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BEHAVIOUR OF STEEL ROPES IN MULTI-SHEAVE SYSTEMS OF TOWER CRANE HOSITING MECHANISMS

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Abstract:
This article discusses issues related to tower cranes, a group of lifting machines used in the construction industry. Vertical transport on a building site is of paramount importance, accounting for approximately 50% of all construction works. Currently, the tower crane is one of the most efficient lifting machines used in construction. It occupies minimal space on the construction site and allows for the fastest possible delivery of materials directly from the storage area to work stations, regardless of the route. This article focuses on the issues related to these devices, limiting the scope to the analysis of the rope system. The use of steel ropes in the hoisting mechanism is crucial for the reliable operation of tower cranes. The basic technical data and construction of a selected crane model chosen for the study are presented. The properties and characteristics of steel ropes used in such systems, as well as criteria for their retirement, are discussed. Subsequently, a method for modelling the rope system and simulating its operation is introduced. The use of computational tools to model the rope bending process in the hoisting mechanism allows for identifying critical points along the rope under specific operating conditions. Selected simulation results are presented in the form of tables and graphs, highlighting the areas most susceptible to wear in this type of rope mechanisms. The article concludes with practical recommendations that may enhance interest in the described method. According to the authors, the method is innovative and promising. Its application can contribute to extending the service life of ropes, facilitating procedures for monitoring their condition, and improving the safety of their use.

Key words: cranes, steel ropes, fatigue wear, rope modelling

INTRODUCTION

Broadly speaking, transportation is a key element of any economic activity. Its role is crucial both for the quality of life of individuals and for the efficient flow of goods. This is crucial for the entire economy, and especially for the construction sector, which cannot function without transport machinery. Transport machinery can generally be divided into equipment for short-distance transport and long-distance transport. Short-distance transport typically takes place within production plants or other facilities, using devices such as various types of cranes, hoists, winches, and on the ground – rail transport, tire-based transport, forklifts, and various types of conveyors. In contrast, long-distance transport includes road, rail, water, and air transportation. According to the definition, transport serves to move various types of materials and can be either continuous or intermittent. Construction transport using tower cranes belongs to short-distance transport with a limited scope. A characteristic feature of the crane is its variability and the freedom to choose the place of sending and receiving the material lifted at construction sites.

The subject literature contains limited mentions of issues related to the operation of rope systems in tower cranes, hoists, or construction winches. This topic was more extensively described and addressed in [1], where an original program was used to simulate the fatigue wear of steel ropes operating in systems conventionally referred to as multi-sheave arrangements [2]. Based on the analysis and model calculations performed using the calculator, it is possible to determine the rope sections that are potentially most exposed to wear and deformation in any tower crane system. In this work an attempt has been made to model the wear of steel ropes in the lifting system of machines such as tower cranes (construction hoists). It contains results obtained by computer simulation using an IT tool developed by the authors. The primary goal of this approach is to safely extend the service life of this type of material handling equipment. The work focuses on the modelling of lifting systems and on the simulation of the wear of steel ropes in a tower crane, which belongs to the lifting equipment group. According to the PN-ISO 4306-1:1999 standard "Cranes. General Terminology", construction cranes, as lifting devices, are machines designed for intermittent operation, intended for lifting and moving loads in space using a hook or another lifting attachment. The broad category of cranes includes: winches, overhead cranes, jacks, lifts and port equipment, off-shore equipment as well as numerous ship lifting machines [3].

Analyzing the literature, the authors did not find any publications related to the issue of facilitating the assessment of the condition of ropes used in winches of construction crane lifting systems, beyond standards specifying the types and forms of wear and tear and the criteria for disposal of these ropes using visual methods [4]. Generally, access to assessing the technical condition of ropes in such facilities is difficult. Therefore, they focused on this issue and proposed a solution that enables the user to precisely determine the location of damage accumulation by utilising a digital model that considers the key operating parameters of the given device. This approach has been successfully applied to assess the condition of ropes used in the winch systems of basic open-pit mining machines [2]. The obtained results inspired the extension of this method to construction cranes. This will lead to longer operating times for the rope, easier procedures for monitoring its condition, and an increased level of safety in its use.

OPERATION AND TYPES OF ROPES USED IN MULTIPLE-SHEAVE SYSTEMS – LITERATURE REVIEW

From the perspective of construction needs, an ideal lifting machine should occupy as little space as possible and enable the rapid and flexible movement of materials directly from the storage area to the work site. Only such a device can simplify the construction technology while simultaneously contributing to lower project costs. As mentioned before, these requirements are best fulfilled by the construction crane, which is the most efficient means of transport.

The industrialization of construction transport initiated the development of tower cranes in the past century, leading to various solutions which are widely used today depending on their mobility capabilities on construction sites. [5, 6, 7].

Many authors dealing with the issue of tower cranes focus mainly on the optimization of spatial design of construction sites as well as on the location and monitoring of building materials and machines in the production zone of construction sites in the context of the efficiency of deliveries using construction cranes [8, 9, 10, 11, 12].

It is estimated that approximately 400,000 such machines are in operation in Poland. There is no publicly available register of such equipment, but its presence in large cities indicates the widespread use of cranes in building works. To ensure the safety of these machines, it is essential to follow the rules regarding the operation of rope systems, which include multi-sheave systems.

Colloquially, multi-sheave systems are referred to as systems for lifting or lowering masses suspended from movable blocks with the use of steel ropes wound onto drive drums and running over rope sheaves (wheels, rollers). In these systems, longitudinal forces act on the ropes, which undergo bending over the sheaves, as well as phenomena occurring at the contact area between the rope and the tread of the rope sheave groove. They are characterized by repeated bending over small-diameter sheaves. Multi-sheave systems are designed for heavy loads. The essence of the system lies in multiplying the number of rope parts (in extreme cases up to several dozen), which allows the largest cranes to achieve lifting capacities of several thousand tons. In such systems, steel wire ropes – thanks to their appropriate flexibility – work together with fixed and movable rope sheave assemblies to multiply the lifting capacity. One of the main operational drawbacks of multi-sheave systems is their relatively large size, which increases along with lifting parameters such as load capacity and lifting height. The D/d parameter (the ratio of the pulley diameter to the rope diameter) reaches a maximum of 30, but in construction cranes it is slightly over 20. The treads of rope sheaves are typically made of cast or structural steel, which results in high stress concentrations due to localized contact pressures. In multi-sheave systems, the ropes operate under considerable tension over extended lengths, and the rope assemblies are often installed in areas that are difficult to access for routine inspection and condition assessment. The operational characteristics of ropes in multi-sheave configurations differ fundamentally from those used in drive systems of mining hoists or aerial cableways. In multi-sheave systems, the work of ropes is related to the construction of the entire crane, which includes various types of ropes, as shown in Fig. 1.

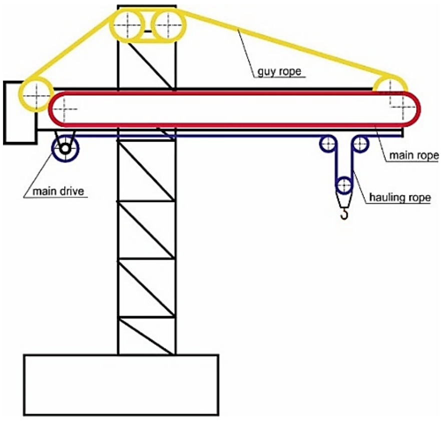


Fig. 1 Tower crane diagram

Ropes are a structural element that also determines the statics of the machine. The risk of failure due to excessive rope wear must be minimized, as it can lead to irreversible damage to the entire machine. Unfortunately, due to the large number of bending cycles, the service life of ropes in multi-sheave systems is limited, and they must be replaced once a certain predefined wear threshold is reached, as is the case in open-pit mining machinery [13]. Wear processes lead to the degradation of the mechanical and structural properties of ropes. Nevertheless, understanding the factors and wear mechanisms that cause changes in the technical condition is crucial for safety. Assessing the technical condition allows for the safe and rational operation of ropes in these devices, and can even extend their service life. Operational studies concern not only the ropes themselves but also the entire system. These include issues related to the investigation of the causes of tower crane accidents [14, 15, 16]. Research also involves conducting structural and mechanical analyses to ensure crane operation safety [17, 18]. Advanced new technologies for monitoring operating conditions are being developed to increase safety [19, 20]. Research is being conducted to reduce the risk and improve safety in the planning and management of construction crane operation [21, 22]. This requires appropriate optimization and configuration of the crane system [23, 24]. To meet these requirements, issues related to the rope system must also be addressed.

The construction of steel wire ropes used in all rope transport systems has a significant impact on their operational durability, including those used in construction cranes. The primary rope constructions for multi-sheave systems are two-strand ropes featuring so-called linear contact of wires within the strands. These ropes are made from a large number of relatively thin wires, which provides them with the necessary flexibility and fatigue resistance. The basic designs are the commonly used Seale (S), Warrington (W), Warrington-Seale (WS), and Filler (F). In the case of transferring very high loads with a low D/d ratio (the ratio of the sheave diameter to the rope diameter), the above-mentioned constructions exhibit low resistance to transverse pressures. In such situations, equally flexible ropes with linear wire contact but constructed from eight strands, as shown in Fig. 2, are recommended.

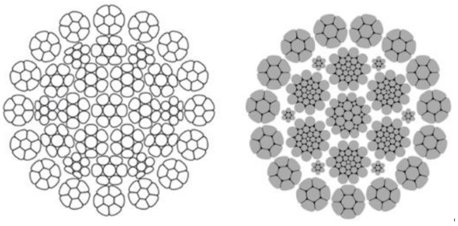


Fig. 2 Cross-sections of multilayer ropes with compacted strands and linear wire contact: left – rope with 7-wire strands; right – rope with F and WS type strands
Source: [26].

To protect against surface (transverse) pressures, these ropes are manufactured with a metal core in the form of an independent wire rope core (IWRC) or independent wire strand core (IWSC). The large number of strands and wires provides adequate flexibility. These ropes, composed of alternating inner and outer layers of strands, also exhibit greater resistance to torque than typical six-strand ropes. This is significant in lifting equipment, as during part of the working cycle, the ropes are loaded only by the weight of the sheave block and the hook. Such conditions may result in the intertwining of individual rope sections. Rope manufacturers for lifting equipment compete by offering diverse technical solutions, as illustrated in Fig. 3.

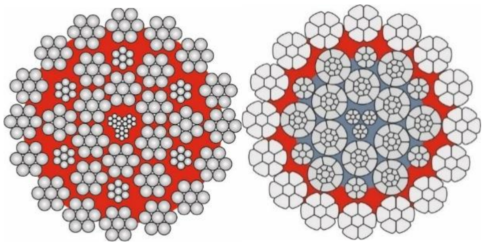


Fig. 3 Cross-sections of multi-layer ropes with linear contact of wires with polymer filling from renowned manufacturers: left – rope with 7-wire strands; right – rope with compacted 7-wire and S-type strands; the polymer filling is marked in red and the grease in grey
Source: [26, 27].

It shows two designs of increasingly popular polymer-filled ropes. It is impossible to describe all the new solutions offered by manufacturers [25], but the trend is clear. Ropes used in construction cranes and offshore installations are becoming increasingly complex in design, and thus more expensive. However, there is limited literature addressing their short service life and operational durability. This highlights the relevance of the present work, whose primary objective is to propose a method for assessing rope condition that would help extend their service life.

The balancing of torque in multilayer ropes is a crucial factor that protects the ropes from twisting and from variations in their lay length during operation. Uncontrolled changes in the lay length of a rope during operation can naturally lead to the breakage of the rope's core layers. Partial resistance to this phenomenon can be achieved by using ropes with multiple layers of strands twisted in opposite directions. Such ropes also exhibit high resistance to pressure, a feature that is absolutely essential for ropes used in block and tackle systems. In surface mining machinery, rope systems constitute a critical mechanical assembly that determines the quality and safety of their operation [28]. The key factors affecting their performance include rope deformations, excessive elongations, and changes in geometric parameters [29]. They have the additional advantage of very high fatigue resistance, several times greater than that of typical double-stranded ropes with linear wire contact. Compacted ropes also offer other benefits, such as a smooth surface and high compactness of both the rope and the strands, which positively affects their resistance to abrasion and corrosion. A relative disadvantage of these ropes is their high cost and fatigue wear, which manifests in the final phase of the rope's service life, characterized by rapid wire breakage, as well as a lack of operational experience in multi-sheave systems. Therefore, the approach proposed in this paper for assessing the condition of such ropes operating in multi-sheave systems is well justified.

CRITERIA FOR REPLACING THE LOAD-BEARING WIRE ROPES OF TOWER CRANES

Tower cranes belong to the crane class [3], and the condition of the ropes operating in the drive systems of the trolleys and lifting systems is determined by visual inspection. This is generally the basic method for assessing the condition of steel ropes in all kinds of lifting equipment. It involves checking for deterioration or damage. If the condition of the rope has deteriorated or any damage is observed, the rope should be inspected against the criteria qualifying it for removal [30].

The quality of lubrication is an equally important element of inspection, as operating a crane with unlubricated ropes is prohibited. There are three basic criteria for removing a rope used in a lifting device. These include:

- reduction in rope diameter,
- excessive corrosion,
- the appearance of wire cracks.

They have different "severity levels" expressed as percentages. If any criterion reaches 100%, the rope must be replaced. However, if a particular criterion has a value below 100%, it must be added to the remaining ones [30], and a total value exceeding 100% disqualifies the rope from further use. The most important criterion refers to the visually detected number of wire breaks. This number directly indicates the rope wires fatigue wear, i.e., a reduction in the rope service life.

Table 1 presents the tolerated (permissible) number of wire breaks. It should be noted that the visual method only identifies wire breaks visible on the outside of the rope, hence the numbers used as a criterion are low Counting the number of broken wires in a rope with a well-lubricated surface is not easy, so identifying the potential locations where these breaks may occur is crucial to the quality of the inspection.

Table 1

Permissible number of visible wire breaks in the rope used in the lifting system of a construction crane hook

Number of visible wire breaks			
Rope sections passing over sheaves and/or wound in a single layer on rope drums		Rope sections wound on a multi-layer drum Sections of rope wound in multiple layers on the rope drum	
Over a length of 6d	Over a length of 30d	Over a length of 6d	Over a length of 30d
3	**5**	**6**	**11**
where: d [mm] nominal diameter of the rope			

Source: [2].

Unfortunately, Table 1 does not take into account the type of rope construction. The wire diameters of ropes with different constructions vary significantly; therefore, these criteria serve more as guidelines for the rope condition inspector rather than as strict standards.

An equally important criterion for rope retirement, alongside the number of broken wires, is a reduction in its diameter. The measurement is performed using a caliper. Measurements are taken at four locations along the rope, and an average value is calculated. This process is time-consuming and requires a workstation for the inspector near the rope. The measurement location should also correspond to the area of greatest wear.

This serves as another argument for implementing the methodology that is the focus and subject of this article.

Table 2 presents the formula for calculating the uniform reduction in rope diameter, expressed as a percentage. If this value reaches 10%, the rope must be replaced.

Table 2

Calculation of the quantitative index of rope diameter reduction

Formula for reducing the diameter of a rope	
$\Delta \mathrm{d} = \frac{\mathrm{d_{ref}} - \mathrm{d_m}}{\mathrm{d}} \cdot 100\ \%$	
Δd [mm]	uniform reduction of the rope diameter
d_{ref} [mm]	The reference rope diameter in its new condition, measured after installation of the unloaded rope. In the absence of available data, the measurement shall be taken before the final connection is made.
d_m [mm]	Mean value of rope diameter measurements
d [mm]	nominal diameter quoted by the rope manufacturer

Source: [31].

In operational practice, other criteria are also applied to assess the condition of ropes used in cranes. For example, an observed increase in diameter may indicate degradation of the rope's core and its corrosion. Visual inspection also detects fretting corrosion, i.e., mass losses. This type of corrosion results from abrasion of the wire surface due to high pressures and a lack of lubrication. During visual inspection, so-called fretting corrosion – i.e., mass loss due to material wear – is also assessed. This type of corrosion results from the abrasion of wire surfaces caused by high contact pressures in the absence of lubrication. Under the influence of changes, the load on the rope wires and the changes in force between the wires of the working rope result in the removal of metal fragments and corrosion products from the surface of the wires.

Friction corrosion is faster than typical corrosion because the wire geometry changes. It primarily occurs in ropes with point wire contact and variable rope loads. It is evident in the inner layers of cable strands working in open-cast mining.

Rope condition monitoring also aims to detect deformation-related damage. These include birdcaging, loose wires and strands, loops, necking, waviness, corkscrewing, flattening, and similar defects. Most damage to steel wire ropes operating in multi-sheave systems is typically located in the regions where the rope winds onto the drive drum or where it bends during the movement of the trolley and hook within the multi-sheave system. Multi-layer spooling has a particularly detrimental effect on rope service life.

To facilitate the assessment of the condition of hoisting ropes, some standards [32] present typical damage cases for ropes used in lifting systems, such as cracks in outer and inner wires, abrasion, corrosion, and some deformations. According to the authors, who are experts in the field of rope operation, each detected damage is specific, and visualising different cases would lead to the creation of albums of typical damage. The question is, who would do this and who would publish it, given such a vast number of different objects? Therefore, this text only includes examples of damage to this type of rope. The authors' practical experience suggests that the primary cause of damage is fatigue, and occasionally, wear due to abrasion on the rollers. Corrosion, if it occurs when using modern ropes with galvanised wire coatings, affects technically degraded and little-used equipment. The examples of rope wear presented in Figures 4 to 6 below should be considered illustrative, as each rope is different.

Fig. 4 An example of corrosion on a rope

Fig. 5 Example of a crack caused by fretting corrosion

Fig. 6 An example of deformation due to improper use

A particularly negative impact on rope durability is exerted by multi-layer spooling. While visually assessing the condition of the rope near the drum is relatively easy due to its accessibility, evaluation of the condition of the rope along the remaining length is significantly more difficult. It must always be remembered that each rope-equipped structure is not solely an object of inspection and control, but is intended to perform work. In this context, a calculator for the number of rope bends in multi-sheave systems of lifting mechanisms (winches) installed on a given structure proves to be very useful. By simulating the operational parameters of the system, it allows for the identification of rope sections where various aforementioned damages may potentially occur. By simulating the system's operating parameters, it allows determining the rope section potentially susceptible to various damages described above. This simulator also enables determining the position of the movable sheave such that the rope section with potentially maximum wear is accessible for visual inspection from a safe and reachable location.

MODELLING THE BEHAVIOUR OF STEEL ROPES USED IN BLOCK AND TACKLE SYSTEMS

The service life, defined as the duration of operation until damage necessitates the retirement of load-bearing ropes in multi-sheave systems, is primarily determined by the number of operating cycles. During each operating cycle, the load-bearing ropes undergo a certain number of bends. This number depends on the system's configuration, specifically the number of sheaves over which the rope is bent, pressed, or subjected to abrasion. Other significant parameters include the rope length, the lifting or lowering height, and the load applied on the hook. Knowledge of the number of bends a rope undergoes during a single operating cycle allows for the prediction of the total service life of the multi-sheave rope. The distribution of bends along the rope length is not uniform. Certain sections of the rope experience a higher number of bends than others. This distribution also varies depending on the lifting height and the working radius of the boom. However, the rope section subjected to a greater number of bends always wears out faster. Therefore, understanding the distribution of bends as a function of rope length is a fundamental starting point and should be crucial for assessing its condition. Determining the number of bends experienced by the lifting ropes as a function of their length is possible with the use of a model describing the geometry and configuration of the multi-sheave system in which the lifting rope is installed. This model essentially assigns to individual rope sections the number of bends they experience during a work cycle, i.e., during a full cycle of lifting and lowering a hook with a load. This modelling assumes that each bend experienced by the rope on a specific sheave adds to the subsequent bends experienced by the same rope section throughout the entire work cycle. Based on studies of ropes currently in operation, it has been repeatedly demonstrated that the maximum wear of steel wire ropes used in multi-sheave systems is concentrated in several characteristic locations. These include rope sections experiencing the highest cumulative number of bends, rope segments resting on sheaves and subjected to loads due to small oscillatory fretting movements, and rope ends [33]. This applies both to the rope fixation at the so-called “dead” end and on the drum. Therefore, in the opinion of the authors of this study, a responsible assessment of the condition of ropes operating in multi-sheave systems should focus on locations where the wear is potentially the highest.

For this purpose, a specialized software tool was developed – an algorithm that, given the geometry and actual dimensions of the rigging in a multi-sheave system, along with specific but realistic operating conditions, calculates the actual number of bends experienced by individual rope segments [34]. This tool essentially functions as a calculator for the number of bends in a given multi-sheave lifting system configuration, determining the bending cycles undergone by each segment of load-bearing ropes operating. Figure 7 presents a simplified schematic of the algorithm’s operation.

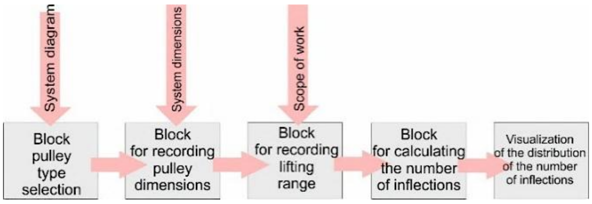


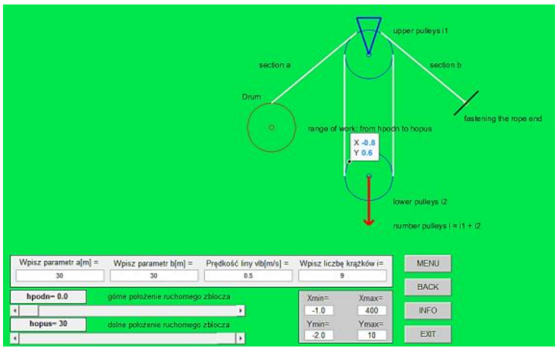
Fig. 7 Simplified computational scheme of the program for determining the number of bends in multi-sheave systems
Source: according to [34].

This algorithm essentially consists of a set of five programs (modules) written in MATLAB. Each module serves a different purpose. The first module is used to select the configuration of the multi-sheave system. Several commonly used multi-sheave system configurations have been implemented, including those with unidirectional and bidirectional bending of the load-bearing rope. Additionally, other kinematic configurations can be input into this module. In the second module, the actual geometric dimensions of the given system are entered: e.g. the number of sheaves, distances to the drive drum, and the so-called "dead end" of the ropes, etc. Module 3 is an interactive tool for entering basic lifting parameters, i.e., the height from which the mass is lifted relative to the ground and the height of lifting. After these parameters have been entered, module 4 calculates the number of bends experienced by the lifting rope along its individual sections. The result is presented graphically as defined in module 5.

Calculations embedded in the appropriate algorithm and performed in this block lead to the calculation of a conventional number of bends according to rope operating schemes presented in relevant literature, e.g., [5]. These schemes have been widely used for over a century to predict the fatigue wear of steel ropes, as defined by Benoit [35] long ago. This enables the comparison of results obtained in various rope systems and designs.

Originally, this tool was intended to determine the number of bends of steel ropes operating in the main winch systems of basic open-pit mining machines [29], floating cranes, port cranes, etc.

It enabled the modelling of the actual kinematic scheme of the ropes operating within the system by taking into account the number of sheaves in both the fixed and movable blocks, as well as the lengths of rope segments between these blocks throughout the full or partial lifting and lowering cycle. Data input is facilitated by an interactive interface screen of the program, shown in Figure 8.



Wpisz parametr a[m] = 30
Wpisz parametr b[m] = 30
Prędkość liny vlb[m/s] = 0.5
Wpisz liczbę krążków i= 9
hpodn= 0.0 górne położenie ruchomego zblocza
hopus= 30 dolne położenie ruchomego zblocza
Xmin= -1.0
Xmax= 400
Ymin= -2.0
Ymax= 10

Fig. 8 Active screen of the software used for entering the geometric parameters of the multi-sheave system and the lifting and lowering heights of the hook in the hoisting mechanism of a tower crane

Source: [34].

The kinematic modelling software for the multi-sheave system accounts for the number of active sheaves, their configuration within a certain range (single- or double-directional bending), and the lengths of rope segments between the drum and characteristic sheaves (such as the upper sheave, lower sheave, and the last sheave), as well as the fixed rope anchorage point (so-called "dead end"). The calculator is a helpful tool for pinpointing potential fatigue damage locations, e.g. wire breaks.

The calculator operates by generating a diagram that shows the number of bends experienced by individual rope segments during a single defined operating cycle. Examples of such diagrams are presented in the analytical section of this article. The cycle includes user-defined upper and lower positions of the load-carrying hook of the multi-sheave system, which can be adjusted depending on the type of lifting or lowering operation. The input data for the calculation system are the specified number of sheaves and the lengths of individual rope sections, as well as the type (direction) of rope bending on the sheaves: unidirectional or bidirectional. Any change in these parameters results in a different course of the generated rope bending diagram. The tool described above has been successfully applied to simulate the operation of ropes working in the main winches of surface mining machines [30]. In a diploma thesis [1], it was demonstrated that this tool can also be effectively used to analyse other rope systems, such as the winches of tower cranes. The results of these analyses are presented in the subsequent sections of this article.

TECHNICAL DESCRIPTION OF THE LIFTING EQUIPMENT SELECTED FOR THE SIMULATION OF HOISTING ROPE OPERATION

The tower crane selected as the technical object for modelling the rope system of the hoisting winch is the Liebherr 550 EC-H 40 Litronic. A schematic representation of the crane is shown in Figure 9. This crane features a so-called “top-slewing” design, where the tower is equipped with a head section. In this type of crane, the tensile forces acting on the jib are also transmitted through tie rods connecting the jib to the tower head.

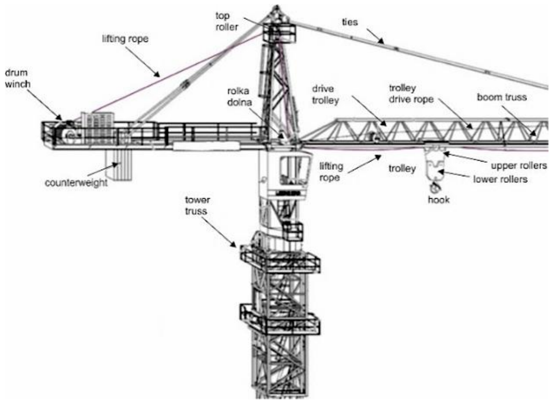


Fig. 9 General construction of the Liebherr 550 EC-H 40 Litronic tower crane

Source: [31].

This means that the working load on the hook, even at large distances from the tower mast, does not cause significant deflection of the jib, but instead induces compressive forces in the tower head [31]. From the perspective of the operation of the hoisting rope in the multi-sheave system, this has little direct impact; however, the rope operates more smoothly in such a configuration, as the rope segments between the sheaves exhibit smaller sags. The crane has a reach (working radius) of 50 m and a lifting height of approximately 27 m. The lifting system is powered by a 110kW winch with a rated torque of 200 Nm. The lifting rope has a diameter of 25 mm. It is made of wires with a strength class of Rm 1960 MPa, which gives it a breaking strength of 570 kN. The rope is wound in nine layers onto a 720 mm diameter drum without grooves. The mechanism responsible for driving the trolley was not analysed in this study.

Simulation of the operation of the hook lifting system of the Liebherr 550 EC-H 40 Litronic crane

The geometric parameters of the hoisting winch system for the selected technical object are presented schematically in Figure 10.

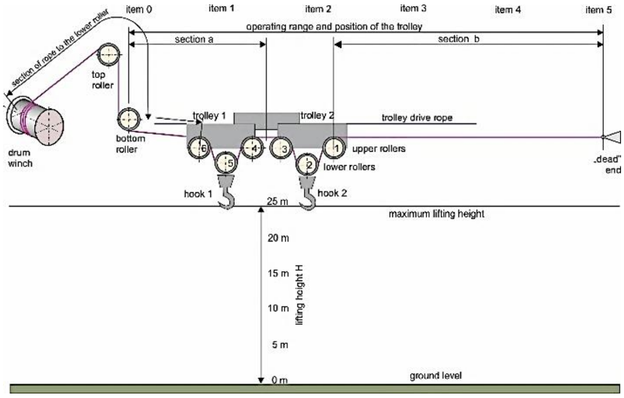


Fig. 10 Diagram and individual dimensions of the lifting system of the 550 EC-H 40 Litronic tower crane, where the lifting height H [m] is measured from ground level, and the trolley moves from position 1 to position 5 for simulation purposes

Based on the actual dimensions of the crane and the distances between individual sheaves, the total rope length in the hoisting system was determined to be 194 m, along with the lengths of individual rope branch segments and the distances between the movable and fixed sheaves. The trolley travel system is not shown, as this aspect was omitted in the present article. The authors believe it is important and should be considered in subsequent analyses. The number of rollers and, as can be seen in the diagram, parameters such as the distance between the lower roller and the drive remain constant for a given kinematic system. Therefore, the rope operation is determined by the lifting height H [m] as well as by the reach and position of the trolleys during the lifting operation. This study does not present data regarding the horizontal movement of the trolleys and the transportation of materials in this manner. Nevertheless, the horizontal operation, i.e., the movement of the trolleys, should be considered in the overall balance of the load-bearing ropes' operation. In the subsequent part of the study, simulations of the hoisting rope system were performed for several hook height positions, taking into account the trolley positions. The input values for the simulation model were the number of rollers in the lifting system, i.e., 6 (out of a total of 9 rollers in the entire system), the distances a [m] and b [m] defining the trolley's position, and the hook lifting height H [m].

These positions are shown in Fig. 7 to illustrate the parameters entered into the model.
Selected simulation results have been given in Table 3.

Table 3
Tabulated results of the simulation of the 550 EC-H 40 Litroniv tower crane operation for four positions of the trolley and four heights of the hook lifting shown in Figure 10

No.	a[m]	b[m]	H[m]	l_p	Max wear	No.	a[m]	b[m]	H[m]	l_p	Max wear
trolley in position 1											
2	10	40	5	10	9-65 m	22	30	20	5	10	29-80 m
3	10	40	10	10	9-85 m	23	30	20	10	10	29-105 m
4	10	40	15	10	9-105 m	24	30	20	15	10	29-130 m
5	10	40	20	10	9-135 m	25	30	20	20	10	29-155 m
trolley in position 2											
7	15	35	5	10	14-65 m	27	35	15	5	10	34-85 m
8	15	35	10	10	14-90 m	28	35	15	10	10	34-110 m
9	15	35	15	10	14-115 m	29	35	15	51	10	34-135 m
10	15	35	20	1	14-140 m	30	35	15	20	10	34-160 m
trolley in position 3											
12	20	30	5	10	19-70 m	32	40	10	5	10	39-90 m
13	20	30	10	10	19-90 m	33	40	10	10	10	39-130 m
14	20	30	15	10	19-120 m	34	40	10	15	10	39-140 m
15	20	30	20	10	19-145 m	35	40	10	20	10	39-165 m
trolley in position 4											
17	25	25	5	10	14-75 m	37	45	5	5	10	44-95 m
18	25	25	10	10	14-100 m	38	45	5	10	10	44-120 m
19	25	25	15	10	14-125 m	39	45	5	15	10	44-145 m
20	25	25	20	10	14-150 m	40	45	5	20	10	44-170 m
where: a [m] – distance from the trolley to the first sheave (roller) on the tower, b [m] – distance from the trolley to the fixed rope anchorage, the so-called "dead end," H [m] – lifting height of the movable block (hook) above ground level, l_p – nominal number of rope bends experienced on a given segment, Max wear – length of the rope segment where the potentially greatest wear may occur.											

Figures 11 and 12 present two example simulation results in the form of graphs showing the number of bends experienced by the load-bearing rope in the multi-sheave system as a function of rope length.

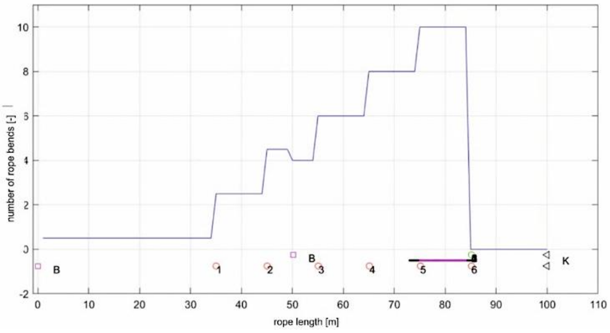


Fig. 11 Simulation results of the hoisting rope operation for the 550 EC-H crane lifting system for the following parameters: a = 35 m, b = 5 m, H = 5 m; where: B – drum, K – "dead" end of the rope, o – position of the sheaves when the hook is on the ground, o – position of the sheaves when the hook is at height H[m], purple – rope segment with the highest number of bends

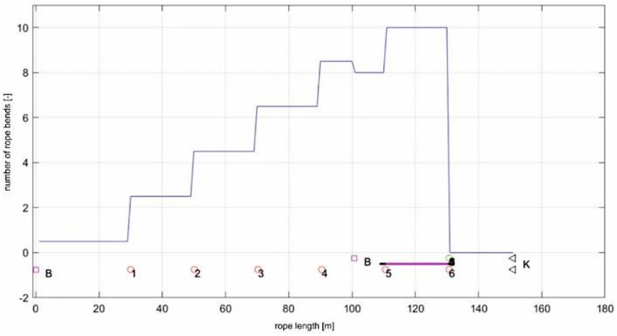


Fig. 12 Simulation results of the hoisting rope operation for the 550 EC-H crane lifting system f or the following parameters: a = 30 m, b = 20 m, H = 10 m; where: o – position of the sheaves when the hook is on the ground, o – position of the sheaves when the hook is at height H[m], purple – rope segment with the highest number of bends

The graphs show which part of the rope is working and which part is being bent. With the use of a simulator, such a graph can be generated for any position of the trolley and the hook.

The most important simulation results, namely the length and the position of the rope section with maximum potential wear, have been presented in Table 4.

The analysis of the results contained in Table 4 allows concluding that in the 550 EC-H configuration crane, the section of the rope with the highest number of bends is between the last two sheaves, i.e. between sheaves 5 and 6.

Table 4
Rope segments with the highest potential wear in the 550 EC-H crane for hook positions as listed in Table 3

No.	Length of rope subject to wear	Rope segment with the highest number of bends [m]	Location of the highest concentration of rope bends	No.	Length of rope subject to wear	Rope segment with the highest number of bends [m]	Location of the highest concentration of rope bends
Location of trolley 1, H = 5 m			In the segment between the 5th and 6th sheave	Location of trolley 3, H = 5 m			In the segment between the 5th and 6th sheave
2	56	9		22	51	9	
3	76	4		23	76	14	
4	96	9		24	101	19	
5	126	14		25	126	24	
Location of trolley 1, H = 10 m				Location of trolley 3, H = 10 m			
7	51	9		27	51	9	
8	76	14		28	76	14	
9	101	24		29	101	19	
10	126	29		30	126	24	
Location of trolley 1, H = 15 m				Location of trolley 3, H = 15 m			
12	51	9		32	51	9	
13	71	14		33	91	14	
14	101	19		34	101	19	
15	126	24		35	126	24	
Location of trolley 1, H = 20 m				Location of trolley 3, H = 20 m			
17	61	9		37	51	9	
18	86	14		38	76	14	
19	111	19		39	101	19	
20	136	24		40	126	24	

CONCLUSIONS

The study highlights the importance of understanding rope behaviour in tower crane hoisting systems through simulation-based analysis. By examining factors such as geometry, wear zones, and operational conditions, the findings demonstrate how simulations can support condition monitoring, optimise rope usage, and extend service life. The following points summarise the key insights and potential developments arising from this research. The basic conclusions and directions of development are presented in points.

1. The simulation results of the rope operation in the hoisting system of the selected tower crane, as presented above, confirm that knowledge of the rope system geometry allows for the identification of potential rope wear zones due to fatigue, abrasion, deformation, etc., under specific operating conditions – namely, the trolley position and the defined lifting height.

2. The simulation-based identification of potential wear zones in the load-bearing ropes of tower crane winches enables positioning of the trolley and the movable block in such a way that the rope remains easily accessible for visual inspection during condition monitoring.
3. Such simulations can be performed for any rope system, under its current operating conditions, and can take into account its specific characteristics.
4. The presented model can be further developed, for example, by including the influence of trolley movement on the behaviour of the load-bearing rope.
5. Wear models of ropes operating in multi-sheave systems allow the integration of rope wear analysis with operational logistics, which may lead to an extension of the overall life service of a single rope by shifting worn segments outside the zones of highest stress. This would, however, require the implementation of new design solutions, such as drums for storing excess rope length.
6. Wear models of ropes operating in multi-sheave systems allow for more rational rope utilization, as the rope does not wear evenly over its entire length, but only on short segments. Therefore, after completing specific lifting operations on one site, the ropes can be reused on other crane systems or under different lifting regimes.
7. Wear models of ropes operating in multi-sheave systems do not account for rope loading (actual stress) during a given cycle, but only for the number of cycles. Further development of these models should incorporate this aspect, as it is a significant factor when compared to similar rope systems in crane applications.
8. The usefulness of rope operation simulations in multi-sheave systems for condition assessment would be significantly improved if the models also accounted for the nature of operation in successive lifting or lowering cycles.
9. Rapidly progressing fatigue wear accompanied by a large number of wire fractures.
10. The rope elongation characteristics are strictly correlated with the fatigue wear.
11. The tested conventional ropes with WS strands, with diameters of 50 mm and 60 mm, do not show a clear durability advantage over the compacted ropes – probably due to the higher manufacturing quality of the compacted ropes.

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