Increasing the Carrying Capacity of Anchor Bolts by Design Modification of the Nut

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Abstract: Prestressed bolted connections are commonly used for anchoring machinery and equipment, where prestress is induced by mechanically tightening the nut to the required torque. To ensure safe and reliable operation, the prescribed tightening procedure must be followed, especially in the case of anchor bolts embedded in a concrete foundation. The paper deals with the problem of anchoring a new casting stand using the original anchor bolts subjected to cyclic loading during rotation of the casting stand base. The aim was to propose a methodology to verify the reliable and safe operation of the original anchoring system, taking into account the current condition of the bolts. In order to assess the actual condition of the anchorage, as well as to determine the necessary prestressing, the authors proposed the use of a modified nut with a lightened first thread, whose shape and dimensions were determined on the basis of the results of numerical modelling using the finite element method. The suitability of the proposed methodology was experimentally verified by carrying out measurements under different loading modes, which took into account the actual operating conditions. The interpretation of the obtained results, including a comprehensive view on the safety of the anchorage, provides relevant evidence of the functionality and effectiveness of the proposed anchorage solution for the new casting rack.

Keywords: Prestressed bolts; Operational measurement; Stress analysis

1 Introduction

Numerous standards deal with the design and connection of bolts (anchor bolts) with concrete [1,2]. In recent years, anchor bolt failures have been studied extensively in many ways, including experimental testing, numerical simulations, and verifications. Delhomme et al. [3] studied the experimental behaviour of anchor bolts under static tensile loading and also analysed the relaxation of these bolts. Li and Liu [4] studied the shear behaviour of the fully grounded bolts through experimental testing, during which the direct shear tests were carried out on three groups of specimens with different bolting angles or grout strengths, measuring shear loads, shear displacements, and strains in bolts. They observed that the bolts failed near the concrete foundation. Gong et al. [5] studied the failure analysis of anchor bolts used to fix a seawater booster pump in a nuclear power plant. They concluded that the failure was due to screw corrosion. The failure modes of anchor bolts under cyclic loading were investigated by Feng et al. [6]. They analysed the mechanical responses of bolts with different diameters and applied different cyclic loads. The behaviour of the bolted joints is also affected by the preload in the bolt. The preloaded anchor bolts were investigated and described in paper [7]. To investigate the bolts' inner force quantities and displacement,

Huang et al. [8] analysed the influence of the anchorage length using the load transfer method. The obtained results confirmed that the increasing anchorage length caused significant unevenness of the interfacial shear stress distribution, and a greater bearing capacity of the anchoring bolt. Yang [9] investigated the mechanism of force evolution in bolts and found that bolts with different anchorage lengths should be used to support roadways with different deformation characteristics. His research concluded that the bolts should be kept in the deformation phase of the anchoring force as much as possible when the surrounding rock deforms. Liu et al. [10] proposed a stress reduction calculation method to calculate the actual stress of the bolt from the measured value registered by the pulse pre-pumped Brillouin optical time domain analysis technology of different types of bolts embedded in concrete with resin as an anchoring agent. However, dynamic loading also affects the lifespan of the bolt joint [11,12]. Trebuňa et al. [13] considered the possibilities of reducing the vibration amplitudes of the converter base through design changes and changes in the pre-stress of the screw connections. However, the high stress in anchoring bolts, among other things, causes serious deformation and damage of equipment, as well as steel constructions [14-16]. Lin and Wu [17] investigated the maximum axial force in bolts, employing conservative failure probability assumptions made by the finite element software. Using numerical simulations performed in Matlab, Zheng et al. [18] analysed the influence of different anchoring methods, changes in surrounding rock properties, bolt properties, and pre-tightened forces on the pre-stress distributions in the bolt body and surrounding rock. Miao [19] reviewed methodologies concerning bolt tightening force measurements and monitoring for loose bolts.

The paper deals with anchor bolts embedded in concrete, which are part of the existing technological chain. For this reason, it is not possible to perform laboratory measurements. This problem was solved by using a modified slotted nut to relieve the first thread, which is the most stressed and is the main cause of failure of the bolted joint. The modification of the slotted nut is primarily associated with an increase in the dimensions of the nut, i.e. its height and external dimensions have been increased.

2 Introduction to the anchoring of the casting pedestal

The continuous casting of slabs is currently the most widely used method, in which the solidification of steel leads to the production of long steel products. Its fundamental principle is that the liquid steel is first infused from a ladle into a tundish and then distributed through many sprues in a vertical direction into water-cooled copper moulds. The ladles, transported by an overhead bridge crane and a casting pedestal, are used to bring the liquid steel from the converter to the tundish. The casting pedestal is used for constraining the casting ladles and their rotation from the reserve position to the casting position, and vice versa. It also serves to drain the molten steel into the emergency containers in case of a failure of the slide cap, and for lowering and lifting the casting ladles during various technological operations. It is a two-position pedestal realised as a lifting and rotating pedestal with a load cell. The supporting structure of the casting pedestal is formed mainly by steel weldments. Their dimensions and shapes are designed in such a way that after the casting ladle filled with liquid steel is placed in the reserve position, the casting pedestal ensures its transfer around the axis of the casting pedestal to the casting position. After casting the steel from this ladle into the tundish to about 25% of the liquid steel content, the second full pan can be placed on the other/opposite traverse side (in the reserve position). If there is only molten slag left in the

casting ladle (approximately 7000 kg), the pedestal is rotated so that the full ladle is moved from the reserve position to the casting position. Selected technical characteristics of the assessed casting pedestal (Fig. 1) are:

- Maximum weight of the casting ladle with metal (steel) 260 000 kg;
- Weight of empty ladle 70 000 kg;
- Ladle lift height 800 mm;
- Pedestal angular velocity 1 rpm;
- Maximum angle of rotation 230°;
- Roller track mean diameter 6 400 mm.

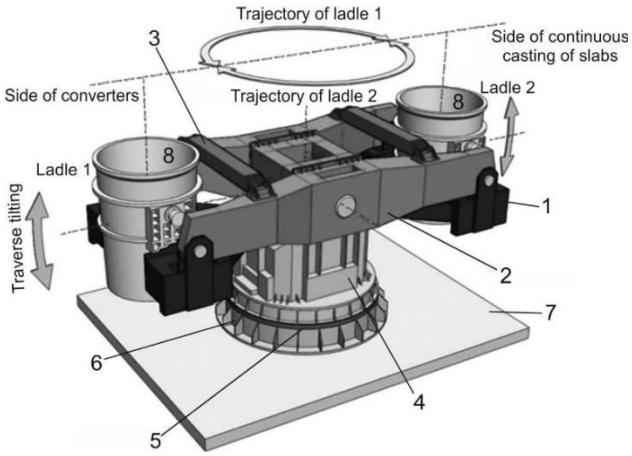


Fig. 1 Basic parts of the casting pedestal: 1—hinging supporting baskets; 2—traverse beams; 3—connecting rods; 4—bearing support pedestals; 5—roller bed; 6—supporting structure; 7—concrete foundation; 8—casting ladles.

As part of the overhaul of the casting pedestal, some supporting members were replaced, but replacement of the anchor bolts embedded in the concrete foundation was not possible. When the original structure was disassembled, damage to the first threads on the concrete foundation side of some of the anchor bolts was found. As already mentioned, their replacement was not possible, or very difficult. Therefore, it was necessary to design another solution to achieve safe operation at the required bolted joint preload. By numerical modelling, a design modification of the nut was proposed to lighten the first threads. Subsequently, experimental measurements were carried out, taking into account real operational conditions. Based on the results obtained, conclusions were drawn on the further operation of the casting pedestal. The value of the considered preload of 180 kN in the bolted joints was taken from the original static calculation. Fig. 2 shows the layout of three types of anchor bolts (34 anchor bolts in total) with basic dimensions, which are used to fix the casting pedestal to the concrete foundation.

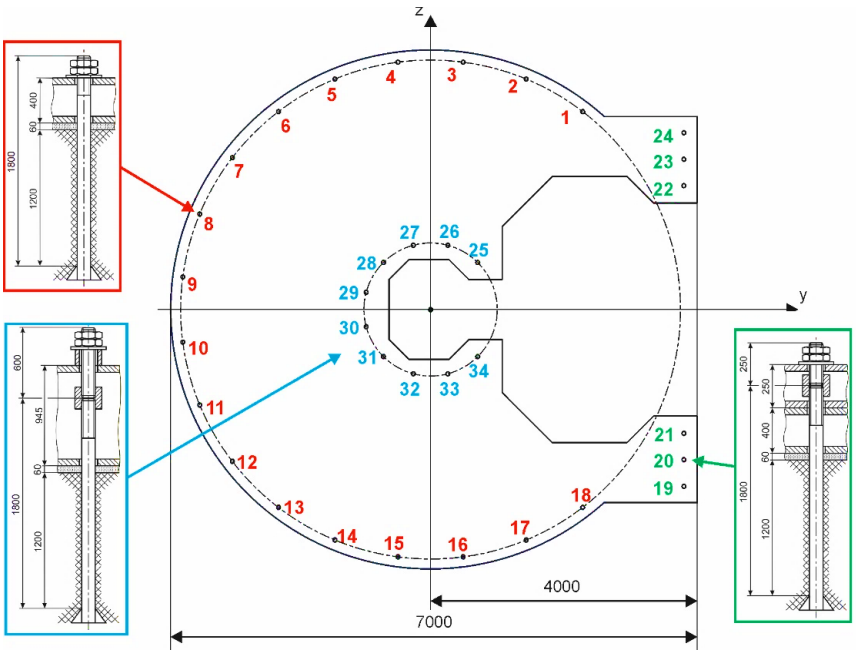


Fig. 2 Basic dimensions of anchor bolts and their layout.

It was necessary to design the methodology of re-anchoring the casting pedestal so as not to damage the bolted connections (releasing the bolts in the concrete foundation), the repair of which would be not only technically and financially very difficult, but also time-consuming. In addition to the machining method, the lifespan of the anchor bolts under investigation is influenced, in particular, by the impact of notched effects, which is most significant and unfavourable during the fatigue loading of machine parts and structures. In the case of the bolt and nut, according to Fig. 3, the decisive design notches are in the following places:

- Location 1—passage of the cylindrical part of the bolt to the head—this location is absent from the anchor bolts;
- Location 2—thread runout;
- Location 3—thread;
- Location 4—bolt thread at the first nut's support thread (the most common cause of failure).

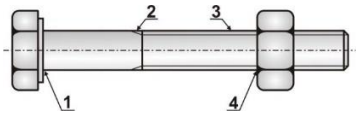


Fig. 3 Notch locations on the bolt.

The fatigue notch factor is most significant in the bolt thread at Location 4. This fact is related to the stress distribution in the bolt thread, which changes significantly in the part of the thread bolted into the nut. The change in stress distribution is caused by the uneven force distribution in the bolt on the individual threads (Fig. 4) due to the different deformations of the bolt and nut.

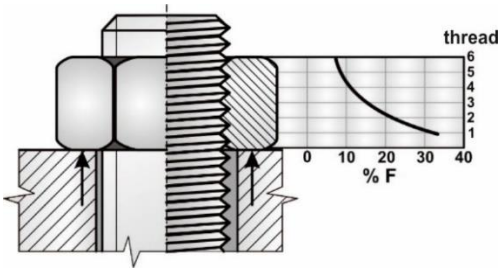


Fig. 4 The uneven force F distribution in the threads.

The first thread of the nut and the corresponding cross-section of the bolt are the most loaded. As a result, the first load-bearing thread exhibits the most significant notch effect, which is caused by the load from the force flow in the shank and the local bending of this most loaded thread. The fatigue notch factor for the threaded part of the bolt depends on the mechanical properties of the bolt, the technologies of its production, the shape of the thread profile, its surface, and the type and height of the nut. From the tests of bolted joints in which the fracture occurs at Location 4 (Fig. 3), it is possible to derive a four- to eight-fold notch effect.

In this paper, a methodology for achieving the required bolted joint preload is proposed and experimentally verified, taking into account the damage to the threads on the bolt. The proposed design modification of the nut achieved the relieving of the first threads on the bolt, thus ensuring the safe and reliable operation of the casting pedestal anchoring.

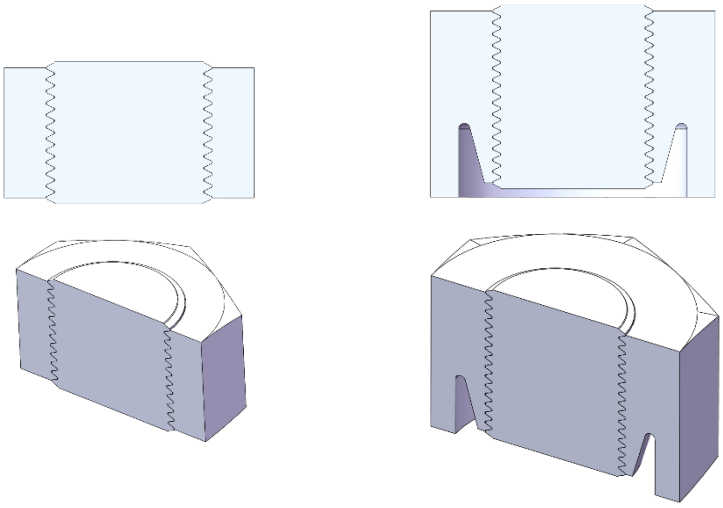
3 Materials and methods

The aim was to design and experimentally verify a methodology for applying the required preload in the anchor bolts of a casting pedestal that had been in operation for less than 30 years. The authors assumed real operational conditions where it was impossible to perform the test tightening of nuts exceeding the allowable values of axial forces in the bolts, as they could not be released from the concrete foundation. In such a case, the new casting pedestal, and thus the entire production, would be undesirably shut down. When proposing the methodology, the authors utilised proven knowledge obtained from the failure of bolted joints, where in similar cases, the damage most often occurred at the place of the first load-bearing thread (see Fig. 3). Nuts with notches were designed and subsequently fabricated using numerical modelling based on the finite element method to achieve the required preload. The notch was used to provide a relieving of the first threads (Fig. 5b). A methodology for measuring the axial forces in the anchor bolts under the operational load was proposed and experimentally verified using dynamometers to verify the functionality of the bolted joint (set preload) and assess the safe operation of the casting pedestal. Before tightening the nuts, a strength calculation of the preloaded anchor bolts was performed to assess their safe operation, taking into account the loading history to date.

4 Proposal of nuts modification using finite element method (FEM)

To reduce the significant notch effect of the normalised thread as much as possible, it was necessary to ensure the best possible quality of its surface at the root of the profile, and to reduce the relative load on the first and second threads. This can be done through structural modifications based on the idea of changing the deformation stiffness of the nut around the first threads. By reducing the cross-sectional area of the nut (contact of the nut with the washer), the conditions for the bending expansion of the nut were created. In addition, when

the normalised nut is tightened to higher torque, plastic deformations and the compression of the first co-locking threads on the nut and bolt occur. Depending on the magnitude of these undesirable phenomena, damage to the bolts occur, which in the case of anchor bolts are extremely technically demanding to replace. Therefore, the authors' attention was on achieving an optimum stress distribution of the co-collecting threads of the nut and bolt. Fig. 5a shows the model of the normalised nut M56, and Fig. 5b shows the nut with the notch formed. As the first threads were relieved, to create a notch with the required dimensions, it was necessary to change the outer dimensions and the total number of threads in the nut, as shown in Fig. 5b. The proposal of the outer dimensions was based on the dimensions of the torque wrench head (Enerpac HXD 120-CC1290).

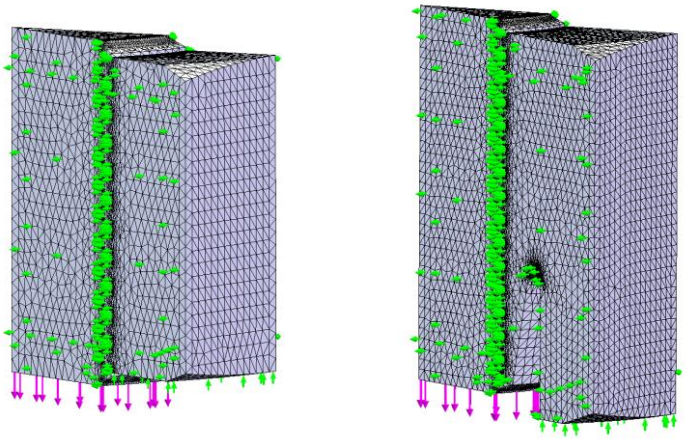


(a) (b)

Fig. 5 Sections through the analysed matrices: (a) normalised nut; (b) modified nut with the designed notch.

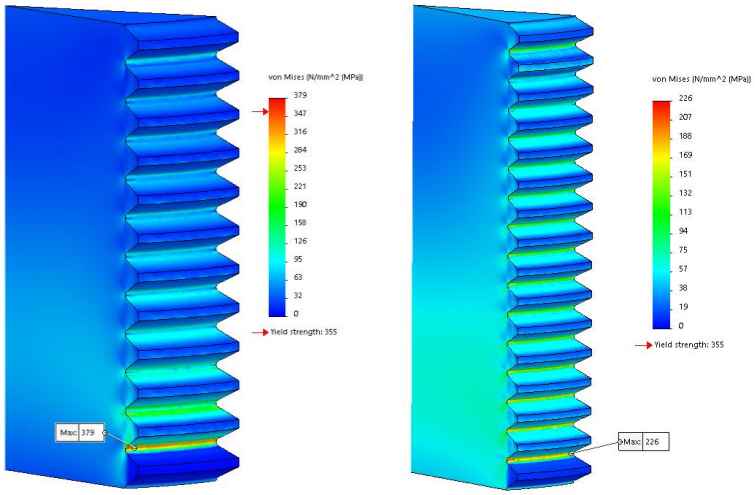
Fig. 6a,b show the bolted joint model with the finite element mesh formed and the boundary conditions defined. By using symmetry, only 1/12 of the overall model was modelled. The nut was simply supported and the bolt was loaded by the force equal to 15 000 N. The mesh of normalised nut M56 consisted of approximately 155 000 volume finite elements with quadratic approximations, and approximately 230 000 nodes. The mesh of the nut with the notch consisted of approximately 456 000 volume finite elements with quadratic approximations, and approximately 668 000 nodes.

The FEM was a qualitative comparison of stress levels for different nut shapes, so for this reason only a static analysis with linear elastic material behaviour was performed. The material properties of the bolt and nut were the same, i.e., the yield strength was 355 MPa and Young's modulus was $E = 2 \cdot 10^5$ MPa . Fig. 7a,b show details of the equivalent stress fields around the first relieved threads. From comparing the values of the maximum equivalent stresses around the thread root (from 379 MPa to 226 MPa), it is clear that the above modification resulted in a reduction of equivalent stress by approximately 40%. When designing the dimensions and shape of the notch, the technological procedure of its production was taken into account.



a) b)

Fig. 6 1/12 of the overall model: (a) normalised nut; (b) designed nut.



(a) (b)

Fig. 7 Fields of equivalent stress around the root of the first thread on the anchor bolt when using: (a) normalised nut; (b) designed nut.

Fig. 8 shows a top and bottom view of the modified nut proposed by the authors.

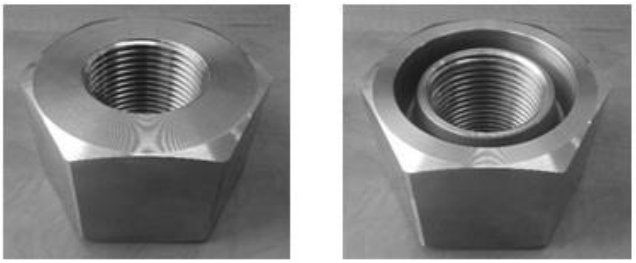
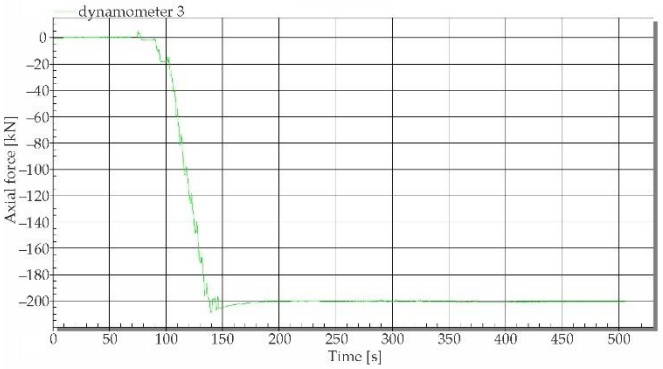


Fig. 8 Top and bottom view of the modified nut.

5 Measurement at operational loading

As already mentioned in the introduction, the first step was to set the required value of the axial force in the prestressed bolted joints. For the adjustment, prototype dynamometers designed by the authors were used, see Fig. 9, Fig. 10a. The dynamometer was designed in such a way that the responding magnitude of the axial force in the bolt induced by tightening the nut could be determined based on its deformation measured by strain gauge sensors. The same dynamometers were used in the second stage for the operational measurement of axial forces during the manipulation of the casting stand. The most stressed bolts No. 8, No. 11, No. 19 and No. 24 (see Fig. 2) were chosen for the operational measurements. The authors had prepared four dynamometers, but at the beginning of the operational measurements one of them was damaged by the operator. Therefore, the operational measurements continued on three anchor bolts.



(a) (b)

Fig. 9 Setting the required preload value (200 kN) in the anchor bolt No. 10.

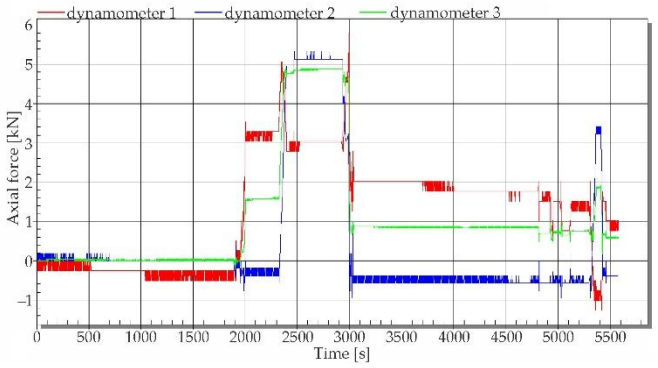
After a detailed analysis of the condition of the anchor bolts, as well as of the measures taken to relieve the first and the other three bolt threads at the nut location, and also taking into account the previous history of the loading of the anchor bolts, the authors determined the preload forces in the individual anchor bolts as follows:

- Anchor Bolts No. 1 to No. 24 should be preloaded to an axial force corresponding to 200 kN, which corresponds to a given state of bolts, nuts, and washers when defining a pressure value of 120 bar;
- Anchor Bolts No. 25 to No. 34 should have a preload with regard to the passage of the thread into the shank as well as the flexibility of the supporting structure, and a lower range of operational axial forces of 180 kN, i.e., approximately 110 bar.

Dynamometers 1 to 4 were used to measure the time changes of the axial forces in the anchor bolts on the casting pedestal. When selecting the anchor bolts under consideration, effort was made to remove the most, or nearly the most loaded bolts. Based on the above requirements, anchor Bolts No. 8, No. 11, No. 19 and No. 24 were selected, which are located on the outer contour of the supporting structure, therefore the preload value was selected at 200 kN. After putting the casting pedestal into testing operation and balancing the strain gauge apparatus connected to the completed measuring chain, the strain gauge measurement of changes in the axial forces in the anchor bolts began. Unfortunately, the first measurements showed that the cabling on Dynamometer 4 was damaged by the operating personnel. Due to the time

duration of the planned outage of the casting pedestal, it was not possible to perform its repair. Therefore, the operational measurement was continued by using only three dynamometers.

The first operational measurements, which were performed only when rotating the casting pedestal without the ladle in the first and second basket, showed that the changes in the axial forces in the bolts did not exceed 6 kN in these measurements. Fig. 10 shows the time courses of changes in the axial forces in Bolts No. 8 (dyn 3), No. 19 (dyn 1), and No. 24 (dyn 2) when rotating the casting pedestal without a ladle in Basket 1 and Basket 2, while the beginning of rotation at approximately 2000 s is from the position of Basket 1 from the reserve to the casting position. After a short interruption of the rotation, the rotation continues and the traverse is lifted. It can be seen from the course that the axial force increments do not return completely to zero after the return of Basket 1 to the reserve position (time 5000 s), which may be caused partly by inaccuracies in the return of the traverse to the same position, and also by the changed geometry due to the position of the rollers on the roller track.



(a) (b)

Fig. 10 Recording of time changes of axial forces when rotating the casting pedestal with empty baskets.

Although these are forces that cause stress in bolts below 3 MPa, i.e., absolutely negligible components in terms of the resulting stress, they testify not only to the condition of the roller track but also to the stiffness of the supporting structure of the casting pedestal.

The following section shows the selected time changes of the axial forces in Bolts No. 8, No. 19, and No. 24. The operator used ladles weighing 70 300 kg (empty) and 241 600 kg (full). Fig. 11 shows the time changes of the axial forces when loading the empty ladle into Basket 1 in the reserve position at about 50 s after the start of the measurement. It can be seen that a positive increase in axial forces occurred in Bolts No. 19 and No. 24, which is caused by the fact that, after loading the empty ladle, the preload in Bolts No. 19 and No. 24 is reduced, and this is reflected by an increase in the deformation part of the dynamometer, resulting in a positive reading on the strain gauge apparatus. Simply put, if the preload in the bolts were not set, it would not be possible to register a decrease in the axial force. At a time of about 100 s, the rotation of the casting pedestal with an empty ladle in Basket 1 started from the reserve position to the casting position, which caused changes in the polarity of the force increments in the bolts when Basket 1 was moved to the casting position. It is evident from the courses that in this operation the axial force range in Anchor Bolt No. 8 is 25 kN, in Anchor Bolt No. 19 it is 13 kN, and in Anchor Bolt No. 24 it is 19 kN. At the end of the time period (Fig. 11), Basket 1 with an empty ladle was in the casting position.

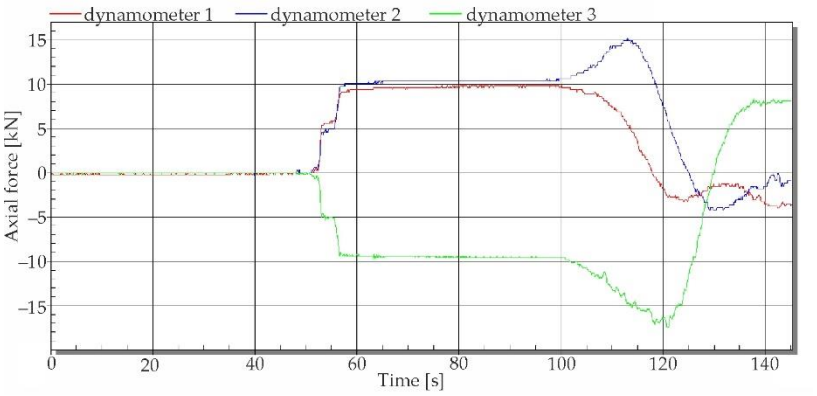


Fig. 11 The time courses of axial forces in Bolts No. 8, No. 19, and No. 24 when loading the empty ladle into Basket 1 and rotating the pedestal to the casting position.

In order to assess the safe operation of the casting pedestal, the following operational modes were examined:

I. Rotation of the pedestal without a ladle in Baskets 1 and 2;

II. Loading the empty ladle with subsequent rotation, and lifting of the ladle in the casting position in Basket 1 and subsequently in Basket 2;

III. Loading a full ladle weighing 241 600 kg into Basket 1 and subsequently into Basket 2, rotating the pedestal, and lifting and launching the basket with the ladle;

IV. Loading the empty and full ladle and handling the pedestal, including the replaced ladles in baskets.

After analysing the time records of changes in the axial forces in the bolts in the above-mentioned operational modes of the pedestal, it was found that the maximum range of changes in the axial forces ΔN_i in the measured bolts is the following: $\Delta N_8 = 61$ kN, $\Delta N_{19} = 60$ kN, $\Delta N_{24} = 61$ kN.

Conclusion

At the outset it should be noted, that as mentioned above, the operational measurements of the time changes of the axial forces were carried out with an empty ladle weight of 70 300 kg and a full ladle weight of 241 600 kg. In the technical characteristics of the casting pedestal defined by the operator, the values of an empty ladle at 70 000 kg and a full ladle at 260 000 kg were defined, which represents a difference of 0.43% in the case of an empty ladle, but in the case of a full ladle its maximum possible weight is 7.1% higher, thus the stress and strain fields in the elastic behaviour of the structure will be higher according to the stated difference, including axial forces. Therefore, in the subsequent analysis, it was necessary to consider their increase by 7.1% at the measured maximum values of an axial force range of 61 kN, i.e., with increased range $\Delta N_{\max} = 65$ kN.

From the analysis of the critical points on the anchor bolts, it can be seen that the replacement of the original nuts with new nuts played a very important role, as the first thread of the bolt in the nut is more than twice as sensitive to the occurrence of a failure as the thread

termination point. The anchor bolt's failure limit is determined by a location which, despite the frequent occurrence of the failure, is a much safer cross-section.

The experimental determination of axial force ranges has shown that the calculation of the forces in the anchor bolts ensures a high value of anchor safety. On the other hand, the force measurement methodology and the interpretation of the results achieved, including a comprehensive view of anchoring safety, provides relevant evidence of the functionality and effectiveness of the proposed solution.

In order to ensure safe operation of the anchoring during the lifespan of new parts for the casting pedestal, and taking into account the accumulation of damage to the anchoring bolts to date, it is necessary to apply the current recommendation of the authors that, when placing a full ladle in the casting pedestal and when rotating it, there should always be an empty ladle or a ladle with molten slag in the other basket. In accordance with the fatigue curve for the material values of the bolt and in the implementation of 35 melts per day, the lifespan of the bolts of the casting pedestal will be approximately 10 years. Otherwise, if a full ladle is always loaded into the casting pedestal and there is not at least an empty ladle on the other side, the lifespan of the anchoring will be reduced to about one third.

Acknowledgements

This paper was supported by the Ministry of Education of Slovakia Foundation under grant projects VEGA No. 1/0516/22, VEGA No. 1/0141/20 and VEGA No. 1/0509/23.

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