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TECHNICAL ARTICLE—PEER-REVIEWED

Steel Wire Ropes Service Life

Limitations of the Application of ISO 4308 on the Design of Storage and Retrieval Machines

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Abstract This paper demonstrates the low life expectancy of the steel wire rope that might be achieved by using the ISO 4308-Part1:2003 for the calculation of the reeving system of a S/R machine. The problem is illustrated with a case study: Calculation of one S/R machine steel wire rope service life. It is also shown that the application of the DIN 15020-Part1:1974, leads to better results on the steel wire rope service life. In response to increasingly demanding customer requirements for high throughput automatic storage systems, S/R machines and VTDs are being pushed to achieve higher number of cycles per hour. The S/R machines are under the scope of EN 528:2008, which states that the ISO 4308-Part1:2003 must be used to calculate and design the steel wire rope reeving system. This standard has been developed for cranes and it takes in account the lifting appliance mode of operation, through the mechanism classification group. However, even the consideration of the most demanding mechanism classification for the steel wire rope calculations may lead to a low service life of the rope. As stated previously, in this paper a S/R machine case study calculation of a steel wire rope service life is made. The lifting system is designed according to the ISO 4308-Part1:2003 and DIN 15020-Part1:1974, and the service life is calculated and compared with the typical requirements for an automatic storage and retrieval warehouse system. Methods like the one developed by Feyrer, may support the machine designer to increase the steel wire rope life expectancy. This method allows the assessment of the impact on the steel wire rope service life of one given improvement in the reeving system design, enabling the designer to balance improvement with cost.

Keywords Steel wire rope · Fatigue life · Bending cycle · Storage and Retrieval machine · Life expectancy · Service life · Sheave

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List of Symbols

a_v	Hoisting acceleration (m/s^2)
b_0 to b_3	Steel wire rope constants for number of bending cycles calculation, according to Feyrer [19] (–)
c	Steel wire rope coefficient according to DIN 15020:1974 [4] (–)
C	Steel wire rope selection factor according to ISO 4308–1:2003 [1] (–)
d_{min}	Minimum steel wire rope diameter (mm)
D_{min}	Minimum drum or sheave diameter according to 15020:1974 [4] (mm)
D_1	Minimum pitch circle diameter of the drum according to ISO 4308–1:2003 [1] (mm)
D_2	Minimum pitch circle diameter of the sheave according to ISO 4308–1:2003 [1] (mm)
$d_{wirerope}$	Selected steel wire rope diameter (mm)
D_{sheave}	Selected sheave diameter (mm)
$fs_1 \ldots fs_4$	Force factors according to Feyrer [19] (–)
f_d, f_L, f_c	Endurance factors according to Feyrer [19] (–)
g	Gravity acceleration (m/s^2)
h_1	Coefficient for pulley diameter calculation according to DIN 15020:1974 [4] (–)
h_2	Coefficient for pulley diameter calculation according to DIN 15020:1974 [4] (–)

$h_{1'}$ Selection factor for the drum according to ISO 4308–1:2003 [1] (−)
$h_{2'}$ Is the selection factor for the sheave according to ISO 4308–1:2003 [1] (−)
i Number or fixed pulleys (−)
K_1' Minimum break force factor according to ISO 2408:1985 [15] (−)
$K1$ Minimum break force factor according to ISO 2408:2017 [16] (−)
K' Empirical factor for minimum breaking load of a given rope construction (−)
l Bending length (m)
n_{hang} Total number of hanging sheaves (−)
n_{stat} Total number of stationary sheaves (−)
$N_{A10(S_{cormax})}$ Number of working cycles Z_{A10}, under the maximum load S_{cormax} (−)
$N_{A10(S_{cormin})}$ Number of working cycles Z_{A10}, without load on the hoisting carriage (only deadload) S_{cormin} (−)
n_{falls} Number of steel wire rope falls (−)
n_t Number of bearing wire ropes (−)
Q Total load (kg)
r Sheave, pulley, and compensating pulley groove diameter (mm)
R_o Minimum tensile strength of the wire used in the rope (N/mm^2)
S Rope tensile force (N)
S_{cormax} Maximum rope tensile force (N)
S_{cormin} Minimum rope tensile force (N)
sZ Regular lay rope (−)
t Rope type factor according ISO 4308–1:2003 [1] (−)
$t_{S_{cormax}}$ Time fraction with maximum load—S_{cormax} (−)
$t_{S_{cormin}}$ Time fraction with no load—S_{cormin} (−)
v_h Hoisting speed (m/s)
zZ Lang lay rope (−)
w Number of alternating bending stresses (−)
w_t Total number of alternating bending stresses in a reeving system (−)
Z_{10} Number of hoisting cycles which, with a certainty of 95%, no more than 10% of the ropes break (−)
Z_{A10} Number of hoisting cycles which, with a certainty of 95%, no more than 10% of the ropes have to be discarded (−)
Z_{Am} Number of hoisting cycles which, with a certainty of 95%, no more than 50% of the ropes have to be discarded (−)
Z_p Practical utilization factor according to ISO 4308–1:2003 [1] (−)
η Wire rope efficiency of one sheave (−)
η_F Efficiency of the pulley block
η_{hang} Hanging sheave efficiency (−)
$\eta_{hangtotal}$ Total efficiency of the hanging sheaves (−)
η_R Efficiency of a rope pulley (−)
η_S Total efficiency of the rope drive (−)
η_{stat} Total stationary sheaves efficiency (−)

Abbreviations

S/R machine Storage and retrieval machine
STK Stacker crane
VTD Vertical transfer device
MBL Minimum breaking load
S.F. Safety factor
KSC-PT Koeber supply chain – Portugal

Introduction

This document demonstrates the low life expectancy of the steel wire rope that might be achieved by using the ISO 4308-Part1:2003 [1] for the calculation of the reeving system of a S/R machine. The case study S/R machine steel wire rope reeving system is presented in Fig. 1. The S/R machines, commonly known as stacker cranes—STK, are under the scope of EN 528:2008 [2] and the VTDs are under the scope of EN 619:2002 + A1 [3]. The requirements of these standards must be fulfilled so that the conformity declaration under CE marking is ensured. Both types of machines are used to transfer loads, typically on the top of pallets, in and out of an automatic warehouse system. When calculating the machine under the scope of EN 528:2008 [2], the manufacturer must refer to ISO 4308-Part1:2003 [1]. When designing a VTD according to EN 619:2002 + A1 [4], it is acceptable to use other recognized codes of practice, therefore the DIN 15020-

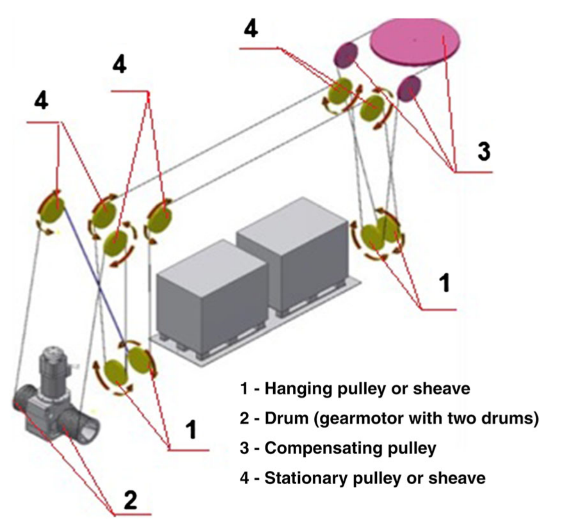

Fig. 1 Reeving system of the case study S/R machine. Extracted from KSC-PT technical documentation [5]. Reprinted with permission

Part1:1974 [4], may also be used. For both machines the design is usually done considering the most demanding classification mechanism to define the steel wire rope diameter, the pulleys diameter, and the drum diameter. However, the requirements of the standard for the steel wire ropes and pulleys design, may not be enough to achieve a high service life, as it will be shown with the case study calculation.

Requirements of EN 580, EN619, DIN 15020 and ISO 4308, for Steel Wire Rope Lifting Appliances

The vertical transfer devices–VTDs—are under the scope of EN 619:2002 + A1:2010[3].[1] According to this standard one VTD is a device with raising and lowering movements of more than 200 mm in the path of conveyors, in which unit loads can be transferred from one defined level to one or more defined levels by a carrying element, refer to Fig. 2. This standard defines the requirements for the suspension elements of the VTD.

The rail-dependent storage and retrieval equipment—S/R machines, commonly known as stacker cranes are under the scope of EN 528:2008[2],[2] refer to Fig. 3, which states that wire rope, drum and pulley diameters shall be calculated according to ISO 4308-1:2003 [1], and defines the minimum values to be considered.

Table 1 presents a synthesis of the requirements for a steel wire rope reeving system, according to the mentioned standards.

Thus, the standard EN 528:2008 [2], for S/R machines, refers to the ISO 4308:2003 [1] for the drive group requirements. The standard EN 619:2002 + A1:2010 [3], for VTDs, only defines that recognized codes of practice shall be considered.

Diameter of the Rope, Drum, and Sheaves on a System Designed According to DIN 15020-Part 1:1974 and ISO 4308-1:2003

Figure 1 shows the case study reeving system of a S/R machine. The pulley size, drum diameter, and steel wire rope diameter were calculated according to ISO 4308-1:2003 [1] and DIN 15020-Part1:1974 [4], and the minimum values of the EN 528:2008 [2] were exceeded. All the requirements for all the components of the reeving system were fulfilled.

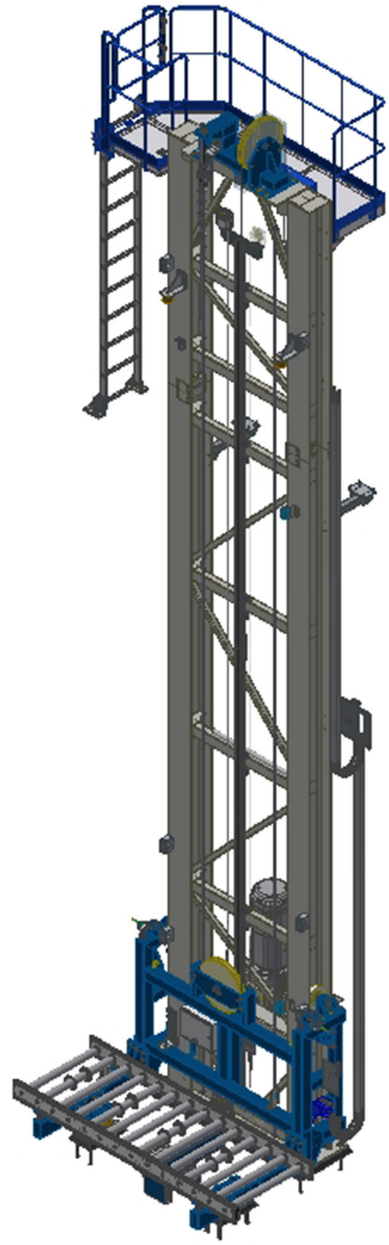

Fig. 2 VTD definition. Steel wire rope VTD designed by the document author for KSC-PT

Table 2 presents the data for the case study S/R machine reeving system of Fig. 1.

The requirements for a steel wire rope to be used in a VTD and a S/R machine are summarized in Table 1. According to EN 619:2002 + A1:2010 [3] and EN 528:2008 [2], the steel wire rope must have a tensile strength of individual wires equal or higher than 1570 N/mm^2, but not exceeding 1960 N/mm^2. The total number of

[1] EN 619:2002 + A1:2010 [3] has a new edition of 2021 that is under revision and balloting.

[2] EN 528:2008 [2] has a new edition of 2021 that is under revision and balloting. In this new edition of 2021 is going to refer to ISO 16625:2013 [22] for steel wire rope systems calculation. In this paper only the harmonized editons (at the date of the document creation) of the standards were considered. The assessment of the ISO 16625:2013 [22], is out of the scope of the present document. However, the author analysed it and it is very similar to the ISO 4308–1:2003 [1], for the issue of this document. The same conclusions would be reached if the case study was done under the ISO 16625:2013 [22], instead of ISO 4308–1:2003 [1].

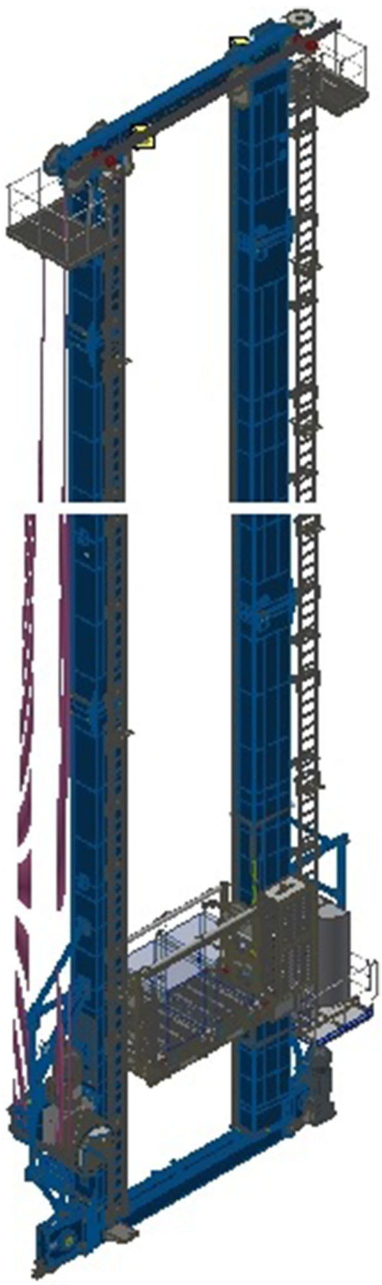

Fig. 3 S/R machine. Double mast stacker crane designed with the contribution of the document author for KSC-PT

wires shall be higher than 114. The steel wire rope with commercial name HD8K PPI [14] has 257 wires and tensile strength of individual wires of 1960 N/mm^2, therefore fulfilling the requirements, refer to Fig. 4 and Fig. 5. The name of this rope according to EN 12385–4:2002 [6] is 8xK26WS-ESWRC.

Figure 6 explains the terminology of the elements of a steel wire rope. Figure 7 shows a non compacted steel wire rope. K means compacted steel wire rope, refer to Fig. 8. Figure 9 explains by itself the designation of the steel wire rope. ESWRC means that the rope core is enveloped with solid polymer, according to Fig. 10. A compacted steel wire rope is advantageous because of the increased filling factor, which decreases the coefficient C, thus decreasing the $d_{\min}$, according to formulae (5). The polymer enveloped rope core stabilizes the steel wire rope structure, acts as a shock absorber, and increases its fatigue life. The rope of this case study will be a Lang lay rope, Fig. 11. On a Lang lay rope the wires in strands and the strands of rope wind in the same direction. Lang lay ropes—zZ—have higher fatigue resistance than regular lay ropes. Regular lay ropes—sZ, Fig. 12, in which the wires wind in one direction and the strands in opposite direction, may be visually inspected, but on Lang lay ropes the internal wires usually break first, so they must be inspected magnetically. More information about steel wire ropes construction, common problems, maintenance, and handling may be found in references [7–12].

After some assessment of the system of Fig. 1, it is possible to observe that the total suspended mass is supported by n_{falls} = 8 rope falls, in a differential system.

$$S = \frac{(\text{Deadload} + \text{Payload}).g}{n_{\text{falls}}} \qquad \text{(Eq 1)}$$

Thus, from (1) the tension $S = 15573$ N. The Deadload is the load of the hoisting carriage plus the load handling devices (typically forks on S/R machines). The Payload is the maximum load weight.

According to DIN 15020:1974 [4], the tension S must be corrected taking in consideration the acceleration forces and the efficiency of the rope drive. Other correction factors shown on this standard are not applicable to S/R machines, since in this type of machines the hoisting carriage is guided along the mast by rollers (opposite from cranes where we have a hook). In a S/R machine, the acceleration force is only vertical. On appendix of this standard, a method is shown on how to calculate the efficiency of the rope drive, using formulae (2). Table 3 shows the values for the efficiency of the pulley block -η_F that will be used to calculate the efficiency of the rope drive—η_S.

$$\eta_S = (\eta_R)^i.\eta_F \qquad \text{(Eq 2)}$$

where

η_S: Is the efficiency of the rope drive.

η_R: Is the efficiency of a rope pulley. For a rope pulley with ball bearings $\eta_R = 0,98$

i: Number or fixed pulleys.

η_F: Efficiency of the pulley block.

$$S_{\text{cormax}} = (\text{Deadload} + \text{Payload}).\frac{(g + a_v)}{\eta_S} \qquad \text{(Eq 3)}$$

where a_v is the hoisting acceleration.

The reeving system should be analyzed as if it is divided in two. Each of them begins on the one of the hoisting

Table 1 Requirements of EN 528:2008 [2] and EN 619:2002 [3] regarding steel wire ropes

	EN 528:2008 [2]	EN 619:2002 [3]	DIN 15020- 1:1974[4] (5 m drive group)	ISO 4308-1:2003 [1] (M8 classification group)
S.F., Z_p, d_{min}	According to ISO 4308–1:2003 [1]. The ratio between the minimum breaking load and the maximum static force for all types of ropes shall be at least 10 for hoist units intended to carry person(s) and at least 5 for other hoist units	According to recognized codes of practice for load spectrum and operating time class. The ratio between the minimum breaking load and the maximum shall be minimum 5, when carrying a person shall be minimum 10	d_{min} calculated by formulae (4).c according to Table 4	Z_p = 9 d_{min} calculated by formulae (4) and (5)
Pulleys diameter	According to ISO 4308-1:2003 [1]. The ratio of the diameter, of pulleys and drums measured at the centerline of the rope, to the nominal diameter of the rope shall be at least 22 to 1	The ratio of the diameter, of pulleys and drums measured at the centerline of the rope, to the nominal diameter shall be according to recognized codes of practice for load spectrum and operating time class, but no less than 22	According to (6) and coefficients from Tables 7 and 8	According to (8) and coefficients from Tables 9 and 10. Angle between sides of the sheave should be between 30° and 60°
Drum diameter	According to ISO 4308–1:2003 [1]	According to recognized codes of practice	According to (6) and coefficients from Tables 7 and 8	According to (7) and coefficients from Tables 9 and 10
Compensating pulley diameter	According to ISO 4308–1:2003 [1]	According to recognized codes of practice	According to (6) and coefficients from Tables 7 and 8	According to (8) and coefficients from Tables 9 and 10
Groove diameter	According to ISO 4308–1:2003 [1]	According to recognized codes of practice	$r = 0,525.d_{wire}$	$r = 0,5375.d_{wire}$ (optimum value)
Fleet angle	According to ISO 4308–1:2003 [1]	According to recognized codes of practice	Max 4°	Max 4°
General requirements	It is permitted to use a single rope	–	-	.
	All wire ropes of one lifting unit shall be of the same size, strength, and construction. If they are intended to carry persons, ropes shall be in accordance with EN 12385–4 [6]	All wire ropes of one lifting unit shall be of the same size, strength, and construction		
	Steel wire ropes shall be made of at least 114 wires. The tensile strength of the wires in the rope shall not be less than 1 570 N/mm^2 but shall not exceed 1 960 N/mm^2	Steel wire ropes shall be made of at least 114 wires. The tensile strength of the wires in the rope shall not be less than 1 570 N/mm^2		
	Rope drums shall be provided with a single continuous spiral groove for each rope	Rope drums shall be provided with a single continuous spiral groove for each rope		

Table 2 Data for calculation of the S/R machine reeving system

Dead load	9000	kg
Payload	3700	kg
Hoisting speed	0,5	m/s
Hoisting acceleration	0,3	m/s^2
Hoisting stroke	13,9	m
Working shifts	2	.
Combined cycle time	30	Cycles/hour
Steel wire rope	8xK26WS- ESWRC, $R_0 = 1960$ N/mm^2	.

Fig. 4 Steel wire rope HD8KPPI data. Extracted from [14]. Reprinted with permission

RCN	Diameter range [mm]	Construction	Number of outer strands	Number of wires	Number of outer load bearing wires	Average fill factor
09	15 – 28,58	8xK26	8	257	208	0,677

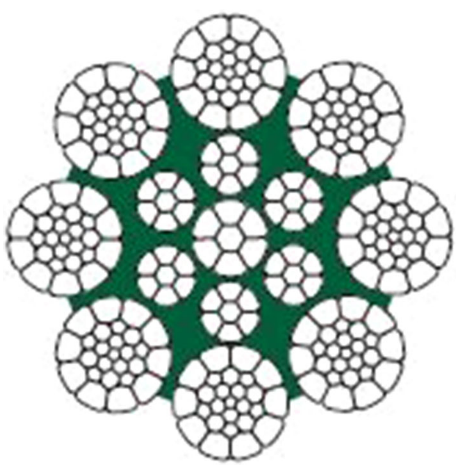

Fig. 5 Steel wire rope HD8KPPI construction. Extracted from [14]. Reprinted with permission

gearmotors drums, refer to Fig. 1, and ends on one side of the compensating pulleys. There are i = 3 fixed pulleys in each of these systems. The number of rope plies, meaning deviations, on the drum and on the hanging pulleys of the hoisting carriage (moving up and down) is n = 3. The compensating pulleys are not to be considered in this assessment. So, by Table 3, η_F = 0,98. From formulae (2) η_S = 0,92 and from formulae (3) S_{cormax} = 17 401 N.

The standard DIN 15020:1974 [4] does not take in consideration the difference on the nominal strength of the individual wires of the ropes for 5 m drive groups, and sets $c = 0,132$ for all of them, refer to Table 4. From formulae (4), $d_{\min} = 17,4\text{mm}$.

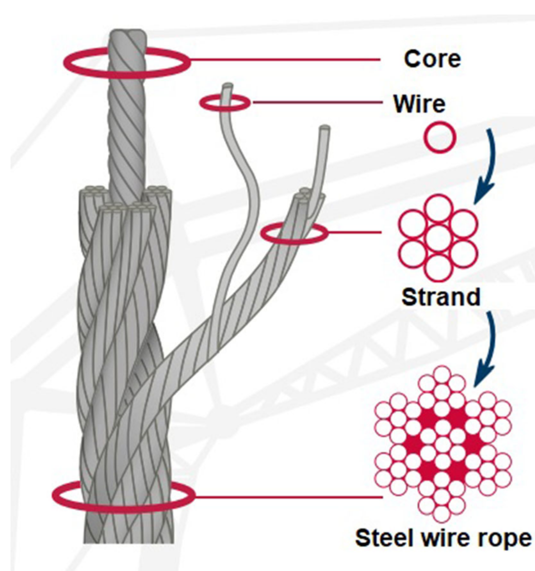

Fig. 6 Terminology of a steel wire rope elements. Adapted from reference[13]. Reprinted with permission

$$d_{\min} = c.\sqrt{S_{\text{cor}}} \qquad \text{(Eq 4)}$$

ISO 4308-1:2003 [1], Sect. 6.3, defines that the S value must be defined taking in account the efficiency of the rope reeving system, but does not give any input on how to calculate it. S_{cor} value will be considered the same as the one calculated by the DIN 15020:1974 [4] on this document.

Fig. 7 Non-compacted steel wire rope [13]. Reprinted with permission

Fig. 8 Compacted steel wire rope [13]. Reprinted with permission

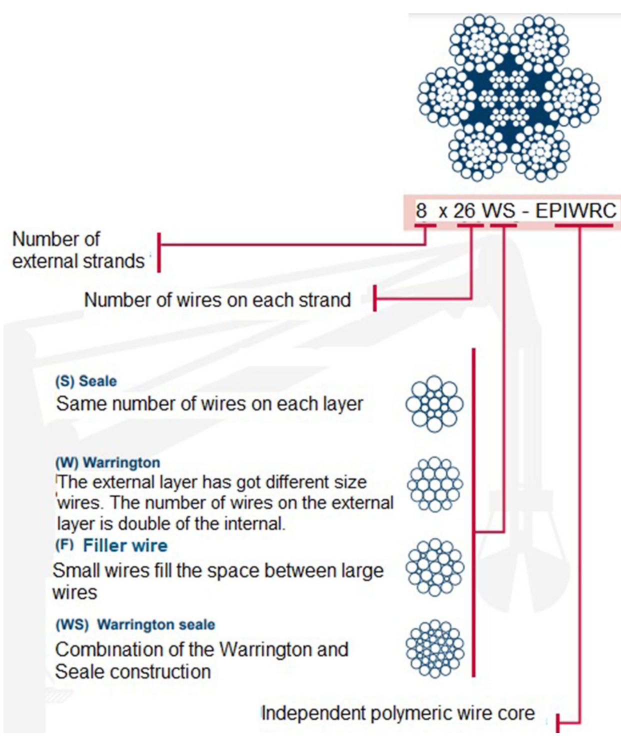

Fig. 9 Explanation of the steel wire rope name. Adapted from reference [13]

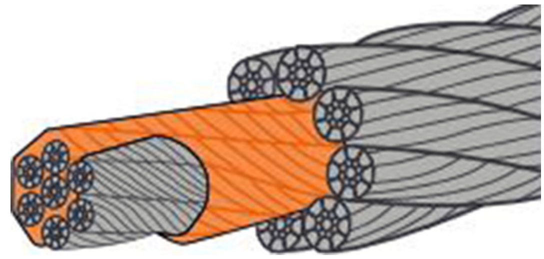

Fig. 10 Rope core enveloped with solid polymer [13]. Reprinted with permission

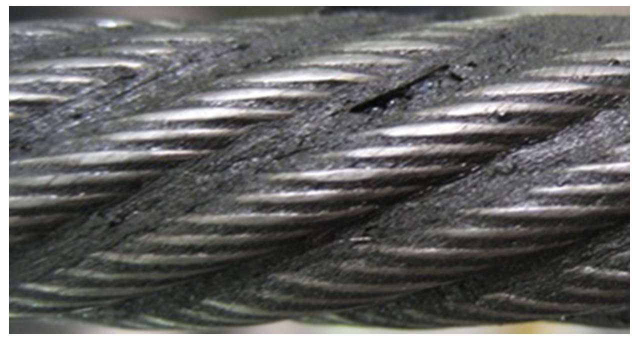

Fig. 11 Lang lay rope. Extracted from KSC-PT technical documentation [5]. Reprinted with permission

Fig. 12 Regular lay rope. Extracted from KSC-PT technical documentation [5]. Reprinted with permission

Regarding the C value[3], ISO 4308-1:2003 [1] defines it for one example with a 6-strand steel wire rope, on Table 1. However, the steel wire rope that is going to be used in this case study is 8 strands. For other types of ropes, refers to ISO 2408:1985 [14] where the values shown in Table 5 are found.

The steel wire rope of this case study has got fiber core, but it is compacted. A more accurate value for K_1' is shown on the most recent ISO 2408:2017 [15], $K1 = 0.330$,[4]

[3] C coefficient in ISO 4308–1:2003 [1] is equivalent to the c coefficient in DIN 15020:1974 [4].

[4] K_1' coefficient in ISO 2408:1985 [15] is equivalent to the $K1$ coefficient in ISO 2408:2017 [16]., as shown in Table 6.

Table 3 Efficiency of the pulley block according to DIN 15020:1974 [4]

n number of rope plies	3
η_F(antifriction bearings)	0,98

Table 4 Coefficient c according to DIN 15020:1974 [4]

	Wire ropes which are not non-twisting		
	Nominal strength of individual wires		
Drive group	1570 N/mm^2	1770 N/mm^2	1960 N/mm^2
5_m	c coefficient = 0,132		

Table 5 Numerical values for K and K', according to ISO 2408:1985 [15]

Group	Rope class	Minimum breaking force factor Fiber core (non-compacted)
4	8 × 19, and	$K_1' = 0,293$
5	8 × 37	

Table 6 Values for compacted strand wire ropes, according to ISO 2408:2017 [16]

Type of rope	Class	Ropes with fiber core MBF factor -$K1$
Single layer compacted wire rope	8 × K19	0,330
	8 × K36	

The rope selection factor – C, is calculated by the formulae (5).

$$C = \sqrt{\frac{Z_p}{K'.R_o}} \quad \text{(Eq 5)}$$

where

C: Is the rope selection factor (minimum).

K': Is the empirical factor for minimum breaking load of a given rope construction (according to Table 3 of ISO 2408:1985 [14]), or provided by the manufacturer.

R_o: Is the minimum tensile strength of the wire used in the rope (N/mm^2).

Z_p: Is the practical utilization factor.

The Z_p values are defined in Table 1 of ISO 4308-1:2003 [1], for each mechanism classification group. For the most demanding classification group M8,[5] $Z_p = 9$.

Table 7 Coefficients h_1 for calculation of the diameter of drums, pulleys, and compensating pulleys, according to DIN 15020:1974 [4]

	h_1 for wire ropes that are not non-twisting		
Drive group	Rope drum	Rope pulley	Compensating pulley
5_m	25	28	18

Table 8 Coefficients h_2, for calculation of drums, pulleys, and compensating pulleys diameter, according to DIN 15020:1974 [4]

		h_2 for	
Description	w_t	Rope drum and Compensating pulley	Rope pulley
Wire rope that runs on the rope drum and over at least 5 rope pulleys with deflection in the same direction	10 and over	1	1,25

Table 9 Selection factors for calculation of drums and sheaves diameter, according to ISO 4308-1:2003 [1]

Classification of the mechanism	Drums $h_{1'}$	Sheaves $h_{2'}$
M8	25	28

Table 10 Rope type factor for calculation of drums and sheaves diameter, according to ISO 4308-1:2003 [1]

Number of outer strands in the rope	Rope type factor -t
8 to 10 with plastic impregnation	0,95

From formulae (5), with $R_o = 1960\text{N/mm}^2$ and $K' = K' = K1 = 0,330$, $C = 0,118$, and from formulae (4) $d_{\min} = 15,6\text{mm}$.

To calculate the minimum drum, pulleys,[6] and compensating pulleys diameter, DIN 15020:1974 [4] considers the coefficients h_1 shown in Table 7, and the formulae (6). The coefficient h_2 depends on the number of alternating bending stresses—w. In each machine cycle, composed by a hoisting movement up and down, a drum contributes with $w = 1$, a pulley that deflects the wire rope in the same

[5] ISO 4301–1:1986 [16] is referred by ISO 4308–1:2003 [1] for calculation of the mechanism classification group. There is a more recent edition of this standard—ISO 4301–1:2016 [17]. The calculation of the classification group of the mechanism will be out of the scope of this document. However, being heavy duty machines, the

Footnote 5 continued
VTDs and S/R machines lay on the most demanding classification group M8. The author calculated the classification group for this case study and confirmed the M8 class. The most demanding drive group according to DIN 15020:1974 [4] is the 5 m.

[6] A pulley according to DIN 15020:1974 [4] is the same component as a sheave according to ISO 4308–1:2003 [1]. Likewise, a fixed pulley is the same component as a stationary sheave.

Table 11 Calculation of diameter of the steel wire rope, drums, pulleys (sheaves), and compensating pulleys

	DIN 15020 (5 m drive group)	ISO 4308 (M8 classification group)
Min wire rope diameter/ Chosen wire rope diameter	$d_{\min} = 17{,}4$ mm/ $d_{\text{wirerope}} = 18$ mm	$d_{\min} = 15{,}7$ mm/ $d_{\text{wirerope}} = 16$ mm
Total number of bending stresses	$w_t = 11$	Not considered by the standard
Pulleys (sheaves) diameter	630 mm	426 mm
Drum diameter	563 mm	380 mm
Compensating pulley diameter	324 mm	288 mm

Table 12 Force factors according to Feyrer [19]

Loading	Force factor
Friction from the load guidance	
•Roller guidance	$fs_1 = 1.05$
•Rope efficiency	$fs_2 = \frac{1}{2}.\left(1 + \frac{1}{\eta_S}\right)$
Parallel bearing ropes	
•Separate sheaves	$fs_3 = 1.0$
Acceleration, deceleration	
•$0.3 < v_h \leq 0.8$ m/s	$fs_4 = 1.1$

direction contributes with $w = 2$ and a compensating pulley contributes with $w = 0$. Refer to DIN 15020:1974 [4], for more details on this assessment. For this case study, analyzing Fig. 1, $w_t = 11$. According to Table 8, with $w_t > 10$, $h_2 = 1{,}25$ for drums and sheaves, and $h_2 = 1$, for compensating pulleys. The values for the diameters of the components of the system shown in Fig. 1 are obtained by using the formulae (6) with the coefficients from Tables 7 and 8.

$$D_{\min} = h_1.h_2.d_{\text{wirerope}} \quad \text{(Eq 6)}$$

The diameters of the steel wire rope drive components are calculated according to ISO 4308-1:2003 [1], by using the formulae (7), and (8), with the factors shown in Table 9 and Table 10.

$$D_1 = h_{1'}.t.d_{\text{wire rope}} \quad \text{(Eq 7)}$$

$$D_2 = h_{2'}.t.d_{\text{wirerope}} \quad \text{(Eq 8)}$$

where

D_1: Is the minimum pitch circle diameter of the drum;

D_2: Is the minimum pitch circle diameter of the sheave;

$h_{1'}$: Is the selection factor for the drum.

$h_{2'}$: Is the selection factor for the sheave.

t: Is the rope type factor according to Table 10.

The steel wire rope of this case study is 8 strand and has got plastic impregnation, so $h_{1'} = 25$, $h_{2'} = 28$, and

Table 13 Wire rope efficiency on one sheave – η, according to Feyrer [19]

$\frac{D_{\text{sheave}}}{d_{\text{wirerope}}}$	$\frac{S_{\text{cor}}}{d^2_{\text{wirerope}}}$	
	50	100
25	$\eta = 99.0$	$\eta = 99.2$
32	$\eta = 99.3$	$\eta = 99.4$

t = 0,95. With these coefficients and factors and formulae (7) and (8), the values of Table 11 were calculated.

Results: Steel Wire Rope Life Expectancy for the Case Study Reeving System

The Feyrer method [19] is going to be applied to estimate the steel wire rope life, considering that all the requirements from the previous standards have been fulfilled, and all the system was carefully designed.

The correction of the S value, with formulae (9), is detailed in the Feyrer reference [19]. The force factors and are shown in Table 12.

$$S_{\text{cor}} = \frac{Q.g}{n_t}.fs_1.fs_2.fs_3.fs_4 \quad \text{(Eq 9)}$$

where

Q: Is the total load (kg)

g: Is the gravity acceleration (m/s^2)

$fs_1 \ldots fs_4$: are the force factors according to Table 12.

n_t: is the number of load bearing wire ropes.

On the S/R machines and VTDs the hoisting carriage is guided by rollers, so $fs_1 = 1.05$. $fs_3 = 1.0$, because the sheaves are separated. The hoisting speed is 0,5 m/s, thus $fs_4 = 1.1$. The rope efficiency factor—fs_2—is calculated by the ratios $\frac{S_{\text{cor}}}{d^2_{\text{wirerope}}}$ and $\frac{D_{\text{sheave}}}{d_{\text{wirerope}}}$, and formulae (13). The wire rope efficiency on one sheave – η used for the calculation of the total efficiency of the rope drive—η_S is shown in Table 13. Defensively, the value $\eta = 99{,}0$ was considered.

According to Feyrer, the efficiency of the rope drive shall be calculated as follows.

Table 14 Calculation of fs_2 and S_{cor}

	$\frac{S_{cor}}{d^2_{wirerope}}$	$\frac{D_{sheave}}{d_{wirerope}}$	Wire rope efficiency, acc. to Table 13	$fs_2 = \frac{1}{2}\cdot\left(1+\frac{1}{\eta_S}\right)$ acc. to Table 12	S_{cormax} formulae (1)	S_{cormin} formulae (1)
ISO 4308-1: 2003 [1] values for rope and sheaves diameter	72	26,6	Aprox. 99%	1,02	18 356 N	13 008 N
DIN 15020: 1974 [4] values for rope and sheaves diameter	55,7	35	Aprox. 99,3% (considered 99% for the calculation)	1,02	18 356 N	13 008 N

Table 15 Example of constants b_0 to b_3 for discard number of bending cycles calculation for a given 8 strands steel wire rope, according to Feyrer [18]

Rope class	b_0 for N_{A10}(Steel wire rope *zZ*)	b_1	b_2	b_3
Warr.Seale 8 × 36	0.188	0.377	6.232	− 1.750

Table 16 Example of endurance factors f_d, f_L and f_c, for the discard number of bending cycles calculation for one 8 strands steel wire rope, according to Feyrer [19]

Steel wire rope diameter -*d*	$f_d = \frac{0.52}{-0.48+\left(\frac{d}{16}\right)^{0.3}}$
Bending length -*l*	$f_l = \frac{1.49}{2.49-\left(\frac{\frac{L}{d}-2.5}{57.5}\right)^{-0.14}}$
8 strands steel wire rope, steel core polymer covered	f_c = 2.05

$$\eta_{stat} = \eta^{n_{stat}} \quad \text{(Eq 10)}$$

$$\eta_{hang} = \frac{1+\eta}{2} \quad \text{(Eq 11)}$$

$$\eta_{hangtotal} = \eta_{hang}^{n_{hang}} \quad \text{(Eq 12)}$$

$$\eta_S = \eta_{stat}\cdot\eta_{hangtotal} \quad \text{(Eq 13)}$$

where

η_{stat}: Is the total stationary sheaves efficiency

n_{stat}: Is the total number of stationary sheaves, n_{stat} = 3

η_{hang}: Is the hanging sheave efficiency

$\eta_{hangtotal}$: Is the total efficiency of the hanging sheaves

n_{hang}: Is the total number of hanging sheaves, $n_{hang} = 2$

η: Is the wire rope efficiency of one sheave, according to Table 13

η_S: Is the total efficiency of the rope drive

Considering $\eta = \frac{99\%}{100\%}$ = 0,99, and with the ISO 4308–1:2003 [1] values for the pulleys, sheaves, and steel wire ropes diameter, from formulae (10), $\eta_{stat} = 0,97$, from (3) η_{hang} = 0,995, and from (12), $\eta_{hangtotal}$ = 0,99. The total efficiency of the rope drive is $\eta_S = 0,96$. In Table 14, S_{cormax} is the tension on the steel wire rope when a load with maximum weight is on the hoisting carriage, and S_{cormin} is the tension on the steel wire rope when there is no load on the hoisting carriage. The S_{cormax} and S_{cormin} values will be calculated through formulae (9), to build Table 14.

This data are going to be used as input values on the calculation program developed by the Stuttgart University [20]. It is out of the scope of this document to dive deeply on the calculation, however for some clarification, the calculation program will compute the number of bending

Table 17 Inputs and results of the application of the calculation program [20]. Example: Calculation of the number of working cycles under the maximum load S_{cormax}, with the values of sheave diameter, wire rope diameter calculated according to ISO 4308, refer to Table 11

Input data		
Number of working cycles	Z_{A10}	.
Rope construction	WS	.
Number of stands	8	.
Rope core	ESWRC	.
Lay direction	zZ	.
Rope tensile force—*S*	18,356	kN
Sheave diameter –*D*	425,6	mm
Nominal rope diameter –*d*	16	mm
Nominal strength -R_o	1960	N/mm^2
Bending length –*l*	27800	mm
Rel. tensile force difference	0	.
Simple bendings per working cycle	11	.
Reverse bendings per working cycle	0	.
Comb. Fluctuating tension and bendings per working cycle	0	.
Results		
Number of working cycles -Z_{A10}	22 500	.

cycles by the formulae (14), with constants and endurance factors given has example in Tables 15 and 16.[7]

$$\log N = b_0 + \left(b_1 + b_3.\log\frac{D}{d}\right).\left(\log\frac{S}{d^2} - 0,4.\log\frac{R_0}{1770}\right) + b_2.\log\frac{D}{d} + \log f_d + \log f_l + \log f_c \quad \text{(Eq 14)}$$

where

D: Is the sheave diameter (mm).

d: Is steel wire rope diameter (mm).

R_o: Is the minimum tensile strength of the wire used in the rope (N/mm^2).

S: Is the rope tensile force (N).

The constants b_0 to b_3 and the endurance factors f_d, f_L and f_c are rope construction related and were gathered by experimentation. They can be found on reference [19], refer to Tables 15 and 16.

The values of the previous paragraphs are now used as inputs on the calculation program. As an example, in Table 17, the input data according to ISO 4308–1:2003 [1], see Table 11, is introduced for calculation of the number of working cycles Z_{A10} with the maximum load on the hoisting carriage – S_{cormax}. Z_{A10} is the number of hoisting cycles which, with a certainty of 95%, no more than 10% of the ropes have to be discarded. The bending length-l, is the length of the wire rope that, in this case study, runs in the higher number of sheaves, thus $l = 2 \times$ Hoisting stroke, approximately, once it is a differential system.

EN 528:2008 [2] does not define a minimum value for the steel wire rope service life. However, in complex systems like the one shown in Fig. 1, due to the requirement for low maintenance stopping times, the typical minimum expectation from the customer would be one year, but 2 years working in two shifts of 8 h, 5 days week would be a good target.

Considering that the S/R machine is with the maximum load 2/3 of the cycle time[8] (combined cycle), Z_{A10} is calculated with formulae (15). Table 18 summarizes the results from the application of the formulae (15), with the input values given by the calculation program [20][9].

Table 18 Summary of the results of the application of the Feyrer method for calculation of the number of working cycles of a steel wire rope

Required number of cycles acc. ISO 4308-1:1986-M8 mechanism class		$Z_{A10} = 43\,200$
Required number of cycles: 2 year/ 2 shifts of 8 hours/5 working days. Combined cycle time: 30 Cycles/hour		240 000 Cycles
	Z_{A10}	Z_{Am}
ISO 4308-1:2003 [1] values for d_{wirerope} and D_{sheave}.	27 198	76 736
DIN 15020:1974 [4] values for d_{wirerope} and D_{sheave}.	102 660	289 457

$$Z_{A10} = \frac{N_{A10(S_{\text{cormax}})}.N_{A10(S_{\text{cormin}})}}{N_{A10(S_{\text{cormin}})}.t_{S_{\text{cormax}}} + N_{A10(S_{\text{cormax}})}.t_{S_{\text{cormin}}}} \quad \text{(Eq 15)}$$

where

$N_{A10(S_{\text{cormax}})}$: is the number of working cycles Z_{A10}, under the maximum load S_{cormax}

$N_{A10(S_{\text{cormin}})}$: is the number of working cycles Z_{A10}, with no load on the hoisting carriage (only deadload) S_{cormin}

$t_{S_{\text{cormax}}}$: is the time fraction with maximum load S_{cormax} (2/3).

$t_{S_{\text{cormin}}}$: is the time fraction without load S_{cormin} (1/3).

Z_{A10} (90% wire ropes will achieve this life before discard criteria)

Z_{Am} (50% wire ropes will achieve this life before discard criteria)

Remark 1: According to Feyrer [18], the values of the table would need to be corrected considering deviations from the optimum design. These F_{N1} to F_{N4} correction parameters take in account a non-perfect lubrication, sheaves groove radius smaller than the defined one, for example. In this document it is considered that the design fulfilled all these requirements, so all the $F_N = 1$.

Remark 2: On this calculation it is considered that the drum diameter is equal to the sheave diameter. The minimum sheaves diameter is bigger than the minimum drum diameter, according to Table 11.

Conclusions

In this case study it was not possible to ensure the minimum number of cycles defined in ISO 4308-1:1986 with the application of the ISO 4308-1:2003 calculated steel

[7] The constants and endurance factors shown on the Table 15 and Table 16, are not necessarily the ones that were used by the calculation program for the case study. They are shown only as an example. These values are part of the know-how gathered by the Stuttgart University in several tests and they are not accessible to the program user. Some steel wire rope manufacturers have determined these values for their manufactured rope but is also part of their non-shareable knowledge.

[8] In a typical application, in a combined cycle the load handling device of the S/R machine will transfer the load (assumed to always have the maximum weight) that is on an input conveyor, to its hoisting carriage. Afterwards, the hoisting carriage will move upwards, and the load handling device (commonly forks) will store the load on the rack. The S/R machine will now move without load to another rack position and transfer another load (with maximum weight) to its hoisting carriage. Then, this load is going to be retrieved in another conveyor (output conveyor).

[9] This definition was found on reference [19], page 277, Table 3.8.

wire rope diameter and sheaves diameter. Moreover, the minimum number of 43 200 cycles is very low in comparison with the duty cycles that the S/R machine may achieve working 2 years in 2 shifts of 8 h, 5 days a week.

The machine will probably not work these two daily shifts constantly with a 30 cycles/hour throughput, and the load on the hoisting carriage may not be always the maximum. However, the number of cycles $Z_{A10} = 27\ 192$ is so far from the required 240 000, that it is possible to say that the required number of cycles will certainly not be achieved. The fact that the ISO 4308–1:2003 does not take in account the number of steel wire rope bendings on each lifting cycle, leads to these poor results on the rope life expectancy. Refer to DIN 15020-Part2:1974 [21] for more information about the discard criteria for a steel wire rope.

By the application of the DIN 15020:1974, the expected number of cycles Z_{A10}, was more than three times higher than the one that resulted from the application of the ISO 4308-1:2003. This happens due to the consideration of the factor h_2 = 1,25 on the sheave diameter calculation. Notice that the R_o of the steel wire rope is not considered for the calculation of the c parameter, for the most demanding mechanism classes. The c value is the same for steel wire ropes with different R_o, and this value is bigger than the C defined by ISO 4308-1:2003. As a result, the calculated steel wire rope diameter $d_{\min}$ is higher than the one obtained from the application of ISO 4308-1:2003. However, this increased d_{wirerope} will have a big economic impact on the machine, and the manufacturer may try to reach to a similar number of cycles by using other solutions with lower economic impact.[10] Nevertheless, it was not possible to reach the Z_{A10} = 240 000 cycles, but it is possible to admit that more than 50% of the ropes would reach 240 000 cycles before discard, since $Z_{\text{Am}} = 289\ 457$. Z_{Am}, occurs before Z_{10}. Z_{10}, is the number of hoisting cycles which, with a certainty of 95%, no more than 10% of the ropes break. This means that it may be possible to estimate that 90% of the steel wire ropes would last the 2 years working 2 shifts of 8 h, 5 days a week, before breaking.

References like Feyrer and the new ISO 16625, currently under ballot, introduce methods to estimate the steel wire rope service life, so that is possible to study the impact on the life expectancy of the rope, of the improvements in the reeving system design. Feyrer, also allows a clearer determination of the S value, setting clearer correction parameters f_s.

[10] The discussion of different solutions to increase the steel wire rope service life is out of the scope of the document. The goal of the document is to assess the steel wire rope life expectancy with the direct application of the ISO 4308–1:2003 [1] and DIN 15020:1974 [4] standard and compare it with the typical requirements from the customers.

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