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What is the impact of the various developments in the field of ropeways on the subsystem "Rope"?

Introduction

Ropeways (rope hauled and / or rope carried means of transportation) are truly not an invention of the 21st century. Nevertheless, their development speed and not least the expansion of their field of operation , especially during the last 10 years, have been increasing and continue to in-crease rapidly!

It is known that when improvements or any kind of changes are taking place in a system, it is necessary to verify constantly and accurately during the design phase the impact of a respective change on every component of that system. This requirement is certainly obvious in the overall field of technology and thus is largely followed. If this requirement is, for whatever reason, ig-nored just once, the system will promptly "acknowledge" the fact by means of an unexpected response. Yet this evident requirement is not always adequately respected when it comes to changes in the environment of ropes.

This is certainly not due to the fact that ropeway engineers are less reliable than others! The reason for this "bad habit" is rather the rope itself; one of the main advantages of a rope is the fact, that it is a "good-natured" subsystem, due to the fact that the rope "announces" its upcoming damage early. Given that those responsible are able to perceive and understand its warning signs, potential major problems can mostly be avoided! However, this additionally means, that the rope mostly does not "respond" immediately as well as not always "very angrily" to our occasional "nasty deeds". This leads to the fact that it is often very difficult to establish the causality between the reason (change in the system) and the respective response of the rope (rope damage). Thus, it is evident that the probability of missing a potential impact is very high, especially if the changes have been carried out both by means of single small steps as well as over longer time, as often happens in the field of ropeways.

The developments in this field evidently follow the well known pattern of our economic system (bigger, faster, lighter, more efficient, etc.), therefore changes are certainly necessary! Keeping this important aspect in mind the author tries to show, by means of three practical examples, how changes, which have been carried out within a ropeway system, influence the rope and its individual sub elements.

Stresses on single elements inside the rope

To estimate the influence of a global change in tensile load on the individual elements of the stranded rope, the radial line load (q_R) with which a strand presses against the respective core will be considered for the case of a rope loaded with the maximum allowed tensile force $S_{max} = \frac{A\sigma_{Br}}{k}$. For this consideration the influence of the bending and torsional moments has been neglected. In addition, it is assumed that adjacent strands do not touch each other.

Based on Feyrer's method [1] for the calculation of the radial line we find:

$q_R = \frac{F_{strand} \cdot sin^2\alpha}{r}$, where $F_{strand} = \frac{S_{max}/n}{\cos a}$.

After substituting $sin\ \alpha$, $cos\ \alpha$ and $S_{max} = \frac{A\sigma_{Br}}{k}$, where A is the metallic area, σ_{Br} the tensile strength of the wire, and k the minimum permitted safety factor, the equation for the radial line load can be finally rewritten as: q$q_R = \frac{\pi^3 c_1{}^2 c_2}{2k\boldsymbol{c_\lambda}\sqrt{(\pi\cdot c_2)^2+\boldsymbol{c_\lambda}^2}}\boldsymbol{\sigma_{Br} d_R}$ **(1)**

Where d_R is rope diameter, c_λ the lay length factor $(\lambda = d_R \cdot c_\lambda)$, c_1 the ratio "strand to rope diameter" $d_S = d_R c_1$ and $c_2 = 1 - c_1$.

When assuming, for purposes of comparison, that both the strand and the core are rigid cylinders with the radii r_1 and r_2, Moduli of Elasticity $E1$ and $E2$, Poisson's ratios ν_1 and ν_2 and that the diameter of the core $d_{Core}=d_R\ c_3$, the resulting maximum Hertzian pressure between the strand and the core (ideal line contact) can be calculated as follows:

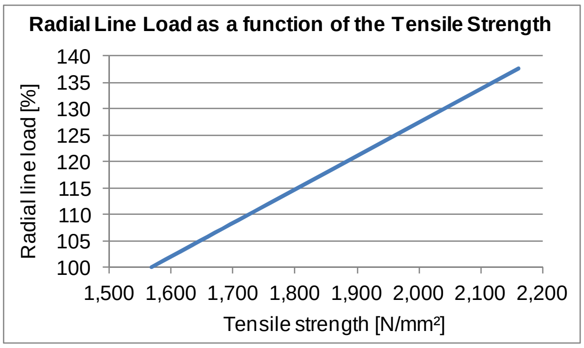
$$p_{Max} = \sqrt{\frac{E}{2\pi r(1-\nu^2)}\frac{F}{l}} \Rightarrow \qquad p_{Max} = \sqrt{\frac{(c_1+c_3)E_1E_2}{\pi d_S c_1 c_3(E_2(1-\nu_1{}^2)+(E_1(1-\nu_2{}^2))}q_R} \quad \textbf{(2)}$$

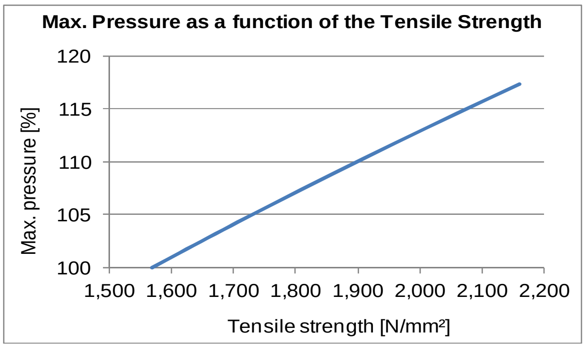
with (1) in (2) ⇒ $$p_{Max} = \sqrt{\frac{(c_1+c_3)E_1E_2}{\pi c_1 c_3(E_2(1-\nu_1{}^2)+E_1(1-\nu_2{}^2))}\cdot\frac{\pi^3 c_1{}^2 c_2}{2k\boldsymbol{c_\lambda}\sqrt{(\pi c_2)^2+\boldsymbol{c_\lambda}^2}}\boldsymbol{\sigma_{Br}}} \quad \textbf{(3)}$$

Daraus sind folgende Erkenntnisse ersichtlich:

Influence of tensile strength „σ_{Br}“

- (1) ⇒ The radial line load is proportional to the tensile strength.
- (3) ⇒ The maximum Hertzian pressure between a strand and the core is proportional to the square root of the tensile strength.

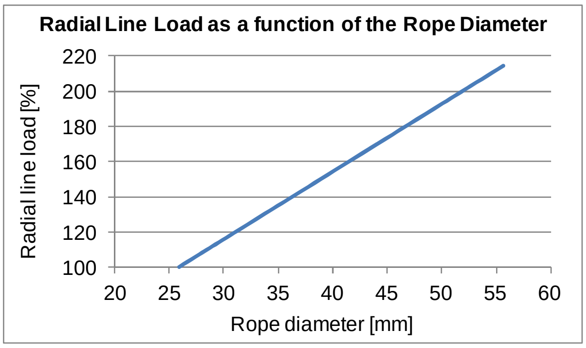


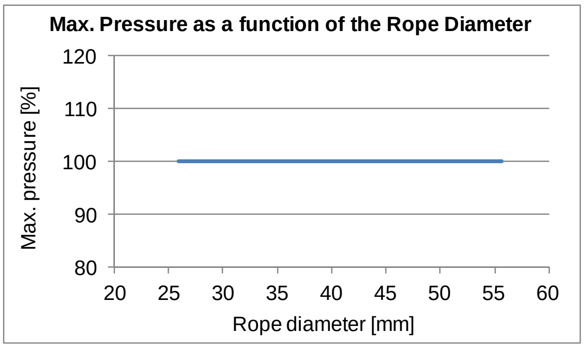


[1] Klaus Feyrer: „Drahtseile“, Bemessung-Betrieb-Sicherheit, Springer Verlag 1994

Influence of the rope diameter d_R

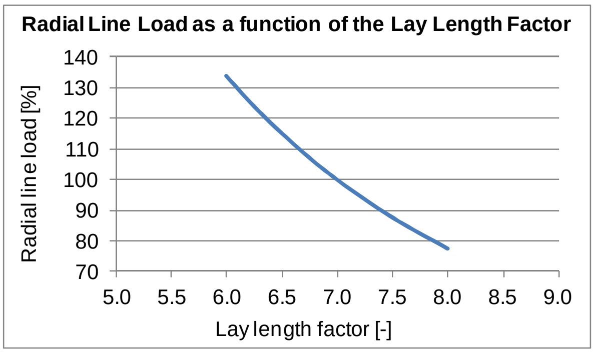
- (1) ⇒ The radial line load is proportional to the rope diameter.
- (3) ⇒ The maximum Hertzian pressure between a strand and the core is independent of the rope diameter.

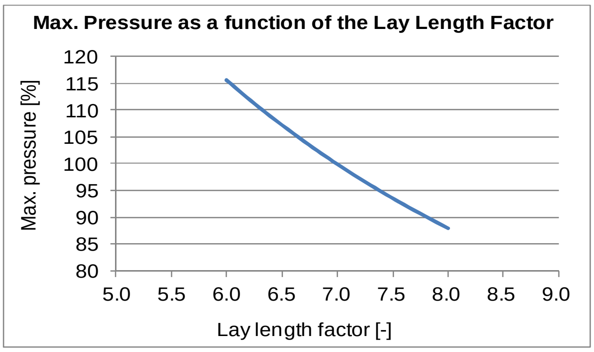




Influence of the lay length factor c_λ

- (1) ⇒ The radial line load is inversely proportional to the square of the lay length Factor.
- (3) ⇒ The maximum Hertzian pressure between a strand and the core is inversely proportional to the lay length Factor.





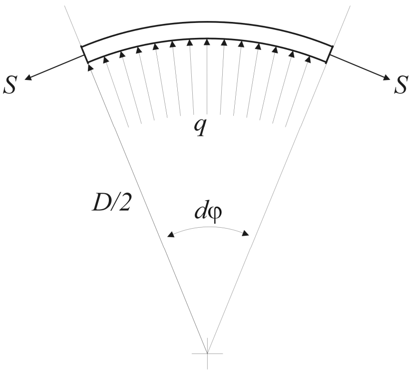
Effects of the above findings

- The fact that the pressure on the core increases with the tensile strength results, where the necessary steps have not been taken, in the core not being able to fulfil its function over time adequately; an earlier contact between the strands and therefore premature wire breaks will be the result. For the same reason it becomes more difficult to keep the permanent elongation of the rope within low limits, as expected by both the ropeway manufacturer and the operator.
- The variation of radial line load and the pressure on the core as a result of variation of the lay length should be considered mainly with regard to the expected reduction of the strand induced vibrations, which can also be achieved by means of adjustment of the ratio "roller spacing to strand pitch" and therefore, due to the fact that the roller distance is fixed, the only available variable parameter is the lay length. In this context it is important to emphasize that in considering the effectiveness of the splice, the lay length ratio must not be allowed to get "too big", otherwise the radial line load, which is indispensable for the splice to function, may get too low with an adverse influence on the splice.

Stresses on the bollard of a track rope

The bollard is most often used in the field of ropeways as a track rope end connection. In the following we will try to calculate the gradual changes of the radial line loads of track ropes on the bollard over the last 40 years:

The highest value of the radial line load *q*, applied from a track rope, wrapped around a bollard (diameter $D_{Bollard}$), on the bollard lining can be calculated as follows:



$q\frac{D}{2}d\varphi = 2S\left(\frac{d\varphi}{2}\right) \Longrightarrow$ $\quad q = 2\frac{S}{D} q = 2\frac{S}{D}$ **(4)**

where *S* is the rope tension.

Taking into account that the minimum permitted $D_{Bollard}/d_R$ ratio ($\frac{D_{Bollard}}{d_R} = c_{Bollard}$) is given by the relevant standard, the equation (4) can be rewritten as follows: $q_{Max} = 2\frac{S_{Max}}{D_{Poller}} = 2\frac{A\sigma_{Br}}{kD_{Poller}} \Rightarrow \quad q_{Max} = \frac{\pi {d_S}^2\sigma_{Br}}{2kD_{Poller}} \Rightarrow$

$$q_{Max} = \frac{\pi \boldsymbol{d_S \sigma_{Br}}}{2k\boldsymbol{c_{Poller}}} \quad \textbf{(5)}$$

When assuming, again for purposes of comparison, that the rope and the bollard are ideally rigid (a cylinder with $r = r_R = \frac{d_R}{2}$ on a plane) the resulting maximum Hertzian pressure between the rope and the bollard can be calculated as follows:

$$p_{Max} = \sqrt{\frac{E}{\pi d_R(1-\nu^2)} q_{Max}} \Rightarrow \qquad p_{Max} = \sqrt{\frac{E_1E_2}{(E_2(1-\nu_1{}^2)+E_1(1-\nu_2{}^2))} \cdot \frac{\boldsymbol{\sigma_{Br}}}{k\boldsymbol{c_{Poller}}}} \quad \textbf{(6)}$$

Influence of the tensile strength σ_{Br}

- (5) ⇒ The maximum radial line load is proportional to the tensile strength.
- (6) ⇒ The maximum Hertzian pressure is proportional to the square root of the tensile strength.

Influence of the rope diameter d_R

- (5) ⇒ The maximum radial line load is proportional to the rope diameter.
- (6) ⇒ The maximum Hertzian pressure is independent of the rope diameter.

Influence of the $D_{Bollard}/d_R$ *ratio* $c_{Bollard}$

- (5) ⇒ The maximum radial line load depends inversely on the $D_{Bollard}/d_R$ ratio.
- (6) ⇒ The maximum Hertzian pressure depends inversely on the square root of the $D_{Bollard}/d_R$ ratio.

Effects of the above findings

The effects of the changes, or of a combination of changes, which have occurred gradually over the years, are illustrated in the following table.

			TW 1 (1970)	TW 2 (1974)	TW 3 (1985)	TW 4 (1995)	TW 5 (2008)	TW 6 (2010)
Diameter of the bollard	D	[mm]	3,600	3,600	3,600	3,650	5,000	6,000
Diameter of the rope	d	[mm]	47.2	48	50	53.8	70	90
D_{Poller}/d_R ratio	**D / d**	**[-]**	**76.27**	**75.00**	**72.00**	**67.84**	**71.43**	**66.67**
Comparisson		*[%]*	*100.00*	*98.33*	*94.40*	*88.95*	*93.65*	*87.41*
Breaking load	MBK	[kN]	2,354	2,384	2,619	3,131	5,513	9,000
Rope tension	S	[kN]	640	735	780	920	1745	2860
Saftey factor	**SF**	**[-]**	**3.68**	**3.24**	**3.36**	**3.40**	**3.16**	**3.15**
Comparisson		*[%]*	*100.00*	*88.18*	*91.29*	*92.53*	*85.89*	*85.56*
Maximal radial line load q_{max}		**[N/mm]**	**351**	**403**	**427**	**497**	**688**	**939**
Comparisson		*[%]*	*100.00*	*114.82*	*121.78*	*141.55*	*196.14*	*267.63*

This means in practice that the prevailing loads of today often exceed the compressive yield strength of the bollard liner, and / or that the cable movement caused by unforeseen diameter reduction of the bollard liner under the existing high pressure, may ultimately result in damage to the rope itself.

In this context, the following steps are necessary to avoid these problems:

- the choice of a bollard liner with a sufficiently high compressive strength and
- the grooving of the liner, at least in the area where the cable runs onto the bollard, thereby reducing the local pressure.

Number of bending cycles (Number of round trips)

A rope in operation is a sub-system with a finite operating life, as it is continually exposed to a fatigue process and in order for fatigue failure to occur, an initiating crack or some discontinuity of the material, a pulsating load, and finally the required number of load cycles up to breakage (under a certain mode of loading) are necessary.

Since the bending stress of a rope running around a sheave is typically the dominant type of fatigue stress, and therefore the number of such bending cycles is the determinant of rope life, it is important to analyze if and how the number of those bending cycles has changed over the years.

In the case of an "endless" (spliced) rope, which is continuously moving in one direction (e.g. as happens in any gondola), the number of bending cycles N which any rope cross section experiences, depends on the rope speed v, the length of the system l, the number of operating hours per day H_{OD} and the number of operating days per year T_{OY}):

$$N = \frac{T_B H_B 3600}{2l/v}$$

Each of these variables has changed over the last 50 years as follows:

- The speed of the most common types of ropeway (chairlift or gondola) has increased from initially less than *3 m/s* (~ 10 ft/s) up to currently *6 m/s (~ 20 ft/s)* and will most probably increase further.
- Although the lengths of the most common types of ropeways remain in the same range, there is a group of ropeways used to connect two bigger systems ("delivery" ropeways), which normally have a short length. The number of this type of system increases continually.
- The number of operating hours per day tends to increase. Especially in the case of ropeways which have illuminated slopes and offer "night skiing". In addition, ropeways used for urban transportation or within airports, etc., are operating practically 24 h/day.
- The number of ropeways which are only in operation during the winter (only for skiing) decreases continually, because the majority remain in operation throughout the whole year offering additional summer activities.

Effects of the above findings

The impact of the increasing number of bending cycles, which a rope experiences yearly are shown in the following table.

These used data originate from a series of detachable gondolas, which have only a drive and a return sheave.

A rope cross section experiences one bending cycle *BC* after running on and off a sheave.

Year	Length [m]	Speed [m/s]	Operating hours per day [h/D]	Operating days per year[D/Y]	Bending cycles per Year [BC/Y]	times the lowest[-]
1953	2,390	2.5	7	120	3,163	x 1.00
1961	2,447	3.5	7	120	4,325	x 1.37
1972	2,280	4	8	135	6,821	x 2.16
1980	2,550	4.5	8	130	6,607	x 2.09
1987	2,035	5	8	210	14,860	x 4.70
1999	932	5.5	8	270	45,888	x 14.51
2008	2,708	6	12	270	25,843	x 8.17
2010	805	6	18	365	176,288	x 55.73

The above table clearly shows that the number of bending cycles has steadily grown over the years. In addition, it can be assumed that this number will continue to grow in the future, due to the fact that the parameters described above continue to grow as well. Particular attention should be paid to the increasing number of "short" ropeways, due to the fact that they look "the same" as ropeways with usual length; but in this case it is frequently overlooked that the number of bending cycles depends inversely on the ropeway length, i.e. the number of bending cycles per time unit increases with decreasing length of the ropeway.

Finally, it is evident that for a given rope quality the useful service life decreases with increasing number of bending cycles per time unit. For this reason, it must be strongly emphasized that where neither the standards nor the rope or ropeway manufacturer indicate any necessary precautions (adjustments of the maintenance intervals), it is the responsibility of the operator to adapt the maintenance schedule, in a way that the higher number of cycles per unit time is adequately taken into account.

Concluding Remarks

It is very important for the author to underline that all the changes indicated above, which have taken place over time, as well as their implied consequences, should not be understood as a hidden recommendation for future "idleness"!

In fact, it seems important to emphasize that insofar as all the influencing factors and parameters are recognized early (during the stage of development), and insofar as they have been properly investigated and accordingly chosen, no unpleasant "surprise" needs to be feared. However, if changes are made based solely on "experience to date " and in the absence of any overall understanding of the consequences of the influencing factors, there is a real risk of a malfunction or even serious damage in the long or even in the short term!