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Theoretical comparison of ISO/WD 16625:2023 with DIN EN 13001-3-2:2015 for the selection and verification of wire ropes for cranes and hoists

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ABSTRACT The paper focuses on a theoretical comparison between the newly designed ISO/WD 16625:2023 and DIN EN 13001-3-2:2015 valid at EU level in the context of the proof of competence of running wire ropes in vertical rope drives of cranes and hoists. The differences between the approaches to the proof of static strength and the proof of fatigue strength are discussed. With the help of the definition of application examples, variations in load spectrum factors and total number of working cycles, for the selected group class A_c3 for a 4/1 reeving system are considered by calculation and the results are compared with each other. There is also a variation of the ratio of the rope bending diameter D to the rope diameter d and the lifting range with an influence on the bending cycles per working cycle. This shows that, compared to DIN EN 13001-3-2:2015, the new ISO/WD 16625:2023 leads to a partially significant increase in the number of wire ropes required over the service life of a crane or hoist by taking into account the maximum tensile force of wire ropes depending on the D/d-ratio. DIN EN 13001-3-2:2015 refers to a single characteristic curve with a defined exponent, which calculates a higher load capacity for a rope in the event of fatigue. However, this results in risks of premature and unpredictable failure. The new ISO/WD 16625:2023 corrects and approximates the realistic fatigue behavior, which increases the safety of crane operation.

KEYWORDS ISO 16625, cranes, hoists, wire rope, proof of competence, static strength, fatigue strength, running rope

1. Introduction

Wire ropes are significant and safety-relevant components in cranes and hoists. In comparison to fixed stationary ropes, wire ropes for lifting and lowering loads during operation are referred to as running ropes. These are characterized by running over sheaves or winding and unwinding on drums. This results in frequent rope bending, which has a significant influence on the service life and discard state of a rope. Decades of research in this field have resulted in a large number of influencing parameters and equations for calculating a rope drive for cranes and hoists. A trial to increase the possibilities in rope drive design using further influencing factors resulted in the national standard DIN EN 13001-3-2:2015 (analogous to EN 13001-3-2:2014) with the corrigendum DIN EN 13001-3-2/A1:2017. Other national standards for the calculation and design of rope drives are the established DIN 15020-1:1974 and the guideline VDI 5020:2024 to be seen as an update of DIN 15020. As international standard the ISO 16625:2013 is available for the selection of wire ropes, drums and sheaves for cranes and hoists. This takes into account the design factor Z_p as a multiplier for the maximum rope force S to determine the minimum breaking force F_{min} for the simplified selection of a rope. The standard is to be replaced in future by a new version with a completely revised proof of competence procedure for running wire ropes. The ISO/TC 96/SC 3/WG 3 working group around Prof. Dr. Markus Golder as project leader has been working on this since 2015. The paper shows the differences compared to DIN EN 13001-3-2:2015. The focus is on the proof of fatigue strength of running ropes. For this purpose, application examples with a variation of relevant parameters are defined and the results are shown in the paper. [1] [2] [3] [4] [5] [6]

2. Specifics of the ISO/WD 16625:2023 and the DIN EN 13001-3-2:2015

2.1. Overview of proof of competences for running ropes

The following conditions are defined for the proof of competence of running ropes. With regard to the design rope force, a distinction is made within the standard between the vertical lifting of loads as the most common application and the general non-directional application. The paper refers exclusively to the proof of competence of vertical lifting and lowering of loads. Stationary ropes are also not considered. Equation (1) must be fulfilled for the proof of static strength. Equation (2) applies to the proof of fatigue strength.

– Proof of static strength

$$F_{\mathrm{Sd,s}} \leq F_{\mathrm{Rd,s}} \tag{1}$$

with $F_{\mathrm{Sd,s}}$ ... design rope force for the proof of static strength

$F_{\mathrm{Rd,s}}$ ... limit design rope force for the proof of static strength

– Proof of fatigue strength

$$F_{\mathrm{Sd,f}} \leq F_{\mathrm{Rd,f}} \tag{2}$$

with $F_{\mathrm{Sd,f}}$ ... design rope force for the proof of fatigue strength

$F_{\mathrm{Rd,f}}$ ... limit design rope force for the proof of fatigue strength

In addition, the standard also allows the proof of competence of multilayer spooling. The calculations in the paper only take into account single-layer spooling.

2.2. Theoretical comparison of the single equations

Proof of static strength

The design rope force for a single rope during vertical lifting essentially depends on the nominal load capacity m_{Hr}, the number of load-bearing ropes at the reeving n_{m} and other factors. Equation (3) is identical for DIN EN 13001-3-2:2015 and ISO/WD 16625:2023. The rope force increasing factors f_{S1} to f_{S3} and the coefficients γ_{p} and γ_{n} are also defined in the same way. There are isolated differences in the calculation of the dynamic coefficients Φ. These are basically dependent on the load combinations A, B and C and thus defined load cases. A selection is shown in Table 1. The dynamic coefficients are identical for load combinations A and B. The emergency stop case is defined by the specific load combination C6. Table 1 shows a difference in the formulation. The specific load combinations C1 and C3 differ in the internal calculation.

$$F_{\mathrm{Sd,s}} = \frac{m_{\mathrm{Hr}} \cdot g}{n_{\mathrm{m}}} \cdot \Phi \cdot f_{\mathrm{S1}} \cdot f_{\mathrm{S2}} \cdot f_{\mathrm{S3}} \cdot \gamma_{\mathrm{p}} \cdot \gamma_{\mathrm{n}} \tag{3}$$

Table 1: Definition of the dynamic factor Φ for different load combinations

DIN EN 13001-3-2:2015	ISO/WD 16625:2023	Load combination and discription
$\Phi = \Phi_2$	$\Phi = \Phi_2$	A1 - Cranes under normal service conditions, hoisting and depositing loads
$\Phi = 1 + \Phi_5 \cdot \frac{a_{\mathrm{vert}}}{g}$	$\Phi = 1 + \Phi_5 \cdot \frac{a_{\mathrm{vert}}}{g}$	A3 - Cranes under normal service conditions, accelerating the suspended load
$\Phi = \Phi_2$	$\Phi = \Phi_2$	B1 - Cranes under normal service conditions, hoisting and depositing loads, with in-service wind and loads from other climatic effects
$\Phi = 1 + \Phi_5 \cdot \frac{a_{\mathrm{vert}}}{g}$	$\Phi = 1 + \Phi_5 \cdot \frac{a_{\mathrm{vert}}}{g}$	B3 - Cranes under normal service conditions, accelerating the suspended load, with in-service wind and loads from other climatic effects
$\Phi = \Phi_{2\mathrm{c}}$	$\Phi = \Phi_{2\mathrm{c}}$	C1 - Cranes under in-service conditions hoisting a grounded load under the exceptional circumstance
$\Phi = \Phi_6$	$\Phi = \Phi_6$	C3 - Cranes under test conditions
$\Phi = \Phi_5$	$\Phi = 1 + \Phi_5 \cdot \frac{a_{\mathrm{NA}}}{g}$	C6 - Cranes with emergency cut-out

The individual parameters in the equations are defined as follows:

Φ_2 ... factor for hoisting a grounded load (load combination A and B)

Φ_{2c} ... factor for hoisting a grounded load (load combination C)

Φ_5 ... factor for dynamic loads arising from acceleration of crane drives

Φ_6 ... factor for effects of dynamic load tests

γ_p ... partial safety factor (A: γ_p = 1,34 / B: γ_p = 1,22 / C: γ_p = 1,1)

γ_n ... coefficient for high-risk applications (γ_n = 1 for normal applications)

The values or the equations for determining the values of the parameters given above are defined in DIN EN 13001-3-2:2015 or DIN EN 13001-2:2021 and ISO/WD 16625:2023 or ISO 8686-1:2012 depending on other variables. The dynamic factors Φ_2 and Φ_5 are defined in the same way in the national and international standard. There are partial differences for Φ_{2c} and fundamental differences for Φ_6. The dynamic factor Φ_{2c} is dependent on defined speeds in accordance with DIN EN 13001-2:2021 and ISO 8686-1:2012 for load combination C. In contrast, different values are defined for hoist drive classes HD1 and HD3. This results in different dynamic factors for these hoist drive classes for the specific load combination C1. All other hoist drive classes for load combination C are defined in the same way. Equations (4) and (5) are defined for determining the dynamic factor Φ_6 in accordance with DIN EN 13001-2:2021.

$$\Phi_6 = \Phi_2 \quad \text{for dynamic test load with 110\% of the hoist load} \tag{4}$$

$$\Phi_6 = 1 \quad \text{for static test load of 125\% of the hoist load} \tag{5}$$

ISO 8686-1:2012 calculates the dynamic factor Φ_6 for test loads taking into account ISO 4310:2009 according to Equation (6).

$$\Phi_6 = 0{,}5 \cdot (1 + \Phi_{2c}) \quad \text{for dynamic test load of 110\% of the hoist load} \tag{6}$$

To fulfill the proof of static strength, the limit design rope force $F_{\mathrm{Rd,s}}$ must be determined according to Equations (7) and (8) depending on the respective standards.

$$F_{\mathrm{Rd,s}} = \frac{F_{\mathrm{u}}}{\gamma_{\mathrm{rb}}} \quad \text{from DIN EN 13001-3-2:2015} \tag{7}$$

$$F_{\mathrm{Rd,s}} = \frac{F_{\mathrm{min}}}{\gamma_{\mathrm{rb}}} \cdot \min(f_{S4}; f_{S5}) \quad \text{from ISO/WD 16625:2023} \tag{8}$$

with F_{u} or F_{min} ... specific minimum breaking force of the rope

γ_{rb} ... minimum rope resistance factor

The new version of ISO/WD 16625:2023 provides for the determination of the limit design rope force with the lower value of the rope force increasing factors f_{S4} and f_{S5}. The factor f_{S4} depends on the rope end connection and can vary between 0,8 and 1. On the other hand, the calculation of f_{S5} is a function of the D/d-ratio. According to the standard, the values for recommended D/d-ratios are between 0.886 for D/d = 11,2 and 0,955 for D/d = 31,5. When comparing f_{S4} and f_{S5}, the lowest value f_{S4} of 0,8 is always used to determine the limit design rope force when using wedge sockets or wire rope clips as rope end connections. The rope force resistance factor γ_{rb} is also determined in DIN EN 13001-3-2:2015 using Equation (9) as a function of the D/d-ratio. The factor is specified in ISO/WD 16625:2023 with γ_{rb} = 2. The value results from the product of the general resistance factor γ_m and the specific resistance coefficient γ_s = 1,82.

$$\gamma_{\mathrm{rb}} = 1{,}35 + \frac{5{,}0}{\left(\frac{D}{d}\right)^{0{,}8} - 4} \geq 2{,}07 \qquad \text{from DIN EN 13001-3-2:2015} \qquad (9)$$

It should be noted that the D/d-ratio for the rope bending diameter D always uses the minimum diameter of the drum, the sheave or the compensating sheave. In DIN EN 13001-3-2:2015, the diameter of the drum is corrected by a factor of 1,125. However, there is no correction in ISO/WD 16625:2023.

Proof of fatigue strength

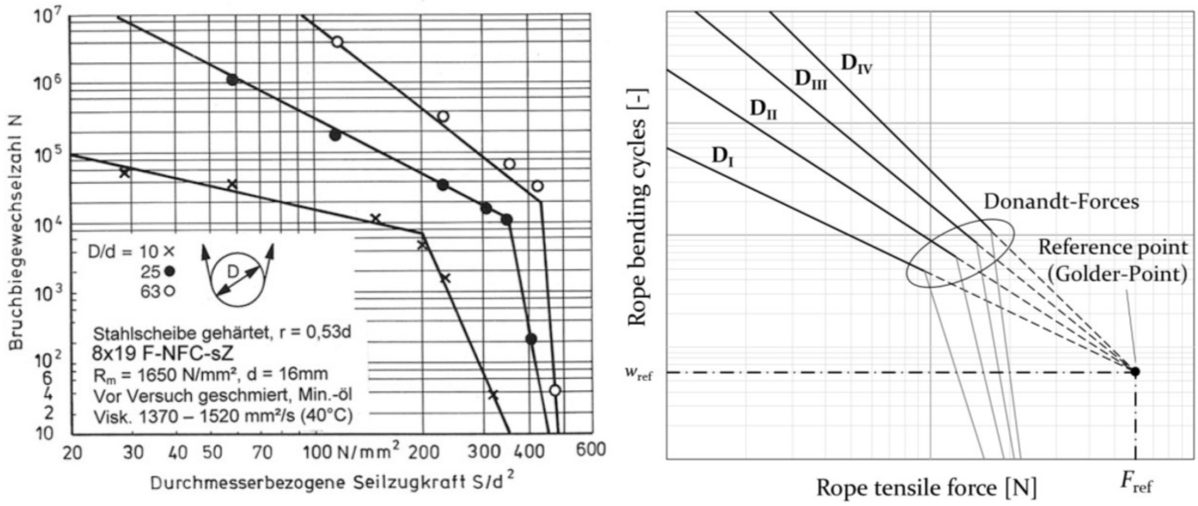
The proof of fatigue strength in DIN EN 13001-3-2:2015 is based on the research results of Feyrer, who initiated the method Stuttgart and carried out a large number of bending fatigue tests on wire ropes. The focus is on the relationship according to Equation (10) between the D/d-ratio and the total number of bending cycles during the design life of a rope w_{tot}. [4] [7] [8]

$$\frac{D}{d} \sim 1{,}125^{\log_2(w_{\mathrm{tot}})} \qquad (10)$$

In the DIN EN 13001-3-2 it is assumed that the design life curve of a rope has a constant gradient of 3 in the form of a straight line in a double-logarithmic representation of the number of bending cycles and specific tensile force. Further details on this Wöhler curve are not known. This curve is used to derive the service life of running ropes for different D/d-ratios via the reference ratio R_{Dd}, with an influence on the rope force increasing factor f_{Fl} and thus on the limit design rope force. Taking into account numerous service life tests on ropes, the approach cannot be reproduced or confirmed in the literature. In addition, a reference point is defined with a number of bendings of $w_D = 5 \cdot 10^5$, which is considered too high. A critical discussion of that value can be found in [9]. With the characteristic value and the total number of bending cycles w_{tot}, the relative number of bending cycles υ_r in DIN EN 13001-3-2:2015 can be calculated according to Equation (11).

$$\nu_{\mathrm{r}} = \frac{w_{\mathrm{tot}}}{w_{\mathrm{D}}} \tag{11}$$

The new ISO/WD 16625:2023 is based on a newly defined reference point, which was determined by a regression calculation using the Stuttgart method for forces. The reference point represents an intersection of the individual Wöhler characteristic curves for different D/d-ratios. It should be noted that the characteristic curves must be extended beyond the Donandt-force. The new reference point is characterized by a lower number of bending cycles w_{ref} with a simultaneously very high rope force F_{ref}. It is a virtual point that can be determined by calculation and is permissible by calculation. Figure (1) shows in (a) an example of different Wöhler curves of a 8x19 rope depending on different D/d-ratios and also shows in (b) the schematic representation of the new approach of ISO/WD 16625:2023. [4]



(a) (b)

Figure 1: (a) Lifetime diagram of a 8x19 rope as an example of the curves of different D/d-ratios [8] and (b) Schematic diagram from ISO/WD 16625:2023 to illustrate the new reference point proposed as the Golder-Point as an extension of the Wöhler curves for individual D/d-ratios [2]

The corresponding number of bending cycles w can be determined from the reference point proposed as the Golder-Point for each rope tension force F according to Equation (12). The number of bending cycles w_{ref} at the Golder-Point can be calculated with the Equation (13) using the factor f_{w} of further influences to w_{ref} (see ISO/WD 16625:2023).

$$w = \left(\frac{F_{\mathrm{ref}}}{F}\right)^{m} \cdot w_{\mathrm{ref}} \tag{12}$$

$$w_{\mathrm{ref}} = 600 \cdot f_{\mathrm{w}} \tag{13}$$

The slope m of the Wöhler curve for the given D/d-ratio is taken into account, which can be calculated according to Equation (14).

$$m = 2{,}6 \cdot log\left(\frac{D}{d}\right) - 1{,}6 \tag{14}$$

The design rope force for the proof of fatigue strength $F_{Sd,f}$ in vertical hoisting of loads can be calculated using Equation (15) for both standards.

$$F_{\mathrm{Sd,f}} = \frac{m_{\mathrm{Hr}} \cdot g}{n_{\mathrm{m}}} \cdot \Phi^* \cdot f_{\mathrm{S2}}^* \cdot f_{\mathrm{S3}}^* \cdot \gamma_{\mathrm{n}} \tag{15}$$

The dynamic factors for the verification of fatigue strength are based on the dynamic factors from Table 1. In addition, a transformation according to Equation (16) is carried out using the maximum number of bending cycles w_{max}. This only applies to the maximum lifting height. To calculate the design rope force, the largest dynamic factor from the comparison of all the dynamic factors for the individual load combinations must be used.

$$\Phi^* = \sqrt[3]{\frac{(w_{\mathrm{max}}-1)+\phi^3}{w_{\mathrm{max}}}} \qquad \text{for } w_{\mathrm{max}} \geq 1 \tag{16}$$

The rope force increasing factors f_{S2}^* and f_{S3}^* can be determined using Equations (17) and (18). The factor f_{S2}^* refers to the actual lifting height above the vertical coordinates z_1 and z_2. In addition, a reference height z_{ref} and the angle β between the falls and the line of action of the force as a function of the coordinate z_2 must be taken into account. Chapter 2.3 shows the derivation for calculating the angle β.

$$f_{\mathrm{S2}}^* = 1 + \left[\frac{1}{\cos\beta(z_2)} - 1\right] \cdot \left(\frac{z_{\mathrm{ref}}-z_2}{z_{\mathrm{ref}}-z_1}\right)^{0,9} \tag{17}$$

$$f_{\mathrm{S3}}^* = f_{\mathrm{S3}} \tag{18}$$

Due to the new approach, the determination of the limit design rope force for the proof of fatigue strength differs significantly between DIN EN 13001-3-2:2015 with Equation (19) and ISO/WD 16625:2023 with Equation (20). In DIN EN 13001-3-2:2015 the limit design rope force is based on the specific minimum breaking force of the rope with a correction by various parameters. In particular, the root of the rope force history parameter has an exponent of 3. In contrast, the estimation of the limit design rope force in ISO/WD 16625:2023 is the minimum of two different terms. The first term often dominates the result. The calculation is based on the reference rope tension force F_{ref}.

In comparison, the exponent of the root is defined by the slope m of the Wöhler curve. This directly takes into account the influence of the D/d-ratio.

$$F_{\mathrm{Rd,f}} = \frac{F_{\mathrm{u}}}{\gamma_{\mathrm{rf}} \cdot \sqrt[3]{s_{\mathrm{r}}}} \cdot f_{\mathrm{f}} \qquad \text{from DIN EN 13001-3-2:2015} \tag{19}$$

with γ_{rf} ... rope resistance factor (γ_{rf} = 7 in DIN EN 13001-3-2:2015)

s_r ... rope force history parameter

f_f ... factor of further influences

$$F_{\mathrm{Rd,f}} = \min\left\{\frac{F_{\mathrm{ref}}}{\gamma_{\mathrm{rf}} \cdot \sqrt[m]{s_{\mathrm{r}}}}; \frac{F_{\mathrm{min}}}{\gamma_{\mathrm{rfD}}}\right\} \qquad \text{from ISO/WD 16625:2023} \tag{20}$$

with γ_{rf} ... rope resistance factor (γ_{rf} = 1,25 in ISO/WD 16625:2023)

γ_{rfD} ... minimum rope resistance factor to prevent from exceeding the Donandt-force depending on the D/d-ratio

s_r ... rope force history parameter

m ... slope of the Wöhler curve

The reference rope tension force F_{ref} is determined by the following Equation (21). The factor γ_{ref} is set to 0,5. It increases the minimum breaking force F_{min} to the reference rope tension force, whereby a survival probability of at least 97,7% is achieved. The factor f_F is a product of various influencing factors (see ISO/WD 16625:2023).

$$F_{\mathrm{ref}} = \frac{F_{\mathrm{min}}}{\gamma_{\mathrm{ref}}} \cdot f_{\mathrm{F}} \tag{21}$$

The rope force history parameter s_r is calculated in the same way for both standards. Equation (22) can be used for this purpose. It is the product of the rope force spectrum factor k_r and the relative total bending cycle number. Depending on the standard, these are calculated according to Equations (23) and (24). In ISO/WD 16625:2023, the factor k_r is also referred to as the rope force bending spectrum factor.

$$s_{\mathrm{r}} = k_{\mathrm{r}} \cdot \nu_{\mathrm{r}} \tag{22}$$

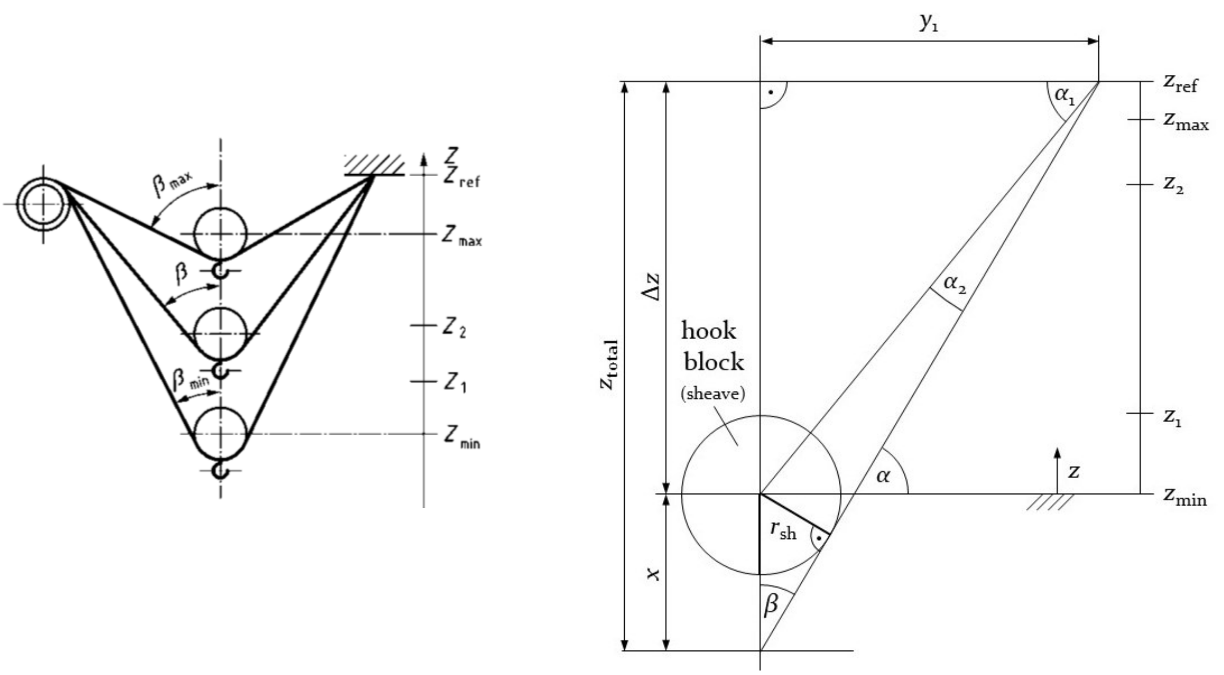
with $$\nu_{\mathrm{r}} = \frac{w_{\mathrm{tot}}}{w_{\mathrm{D}}} \qquad \text{from DIN EN 13001-3-2:2015} \tag{23}$$

$$\nu_{\mathrm{r}} = \frac{w_{\mathrm{tot}}}{w_{\mathrm{ref}}} \qquad \text{from ISO/WD 16625:2023} \tag{24}$$

The relative number of bending cycles υ_r differs considerably between the standards due to the very different values of w_D and w_{ref}. In relation to the total number of bending cycles w_{tot}, the relative number of bending cycles in ISO/WD 16625:2023 is significantly higher. The high value of w_D implies a long design life of the rope, which does not correspond to reality.

2.3. Derivation of the angle beta between falls and line of action of the force

At the proof of fatigue strength, the consideration of the lifting range $\Delta z = z_2 - z_1$ has a major influence on the number of bending cycles w during a cycle and on the required number of ropes during the service life of a crane or hoist. If the lifting height is specified as the full lifting range, the maximum number of bending cycles w_{max} is reached in the system during a cycle. Depending on the application, there are often limited lifting ranges during operation. As a result, the rope also experiences a lower number of bending cycles during a cycle, which has a positive effect on the design life of the rope. To calculate the rope force increasing factor f_{S2}^* according to Equation (17) for non-parallel rope falls, the angle β depends on the vertical coordinate z_2. The maximum lifting height results in the angle β_{max}, which is often a geometric specification in a rope drive. An equation for $\beta(z_2)$ can be derived from Figure 2 so that deviating lifting heights can also be taken into account mathematically during the proof of fatigue strength.



(a) (b)

Figure 2: (a) Diagram to define the angle ß between the falls and the line of action of the force with all coordinates [2] and (b) graphic to derive the angle ß as a function of the coordinate z_2

In the first step, the distance y_1 can be described using Equation (25). By inserting the angle β_{max} for the full lifting height z_{max} of the hoist, a fixed system value is obtained. A reference height z_{ref} to be defined and the diameter of the rope sheave $D_{sheave} = 2 \cdot r_{sh}$ must also be taken into account.

$$y_{\text{rb}} = \tan(\beta) \cdot \left[(z_{\text{ref}} - z) + \frac{D_{\text{sheave}}}{2 \cdot sin(\beta)}\right] \tag{25}$$

In the second step, Equation (26) can be formulated on the basis of Figure 2. This represents a function of the angle β as a function of the freely selectable coordinate z. The determined value y_1 must be used. The equation can be used to determine the corresponding angle $\beta(z_2)$ for the coordinate z_2 in order to determine f_{S2}^* for any lifting height.

$$\beta(z) = 90° - \left[arctan\left(\frac{z_{\text{ref}} - z}{y_1}\right) + arcsin\left(\frac{D_{\text{sheave}}}{2 \cdot \sqrt{(z_{\text{ref}} - z)^2 + {y_1}^2}}\right)\right] \tag{26}$$

The correlations apply to DIN EN 13001-3-2:2015 and ISO/WD 16625:2023, as the calculation of f_{S2}^* is the same for both standards.

3. Application examples for calculation comparison

3.1. Classification of cranes and hoists

The classification of cranes and mechanism, including hoists, is currently defined by the standards DIN 15020:1974, FEM 9.511:1986, DIN EN 13001-1:2015 and ISO 4301-1:2016 (successor to ISO 4301-1:1986). The older standards relate to the classification of drive groups or classification of mechanism, taking into account the load spectrum and the total duration of use. The new ISO 4301-1:2016 standard is based on load spectrum and cycles. In this context, these new class designations will be used in actual and future standardization. Older classes with defined total durations of use can only be assigned to the new classes with defined cycles if the lifting speed and lifting height are taken into account. The average lifting time required for the transformation can be determined from this. Table 2 shows the new group classification of cranes and mechanism.

Table 2: Classes A_C for group classification of cranes and hoists according to ISO 4301-1:2016

Class Q_p	Load spectrum factor K_p	Class U with total number of working cycles C and class A_c									
		U0	U1	U2	U3	U4	U5	U6	U7	U8	U9
		1,6E+04	3,15E+04	6,3E+04	1,25E+05	2,5E+05	5,0E+05	1,0E+06	2,0E+06	4,0E+06	8,0E+06
Q_p0	0,0313	A_c03	A_c02	A_c01	A_c0	A_c1	A_c2	A_c3	A_c4	A_c5	A_c6
Q_p1	0,0625	A_c02	A_c01	A_c0	A_c1	A_c2	A_c3	A_c4	A_c5	A_c6	A_c7
Q_p2	0,1250	A_c01	A_c0	A_c1	A_c2	A_c3	A_c4	A_c5	A_c6	A_c7	A_c8
Q_p3	0,2500	A_c0	A_c1	A_c2	A_c3	A_c4	A_c5	A_c6	A_c7	A_c8	A_c9
Q_p4	0,5000	A_c1	A_c2	A_c3	A_c4	A_c5	A_c6	A_c7	A_c8	A_c9	A_c10
Q_p5	1,0000	A_c2	A_c3	A_c4	A_c5	A_c6	A_c7	A_c8	A_c9	A_c10	A_c11

The transformation of Table 2 leads to Table 3, in which the total working cycles as a function of the load spectrum factor K_p and the classes A_c0 to A_c6 are shown as examples.

Table 3: Total number of working cycles for the classes A_c0 to A_c6

Class Q_p	Load spectrum factor K_p	Class A_c and total number of working cycles C						
		A_c0	A_c1	A_c2	A_c3	A_c4	A_c5	A_c6
Q_p0	0,0313	125.000	250.000	500.000	1.000.000	2.000.000	4.000.000	8.000.000
Q_p1	0,0625	63.000	125.000	250.000	500.000	1.000.000	2.000.000	4.000.000
Q_p2	0,1250	31.500	63.000	125.000	250.000	500.000	1.000.000	2.000.000
Q_p3	0,2500	16.000	31.500	63.000	125.000	250.000	500.000	1.000.000
Q_p4	0,5000	8.000	16.000	31.500	63.000	125.000	250.000	500.000
Q_p5	1,0000	4.000	8.000	16.000	31.500	63.000	125.000	250.000

3.2. Example of a hoist and variation of specific parameters

For the practical comparison of DIN EN 13001-3-2:2015 and ISO/WD 16625:2023, a concrete example is defined by specifying selected parameters for the hoist according to Table 4 and for the rope according to Table 5. In addition, individual parameters are varied in order to be able to assess their influence on the verification process more precisely. Based on a hoisting speed of 8 m/min, the selected class A_c3 can be assigned to drive group 2m or class of mechanism M5 via the specified lifting height of 10 m.

Table 4: Parameter of the hoist

Group classification	-	A_c3 (2m/M5)
Nominal Load	m_{Hr}	6,3 t
Lifting height	z_{max}	10 m
Maximum Hoisting speed	$v_{h,max}$	8 m/min
Hoisting creep speed	$v_{,h,CS}$	1,33 m/min
Acceleration	a_{vert}	0,25 m/s^2
Acceleration due to emergency cut-out	a_{NA}	0,5 m/s^2
Hoist drive class	-	HD3
Hoisting class	-	HC1
Reeving system	-	4/1
Angle between falls and action line of the force	β_{max}	30°
Fleet angle	δ	4°

Table 5: Properties of the rope

Type of the rope	-	non-rotation resistant
Rope lubrication	-	internal lubrication
Rope end fastening	-	Wedge socketing
Minimum breaking force	F_u / F_{min}	169.900 N
Tensile strength of wire / Rope Grade	R_r	2.160 N/mm^2
Diameter	D	13 mm
Number of outer strands	n_{AL}	8

The D/d-ratio and the lifting range are defined as parameters for an investigation. Table 6 shows the recommended D/d-ratios for the respective classes A_c, based on ISO/WD 16625:2023. By multiplying by the rope diameter d, the rope bending diameter D can be calculated as a geometric value for a drum or sheave. In addition to selecting the D/d-ratio for class A_c3, a smaller and a larger ratio are also selected for comparison.

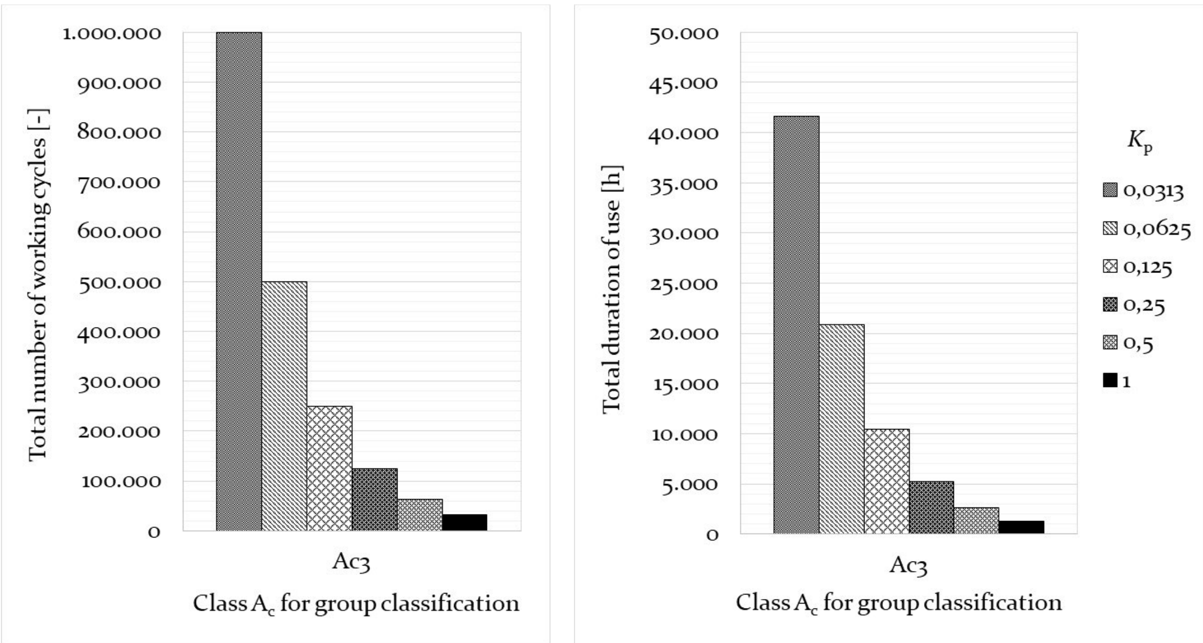
Table 6: Commonly used values of D/d-ratio [2] and selection of various D/d-ratios for the comparison

		Case 1		Case 2		Case 3	Case 4	Case 5	Case 6		
Class A_c		A_c1	A_c2	A_c3	A_c4	A_c5	A_c6	A_c7	A_c8	A_c9	A_c10
D/d	[-]	11,2	12,5	14,0	16,0	18,0	20,0	22,4	25,0	28,0	31,5
d	[mm]	13	-	13	-	13	13	13	13	-	-
D	[mm]	145,6	-	182	-	234	260	291,2	325	-	-

The target of the calculation of different load ranges is to investigate the influence of the resulting number of bending cycles per cycle on the design life of the rope. It is assumed that significantly fewer ropes will be required for a crane during its service life if the actual lifting range is narrowed down more precisely. Table 7 shows three cases that were defined for investigation. It can be seen that the reduction in the lifting range causes a reduction in the number of bending cycles w_i.

Table 7: Various cases of lifting ranges

			Case 1	Case 2	Case 3
Lifting range		[mm]	10.000	6.000	3.000
Lower position	z_1	[mm]	0	0	1000
Upper position	z_2	[mm]	10.000	6.000	4.000
Number of bending cycles	w_i	[-]	9	7	5



(a) (b)

Figure 3: Example of class A_c3 with (a) the representation of the number of working cycles and (b) the representation of the total running time as a function of the load spectrum factor for a lifting speed of 8 m/min and a lifting height of 10 m

In addition, the various load spectrum factors and the total number of working cycles C are examined during the proof of fatigue strength for the selected class A_c3 in accordance with Table 3. Figure (3) shows the number of cycles graphically. Taking into account the maximum lifting speed and the lifting height, the total duration of use can be derived. For example, the number of 500.000 cycles with a load spectrum factor of 0,5 means a total duration of use of approximately 20.800 hours.

It is assumed that the rope force spectrum in this application example is identical to the load spectrum of the crane. It should be noted that the rope force spectrum can be a different load spectrum to the load spectrum of the crane or hoist in a real application. The load spectrum of the crane is expressed by the load spectrum factor K_p depending on the class Q_p (see Table 3 or Table 4). The frequency of high, medium and low loads is taken into account and summarized in one value. The comparative calculation between the standards is based on an equivalent load spectrum, which leads to the same values as K_p when using a defined calculation rule to determine the rope force spectrum factor $k_{r.DIN}$ in DIN EN 13001-3-2:2015. However, the rule in ISO/WD 16625:2023 is different and depends on the gradient m of the Wöhler characteristic. This results in different rope force spectrum factors $k_{r.ISO}$. Equation (27) generally applies.

$$k_{r.DIN} \neq k_{r.ISO} \qquad \text{for the same rope force bending spectrum} \qquad (27)$$

Table 8 shows the usable values $k_{r.ISO}$ for ISO/WD 16625:2023 depending on the D/d-ratio with influence on the slope m as equivalent to $k_{r.DIN}$ for DIN EN 13001-3-2:2015.

Table 8: Rope force bending spectrum factors $k_{r.ISO}$

Class Q_p	Rope force bending spectrum factor $k_{r.DIN}$	D/d-ratio and rope force bending spectrum factor $k_{r.ISO}$					
		11,2	14	18	20	22,4	25
Q_p0	0,0313	0,1514	0,1150	0,0874	0,0786	0,0703	0,0634
Q_p1	0,0625	0,1544	0,1238	0,1018	0,0951	0,0890	0,0840
Q_p2	0,1250	0,2794	0,2337	0,1978	0,1862	0,1755	0,1665
Q_p3	0,2500	0,4333	0,3850	0,3446	0,3310	0,3180	0,3069
Q_p4	0,5000	0,6585	0,6197	0,5854	0,5735	0,5620	0,5522
Q_p5	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000

4. Results of the calculation of the application examples

4.1. Proof of static strength

The comparison of the proof of static strength for running ropes shows almost identical results between DIN EN 13001-3-2:2015 and ISO/WD 16625:2023 for the design rope force. The minor adjustments to the dynamic factors for the calculation of the load combinations C1 to C6 have no significant effect. This is shown in Figure (4).

However, the changes in the equations for determining the limit design rope force have a decisive influence on the level of the limit design rope force. DIN EN 13001-3-2:2015 shows a dependency on the D/d-ratio through the defined minimum rope resistance factor according to Equation (9). The higher the ratio, the higher the limit design rope force. The correction in ISO/WD 16625:2023 results in a constant limit design rope force without dependence on the D/d-ratio. Figure (5) shows the results.

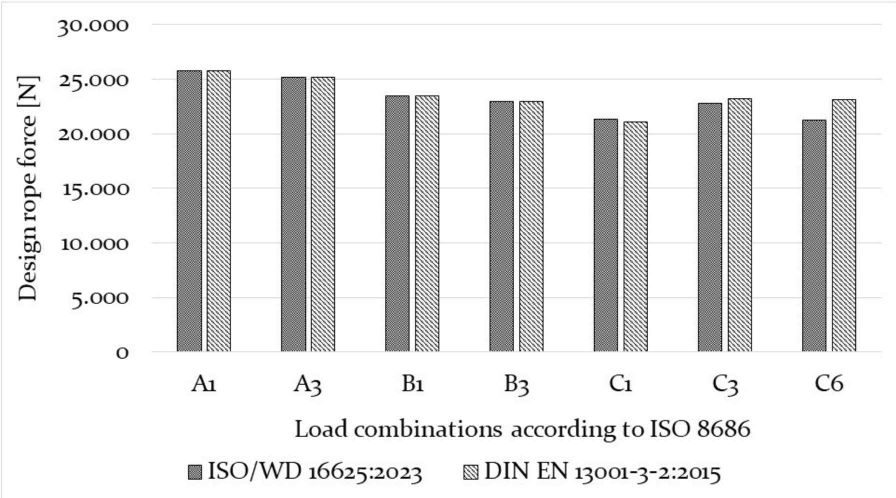


Figure 4: Design rope force depending on the various load combinations and the different standards

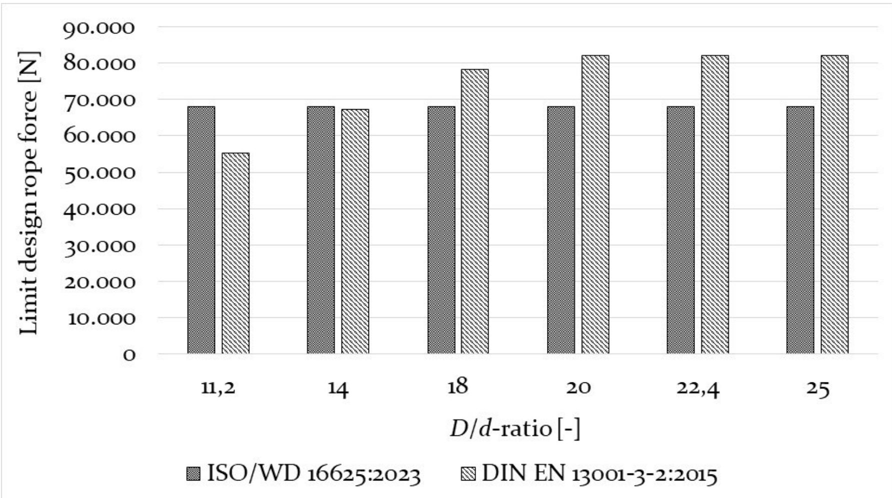


Figure 5: Limit design rope force depending on the various D/d-ratios and the different standards

For the recommended D/d-ratio of 14 for the class A_c3 of the hoist drive, there are no significant differences when comparing the standards. The largest design rope force of all load combinations was used here, which is 25.766 N for both standards. It should be noted that in both cases this is the design rope force of load combination A1. Due to the high partial safety factor γ_p with a value of 1,34 for load combination A compared to load combinations B and C, this often results in the highest rope forces in the calculation. The limit design rope force is 67.311 N for DIN EN 13001-3-2:2015 and 67.960 N for ISO/WD 16625:2023. Figure (6) shows the result that the proof of static strength is fulfilled for both standards.

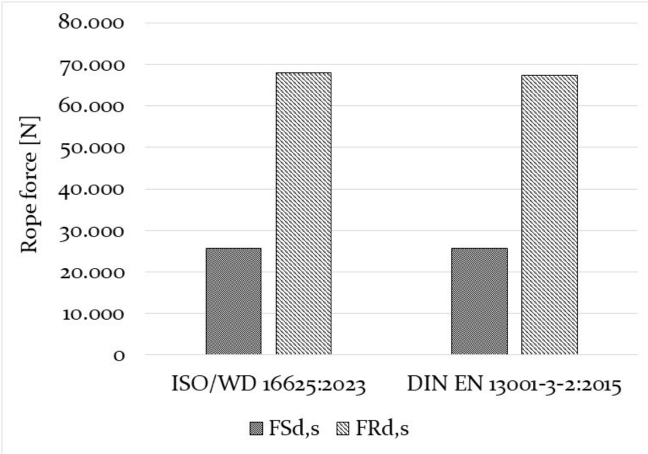
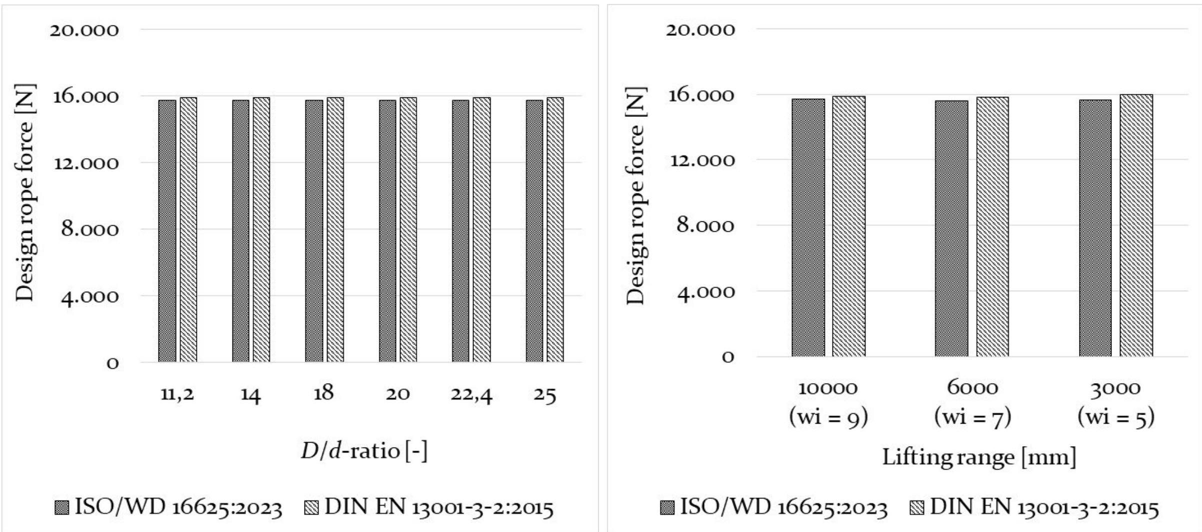


Figure 6: Proof of static strength for the highest value of the design rope force $F_{Sd,s}$ of all load combinations compared to the limit design rope force for the recommended D/d-ratio of 14

4.2. Proof of fatigue strength

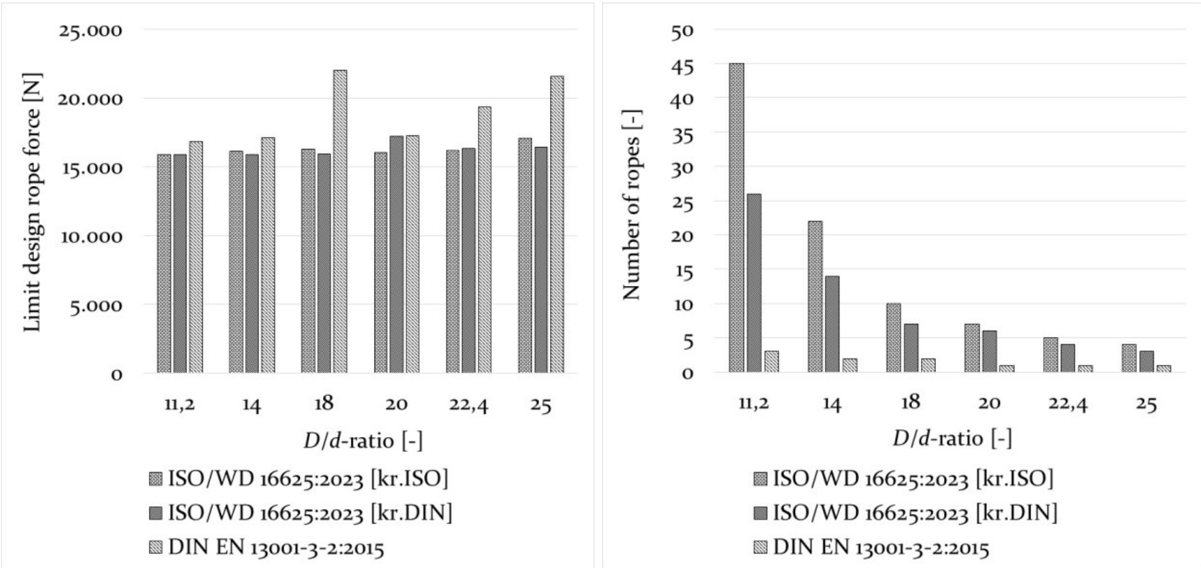
In Figure 7 is shown the design rope force depending on the D/d-ratio, the standards and the lifting range. The forces are on the same level. There is no significant difference, which is also due to the single equations for the calculation of the design rope force.



(a) (b)

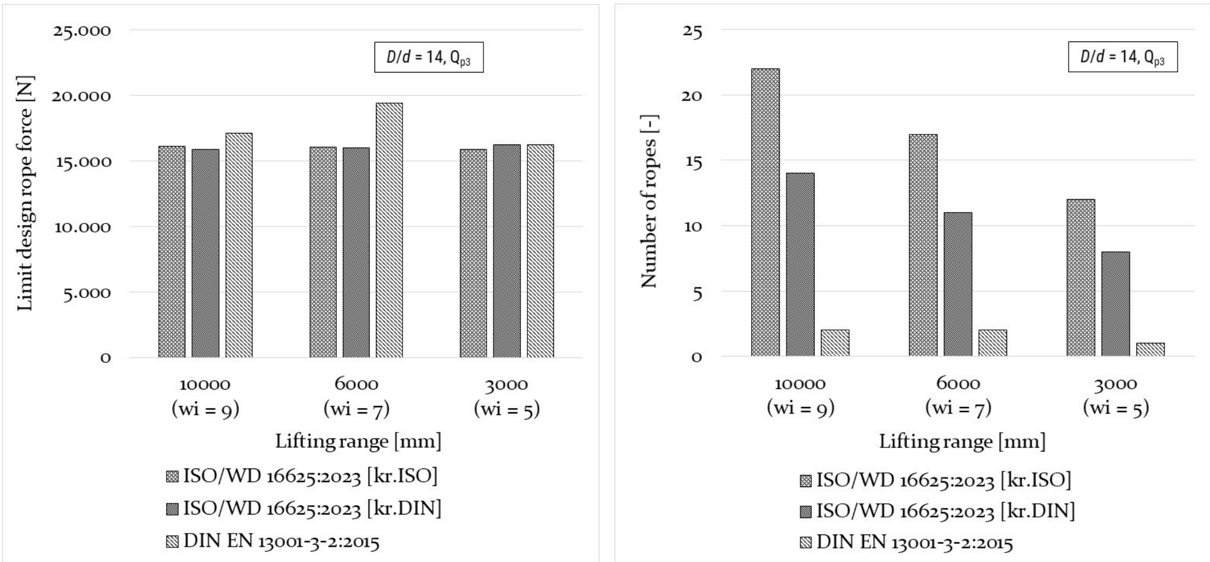
Figure 7: (a) Design rope force for different D/d-ratios and (b) design rope force for different lifting ranges

Figure 8 shows the limit design rope force as a function of various D/d-ratios and the two standards. The results focus on the rope force bending spectrum factor of 0,25 and the full lifting range of 10 m. The figure also shows a diagram of the number of ropes required for the service life of the crane or hoist. There are considerable differences between the standards here. However, the diagram also shows that a lower ratio of the rope bending diameter D to the rope diameter d results in a higher number of ropes. The higher the D/d-ratio, the lower the number of ropes. It should be noted that the recommended D/d-ratio of 14 according to ISO/WD 16625:2023 for class A_c3 requires a high number of ropes. In this application, a D/d-ratio of 20 is more advantageous. The diagrams show also a general distinction between the application of the rope force bending spectrum factor $k_{r.ISO}$ and the rope force bending spectrum factor $k_{r.DIN}$ in the results of ISO/WD 16625:2023. The aim is to show that the value of the factor has a significant influence on the number of ropes during the service life of the crane at small D/d-ratios. If the rope force bending factor $k_{r.DIN}$ is inadvertently used in accordance with the load spectrum factor K_p for cranes or hoists in the proof of competence of the new ISO/WD 16625:2023, it favors the number of ropes over the factor $k_{r.ISO}$. Chapter 3.2 shows that it is necessary to select the same load spectrum when comparing the standards, which leads to different rope force bending factors.



(a) (b)

Figure 8: (a) Diagram of the limit design rope force as a function of the D/d-ratio and (b) diagram of the corresponding number of ropes as a function of the D/d-ratio for a rope force bending spectrum factor of 0,25 and a lifting height of 10 m with a number of bending cycles $w_i = 9$

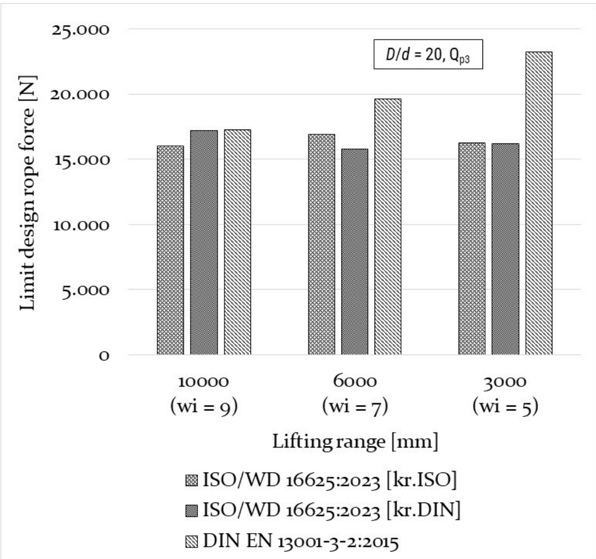


(a) (b)

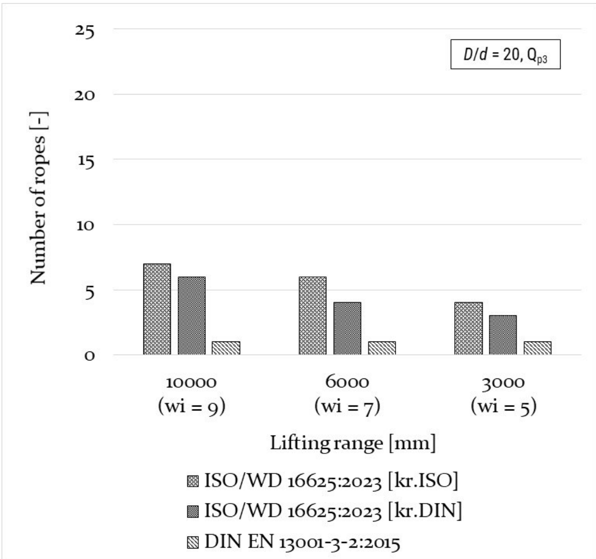
Figure 9: (a) Diagram of the limit design rope force as a function of the lifting range and (b) diagram of the corresponding number of ropes as a function of the lifting range for the class Q_p3 and the ratio $D/d = 14$

Figure 9 shows the limit design rope forces and the corresponding number of ropes for the class Q_p3 and different lifting ranges, which represent the number of relevant bendings per movement. The results apply to a D/d-ratio of 14. The limit design ropes forces are influenced by the number of ropes for the service life of the crane or hoist. In all cases, the number of ropes is selected in such a way that a sufficiently high limit load capacity is achieved, which leads to compliance with the proof of fatigue strength.

Figure 10 shows the limit design rope forces and the corresponding number of ropes for the class Q_p3 and the same different lifting ranges in case of a D/d-ratio of 20 for comparison. The results clarify that the number of ropes required decreases as the lifting range becomes smaller. This trend can be clearly seen in ISO/WD 16625:2023. However, significantly more ropes are required compared to DIN EN 13001-3-2:2015. The diagrams also make it clear that the D/d-ratio has a significant influence on the number of ropes. The results confirm the evaluation of Figure 8 that the ratio D/d = 20 in the application example leads to better results with a lower number of ropes than the ratio D/d = 14.



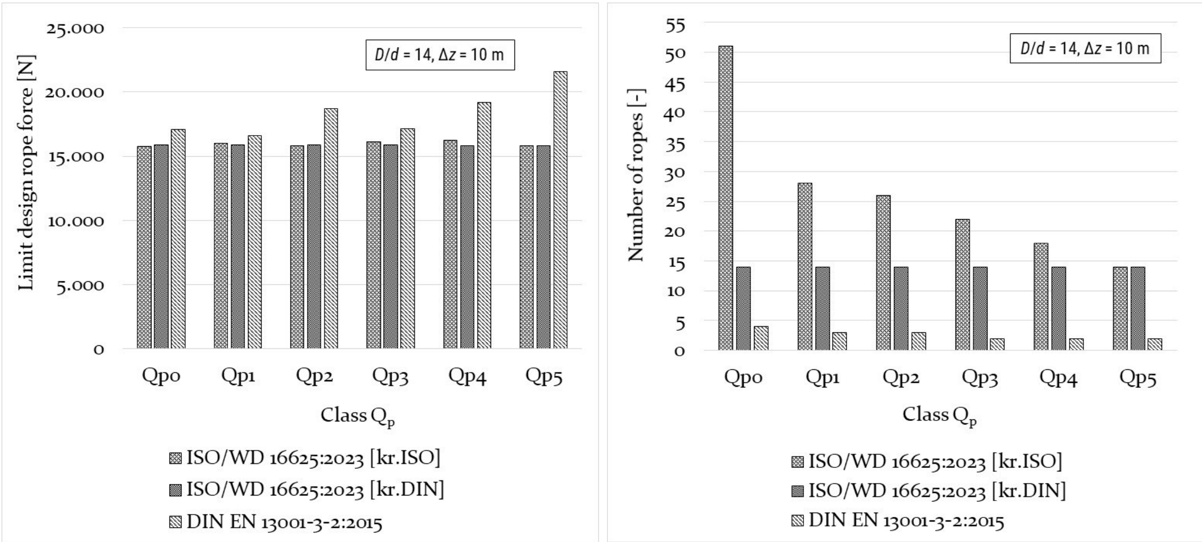
(a)



(b)

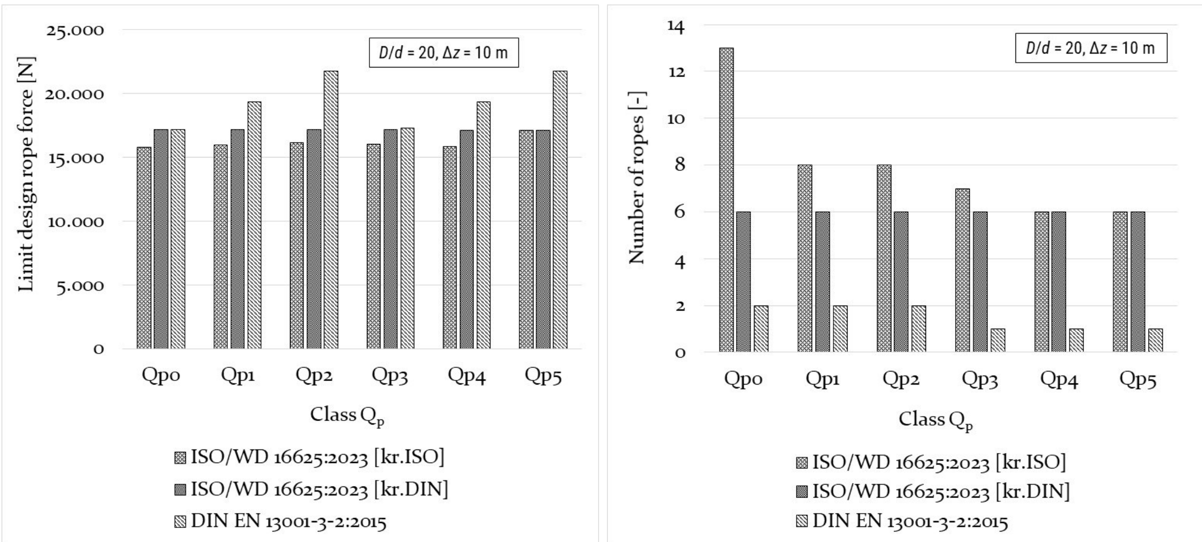
Figure 10: (a) Diagram of the limit design rope force as a function of the lifting range and (b) diagram of the corresponding number of ropes as a function of the lifting range for the class Q_p3 and the ratio D/d = 20

The diagrams in Figure 11 illustrate the limit design rope force and the number of ropes required for the D/d-ratio of 14 and the various classes Q_p, which represent the respective rope force bending factor k_r depending on the standard (see Table 8). Once again, the number of ropes is selected in all cases so that the proof of fatigue strength is reliably fulfilled. Figure 12 shows the values for the same parameters at a D/d-ratio of 20 for comparison. A high number of ropes is necessary, particularly for the D/d-ratio of 14, especially for low loads and a high number of cycles. The results clearly show that significantly fewer ropes are required with a D/d-ratio of 20.



(a) (b)

Figure 11: (a) Diagram of the limit design rope force as a function of the classes Q_p (which represent the corresponding rope force bending spectrum factor k_r) and (b) diagram of the respective number of ropes for a lifting height of 10 m and the ratio $D/d = 14$



(a) (b)

Figure 12: (a) Diagram of the limit design rope force as a function of the classes Q_p (which represent the corresponding rope force bending spectrum factor k_r) and (b) diagram of the respective number of ropes for a lifting height of 10 m and the ratio $D/d = 20$

5. Discussion

The comparison of the proof of static strength for rope drives between the standards DIN EN 13001-3-2:2015 and ISO/WD 16625:2023 leads to the conclusion that the two standards do not show any significant differences in the proof of static strength. This means that the minor deviations in the results are due to a significant adjustment of the minimum rope resistance factor γ_{rb}. The ISO/WD 16625:2023 interprets the factor independently of the D/d-ratio, so that the same limit design rope force results for each D/d-ratio. This influence existed in DIN EN 13001-3-2:2015.

There are considerable differences between the standards for the proof of fatigue strength, as the design concept in ISO/WD 16625:2023 has changed fundamentally. Both standards specify a reference point that is defined differently. The new approach in ISO/WD 16625:2023 defines a virtual point in the extension of the individual Wöhler curves. This point was determined by Prof. Dr. Markus Golder. It is recommended that the designation also be used as the Golder-Point in future. All Wöhler curves for different D/d-ratios intersect at this point. This means that the approach takes the respective Wöhler properties into account. In contrast, DIN EN 13001-3-2:2015 seem to be based on a single Wöhler curve with a defined exponent of 3. This could not be confirmed using established calculation methods and design life tests, which led to the new approach according to ISO/WD 16625:2023. However, it should be noted that a significantly higher number of ropes is mathematically required during the service life of a crane or hoist. The investigation in the paper carried out for a class A_c3 hoist resulted in very high differences. It makes sense to extend the investigation to other classes and to generate additional findings for the proof of fatigue strength on the basis of further parameter studies. It should always be noted that ISO/WD 16625:2023 stipulates that if the intended number of ropes l_r to be used during the service life of the crane is greater than 1, the design life of the specified rope should correspond to at least two periodic inspection intervals.

The shown comparison between the two standards represents the respective proof of competence procedure for a defined rope drive with the specification of a rope diameter and other technical parameters. However, the standards and ISO/WD 16625:2023 in particular can also be used from the outset when designing and dimensioning a rope drive system. The required rope specification and a suitable D/d-ratio can be determined by defining crane specifications and the intended number of ropes during the service life of a crane or hoist.

Acknowledgement

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References

[1] VDI 5020:2024: Berechnung von Seiltrieben in Hebezeugen. Verein Deutscher Ingenieure e.V., Düsseldorf 2024.

[2] ISO/WD 16625:2023: Cranes and hoists — Selection of wire ropes, drums and sheaves.

[3] Anders, M.: Ein Beitrag zur Lebensdauerabschätzung laufender Drahtseile. Dissertation. Fakultät für Maschinenwesen. Technische Universität Dresden, 2023. URL: https://nbn-resolving.org/urn:nbn:de:bsz:14-qucosa2-854584

[4] Reinl, J.; Golder, M.: Wire ropes in Crane Applications – Current State of the Standardization Work of ISO/WD 16625. innoTRAC Journal. Volume 1 (2020), pp. 37–46. URL: https://doi.org/10.14464/innotrac.v1i0.456

[5] Golder, M.; Reinl, J.: Wire ropes in crane applications – Current state of the standardization work of ISO/WD 16625 – Requirements and Objectives. 9. Erfahrungsaustausch: Erfahrungen mit der Anwendung der EN 13001 "Krane – Konstruktion – allgemein", Essen, 29. November 2021. URL: https://nbn-resolving.org/urn:nbn:de:bsz:ch1-qucosa2-771928

[6] Anders, M.; Briem, U.; Novak, G.; Steinbach, G.: New German Guidline VDI 5020 for rope drive design. 27 Sept. 2022, Proceedings of OIPEEC Conference 2022 and 7th International Stuttgart Ropedays. S. 303-316.

[7] Golder, M.; Anders, M.; Novak, G.; Eiwan, Ch.: New approach for ISO 16625 in Proceedings of the XXIII International Conference on Material Handling, Constructions and Logistics, MHCL 2019, Vienna, Austria

[8] Feyrer, K.; Wehking, K.-H.: FEYRER-Drahtseile. Bemessung – Betrieb – Sicherheit. 3. Auflage. Springer-Verlag GmbH Deutschland, 2018. ISBN 978-3-642-54296-1 (eBook)

[9] Anders, M.; Ryk, D.; Steinbach, G.: Betriebsdauer und Sicherheit der Seiltriebe - Einfluss auf die Seiltriebauslegung. Tagungsband. 26. Kranfachtagung, Technische Universität Dresden, pp. 117-130, 2018.

Generally used standards for the creation of the paper:

[10] DIN EN 13001-1:2015: Krane – Konstruktion allgemein. Teil 1: Allgemeine Prinzipien und Anforderungen. Deutsche Fassung EN 13001-1:2015.

[11] DIN EN 13001-2:2021: Krane – Konstruktion allgemein. Teil 2: Lasteinwirkungen. Deutsche Fassung EN 13001-2:2021.

[12] DIN EN 13001-3-2:2015: Krane – Konstruktion allgemein. Teil 3-2: Grenzzustände und Sicherheitsnachweis von Drahtseilen in Seiltrieben. Deutsche Fassung EN 13001-3-2:2014.

[13] DIN EN 13001-3-2/A1:2017 Krane – Konstruktion allgemein. Teil 3-2: Grenzzustände und Sicherheitsnachweis von Drahtseilen in Seiltrieben. Deutsche Fassung EN 13001-3-2:2014/prA1:2017.

[14] FEM 9.511:1986: Berechnungsgrundlagen für Serienhebezeuge. Einstufung der Triebwerke.

[15] ISO 4301-1:1986: Cranes and lifting appliances – Classification – Part 1: General.

[16] ISO 4301-1:2016: Cranes – Classification – Part 1: General.

[17] ISO 8686-1:2012: Cranes – Design principles for loads and load combinations – Part 1: General

[18] ISO/WD 16625:2013: Cranes and hoists – Selection of wire ropes, drums and sheaves.