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SAFETY MANAGEMENT AT THE DESIGN STAGE OF ROTATION NODE IN MOBILE CRANE

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Abstract: The article analyzes the safety aspects related to the construction and operation of a mobile crane. The load-bearing capacity of the boom sub-assembly rotation node was tested in a mobile crane. When identifying the load, the uneven compliance of the supporting components was taken into account. The considerations are illustrated with an example of a mobile crane slewing bearing with a lifting capacity of 50 tons. The basic problems of building the computational model are discussed and the results of the load bearing capacity of the slewing ring bearing for different positions of the load-bearing component of the tested machine are presented. An analysis of the load of the rolling elements in a slewing ring bearing was carried out and the reasons for changes in the load capacity in relation to the methods of calculating the load capacity, assuming non-deformability of the bearing rings, were indicated. It has been shown that deformations of the supporting frames are so large that they significantly change the distribution of forces transmitted by individual bearing rollers.
Keywords: safety management, mobile crane, slewing bearing, FEM

1. INTRODUCTION

Research shows that the company's employees, among others, as users of these devices, contribute to the main sources of safety risk during the operation of lifting devices. That is why it is extremely important not only to be able to assess security threats in the organization, but also to use managerial skills that have an impact on shaping the right attitudes and behavior of employees (Dziuba et al., 2020; Ulewicz and Lazar, 2019). In addition to errors related to the operation of cranes, threats may also be caused by errors made at the design stage of these devices.
The mechanisms of rotation of crane and lifting devices are most often constructed with the use of roller slewing bearings. These are machine components that carry the entire load resulting from the operation of the machine. Their special features, which owe their high load capacity with a relatively compact structure and relatively small

dimensions, they cause used not only in classic machines and devices, such as excavators, all kinds of cranes and other construction machines, military vehicles, but are also widely used in wind turbines, rail vehicles and many other devices (Kania, 2012; Derenda et al., 2018).

The load capacity of slewing bearings usually limits the maximum value of external loads of the designed device, and its correct determination is an important part of the working machine's calculations. Slewing bearings are usually selected to the extreme, i.e. so that their operation is at the limit of strength. This requires careful and accurate calculations of their operational parameters, the most important of which is the static load capacity, and more and more often supplemented with additional criteria from assembly, durability to determination of resistance to motion (Kania et al., 2012; Kania and Śpiewak, 2014). It should be borne in mind here that in many devices, damage or destruction of the slewing ring bearing may cause catastrophic accidents (Fig. 1). In addition, it requires long-term shutdown of the device and generates high repair costs (Kardas, 2016).

When building numerical models of rotation nodes, it is important to take into account the flexibility of the machine load-bearing structures to which the slewing bearing is attached. The correct numerical model of the working machine, bearing and its mounting allows for the analysis of the internal load in the bearing, thanks to which it is possible to determine its load capacity, recognize points of excessive load and remove them at the machine design stage. Structures of support should ensure load distribution without excessive stacking and concentrations that lower the bearing capacity, cause its accelerated wear and cause a significant reduction in durability (Kania and Krynke, 2013; Krynke et al., 2014). Moreover, a correctly identified load distribution allows for the determination of the load levels of the raceways and rolling parts as well as the correct selection of the contact parameters.

Fig. 1. Examples of catastrophes caused by damage to slewing bearings in cranes
Source: own study

In this study, the load capacity of the slewing mechanism used in the mobile crane was analyzed. The influence of the stiffness of the supporting and load-bearing structures on the load capacity of the bearing arrangement was assessed.

2. SAFE OPERATION OF SELF-PROPELLED CRANES

Activities related to the use, operation and maintenance of the crane should be carried out in accordance with the operating manual prepared by the manufacturer, with the workplace manual prepared by the operator and with the provisions on technical inspection (Klimecka-Tatar and Niciejewska, 2016). Frequent visual inspection of the crane's condition by the operator is important (Knop, 2020; Ulewicz et al., 2020). The manual should be kept at the crane operating site, within easy reach of the crane operator. Failure to follow the operating manual or its absence at the workplace is one of the most serious offenses against the safety of employees (Tabor, 2013; Pacana and Woźny, 2016).

When working with a mobile crane, they should be specified (Woźny, 2020):

- parameters of the loads carried,
- the place of lifting and the place of depositing the load in correlation with the crane's lifting capacity,
- for the operator, hook operator and signaller - in appropriate cases, workplace instructions for each activity performed by them. These instructions should be strictly followed.

When starting work, the operator must designate the crane operating area where there is a risk to human health or safety, e.g. by fencing the work area with foldable barriers or warning tape. No outsiders may be in this area (Tabor, 2015).

The crane must never be placed on unstable ground. In the case of too soft, loose ground, the support surface should be increased. You should also be extremely careful near the edges of deep trenches.

It is very important to ensure the crane's stability (Fig. 2). It is therefore necessary to check all the elements responsible for the crane's stability (Tabor, 2014):

- select the appropriate support spacing for the load limiter configuration and secure the supports against possible sinking into the ground,
- correct leveling of the crane. The tilt of the vehicle with the crane in any direction must not exceed that permitted in the instructions,
- always after lowering the load (and in the transport position), the extension of the support cylinders should be corrected to avoid loss of the crane's stability.

The type of crane and lifting accessories should be selected taking into account their parameters and intended use. It is not allowed to commission reloading work for which the crane is not designed, in particular the crane's permissible lifting capacity must not be exceeded. Always move loads slowly and gently, watch the crane's movement indicators and watch out for wind speed so that the crane does not sway.

In addition, remember that you must never (Niciejewska and Kiriliuk, 2020):

- tear out loads frozen to the ground or sunk in it,
- pick up uneven loads,
- increase the load already lifted,

- sway the load,
- pull the load diagonally,
- load the crane inconsistently with the lifting capacity characteristics.

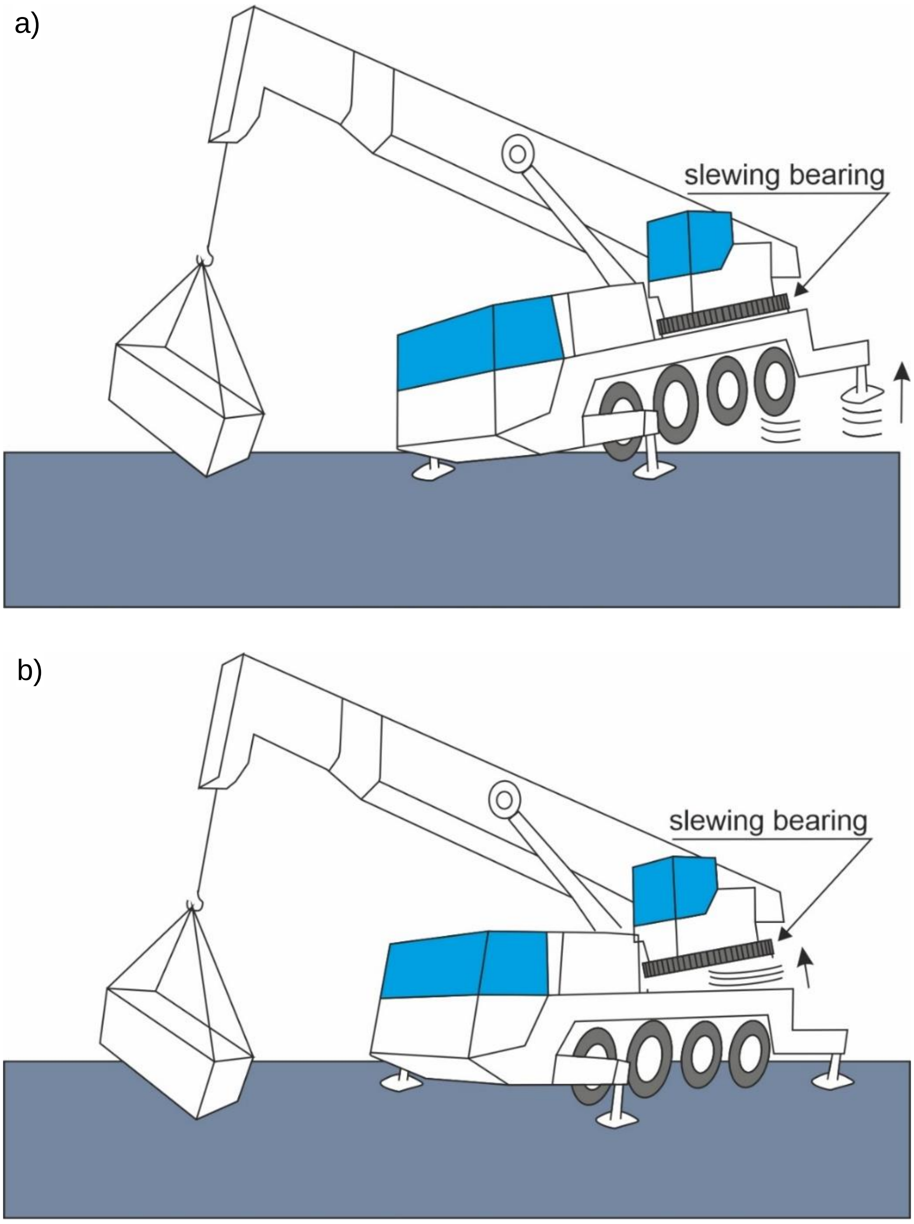


Fig. 2. Loss of crane boom stability as a result of carrying too much load (a) and damage to the slewing ring bearing (b)

Source: own study

In a self-propelled crane, the most critical safety element is, among others: slewing bearing. It is the element that performs the function of rotation of the boom around the vertical axis. Errors at the design stage of this element, as well as improper operation, can damage the slewing ring bearing. This failure may cause the crane jib to break away (Fig. 2b).

The jib detachment from the crane's supporting component may also occur as a result of breaking the bolt connection securing the crane jib to the slewing bearing or securing the slewing bearing to the chassis.

2. OBJECT OF CONSIDERATION

The subject of the considerations is a slewing bearing used in the rotation mechanism of the DST - 5050 mobile crane body (Fig. 3). Only catalog bearings are used for this type of machines. In the case of the above crane, a cross roller bearing with a rolling diameter of 1400 mm and catalog symbol 1.KW.Z.T.50.1390.3.3.01 (Fig. 4) was used (ZAFAMA 1997). The crane load characteristics are show in Figure 5.

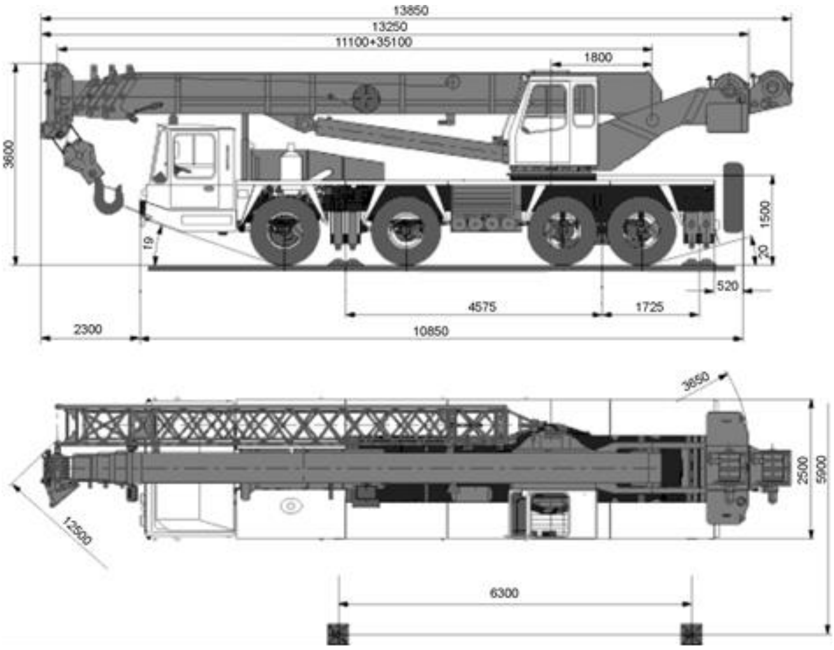


Fig. 3. View of a mobile crane

Source: own study

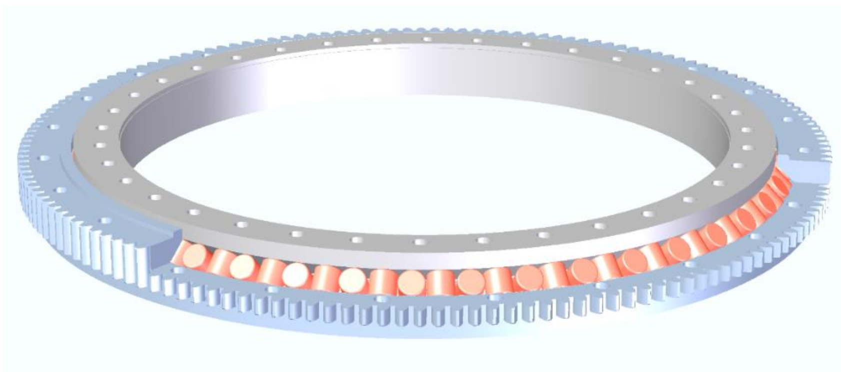


Fig. 4. Structure of a cross roller slewing bearing

Source: own study

The rollers in a cross bearing are arranged alternately, i.e. half of the total number of rolling elements work with one pair of raceways, the rest with the other. Thus, there are two calculation rows for the rolling parts. The row in which the roller load is the result of the sum of the effects of the axial force *Q* and the tilting moment *M* is called the carrying row, the second row, where the load is the difference of force and moments - the supporting row.

The chassis frame of the analyzed crane consists of a ring girder in the form of a thick-walled sleeve with a flange for mounting the bearing. The collar was additionally reinforced with 12 stiffening ribs. The loads from the ring girder are transferred to the stringers made of sheets welded together, forming closed box sections. In the central part of the chassis, there is a reinforcement made of metal sheets in the shape of a truncated cone.

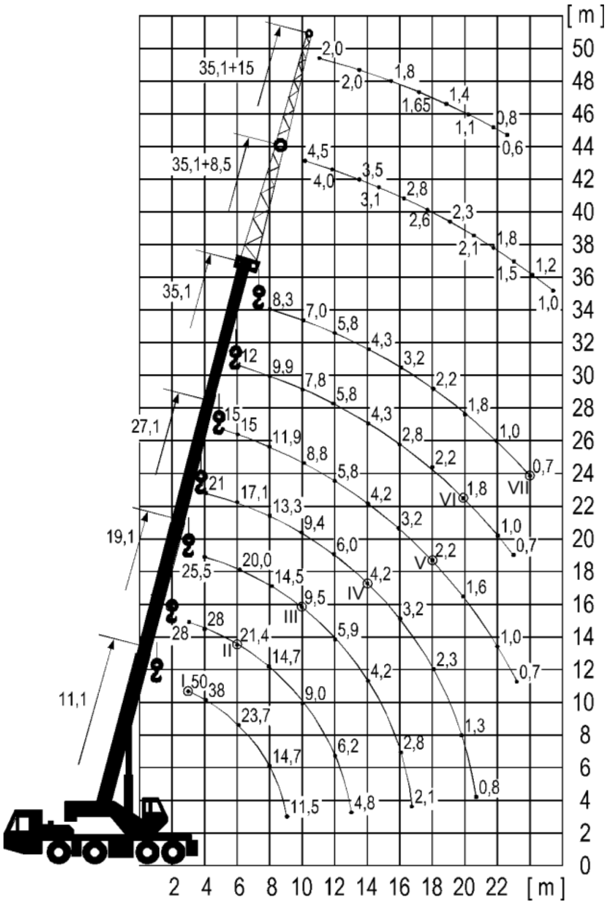


Fig. 5. Crane load characteristics

Source: own study

The body frame consists of a plate to which the seat of the inner bearing ring is welded from below. From the top, vertically positioned lateral girders closed from plates welded together are welded together, used to fasten the jib arm. The hydraulic cylinder moving the boom is bolted to the reinforced sheets in the rear part of the body. These sheets are additionally connected with each other with internal stiffening ribs (Fig. 6).

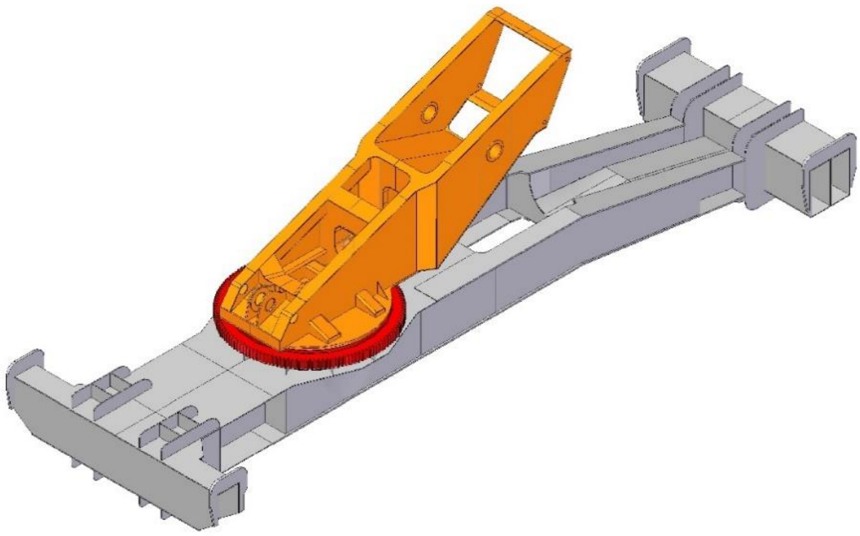


Fig. 6. Geometric model of the analyzed mobile crane
Source: own study

5. NUMERICAL CALCULATION MODEL

A discrete model of a slewing ring bearing with supporting structures was built. The bearing rings as well as the body and chassis frames are discretized with solid elements. The finite element mesh is shown in Figure 7. The rollers were modeled by bar elements with an appropriate cross-section, which used nonlinear material characteristics corrected by taking into account the susceptibility of finite elements in the raceway model. These characteristics allow the load to be transferred only when the bars are compressed. The method of determining the cross-sections of the rod modeling the rollers and the material characteristics is presented in the paper (Kania 2012).

The bolts are modeled with special preload beam elements. The preload of the bolts was assumed in accordance with the guidelines of the bearing manufacturer, assuming class 12.9 bolts.

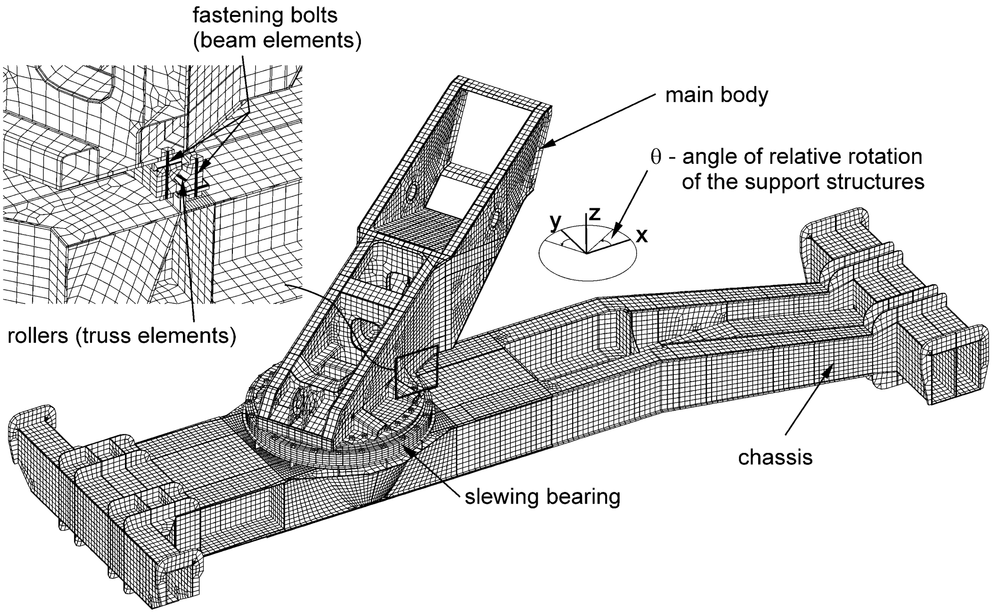


Fig. 7. FEM model of the analyzed mobile crane

Source: own study

The load on the frame was applied to an additional structure modeling the crane jib, built with beam elements. On the selected nodes of the lower frame, in the place where there are supports in the actual structure, rigid constraints are imposed, which do not allow the displacement of the nodes. The calculations were performed taking into account the geometric and physical nonlinearities. Newton's iterative technique was used.

6. IDENTIFICATION OF LOADS IN A SLEWING BEARING RING

The calculations were carried out for various eccentricities of the vertical (axial) force and different load levels according to the operating points were marked with Roman numerals on the crane load characteristic shown in Fig. 5. The tested mobile crane operating points marked on the catalog characteristic of the bearing capacity determined with infinitely stiff rings are shown in Fig. 8.

Additionally, the catalog characteristics of the bearing capacity, for comparison purposes, were marked with the characteristic of the capacity obtained for the bearing with flexible rings, mounted on the rigid machine seats (curve), and the characteristic determined for the bearing installed in the crane, at the angle of rotation of the body equal to $\theta = 45$ °. The significant reduction in bearing capacity with high axial loads Q is caused by deformations of the machine body. The crane's load-bearing frames have the lowest stiffness in the neutral axis of the tilting moment M. Hence, the greatest deformations in these places will occur at high axial loads Q. The characteristics of the crane loads (Fig. 4) show that the axial load of the bearing does not exceed 50 tons at the smallest eccentricity load, which is $e = 3$ m.

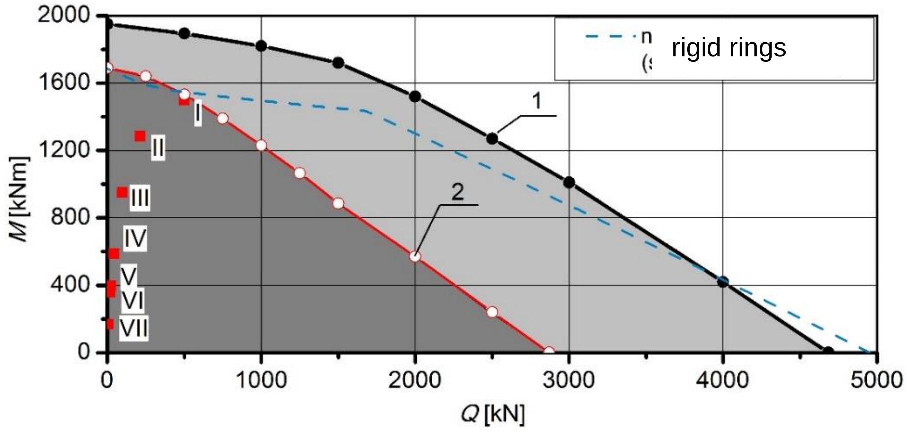
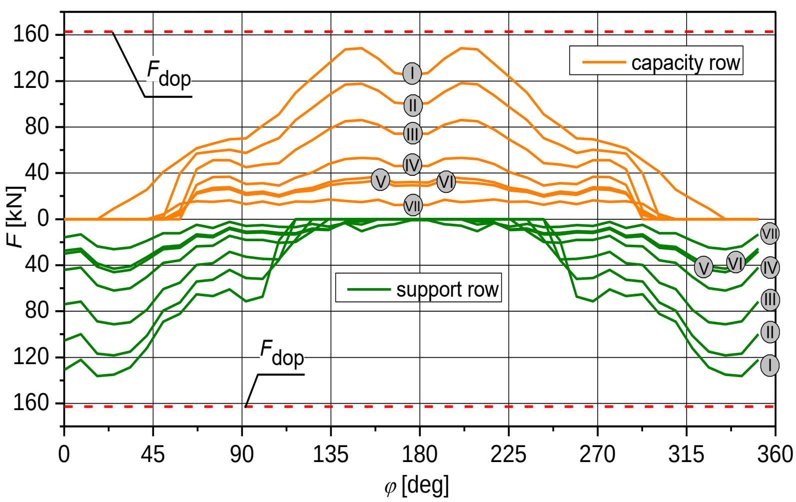


Fig. 8. Characteristics of the bearing capacity with marked work points of the mobile crane (1 - the catalog capacity taking into account the flexibility of the bearing rings, 2 - bearing capacity of the bearing installed in the crane at the angle of rotation of the body $\theta = 45°$)
Source: own study

Fig. 9 shows the distribution of the internal load in the bearing for various points of the crane's load characteristics, for a zero rotation angle of the body. The influence of deformation of the supporting structures is visible, however, there are no clear "hard points" that would significantly increase the load on the rollers locally. Therefore, it can be concluded that the crane frame structure has no glaring errors, but the bearings used are heavily loaded. At the maximum loads of the cranes, the bearing works at the limit of its load capacity.



	m	11,1 - 33,1 m T
I	3	50
II	6	21
III	10	9.5
IV	14	4.2
V	18	2.2
VI	20	1.8
VII	24	0.7

Fig. 9. The distribution of the internal load in the bearing of a mobile crane at different operating points of the crane for the angle of rotation of the body $\theta = 0°$
Source: own study

The main problem in designing the rotational nodes of machines is to provide the rolling system with an appropriate support so as to obtain an even load transfer by the rolling elements. Numerous experimental and operational studies (Smolnicki, 2013) and the results of numerical simulations (Mazanek and Krynke, 2011, Krynke and Borkowski, 2014) prove that not only the global stiffness of the support components is important, but also its distribution along the bearing ring.

It should be borne in mind that both the rigidity of the body frame and the rigidity of the mobile crane chassis are not uniform across the entire surface of the seats around the bearing circumference. This diversity can affect the loads on some rolling parts to a different extent at different angles of the body relative to the chassis. In order to verify the above thesis, calculations of the internal load distribution in the bearing of a mobile crane at different angles of the body position were performed.

Figure 10 shows the distribution of the maximum roller loads in the calculation rows of the crane bearing for successive positions of the body rotation in the range of angles $\theta = 0°÷180°$ with an angular scale every 10°.

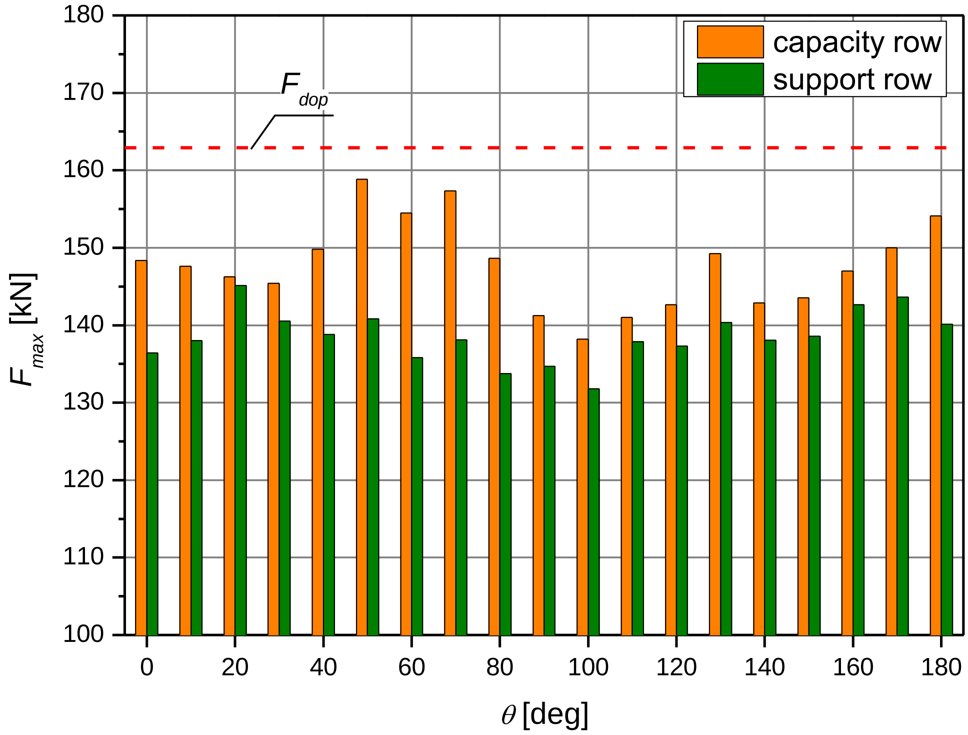


Fig. 10. Maximum loads on the rolling parts at different positions of the body (angle θ) in a crane carrying a load of 50 tons at a length of 3 m

Source: own study

The presented distribution shows that the most loaded are the rolling elements during crane operation at the angle of the body position of $\theta = 50°÷70°$, in this operating range of the crane there is also the greatest variation in the loads of the carrying rollers and supporting rollers. The crane body is characterized by different stiffness around the bearing circumference. It has the greatest rigidity in the place of mounting the main cylinder of the crane jib arm. For such an angle of the body position, this place is located above the main chassis longitudinal member, which is additionally reinforced with a truncated cone-shaped sheet at this point. Such an arrangement of the body and chassis causes that the local stiffeners of these structures are above each other, which in turn causes a greater load on the rolling elements located in this place. The angle of body position θ = 100° is the most favorable angle of body rotation during crane operation due to the operation of the bearing. For this position, the greatest local body stiffening (main cylinder attachment point) is above the part of the chassis which has the lowest stiffness at this point. The differences in the forces transmitted by the rolling elements at different positions of the crane's body are approx 17%.

7. CONCLUSION

In lifting devices, a lot of attention is paid to safety. This is due to the fact that damage or destruction of critical parts of these machines can cause catastrophic accidents. The key element for the safe operation of a mobile crane is a slewing ring bearing.

The analyzes carried out in this article show that the actual load capacity of slewing ring bearings mounted in a working machine with a complex shape of support structures is definitely lower than the catalog load capacity of the bearing, which assumes non-deformability of bearing rings. The differences in the bearing load capacity for different machine positions are also important. This is due to the uneven distribution of the internal load in the bearing.

The presented FEM model of a mobile crane allows to determine the influence of deformability of supporting structures and the non-uniformity of their flexibility to the load of rolling elements in a cross bearing. The analyzed bearing for the existing mobile crane is a highly loaded bearing. For the maximum crane load and selected body positions, the load on some rollers is limited. Even a 25% reserve of the catalog load capacity (Fig. 7) does not compensate for the effects of deformation of load-bearing structures. Therefore, when designing the structure of the machine supporting frames, it is necessary to conduct a thorough analysis not only of the bearing dimensions, but also of the stiffness of the supporting frames as well as the bolted connections of individual units. Additional degradation of the bearing in the form of wear during operation may cause its load capacity to drop. This, in turn, increases the risk of its damage, which can lead to a catastrophe during the operation of such a crane.

The proposed method of calculating the actual load capacity of slewing slewing bearings in the form of a diagram of the total load capacity enables a comprehensive assessment of the load capacity of the bearing. It can be recommended to designers of new devices, and it can also be used by users of existing devices. The presented example confirms the above statement.

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