Service Life of Steel Wire Suspension Ropes

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Keywords: Suspension rope, safety factor, bending cycles, EN81-1, tensile load

Abstract. The life of a suspension rope system depends on a number of factors: the overall maintenance of the ropes in terms of sufficient lubrication and tension, but more importantly the initial system design. An analysis of the EN81-1+A3 (2009) Annex N safety factor equation on four case studies was performed on a number of lifts with 2:1 reeving ratios to determine the minimum and actual safety factors for the suspension rope system. By using equations that are generally used within the wider steel wire rope industry for ropes 'running over sheaves', the actual performance of bending cycles was assessed for the four cases studied and converted into an expected number of trips.

The paper will show from the case study results that the number of bending cycles performed varied greatly for each lift with exchange periods of between 3.5 and 11 years. The results show that small changes in various parameters will raise the number of bending cycles significantly. The result of adjusting parameters to reduce the tensile load on the ropes, the increase in traction sheave diameter and using a traction sheave groove that reduces fatigue on the rope is to have ropes that will last significantly longer, with a larger number of bending cycles being performed.

High use lifts that are reeved at 2:1 or more, especially in low rise applications should consider increasing the suspension rope safety factor in order that reasonable service time is given to reduce costs to the end client.

1 INTRODUCTION

The downturn of the many economies in the world and especially in Europe has affected the incomes of many businesses and individual persons. The result of this economic downturn for the Lift Industry is that competition has caused the reduction of prices for the installation of new lifts, which are attributed to the cost of materials (especially electrical and computerised areas of the lift), the manufacturing process, and installation methods designed for faster installations. The service performed on lifts has been streamlined along with contract times for an Engineer to service the lift being also reduced in line with the competition prices required to gain or retain maintenance contracts.

With customers now demanding higher quality services for a lower price, the knowledge that suspension rope future replacement that is inevitable, costly and can be more regular than expected depends on the lift characteristics. For the customer to be satisfied they want the lift to remain in operation with down time of the lift kept to an absolute minimum and naturally the costs incurred on the lift also kept to a minimum. The life of the suspension rope will be regarded as important as the replacement can be costly and down time of the lift may also have an effect on the income revenue stream of the business. The service life of the steel wire suspension rope is assessed in the MSc Dissertation by P. Ryan [1] for initial design and inspection.

2 BENDING CYCLES FOR RUNNING ROPES OVER SHEAVES

Professor K.Feyrer of the University of Stuttgart developed an equation that calculates the 'Bending Cycles for Running Ropes over Sheaves' before the "discard point" and is therefore suitable for the lift industry (see Eq. 1[2]). The discard criteria according to tests performed by Stuttgart University is when the nominal bending cycles have been reached, this is defined when;

'There is a 95% probability that not more than 10% of the ropes have to be discarded'

2.1 Bending Cycles (N_{A10})

$$\log N = b_0 + \left(b_1 + b_4 \times \log\frac{D}{d}\right) \times \left(\log\frac{S}{d^2} - 0.4 \times \log\frac{R_0}{1770}\right) + b_2 \times \log\frac{D}{d} + b_3 \times \log\frac{d}{do} + \frac{1}{b_5 + \log\frac{l}{d}} \quad (1)$$

Where;

S is the dynamic tension per rope and is calculated

$$S = \frac{\frac{(P+0.5Q)gn}{r}}{n_T} \times f_{S1} \times f_{S2} \times f_{S3} \times f_{S4} \quad (N) \quad (2)$$

f_{S1-4} – Values are taken from table 3.12 of Feyrer [2]

f_{S1} – Roller or sliding shoes on guide rails

f_{S2} – Rope efficiency

f_{S3} – The equalisation of the rope tensions across all ropes

f_{S4} – The contract speed. Tension on ropes occur during acceleration.

b_0 to b_5 – Are constants for the type of rope and are taken from table 3.14b of Feyrer [2]

D – Traction sheave diameter

d – Rope diameter

l – Length of most stressed part of rope

The most stressed part of the rope is the length of rope (l) that runs over the traction sheave and the most number of pulleys in the system. This is determined by mapping the rope to find a dimension in millimeters that will be entered into Eq. 1.

The N (N_{A10}) value calculated will reduce as "Endurance Factors" are considered to give a corrected number of bending cycles (N_{A10cor}).

$$N_{A10cor} = N \times f_{N1} \times f_{N2} \times f_{N3} \times f_{N4} \quad (3)$$

The endurance factors are taken from table 3.15 of Feyrer [2]

f_{N1} – Ropes are well lubricated

f_{N2} – Type of rope construction and the number of strands

f_{N3} – Traction sheave groove type and angle (V groove, U undercut groove and U groove)

f_{N4} – The ropes are without any skew

For the number of bending cycles to be calculated any U groove pulleys in the system are deemed to have an endurance factor f_{N3}=1.0

2.2 Number of trips to and from the main stop (Z_A)

The calculated bending cycle value (N_{A10}) from Eq. 1 for U groove pulleys in the system along with the corrected bending cycle value (N_{A10cor}) is then used to calculate the number of trips to and from the main stop (Z_A).

$$Z_{A10} = \frac{1}{\frac{1}{N_{corT}} + \frac{1}{N_{corP}}} \tag{4}$$

2.3 Number of journeys

The calculated figure in Eq. 4 of trips to and from the main stop will have the Holeschak factor (HF) applied to determine the number of "journeys" the lift would make before the ropes have reached their discard point. The Holeschak factor is a study of lift journeys performed as lifts can have many journeys recorded while travelling to and from the main stop. There are 3 different sections that can be used in Eq. 5.

$$\frac{Z_{A10}}{HF} \times 100 \tag{5}$$

$$\text{Residential} = 100 \times No\ of\ Floors\ above\ main\ stop\ floor^{-0.115} \tag{6}$$

$$\text{Commercial} = 100 \times No\ of\ Floors\ above\ main\ stop\ floor^{-0.278} \tag{7}$$

$$\text{Industrial} = 100 \times No\ of\ Floors\ above\ main\ stop\ floor^{-0.381} \tag{8}$$

At this point Eq. 5 will give an expected number of journeys with the type of building calculation applied, that can be seen on the lift more visibly via the trip counter that is usually fitted into the lift controller.

3 SAFETY FACTOR EQUATION

From the bending cycles in Eq. 1 and the 'correction factors' by Feyrer [2], the 'Committee for European Normalisation' (CEN) in their consultation and writing of the EN81-1 [3] standard, that was harmonised on July 1st 1999, looked at the creation of a Safety Factor equation in Annex N that took into consideration a 'Life Expectancy'.

The designed safety factor equation takes into consideration the factors of traction sheave groove type, the amount of pulleys in the system, the traction sheave groove, the amount and diameters of pulleys, the rope diameter and traction sheave to rope diameter ratio to give a minimum predicted life of 600,000 bending cycles as detailed in Andrew and Kaczmarczyk [4] and Schiffner [5]. The derived Eq. 9 takes all the factors and equates a minimum safety factor.

$$S_f = 10^{\left(2.6834 - \frac{\log\left(\frac{695.85 \times 10^6 \times N_{equiv}}{\left(\frac{Dt}{dr}\right)^{8.567}}\right)}{\log\left(77.09\left(\frac{Dt}{dr}\right)^{-2.894}\right)}\right)} \tag{9}$$

Dt – Traction sheave diameter

dr – Rope diameter

N_{equiv} – Total equivalent pulley factor

Where the equivalent pulley factor is calculated by:

$$N_{equiv} = N_{equiv(t)} + N_{equiv(p)} \qquad (10)$$

$N_{equiv(t)}$ – Traction sheave equivalent pulley factor

$N_{equiv(p)}$ – Diverter equivalent pulley factor

Where $N_{equiv(t)}$ is taken from Table 1 based on groove type chosen and $N_{equiv(p)}$ is calculated from the amount of pulleys in the suspension system in Eq. 11.

$$N_{equiv(p)} = Kp(Nps + 4Npr) \qquad (11)$$

Nps – Number of Simple bend pulleys

Npr – Number of Reverse bend pulleys

The factor of ratio between the traction sheave and the average of all diverter pulleys is calculated by:

$$Kp = \left(\frac{Dt}{Dp}\right)^4 \qquad (12)$$

Dt – Traction sheave diameter

Dp – Average diameter of all pulleys

Table 1: Based on criteria contained in Annex N of EN81-1+A3 (2009)

Table N.1

V-grooves	V-angle (γ)	--	35°	36°	38°	40°	42°	45°
	$N_{equiv(t)}$	--	18,5	15,2	10,5	7,1	5,6	4,0
AC U-/V- AC Undercut grooves	U-angle (β)	75°	80°	85°	90°	95°	100°	105°
	$N_{equiv(t)}$	2,5	3,0	3,8	5,0	6,7	10,0	15,2

When the safety factor for the lift has been equated from Eq. 9, the traction calculations according the EN81-1+A3 (2009) Annex M must be performed with 3 primary conditions that apply to satisfy compliance to 9.3 of EN81-1+A3 (2009).

1. Traction must be maintained when the car is being loaded to 125% of contract load.
2. Traction must be maintained when performing an Emergency Stop so that the deceleration rate does not exceed the buffer deceleration rate.
3. Traction must be lost when the counterweight is on the buffers and the machine is driving in the up direction.

4 CASE STUDIES

Four case studies were performed where the minimum safety factor required in Annex N of EN81-1 [3] and actual safety factor were calculated using Eq. 9. For each of the case studies the "bending cycles" according to Feyrer [2] were calculated using equations 1, 4 & 5 to allow a comparison.

Table 2: Case Study findings

	C1		C2	C3	C4	C5	C6	C7
	MINIMUM & ACTUAL EN81-1 ANNEX N SAFETY FACTOR		BENDING CYCLES ACCORDING TO FEYRER (N_{A10})	TRIPS ACCORDING TO FEYRER FOR ALL PULLEYS. WITHOUT HOLESCHAK FACTOR	TRIPS ACCORDING TO HF (Z_{A10}) FROM C3	ON SITE TRIP COUNTER BETWEEN ROPE EXCHANGES	DIFFERENCE IN TRIPS CALCULATED IN C4 TO ACTUAL IN C5	ACTUAL TIME BETWEEN ROPE EXCHANGE
	Minimum	Actual						
Case Study No 1	17.30	21.44	774,843.4	260,014.6	353,145.35	700,000	- 346,854.65	3.5 years
Case Study No 2	16.83	21.15	5,043,110.63	2,101,296	3,287,009	5,700,000	- 2,412,991	10 years
Case Study No 3	16.79	25.31	2,995,707.095	776,588.89	1,054,743.9	2,670,000	- 1,615,256.1	11 years
Case Study No 4	17.44	20.075	634,590.81	396,062.06	537,921.698	600,000	- 62,078.3	4 years

In Case Studies 1 and 4 the actual EN81-1+A3 (2009) Annex N safety factor is 21.44 and 20.075 respectively as shown in C1 of Table 2, with the ropes calculated to last for slightly above the discard N_{A10} value of 600,000 bending cycles as seen in the C2 section of Table 2 (Case Study 1 – 774,843.9 and Case Study 4 – 634,590.81) prior to exchange. The calculated number of 'round trips' that were converted from the bending cycles from C2 can be seen in C3 where the amount of diverting pulleys and the traction sheave have been taken into consideration for the discard number of round trips Z_{A10} (Case Study 1 – 260,014.6 and Case Study 4 – 396,062.06).

When the Holeschak Factor in C4 is then taken into consideration the actual number of trips of the lifts in Case Studies 1 and 4 are less than the recorded number prior to the exchange of the suspension ropes:

- Case Study 1 – calculated in C4 = 353,145.35 trips with actual trips at 700,000 in C5.
- Case Study 4 – calculated in C4 = 537,921.698 trips with actual trips at 600,000 in C5.

In Case Studies 2 and 3 the actual safety factor EN81-1+A3 (2009) Annex N safety factor is 21.15 and 25.31 respectively as shown in C1, with the ropes calculated to last for well in excess of the discard N_{A10} value of 600,000 bending cycles as seen in C2 (Case Study 2 – 5,043,110.63 and Case Study 3 – 2,995,707.095) prior to exchange.

The calculated number of 'round trips' that were converted from the bending cycles from C2 can be seen in C3 where the amount of diverting pulleys and the traction sheave have been taken into consideration for the discard number of round trips Z_{A10} (Case Study 2 – 2,101,296 and Case Study 3 – 776,588.89).

When the Holeschak Factor in C4 is then taken into consideration the actual number of trips of the lifts in Case Studies 2 and 3 are less than the recorded number prior to the exchange of the suspension ropes:

- Case Study 2 – calculated in C4 = 3,287,009 trips with actual trips at approximately 5,700,000 in C5
- Case Study 3 – calculated in C4 = 1,054,743.9 trips with actual trips at approximately 2,670,000 in C5

The figures in C4 for all Case studies would indicate that the rope inspection may not have captured that the ropes meeting the discard criteria until the ropes had deteriorated substantially. The calculated trips for all cases in C4 against the on-site recorded readings in C5 indicate that the rope either did not deteriorate or that the ropes had already met the discard criteria and should have been exchanged earlier than they were? The fact that all the lifts had the ropes exchanged later than the calculated number would suggest that they were not changed at a time that was required and they remained in service when they should have been replaced.

If the suspension ropes were to be exchanged at the journeys specified in section C4 where the ropes have been calculated to have met the discard criteria that '*There is a 95% probability that not more than 10% of the ropes have to be discarded* (N_{A10}) which is transferred to trips according to Holeschak Factor (Z_{A10}) in section C4, then the following would have occurred from the information in Table 3.

Table 3: Exchange time of ropes according to calculated trips.

Case Study No1	$\frac{C4}{C5} \times C7 = \frac{353{,}145.35}{700{,}000} \times 3.5$	= 1.77 years to exchange
Case Study No2	$\frac{C4}{C5} \times C7 = \frac{3{,}287{,}009}{5{,}700{,}000} \times 10$	= 5.77 years to exchange
Case Study No3	$\frac{C4}{C5} \times C7 = \frac{1{,}054{,}743.9}{2{,}670{,}000} \times 11$	= 4.34 years to exchange
Case Study No4	$\frac{C4}{C5} \times C7 = \frac{537{,}921.698}{600{,}000} \times 4$	= 3.58 years to exchange

4.1 Cost Implications of changing system parameters

Using Case Study 1 where the calculated number of trips in C4 in table 2 is 353,145.35 to alter some system parameters and view the effects on the expected number of bending cycles $(\boldsymbol{N_{A10}})$**.** Then view the cost increase of the initial design and compare to the cost over the life of the lift that is estimated at 20 years.

System changes.
Increase sheave diameter to 480 mm from 400 mm and increase number of ropes from 5 to 6. The change of system parameters was then recalculated and gave results as shown in Table 4.

Table 4: Comparison of changes in sheave and rope for operational cycles

Scenario	10mm Ropes Drako-250T (IWRC) at Fmin 67.7KN	Minimum Annex N Safety Factor	Actual Annex N Safety Factor	Bending cycles N_{corA10}	Journey cycles Z_{A10} with Holeschak Factor
1 (existing)	5 ropes with sheave diameter 400mm	17.30	21.44	774,843.4	353,145.35
2 (new)	Case a) Sheave diameter 480mm. Ropes increased from 5 to 6	15.729	25.83	2,673,426.57	1,218,450.13

Initially it can be seen for the increase of 20% of the traction sheave diameter and one extra rope that there has been an increase of approximately 345% for the expected performance of bending cycles (N_{corA10}) and trips (Z_{A10}), this relates to an estimated life increase from the current approximate life before exchange to over 10 years from 3.5 years.

The cost of the increase in costs for the materials was given by Sharkey Lifting Ireland for suspension ropes, Ziehl Abegg UK for machine and diverter pulley costs.

Table 5: Comparison of cost over 20 years if initial design changed for Case Study 1

Scenario	Cost increase for sheave and rope at initial design	Number of ropes	Cost of Ropes for 90 Metres	Labour and equipment charge for re-roping	Estimated number of rope exchanges	Cost over 20 year life of life.
1	N/A	5	€1,516.50	€6,500.00	5	**€40,082.50**
2	€910.30	6	€1,819.80	€6,500.00	1	**€9,230.10**

The labour cost to perform the re-roping of the lift along with the cost of the ropes is detailed and details a significant lift life cycle cost saving for minimal initial investment.

5 CONCLUSION

All lifts in Case Studies had mid to high usage and are multi reeving systems at 2:1 with many diverting pulleys, these lifts represent a common situation today as there are now many lifts that being installed as Machine RoomLess (MRL) and will have a minimum reeving ratio of 2:1 with machine at top of shaft and therefore having 3 diverting pulleys (2 on the car and 1 on the counterweight). Case Study 1 is an MRL with the machine in the pit area and has 6 diverter pulleys; this will be the case for all MRL's that have a machine in the pit. There are also MRL's for heavy duty (normally over 2,000 KG minimum) that will have a roping arrangement at 4:1, this will have 7 pulleys.

The EN81-1 Annex N safety factor calculation according to Berner [6] is based on information on lift built before 1980 using fibre core ropes. Lifts at that time were predominantly reeving at a 1:1 ratio and therefore would have had ZERO pulleys, discounting the diverter under the drive machine (double wrap machines being the exception), where the bending cycles that occurred would have been 2 per round trip. Also due to the diverter under the machine the angle of wrap would have been less than 180 degrees causing the traction sheave groove be manufactured to give the required traction (to meet Annex M of EN81-1+A3 (2009)) or to increase the diameter of the traction sheave using the same groove to give the required traction.

The normal case of lifts currently used is to have a wrap of 180 degrees (both MRL and Machine room) and with space a premium the minimum traction sheave to rope diameter (D/d) measurement according to EN81-1+A3 (2009) of 40:1 being desirable.

From the Case Studies the choice of groove, the diameter of the rope ratio to the diameter of the sheave and the tensions applied (static and dynamic) have a major effect on the life of the rope in terms of the bending cycles they will perform until they reach the discard point.

6 FURTHER WORK

The safety factor equation (Eq. 9) as stated by Berner [6] was designed for fibre core ropes and this is borne out with numerical constants for fibre core ropes with Table 3.14b (Discarding number of bending cycles N_A) of Feyrer [2] showing constants that are replicated in the safety factor equation ($b_2 = 8.567$ and $b_4 = -2.894$ for fibre core ropes).

To have an altered safety factor equation that replicated the different constants of other rope types, especially the other most commonly used rope type - Independent Wire Rope Core

(IWRC) where $b_2 = 8.056$ and $b_4 = -2.577$ for example, the location of the constants from Table 3.14b of Feyrer [2] and $b2$ and $b4$ in the safety factor equation are highlighted in Eq. 13.

$$S_f = 10^{\left(2.6834 - \frac{\log\left(\frac{695.85\times10^6\times N_{equiv}}{\left(\frac{Dt}{dr}\right)^{b2}}\right)}{\log\left(77.09\left(\frac{Dt}{dr}\right)^{b4}\right)}\right)} \tag{13}$$

The effect of the b_2 and $b_4$constants on the minimum safety factor to be determined by further work after confirmation that the base equation remains. On inspection of case studies 1 and 4 (where IWRC ropes are used) case study 1 moves from 17.29 to 18.66 and case study 4 moving from 17.44 to 18.86 for IWRC. This equates to an approximate 8% increase of the minimum safety factor required in both cases.

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BIOGRAPHICAL DETAILS

Patrick Ryan has worked for Schindler Ireland since 1994 after working for Schindler UK since 1988. He served an apprenticeship with Express Lifts in Birmingham from 1980 and worked for them for 8 years. He holds a HNC in Electrical & Electronic Engineering from Birmingham Polytechnic (now University of Central England) and holds an MSc in Lift Engineering from The University of Northampton gained in 2013.