PROCESS MODELING OF INCREASING RELIABILITY OF ASSEMBLY RESPONSIBLE CONNECTIONS

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Abstract:
Questions of increased reliability of responsible connections at a stage of their assembly are considered in the paper. This step provides the necessary operational characteristics of outputs. The special place among such responsible connections is occupied with the group threaded connections. Their assembly technology provides reception in fixing details normalized relatively identical axial efforts in regular intervals loading a sealing layer. The presented work results of experimental research on the group threaded connection assemblage process are given. Alternate calculations of efforts change in tightened pairs of threaded connections and their graphic interpretation are presented. An algorithmic calculation model of overload factors for fixing details has been developed. Recommendations about the use of the received settlement dependences, taking into account comparative theoretical and experimental data on assembly of group threaded connection, are offered.

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1. INTRODUCTION

The assembly process largely determines the efficiency of production for various industries. One of the main trends in increasing such efficiency is the provision of reliability indicators of the products throughout its operational period [1-6]. The problems of operational reliability research are devoted to a relatively large number of works related to various areas of business: mechanical engineering [7-11], metallurgy [12-15], mining [16-18] and lifting and transport [19,20], which confirm that the foundations of the necessary operational reliability are laid down during assembly operations. In turn, obtaining the required indicators depends primarily on the quality of various connections, among which the most common are threaded connections that make up 25 to 35% of all other connections, and the labor intensity of their assembly in some cases reaches 50% from the total amount of assembly work [21-22]. The impact of tightening on product performance has been a concern for several decades. Research [21-26] presented justified recommendations for use for the same type of products, including small threaded connections and various versions of automated, automatic and rotary assembly. A significant number of mechanized tightening tools have been developed for threaded joints of medium and large diameters, which differ in design features and principles of operation. These portable threaded joints are characterized by static and shock mechanisms [27-34].

A special group of connections are group threaded connections. The technology of their assembly provides for the production of fastening parts (bolts, double-end bolts, etc.) of such relatively identical axial forces, at which the elastic deformations of the tightened parts during the steady mode of operation of the machine will be within certain normalized limits that ensure the joint density. The difficulty of ensuring uniform loading of the fastening parts is associated with a decrease in axial forces in previously tightened bolts during alternating tightening of the following bolts.

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Issues of uneven tightening forces in group threaded joints were investigated [35-40]. This consideration was continued by Zhitnikov B. Yu, who proposed synchronous tightening of threaded connections using multi-spindle high-precision equipment [37-42]. However, in most cases, it is not possible to use stationary assembly machines and multi-spindle installations to assemble large threaded joints. A certain problem exists in repairs [39], for example, of metallurgical and petrochemical equipment (Fig. 1). In the case of annular symmetrical joints, where the threaded parts are arranged in a circle [24], it is recommended to simultaneously tighten two diametrically opposite nuts using a two-position hydraulic wrench (Fig. 2).

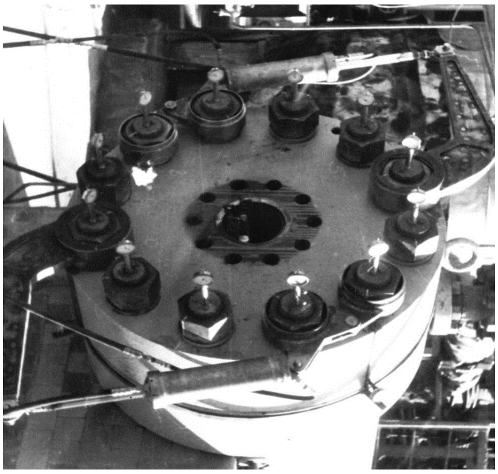


Fig. 1. Flange connection of a cover of the smoke valve of an air heater of a blast furnace

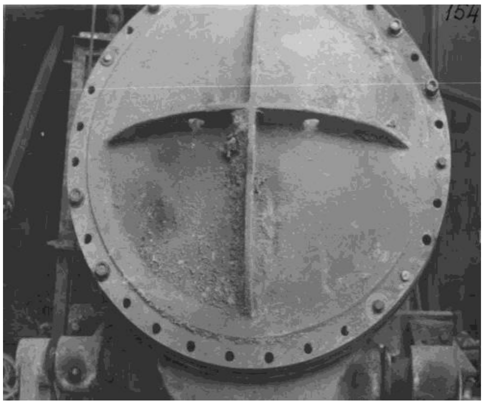


Fig. 2. Tightening of large threaded connections with the help hydraulic wrench

2. MATERIALS AND METHODS

Symmetrical tightening allows the loading of joint parts to be more evenly, prevents flange skew, and avoids loading bolt rods with bending moments. The design diagram of this process is shown in Fig. 3 [40]. On the scheme, fasteners are represented in the form of elastic elements with axial pliability λ_0, and the intermediate details of a joint placed under them – with axial pliability λ_1. These elastic elements are divided by the rigid (conditionally not deformed) diaphragm having the flange form.

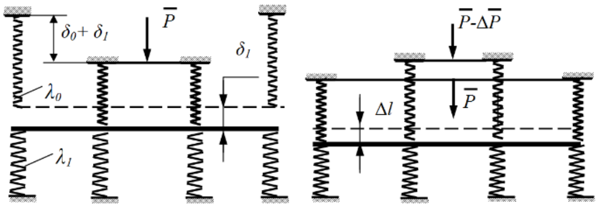


Fig. 3. Loading of fasteners of group threaded connection at their pair torqueing [40]: *a*) initial loading of the first couple; *b*) subsequent loading of the second couple

The even number of fasteners and their symmetric arrangement on the flange provides a possibility of carrying out a pair torqueing of the group threaded connection.

Let us analyze the extent of loading of fastening parts at their pair tightening. When loading the first pair of bolts effort $P = 2Q_i$ (Fig. 3a). Thus bolts will receive lengthening

$$\delta_0 = P \cdot \lambda_0, \qquad (1)$$

where are:

δ_0 - lengthening (deformation) of a bolt;

λ_0 - factor of an axial yield of tightened bolts.

Under the influence of this loading of a detail of a joint will be compressed on size.

$$\delta_1 = P \cdot \lambda_1, \qquad (2)$$

where is:

λ_1 - factor of an axial yield of pulled together details.

The subsequent torqueing of the second couple of bolts before the same effort *P* will lead to additional deformation of details of a joint whose numerical value depends on the added effort and pliability of elements of connection:

$$\Delta l = P \cdot \frac{\lambda_0 \cdot \lambda_1}{\lambda_0 + \lambda_1} = P \cdot \lambda_0 \cdot \frac{\eta}{1+\eta}. \qquad (3)$$

At the same size *Δl* bolts of earlier tightened couple will be extended that will lead to reduction of their loading by size:

$$\Delta P = \frac{\Delta l}{l_0} = P \cdot \frac{\eta}{1+\eta} = P_{\psi}^{(2)}, \qquad (4)$$

where $\eta = \frac{\lambda_1}{\lambda_0}$ - a relative flexibility of threaded connection.

As has shown in the power analysis of this process [37,38], for the group threaded connection containing *n=2N* of fasteners after torqueing of the last N-th couples, these details can be loaded unevenly since:

$$\Delta P_k^{(N)} = P - \Delta P_k^{(N)} < P, \quad (5)$$

and common effort of torqueing:

$$Q_N = \sum P_k^N < P \cdot N, \quad (6)$$

won't provide achievement of implementation of the requirement about tightness of a joint.

It is evident that the definition of the extent change of loading of earlier tightened fasteners of the group threaded connection becomes relevant when developing an optimum algorithm of their assembly, determining a necessary number of rounds of torque, and the choice of necessary efforts in fasteners.

The issues under consideration can be addressed in two ways:

1. Sequentially tightening each of the fastening pairs to different forces in one round so that at the end of the round, all the fastening parts are tightened to the same required force,
2. Implementation of multipass tightening, when necessary forces in fasteners are achieved in several rounds.

The goal of this work is the development of an algorithmic model of the assembly process of group threaded connections, allowing us to define the dependences of axial efforts in the tightened fasteners from the design features of the threaded connection, the pliability of the elements and also to count overload coefficients in the group threaded connection at the smallest number of rounds.

For realization of a goal and according to requirements of ensuring sealing of a joint data of the conducted earlier experiments of the group threaded connection condensing a cover of a chemical vessel of high pressure have been analyzed (Fig. 4).

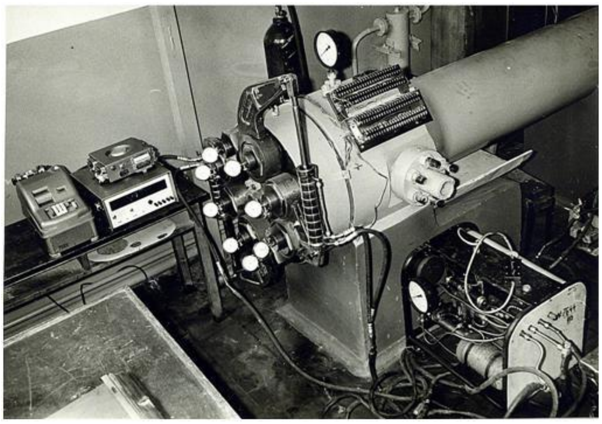


Fig. 4. Process of assembly of the group threaded connection

Fastening of a cover in this unit is carried out by eight stud-bolts (n=8 and N=4) with a threaded of *M* 76 which diameter of a bolt core d_0=70 mm, working length l_0=190 mm. The vessel cover height h_1=190 mm is condensed with steel ring laying with diameters D_1=340 mm and d_1=320 mm which thickness l_1=12 mm.

2.1 Calculation of Suitability of Joint Parts

Taking into account parameters on the known recommendations [41] were found of pliability of a joint details and two at the same time tightened stud-bolts:

$$\lambda_1 = \lambda'_1 + \lambda'', \quad (7)$$

$$\lambda_0 = \frac{l_0}{E_0 F_0} = \frac{4 l_0}{E_0 \pi d_0^2}, \quad (8)$$

where are:

λ'_1 - pliability of two ring sites of a cover under the tightened nuts, which outer diameter d =135 mm;

λ'' - pliability of laying;

E_0 - the module of elasticity of stud-bolt material,

The dependence was applied to calculation of pliability of two ring sites of a cover under the tightened nuts (taking into account replacement of a pressure cone with the cylinder):

$$\lambda'_1 = \frac{4 h_1}{E\pi\left[(a+h_1)^2 - d_0^2\right]}. \quad (9)$$

The pliability of ring laying was calculated by a formula [41]:

$$\lambda'' = \frac{8 l_1}{E\pi\left(D_1^2 - d_1^2\right)}. \quad (10)$$

3. RESULTS

3.1. Control of Extension of Each Stud

Based on the calculation carried out on the above-stated dependences Eq. (7) to (10) and considering the specified parameters, the relative pliability of connection is η = 0,055.

The group threaded connection was assembled before the normalized effort corresponding to lengthening Δl = 0,15 mm in pairs by on-off hydraulic box wrench. The lengthening of each stud-bolt at its torqueing was measured by the indicator of hour type installed at its end face, which leg contacted to the core placed in an axial opening of a stud-bolt (Fig. 2). Results of these measurements are given in Table 1.

Table 1. Results of a pair torqueing of the group threaded connection with 8 stud-bolts

№ round	Numbers of stud-bolts	Lengthening of stud-bolts with numbers							
		1	2	3	4	5	6	7	8
1	1-5	0.152	0	0	0	0.15	0	0	0
	3-7	0.145	0	0.15	0	0.14	0	0.15	0
	2-6	0.13	0.15	0.147	0	0.125	0.15	0.138	0
	4-8	0.12	0.145	0.131	0.15	0.111	0.145	0.125	0.15
2	1-5	0.15	0.14	0.13	0.148	0.15	0.14	0.115	0.146
	2-6	0.145	0.15	0.125	0.146	0.148	0.15	0.121	0.143
	3-7	0.143	0.148	0.15	0.142	0.146	0.145	0.15	0.141
	4-8	0.14	0.145	0.149	0.155	0.145	0.141	0.145	0.153
3	1-5	0.152	0.143	0.148	0.15	0.15	0.141	0.143	0.149
	2-6	0.149	0.15	0.149	0.146	0.149	0.15	0.141	0.147
	3-7	0.149	0.149	0.15	0.144	0.149	0.149	0.15	0.145
	4-8	0.148	0.149	0.149	0.152	0.149	0.149	0.15	0.151

As can be seen from the table, it took three rounds to get the normalized effort in the traditional way.

3.2. Analysis of Tightening Parameters in one Round

For clarification of a possibility of torqueing of such connection for one round the following calculations have been done.

At implementation of torqueing for one round everyone *k*-th couple it has to be loaded before effort:

$$P_k = \xi_k \cdot P. \tag{11}$$

where are:

P - the rated (required) effort of torqueing;

ξ_k - overload coefficient of k-th couple at its torqueing.

The specified unevenness of preliminary loading of the tightened details complicates carrying out the analysis of the distribution of efforts in fasteners in the course of their torqueing. When calculating overload coefficients ξ_k it is necessary to consider that the extent of the decrease in efforts in earlier tightened bolts depends not only on their quantity but also on the range of loading of the tightened i-th couple (from zero value before effort $P_i = \xi_i \cdot P$). To determine the required values of the coefficients ξ_k the change of axial forces in the details of the group screw connection with this method of inhalation was analyzed.

Loading of the first couple of bolts by effort $P_1^{(1)} = \xi_1 \cdot P$ don't reduce of loading in earlier tightened details and details of a joint will be compressed at a size $\delta_1 = \xi_1 P \cdot \lambda_1$. After torqueing of the second couple of bolts by effort $P^{(2)} = \xi_2 \cdot P$ the pulled together details will receive additional deformation of compression Δl_2 and their loading will become equal:

$$Q_2 = \xi_2 P + \frac{\Delta l_2}{\lambda_1}. \tag{12}$$

This additional deformation will lead to unloading of earlier tightened couple of bolts at a size $\Delta P^{(2)} = \frac{\Delta l_2}{\lambda_0}$ and the total axial effort in bolts of this couple will become equal $P_1^{(2)} = \xi_1 P - \Delta P^{(2)} = \xi_1 P - \frac{\Delta l_2}{\lambda_0}$ and common effort in bolts after the second torqueing will make:

$$Q_2 = \xi_2 P + \left(\xi_1 P - \frac{\Delta l_2}{\lambda_0}\right). \tag{13}$$

Equating expressions Eqs. (12) and (13) we will define this additional deformation:

$$\Delta l_2 = \xi_2 P \frac{\lambda_0 \cdot \lambda_1}{\lambda_0 + \lambda_1}. \tag{14}$$

Taking into account it decrease in axial effort in bolts of the first couple after the second torqueing will make:

$$\Delta P^{(2)} = \xi_2 P \frac{\lambda_1}{\lambda_0 + \lambda_1} = \xi_2 P \frac{\eta}{1+\eta}. \tag{15}$$

Then bolts of the first couple will be tightened by effort:

$$P_1^{(2)} = \xi_1 P - \xi_2 P \cdot \frac{\eta}{1+\eta} = P\left(\xi_1 - \xi_2 \cdot \frac{\eta}{1+\eta}\right). \tag{16}$$

At the same time the common axial effort in fasteners after the second torqueing will become equal:

$$Q_2 = \xi_1 P - \xi_2 P \cdot \frac{1}{1+\eta} + \xi_2 P = P\left(\xi_1 - \xi_2 \cdot \frac{1}{1+\eta}\right). \tag{17}$$

The torqueing of the third couple of bolts before effort $\xi_3 P$ will be resulted by reduction of axial efforts in couples of bolts of the first and second torqueings at a size $\Delta P^{(3)} = \frac{\Delta l_3}{\lambda_0}$. Then the effort in the first couple after the third torqueing will be:

$$P_1^{(3)} = \xi_1 P - \xi_2 P \cdot \frac{\eta}{1+\eta} - \xi_3 P \cdot \frac{\eta}{1+2\eta} = P\left(\xi_1 - \xi_2 \cdot \frac{\eta}{1+\eta} - \xi_3 \cdot \frac{\eta}{1+2\eta}\right). \tag{18}$$

and in the second couple:

$$P_2^{(3)} = \xi_2 P - \xi_3 P \cdot \frac{\eta}{1+2\eta} = P\left(\xi_2 \cdot \frac{\eta}{1+\eta} - \xi_3 \cdot \frac{\eta}{1+2\eta}\right). \quad (19)$$

Therefore, after *i*-th torqueing of connection by effort $P_{\square}^{(i)} = \xi_i P$ of effort in each of all earlier tightened (*i*-1) couples will decrease at a size of torqueing of the last *N*-th couples:

$$\Delta P_{\square}^{(i)} = \xi_i P \cdot \frac{\eta}{1+(i-1)\eta} = \xi_i P \cdot \psi \quad (20)$$

where $\psi_i = \frac{\eta}{1+(i-1)\eta}$ - coefficient of unloading of earlier tightened couples at *i*-th torqueing.

The carried-out analysis allows establishing that after the end of a round (implementation of torqueing of the last *N*-th couples) total axial efforts in pairs of fasteners will be distributed as follows:

$$\begin{aligned} P_1^{(N)} &= P\left(\xi_1 - \xi_2 \cdot \psi_1 - \xi_3 \cdot \psi_2 - \cdots - \xi_N \cdot \psi_{(N-1)}\right) \\ P_2^{(N)} &= P\left(\xi_2 - \xi_3 \cdot \psi_2 - \xi_4 \cdot \psi_3 - \ldots - \xi_N \cdot \psi_{(N-1)}\right); \\ P_3^{(N)} &= P\left(\xi_4 \cdot \psi_3 - \xi_5 \cdot \psi_4 - \ldots - \xi_N \cdot \psi_{(N-1)}\right); \quad (21) \\ P_{(N-1)}^{(N)} &= P\left(\xi_{(N-1)} \cdot \psi_{(N-2)} - \ldots - \xi_N \cdot \psi_{(N-1)}\right); \\ P_N^{(N)} &= P \cdot \xi_N. \end{aligned}$$

Considering that after the termination of torqueing for one round total effort in each pair of fasteners have to equal to rated effort *P* we will receive the similar system *N* of the equations establishing dependence between the overload coefficients providing a one-roundabout torqueing of connection to the required level:

$$\begin{aligned} \xi_1 &= 1 + \xi_2 \cdot \psi_1 + \xi_3 \cdot \psi_2 + \ldots + \xi_N \cdot \psi_{(N-1)}; \\ \xi_2 &= 1 + \xi_3 \cdot \psi_2 + \xi_4 \cdot \psi_3 + \ldots + \xi_N \cdot \psi_{(N-1)}; \\ \xi_3 &= 1 + \xi_4 \cdot \psi_3 + \xi_5 \cdot \psi_4 + \ldots + \xi_N \cdot \psi_{(N-1)}; \\ \xi_{(N-2)} &= 1 + \xi_{(N=1)} \cdot \psi_{(N-2)} + \xi_N \cdot \psi_{(N-1)}; \quad (22) \\ \xi_{(N-1)} &= \xi_N \cdot \psi_{(N-1)}; \\ \xi_N &= 1;. \end{aligned}$$

The regularity of change of overload coefficients of consistently tightened couples follows from this system of the equations:

$$\xi_k = \xi_{(k+1)} \cdot (1 + \psi_k). \quad (23)$$

3.3. Calculation of Overload Factor

Regularity Eq. (23) allows to receive an algorithm (Fig. 5) for implementation of calculations with use of the computer of overload coefficients of fasteners of the group threaded connection.

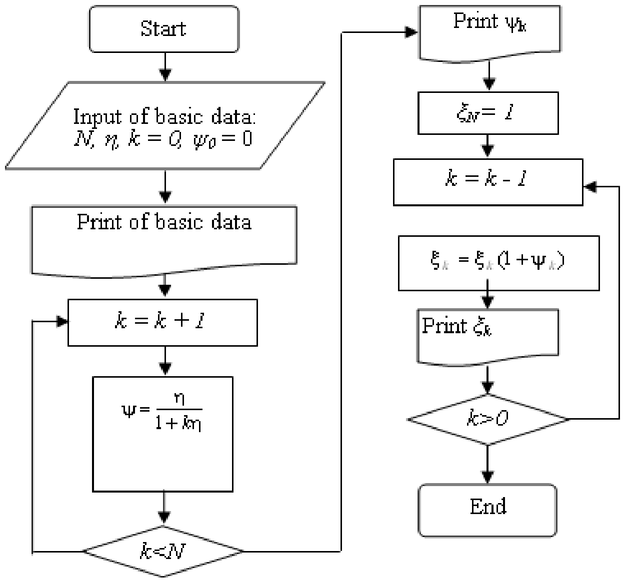
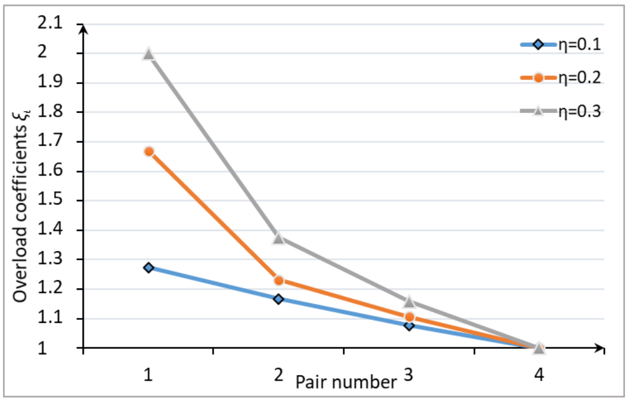


Fig. 5. Calculation algorithm of overload coefficients of fasteners of the group threaded connection

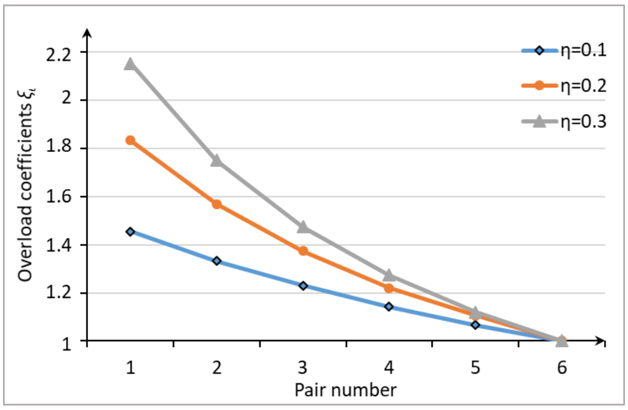
On this algorithm calculations of overload coefficients are carried out. Results of calculations are presented in Table 2, and an example their graphic interpretation is on Fig. 6.

Table 2. Overload coefficients of fasteners at their torqueing for one round

Pair number	Overload coefficients ξ_i								
	N=4			*N*=6			*N*=8		
	η=0.1	η=0.2	η=0.3	η=0.1	η=0.2	η=0.3	η=0.1	η=0.2	η=0.3
1	1.273	1.67	2	1.4544	1.833	2.154	1.636	2.122	2.504
2	1.167	1.231	1.375	1.333	1.57	1.7503	1.4999	1.857	2.034
3	1.077	1.106	1.1579	1.2307	1.374	1.474	1.3845	1.625	1.788
4	1	1	1	1.1428	1.22	1.273	1.285	1.444	1.5445
5				1.0667	1.106	1.12	1.2	1.2999	1.359
6				1	1	1	1.125	1.1818	1.2135
7							1.0558	1.0833	1.09677
8							1	1	1



a)



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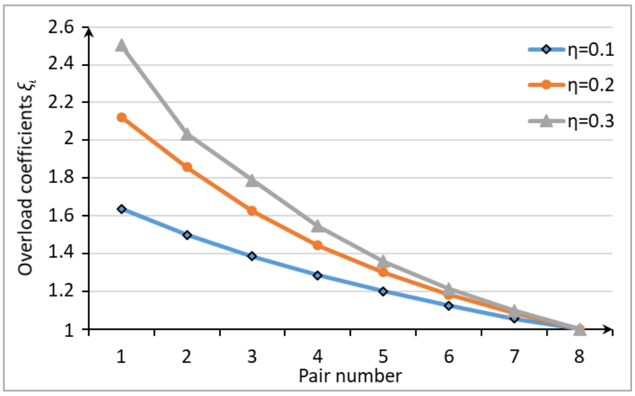

c)

Fig. 6. Degree of an overload of fasteners at torqueing for one round at different number of threaded pairs N: a) N=4; b) N=6 and c) N=8

4. DISCUSSION

The analysis of the presented theoretical dependences shows that at a large number of the tightened couples and high relative pliability of the group threaded connection; numerical values of overload coefficients under the terms of durability of fasteners complicate use of technology of torqueing for one round. The recommended number pairs N shouldn't exceed 8.

Comparative theoretical and experimental data on assembly of the group threaded connection with the number of couples equal to four are presented in Table 3.

Table 3. Degree of torqueing of the group threaded connection at N=4

Number of the tightened couple	**1**	**2**	**3**	**4**
Calculated values at η=0.055	0.8390	0.8941	0.9449	1.0000
Experimental values at η=0.055	0.7700	0.8467	0.9667	1.0000

In the future research is planned to be conducted on the process of implementing multi-round tightening, in which the necessary forces in the fasteners are achieved in several rounds.

5. CONCLUSION

In the research, the analysis of the assembly process of responsible group threaded connections in the mode of their torqueing for one round is made. The theoretical and experimental research conducted on this process will allow for increased reliability of assembly operations on the basis of their preliminary modeling.

The offered algorithmic model of technological process allows the calculation of overload coefficients of fasteners at various pliability of elements of a joint for the symmetric flange. Proceeding from conditions of the durability of fasteners, it is recommended to carry out torqueing for one round for a certain set of parameters of the group threaded connection with a number of couples no more than eight.

In the process of tightening parts of a group threaded connection, there is a decrease in the degree of loading of previously tightened fastening parts during the tightening of subsequent ones. The intensity of such a decrease in axial forces increases with increasing relative compliance of the connection elements. Therefore, to ensure uniformity of loading of flange joints repeated tightening of parts of the group threaded connection is required.

Conflicts of Interest

The author declares no conflict of interest.

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