated.
- The most likely sequence of the accident was reconstructed.

1 Introduction

Statistically, areal ropeways are one of the safest transportation systems [1, 2]. In particular, rope fractures rarely occur, thanks to a high level of inherent redundancy provided by its construction, made up of stranded single wires [3]. The condition of the rope is monitored periodically with regards to wear and fatigue thus allowing the rope to be replaced before the residual load capacity would become critical [4]. With this background, the ropeway accident in focus of the present paper, caused by fast fracture of a winch rope, is peculiar.

The bi-cable reversible aerial ropeway was built in the 1970s as a winch system exclusively for goods transport (Fig. 1). The drive unit of the winch, consisting of a diesel engine, a gear transmission and a shoe brake, was located in the upper station and was operated by mechanical handles without an electrical control system. The carriage rolled between the upper and lower stations along the 1 km long stationary track rope which was supported by 3 pillars. During uphill transport, the winch rope pulled the carriage up with a velocity of up to 3 m/s. During downhill transport, the carriage was driven solely by gravity, while the winch rope acted only as a speed regulator, transmitting the braking force from the drive unit to the carriage. In accordance to the more lenient regulations for freight ropeways [5] compared to ropeways for human transport [6], the carriage was not equipped with an emergency brake [7].

Fig. 1: Upper station of the ropeway with superimposed sketch

Before the accident, a farmer loaded the carriage in the lower station and unlawfully also sat in it. He instructed the operator of the winch by cell phone to pull up the carriage. As the carriage passed the last pillar, the operator was shocked to spot his colleague in the carriage and brusquely stopped the winch. The carriage rolled out due to the inertia forces almost touching the upper station, thereby causing a slack in the winch rope (Supp. 1). The carriage came to a stop. Then, the downhill force accelerated the carriage in the opposite direction. According to witnesses, after a backward rolling distance of the carriage by roughly 1 m the rope stretched again and in that moment it fractured. The brakeless carriage sped downwards along the track rope still carrying the farmer and eventually crashed into the lower station leading to his death.

Undoubtedly, the fracture was triggered by the dynamic load peak due to the inertial force of the backwards rolling carriage. However, it was crucial to clarify if additional negative factors, like a pre-damage of the rope or an additional extraordinary load significantly favoured the fracture.

2 Preliminary investigations

2.1 Fundamentals

For legal reasons, the judge ordered the failure analysis only two years after the accident. By that time the ropeway was fully replaced by a new one, therefore an onsite inspection was not possible. The only available fundamentals for the failure analysis were, besides court records, two sections of the winch rope; each with one fractured end, labelled by the police to be both sides of the same fracture (Fig. 2). In the present paper, these two rope sections and their fracture brushes are referred to as follows:

- W: winch side (uphill) section. This sample with an arbitrarily predefined cut length of 4 m was wrapped up from the winch by the police.
- C: carriage side (downhill) section. The un-fractured end of this rope section was directly attached to the crashed carriage. Therefore, the length of this remnant section (0.7 m) corresponds to the distance of the fracture from the carriage.

Fig. 2: Winch rope sections W and C with fracture brushes (circles). See also Supp. 3.

2.2 Macroscopic findings

The winch rope in common cross lay design has a nominal diameter of 6 mm (Fig. 3). The 6 strands are made up of 7 carbon steel wires each and are wrapped around a fibre core (e.g. design type: 6x7-FC).

Fig. 3: Cross section and surface of the winch rope

The guaranteed fracture load for the nominal strength of the wires (grade) of 1960 MPa is $F_g = 23.4$ kN [8]. The main visual findings of the rope segments are summarised below:

- **Surface:** The surface of the rope sequences was significantly corroded and showed mechanical wear (Fig. 3), not surprising after 20 years of open air service. Although the maximum diameter shrinkage of 13.6% was already at borderline [9], no fractured wires were detectable besides the fractured brushes.
- **Fixation:** The low-grade fixation of the winch rope to the carriage, including mirror inverted mounted rope clamps, survived the accident without fracture of any wires. This means that the stress conditions for the rope at the fractured cross section had to be even worse than at the fixation (“weakest link”).
- **Fracture brushes:** The fracture brushes are compact. In the case of an overload fracture of an intact or uniformly weakened rope, the fracture brushes would be significantly longer and more spread out with larger differences in the length of the fractured wires and strands.
- **Single wire fractures:** A part of the single wires show conical fracture geometry (Fig. 4/a), which is a characteristic of predominant tension overload of ductile wires. Many wires, however, show shear fracture (Fig. 4/b), which has originated from lateral pressure prior to or during the fracture [10].

a) conical fractures in brush W

b) shear fractures with surrounding indentations in brush C

Fig. 4: Dominant fracture types of the wires in the brushes C and W

In general, the visual findings point against the typical failure mechanism of a winch rope due to fatigue or fretting [4, 11-13], but towards an overload fast fracture under local effects. Essentially, two different kinds of local effects come into consideration: either a mechanical pre-damage of the rope or an extra stress on the rope superimposed on the regular tensile stress. In the focus of the subsequent investigation was the question: which of these two possible local effects favoured the fracture.

The only place where extra stress could have acted on the rope at the moment of the fracture was on the winch. In fact, the slack in the rope caused the outer winding on the winch to cross each other (Fig. 5), representing a potential area for excessive lateral pressure due to sharp bending. But the rope section C of a length of 0.7 m is too short to have reached the winch at the moment of the fracture (Fig. 1). Therefore, by excluding the option of extra stress, a pre-damage of the rope seemed to be evident.

Fig. 5: Winch without wrapping mechanism. Detail: crossing rope windings. (photo of the police)

However, this preliminary conclusion turned out wrong, as a closer view to the fractured brushes revealed that they did not match and complement each other:

- Two strands of the brush W are roughly 5 cm shorter than the others without two matching longer strands in the brush C (Fig. 2).
- The portion of wires with shear fracture in the brush C is significantly higher than in the brush W ($\approx 2/3$ vs. $\approx 2/5$).

Consequently, the winch rope had fractured twice and there is a missing section between the fracture brushes C and W. The primary fracture must have occurred at the brush W: Otherwise the missing rope section would have remained at the upper station and most probably been spotted there by the police. Furthermore, there is no plausible explanation for a subsequent force increase in the winch side rope fragment, which would be a physical precondition for a second fracture.

The fracture W was by the unknown length of the missing section closer to the winch than the fracture C. Indeed, as the length of the missing rope section is unknown, it is even possible that the fracture W occurred on the winch. Therefore, the previously made conclusion of excluding local extra stresses turned out to be wrong.

3 Main investigations

3.1 Overview

The goal of further investigations was to check the plausibility of the following hypothesis: *The first fracture occurred on the winch at an intact cross section of the rope.* For the plausibility of this hypothesis two main preconditions have to be fulfilled:

- **Precondition “force peak”:** The dynamic force due to the jerky tightening of the slack rope could have been large enough to trigger the fracture.
- **Precondition “weakest link”:** The weakening of the rope on the winch could have been worse than at the fixation to the carriage.

In order to check these two preconditions, firstly tension tests were carried out on three rope samples, one of them enclosing the fixation to the carriage. Then, based on the obtained fracture loads and the elastic characteristic of the rope, the critical roll back speed for rupture of the rope was calculated. Finally, the load capacity reduction of the rope at a crossing point of two windings on the winch was experimentally investigated.

3.2 Tension tests of the winch rope

The number of samples was limited due to the short length of the obtained rope sections. From the section W, two regular samples were tested according to [9]. The only sample from section C included the fixation to the carriage. For smooth load applications, all cut rope ends were equipped with cast head. The tension tests were performed in a universal testing machine Zwick type 1484 (Zwick GmbH & Co, Germany), equipped with a 200 kN load cell.

The two regular samples fractured at nearly identical tension force, by 13% below the guaranteed ultimate load for new condition (Fig. 6). Almost all wires showed conical cup fracture. The third sample with the fixation failed at the clamp, around 20% below the ultimate load of the regular samples. The corresponding ultimate load of $F_c = 16.3$ kN represents the highest possible tension force in the rope during the entire accident.

Fig. 6: Ultimate load of the samples (left) and tested samples (right). A and B: regular samples, C: sample enclosing the fixation

Based on the force-elongation diagrams of the regular samples (Supp. 2), the elongation is approximately linear up to $F = 17$ kN, with a stiffness coefficient of $k = 1.25$ mm / kN·m. This rope parameter is a required input in the calculation of the dynamic peak force (Sec. 3.3)

3.3 Estimation of the critical roll back speed

In order to clear whether the rope could have been overloaded by the inertial force of the backwards rolling carriage, the energy balance approach [14, 15] was used. By sudden stretching of the slacked rope, the kinetic energy of the backwards rolled carriage E_c was converted primarily into elastic energy of the winch rope (E_w) and of track rope (E_T). An overload fracture was possible if the kinetic energy of the carriage could have exceeded the summarised energy absorption capacity of both ropes:

$$E_w > E_{w,max} + E_{T,max} \quad (1)$$

The following calculation of the critical roll back velocity of the carriage is based on the conservative assumption that the fracture occurred by chance just slightly below the level of the measured failure load of the fixation (F_c). A larger tension force can be excluded as the rope was not damaged at the fixation after the accident. The corresponding upper limit of energy absorption capacity of the stretched winch rope segment between the winch and the carriage until fracture is given by the following equation:

$$E_w = \frac{k \cdot L \cdot F_c^2}{2} = 365 \text{ J} \quad (2)$$

- $k = 1.25 \frac{\text{mm}}{\text{kN} \cdot \text{m}}$: elastic modulus of the winch rope according to Sec. 3.2
- $L = 2.2$ m: length of the jerkily stretched rope segment between the winch and the carriage, rather overestimated based on Fig. 1
- $F_c = 16.3$ kN: upper limit of tension force until fracture according to Sec. 3.2

For the conservative estimation of the energy absorbed from the track rope, the carriage is assumed to be in the middle of the field between the pillar and the upper station (Fig. 7).

P1: Position of the carriage at stop of the winch

P2: Position of the carriage at the jerky stretch of the winch rope

Fig. 7: Sketch of the underlying model for calculation of the energy absorption capacity of the track rope

The normal component of the winch rope force $F_{c,n}$ on the chord of the track rope can be calculated as:

$$F_{c,n} = F_c \cdot \sin(\varepsilon) = 8.15 \text{ kN} \quad (3)$$

- $F_c = 16.3 \text{ kN}$: upper limit of tension force until fracture of $F_c = 16.3 \text{ kN}$ (Sec. 3.2)
- $\varepsilon = 30^\circ$: angle between the track rope and the winch rope, estimated based on Fig. 1

The corresponding vertical movement of the carriage due to the increased sag of the track rope, superimposed on its position just before the stop of the winch, can be estimated as follows:

$$\Delta u \approx \frac{f \cdot (F_{c,n} - F_{reg,n})}{4 \cdot F_T} = \frac{f \cdot (F_{c,n} - m \cdot g \cdot \sin(\alpha) / \cos(\varepsilon))}{4 \cdot F_T} = 0.144 \text{ m} \quad (4)$$

- $F_{reg,n}$: normal component of the regular pull force of the winch rope to the track rope (neglected drag force)
- $F_T = 79 \text{ kN}$: approximately constant tension force in the track rope ($\varnothing 22 \text{ mm}$), based of its ultimate load of 315 kN [16] and an estimated safety factor of the track rope of 4, based on [5, 17]
- $\alpha = 16^\circ$: slope of the track rope at the carriage, estimated based on Fig. 1
- $f = 6.3 \text{ m}$: length of the track rope field, estimated based on Fig. 1
- $m = 300 \text{ kg}$: estimated total mass of the fully loaded carriage

The corresponding energy absorbed in the track rope until the fracture of the winch rope amounts to:

$$E_T \cong \Delta u \cdot \left(\frac{F_{c,n}}{2} - m \cdot g \cdot \cos(\alpha) \right) \cong 180 \text{ J} \quad (5)$$

The critical roll-back velocity of the carriage to fracture the rope is:

$$v_{crit} \cong \sqrt{2 \cdot \frac{E_{W,max} + E_{T,max}}{m}} = \sqrt{2 \cdot \frac{545 \text{ J}}{300 \text{ kg}}} = 1.91 \frac{\text{m}}{\text{s}} \quad (6)$$

This result is discussed in Sec. 4.

3.4 Sensitivity analysis of the rope's ultimate load on lateral pressure

The published investigations on moving ropes under bending are focussed on the most common failure mechanism, fretting fatigue [11-13, 18]. According to the experimental study of Reinelt et al. [19] on single wires crossing each other by 90° , the reduction of the residual fracture load is approximately linearly proportional to the applied lateral force, whereas the sensitivity of wires with higher tensile strength is larger. The direct application of those results to a rope with superimposed one-sided pressure and bending stresses is not possible. The lack of applicable literature source for this specific case of the accident necessitated the conduction of its own study.

There are theoretical approaches describing the highly complex stress distribution in a rope, eg. [20, 21]. Nevertheless, for the present failure analysis the experimental approach promised more reliable results combined even with less effort. A new rope of the same type as the original winch rope was used. The local stress condition in the rope at a crossing point of two windings was simulated in a test setup shown in Fig. 8 and Supp. 3. For tensioning of the rope, the same testing machine was used as for the tensile tests. The lateral pressure was applied in the middle of the sample, with help of an elastic suspended triple rope deflector. It consisted of two pulleys, fixed on a stiff support plate at a distance of 480 mm from each other and a hardened steel bolt between them. The pulleys had ball bearings for negligible rotational resistance. The hardened bolt was positioned perpendicular to the rope, simulating a cross point of two windings on the winch. The lateral position of the bolt relative to the common plane of the pulley axes, and hence also the deflection angle of the rope over the bolt, was smoothly adjustable. In the tests two bolts with different diameters were used: In the standard configuration the diameter was equal to those of the rope (6 mm) and for sensitivity analysis 4 mm.

Fig. 8: Test setup for tension test with lateral load due to sharp lateral bending

First of all, the ultimate load of the rope under pure tension (i.e. $\beta = 0^\circ$) was measured on two samples and found to be 27.2 kN and 27.7 kN. The average of these values $F_{u,0} = 27.4$ kN was defined as the reference ultimate load for the subsequent load tests with lateral pressure. Then, the tension force F was set at a preassigned percentage (5%, 10% etc.) below $F_{u,0}$. This force level was held constant by the test machine while the deflection angle was continuously increased with a maximum rate of $10^\circ/\text{min}$ until the rope fractured.

As expected, all samples fractured at the bolt with clear correlation between the deflection angles at fracture and the portion of the shear-fractured wires.

Fig. 9 shows the reduction of the ultimate load of the rope as a function of the deflection angle. The measured data points are well approximated by the following quadratic regression function:

$$r[\%] = 1.14 \cdot \beta - 0.0082 \cdot \beta^2 \quad (\beta \text{ in degree, regression coefficient } r^2 = 0.987) \quad (7)$$

The effective reduction is rather underestimated by this equation as the slide of the initially slack windings over each other by increasing load induces additional shear forces, whose effects were not simulated in the test setup.

As a rule of thumb for $\beta < 25^\circ$, the reduction of the load capacity in percentage is by chance numerically equal to the deflection angle in degree; i.e. a deflection angle of $\beta = 15^\circ$ reduces the ultimate load by around 15%. The results of the two experiments with a reduced bolt diameter of $\varnothing 4$ mm are scattered around the results of the bolt with diameter $\varnothing 6$ mm, indicating a negligible effect of this test parameter within this range.

Fig. 9: Reduction of the ultimate load of the rope as a function of the deflection angle (see also Supp. 3)

4 Discussion and conclusion

The two main preconditions for the hypothesis “the rope could have fractured due to dynamic load peaks in the winch” established in Sec. 3.1 can be evaluated as follows:

Precondition “force peak”: The heavy loading of the carriage and the low energy absorption capacity of the short winch rope resulted in a low critical roll back velocity of $v_{crit} = 1.91$ m/s (Sec. 3.3), which is considerably below the regular transport speed of 3 m/s. With this clear result the neglected energy loss due to rolling friction of the carriage and the finite deceleration angle of the winch are accounted for.

Precondition “weakest link”: The load capacity of the fixation was reduced by 20% (Fig. 6). The weakening of the rope at a cross point exceeds this level if the deflection angle is larger than 20° (see β for a reduction of 20% in Fig. 9). The deflection angle could have exceeded this limit at a crossing point significantly, as demonstrated graphically in Fig. 10 and also shown by the following rough calculation of the angle between the common asymptotes of two circles stacked on each other (representing the rope and the winch):

$$\beta \cong 2 \cdot \arccos \frac{k-1}{k+1} = 31^\circ \quad (8)$$

- $k \cong 55$: quotient of the winch’s and rope’s diameter, rather overestimated based on Fig. 5 (The permitted limit for the first rope layer is $k = 40$ [5].)

Remark: The cross point, where the primary fracture occurred, had to be located near the nip point of the rope on the winch; otherwise the tension force at the crossing points would significantly reduce by the friction between the windings.

It can be concluded that both preconditions could have been fulfilled at the moment of the accident, therefore the primary fracture can be explained without an indispensable pre-damage of the rope.

Fig. 10: Winch with geometrical proportions similar to the winch of the accident. The angle between the tangents of the rope beside the crossing point of two windings is significantly larger than 20° .

Even though the load capacity reduction of the rope at a cross point of two windings is considerable, there is still a substantial safety margin against fracture as long as the tension force remains within the regular range. Only the unfortunate combination of the excessive dynamic load peak due to the jerky stretching of the rope and the load capacity reduction at the crossing point of two windings could have led to the fracture of the winch rope.

After the primary fracture, the carriage sped down with the attached fractured section of a length of around 2 m free floating in the air. It is possible that this rope section was put in the gap between the

track rope and its support-saddle by the farmer in order to stop the carriage. Obviously, the truncated missing rope section fell to the ground between the stations, outside the focus of the onsite investigations by the police. This hypothesis is supported by the high portion of shear fractured wires at the fracture C, by the flat shape of the brush C (Supp. 4) and by the fact that the track rope fell down from a support-saddle during the uncontrolled speeding down of the carriage (Supp. 5).

5 Outlook

The obtained empiric correlation between the deflection angle and the residual load capacity is valid only for the investigated rope type under the particular test conditions. For more general results additional parameter variation would be necessary, e.g. the design and the diameter of the rope, the nominal tensile strength of the wires (i.e. the grade of the rope) and the crossing angle of the windings.

A further relevant parameter seems to be the sequence of the axial and lateral loading, indicated by two random experiments. In those experiments, first the deflection angles were fixed and afterwards the tension force was increased until fracture, i.e. the tension and the lateral loads were increased simultaneously. The residual load capacity of the rope at a given deflection angle was found to be roughly 20% higher compared to the results shown in Fig. 9. The difference may come from the higher initial lateral and bending stiffness of a pre-tensioned rope and therefore it's reduced capability to adapt its geometry by deformation. Therefore, the presented procedure represents a worst case loading scenario.

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Captions

Fig. 1: Upper station of the ropeway with superimposed sketch

Fig. 2: Winch rope sections W and C with fracture brushes (circles). See also Supp. 3.

Fig. 3: Cross section and surface of the winch rope

Fig. 4: Dominant fracture types of the wires in the brushes C and W

Fig. 5: Winch without wrapping mechanism. Detail: crossing rope windings. (photo of the police)

Fig. 6: Ultimate load of the samples (left) and tested samples (right). A and B: regular samples, C: sample enclosing the fixation

Fig. 7: Sketch of the underlying model for calculation of the energy absorption capacity of the track rope

Fig. 8: Test setup for tension test with lateral load due to sharp lateral bending

Fig. 9: Reduction of the ultimate load of the rope as a function of the deflection angle (see also Supp. 3)

Fig. 10: Winch with geometrical proportions similar to the winch of the accident. The angle between the tangents of the rope beside the crossing point of two windings is significantly larger than 20° .