The paper presents an unconventional method of determining joint diagrams for foundation bolted joints of heavy machinery and equipment, with bolts anchored in a concrete block using special polymer material EPY. It includes a continuation and development of the problems discussed in Part I, which shows the specificity of these joints that distinguishes them from conventional bolted joints. It also shows a way of determining a joint diagram for an assembly state of these joints. Part II of this elaboration is devoted to the determination of a joint diagram for the examined bolted joint under operating conditions. This joint diagram is different from that designated for the assembly state. It has been obtained on the basis of many separate numerical calculations, performed with ANSYS FEM system. A practical way of using this diagram is also shown, and finally conclusions of cognitive and practical meaning were formulated.

Key words: foundation bolted joints, polymer plastic, modeling, calculation, joint diagrams

1. INTRODUCTION

This study is devoted to problem of modeling and calculation of modern foundation bolted joints of heavy machinery and equipment, generating large dynamic forces and vibrations, with bolts embedded in concrete blocks and anchored using special polymer plastics. Such solutions are the result of progress made in this area of technology in recent years. They are used widely in practice today, both in foundation repair and modernization of old machinery and equipment, as well as in seatings of new objects of this type [1, 2, 3, 5, 7].

All of this study consists of two parts. Part I presents the specificity of these bolted joints, which distinguishes them from conventional bolted joints. It has been
shown that due to the complexity of the design and material of such a bolted joint (made of steel, plastic and concrete) and the coupling appearing in the fields of stresses and strains in the bolt and the parts to be assembled, one can not determine for it joint diagrams using the known simple methods and formulas given in the VDI guidelines [6] and in widely available literature. This issue is illustrated by the example of the joint diagram, determined for the assembly state of such a bolted joint.

The main aim of Part II of this study is to determine a joint diagram for the considered bolted joint, for the case when operational forces are applied to it. In contrast to conventional models and calculation methods of bolted joints (see [4], Fig. 2), in this case, the joint diagram obtained for the operational state does not coincide with the joint diagram determined for the mounting state of the joint. To determine this it requires a number of separate calculations, which can now be done relatively easy using FEM system ANSYS.

2. ANALYSIS OF THE OPERATIONAL STATE OF THE INVESTIGATED BOLTED JOINT

In the case of conventional bolted joints, i.e. those in which the connecting and connected elements can be separated (in a physical or symbolic way), and are treated as independent each other, joint diagrams for the operational state overlap with those for the assembly state (see [4], Fig. 2). In the bolted joint considered here (Fig. 1) such separation can not be made, and in this case joint diagrams for the operational state do not overlap with joint diagrams of the assembly state.

Fig. 1. Foundation bolted joint of a reciprocating compressor (a) and its joint diagram for the assembly state (b)
Determination of the joint diagram for the operational state in this case is somewhat complex. It requires quite a lot of numerical calculations of stresses and deformations that can be performed using FEM. The starting point for these calculations is a correctly determined assembly state of loads and deformations for the system. It has been determined in [4] and is shown in Fig. 1b. For the assembly state it was assumed that the bolt is preloaded with the compressive force $F_m = 170$ kN. According to the law of action and reaction, the same force exerts pressure on the joined elements in the location of the nut. In this state, the total extension of the bolt is $f_{sm} = 0.177$ mm, and the total compression of the joined elements $f_{pn} = 0.066$ mm (Fig. 1b).

In order to determine a joint diagram for the operational state of this joint it was assumed (for simplicity’s sake) that a given external (operating) load $F_e$ is applied to it in the contact plane of the nut with the steel plate (Fig. 2a, b) and acts along the axis of the bolt. First, it was assumed that the external load acts tensioning, and later – compressing on the considered joint. Gradually increasing the value of external load $F_e$, distributions and values of normal stresses $\sigma_y$ in cross-section II-II of the investigated joint, i.e. in the cross section of the bolts and in the contact area between the steel plate and plastic chock (Fig. 2c) were determined.

Examples of the obtained distributions and values of stresses $\sigma_y$ in this section, evaluated for $F_e = 0$ (i.e. for the assembly state) and for $F_e = 100$ kN and $F_e = -100$ kN, respectively, are shown in Fig. 2d, e, f. Then, on the basis of these stresses, using the appropriate numerical integration, the values of the forces $F_s$ and $F_p$ in the bolt and assembled parts were determined.

Calculations were performed in a wide range of variations of external load $F_e$, assuming that it will not exceed the yield strength or the strength of the material of the bolt. The results of these calculations, as the functions of external load $F_e$ are shown graphically in Fig. 3. The idea here was to check the correctness of the calculation results. In particular, this concerned checking the correctness of the obtained characteristics and the limit values of the service load at which the residual clamping force $F_r$ in the joint or the force $F_s$ in bolt drops to zero. In this case, these values are, respectively: at extension load $F_{emax} = 235$ kN and at compression load $F_{emin} = -540$ kN (Fig. 3).

The calculated characteristic is of practical relevance only for such external loads at which the residual clamp force $F_r$ acting on the joint does not drop below an acceptable minimum. In the state of assembly the forces in the bolt and joined elements have the same value and are equal to the preload ($F_s = F_p = F_m = 170$ kN). After applying an external tensile load $F_e$ to the joint under the nut, the force in the bolt will increase by an additional amount $F_{se}$ and will be equal to the sum $F_s = F_m + F_{se}$, and the clamping force in the joined elements will be reduced by the amount $F_{pe}$ and will be equal to $F_p = F_m - F_{pe}$. 
Fig. 2. Modeling of the investigated bolted joint and calculation results for the stresses $\sigma_y$ obtained by using the FEM.

It is worth noting that the external load $F_e$, applied to the joint under the nut, produces only a relatively small increase of the force in the bolt. The majority of this force causes a reduction of the clamp force in the joined elements. The values of these additional forces $F_{se}$ and $F_{pe}$ for a given external load $F_e$, can be easily read from the graph given in Fig. 3. The proportions of these forces depend on the flexibility of the bolt and assembled parts.

Too large increments of the load in the bolt can make its break, especially when it changes periodically. On the other hand, too great reduction of the clamping force in the joined elements can cause the loosening of the bolted joint.
Fig. 3. Characteristic of the investigated bolted joint showing the dependence of the total forces in the bolt \( F_s \) and connected elements \( F_p \) and their increments \( F_{se} \) and \( F_{pe} \) from a given external load \( F_e \).

Fig. 4 shows the joint diagram for the tested joint, which expresses graphically the dependence of the operational forces \( F_s \) and \( F_p \) and their increments \( F_{se} \) and \( F_{pe} \), on the deformation increments \( f_{se} \) and \( f_{pe} \), of the bolt and joined elements induced by a given external load \( F_e \). The starting point in determining this diagram was the joint diagram for the assembly state, corresponding to the preload of \( F_m = 170 \, \text{kN} \) (Fig. 1b). In this state the forces \( F_s = F_p = F_m \) and the assembly deformations of the bolt and joined elements, are respectively: \( f_{sm} = 0.177 \, \text{mm} \) and \( f_{pm} = 0.067 \, \text{mm} \). For this state zero values were adopted for the external force \( F_e \) and for the service deformations \( f_{se} \) and \( f_{pe} \) (Fig. 4).

Fig. 4 also presents (for comparison purposes) the joint diagrams for the assembly state of the tested joint, obtained earlier [4]. It is worth noting that the joint diagram for the operational state does not coincide here with the joint diagrams for the assembly state, in contrast to what takes place in the conventional theory for modeling and calculation of bolted joints. It follows from this that the assembly joint diagram determined for the considered bolted joint can not be extrapolated and taken as a joint diagram for its operational state. These two joint diagrams have only one common point for the operational force \( F_e = 0 \). Beyond that point the joint diagrams are different and require separate calculations for mounting and operating conditions.
Fig. 4. Joint diagram for the operational state of the investigated bolted joint

Joint diagrams for the operational state play an important role in the visualization and analysis of the behavior of bolted joints under normal operation. The below example is an illustration for that. For the analysis the bolted joint presented in Fig. 2a tighten with a mounting force $F_m = 170$ kN was adopted. It was assumed that an external cyclic load $F_e = F_a \sin \omega t$, where $F_a$ is the amplitude of this load acts on this joint. For calculations it was assumed that $F_a = 70$ kN.

For the visualization and influence analysis of the given external load on the behavior of the joint under study the designated joint diagram for the operational state, shown in Fig. 4, was adopted. Time course of the given external load and its effects on the bolt and the elements combined, are shown graphically in Fig. 5. From the graphs placed on the right side in Fig. 5 it can be seen that the bolt is not subjected to the full amplitude of the external load. Only a small part of the external load (in this case, ca 28 %), is transferred to the bolt and causes in it alternately increasing and decreasing the mounting force $F_m$. The remainder – greater part of the external load will alternately reduce and increase the clamping force of the joined elements. The proportions of these forces depend on the operating flexibility characteristics of the bolt and connected elements. The graph at the bottom in Fig. 5 shows the time courses of increase and decrease in deformations occurring in the bolt and connected elements, resulting from the external load.
The alternating forces in the bolt must not be too large because of the fatigue phenomenon of the material and the fact that bolts can simply break off. However, too large drops of the clamping force in the joined elements can cause loosening of the bolts and an increase in vibration. From this example it is evident that joint diagrams for the operational state of the foundation bolted joints can be an essential scientific help in solving many contemporary problems. In particular, this applies to increasing reliability and durability of attachment systems and reduces vibrations of heavy machinery and equipment that generate large dynamic forces.

3. CONCLUSIONS

The paper discusses the problem of modeling and calculation of modernized foundation bolted joints of heavy machinery and equipment, using special polymer plastics. These materials are increasingly used for anchoring bolts in concrete block foundation and for chocks under the installed objects.
The study showed that for such foundation bolted joints joint diagrams, both for the assembly and operation state, can not be determined using the conventional methods and formulas, known from textbooks and standards for bolted connections.

The complexity of the bolted joint analyzed in this paper lies in the fact that either in a real or symbolic, the connecting element (bolt) and the connected elements cannot be separated in it and cannot be treated as independent of one other. Such a separation is the basis of the known (conventional) methods of modeling and calculation of bolted joints. In the bolted joint considered in this paper such a separation is impossible, because of the strong coupling of the stress and strain fields occurring in the bolt and connected parts. This coupling occurs through the foundation in which the bolt is anchored.

Another problem is the complicated geometric and material structure of the system investigated. It makes it impossible to use any of the known methods and formulas, available in standards and literature. The study further showed that, in adopting an appropriate model for the tested system and using the finite element method we can now obtain an effective solution to the task with due regard for the real geometrical and material features of the modeled object.

Joint diagrams for modernized foundation bolted joints determined in this way play a significant theoretical and practical role. They provide a scientific basis for strength analysis, comparative assessment and rational designing of such connections. Above all, they are necessary for modeling and analyzing dynamic properties of mounting systems of heavy machinery and equipment, installed on concrete foundations. In the modern approach such objects should be treated as integrated dynamic systems, consisting of three main parts, namely: machinery (treated as a vibration generator), the foundation and the mounting system. Many studies and practice show [1, 2, 5, 7] that the weakest links in these systems are now usually the mounting systems. Therefore, many attempts have been made in the recent years to improve this situation.

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REFERENCES


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