RAFAŁ GRZEJDA*

DETERMINATION OF BOLT FORCES FOR THE ASSEMBLY CONDITION OF A BOLTED FLANGE CONNECTION

In the paper modelling and calculations of an asymmetrical bolted flange connection at the assembly stage are presented. The physical model of the joint is based on a flexible flange element that is connected with a rigid support by means of hybrid elements, which substitute bolts. Between the flange element and the support, the nonlinear Winkler model of a contact layer is taken into consideration. A computational model of the system is proposed, which makes it possible to analyze how the tightening sequence affects the preload distribution both during the bolted flange connection’s assembly and after it has been completed. Results obtained from the calculations are compared with experimental research described in [6].

Key words: bolted flange connection, assembly condition, preload

1. INTRODUCTION

Bolted flange connections applied in mechanical engineering are usually designed as preloaded joints. In such a way designers are able to provide them adequate load-carrying ability, stiffness and fatigue resistance. In these types of connections, like in the case of single-bolted joints [4], the calculation process consists of two states of loading and deformation:
– the assembly state – when the joint is mounted,
– the operational state – when the preloaded joint is loaded by an external force.

In the literature, the assembly state of the bolted flange connection is commonly omitted in calculations. The authors assume an equal force in all of the bolts and uniform clamping of joined elements after the preloading process [12, 19]. Meanwhile, the final tension of the joint at the end of its assembly operation depends on the way of bolt tightening. It is described in works [9, 14, 15]

* Dr inż. – Faculty of Mechanical Engineering and Mechatronics, West Pomeranian University of Technology, Szczecin.
through example of a symmetrical bolted flange connection model. On diversification of a contact pressure between joined elements may impact also flange imperfections [3, 8]. On the other hand, a common cause of bolted joint leakage is an incorrect value of the preload [2]. It is set out in works [10, 11], where through example of a two-dimensional symmetrical bolted flange connection model, boundary conditions which ensure leaktightness of the joint are derived.

In previous papers [17, 18] some results of theoretical investigations for the preloading process of an asymmetrical bolted flange connection, composed of a flange element fastened to a rigid support, were released. In proposed models of the joint, bolt holes were not taken into consideration and bolts were treated as linear springs. In the current paper some new results of investigations for the preloading process of an analogical model of the joint are presented. In the new model, bolt holes are taken into account and bolts are treated as hybrid elements consisted of a flexible plain part of the bolt and a rigid bolt head [5]. For modelling and calculations of the bolted flange connection the finite element method (FEM) [1] is used.

2. PHYSICAL MODEL OF THE BOLTED FLANGE CONNECTION

A general structure of the bolted flange connection model results from an idea presented in articles [17, 18]. The model of the joint is based on a flexible flange element that is fastened to a rigid support by means of k hybrid elements [5], which substitute bolts (Figure 1b). Spring properties of the i-th bolt’s model (for \(i = 1, 2, \ldots, k\)) are determined from the relation [16]

\[
c_{yi} = \frac{1}{\sum_{n=1}^{k} c_{ni}}
\]

where \(c_{ni}\) denotes the stiffness coefficient of the n-th bolt’s fragment.

A contact layer between the flange element and the support is modeled as the nonlinear Winkler model, which is described by means of \(l\) one-sided nonlinear spring elements, defined by the following relationship

\[
R_j = A_j \cdot f(u_j)
\]

where: \(R_j\) is the force in the centre of the j-th elementary contact area, \(A_j\) is the j-th elementary contact area and \(u_j\) is deformation of the j-th nonlinear spring element (for \(j = 1, 2, \ldots, l\)).
The equation of system equilibrium (Figure 1c) can be written in the form
\[ K \cdot q = p \]  
(3)
where: \( K \) is the stiffness matrix, \( q \) is the displacements vector and \( p \) is the loads vector.

In the assembly state, the loads vector \( p \) is composed of preloads \( F_{wi} \) [5] (Figure 1c). The displacements vector \( q \) is determined using the following formula [5, 17]
\[ q = \text{col}(q_B, q_F, q_C) \]  
(4)
where: \( q_B \) is the displacements vector of bolts, \( q_F \) is the displacements vector of the flange element and \( q_C \) is the displacements vector of nonlinear springs.

Thus, (3) can be rewritten as follows [5, 17]
\[
\begin{bmatrix}
K_{BB} & K_{BF} & 0 \\
K_{FB} & K_{FF} & K_{FC} \\
0 & K_{CF} & K_{CC}
\end{bmatrix}
\begin{bmatrix}
q_B \\
q_F \\
q_C
\end{bmatrix}
= p
\]  
(5)
where: \( K_{BB}, K_{FF}, K_{CC} \) are the stiffness matrices of subsystems \( B, F, C \) and \( K_{BF}, K_{FB}, K_{FC}, K_{CF} \) are the matrices of elastic couplings among subsystems \( B, F, C \).

On the grounds of so defined model of the bolted flange connection, bolt forces both during the joint’s assembly and after it has been completed can be evaluated.
The preloading process of the connection consists of \( k \) steps, in pursuance of the number of bolts in the joint. During the first bolt tightening, the system is composed of a flange element resting on a nonlinear elastic foundation. In this first step, the system is loaded by the force \( F_{ml} \) which is the preload of the bolt No. 1 (Figure 2). Then, in the equation (5) the stiffness matrix of the bolts subsystem \( K_{BB} \) is not taken into account. Thus, the equation of system equilibrium can be written as follows [5, 17]

\[
\begin{bmatrix}
K_{FB} \\
0
\end{bmatrix} \cdot q_B + \begin{bmatrix} K_{FF} & K_{FC} \\
K_{CF} & K_{CC}
\end{bmatrix} \begin{bmatrix} q_F \\
q_C
\end{bmatrix} = 0
\]

(6)

As a result of solving the equation (6) one obtains, among others, the displacements vector of nonlinear springs \( q_C \) which defines initial deformation of these springs in the second step of joint tightening

\[
q_C = \text{col}(q_{C1}, q_{C2}, ..., q_{Cj}, ..., q_{Ci})
\]

(7)

In the next steps of joint tightening (for \( i = 2, ..., k \)), at this point, where the last preload was imposed, the next hybrid element is taken into consideration. Therefore, in the equation (5) the stiffness matrix of the bolts subsystem \( K_{BB} \) is now taken into account. In the next steps, this matrix has been complementing with the elements, which were preloaded in the previous step of computations. In the current step of joint tightening, the stiffness matrix of the bolts subsystem \( K_{BB} \) is a constant part of the stiffness matrix \( K \), and the stiffness matrices \( K_{CC} \) and \( K_{CF} \) are a variable part of the stiffness matrix \( K \).
As a result of solving the equation (5) one obtains the displacements vector of bolts $q_B$

$$q_B = \text{col}(q_{B1}, q_{B2}, ..., q_{Bi}, ..., q_{Bk})$$  \hspace{1cm} (8)

Final displacements of bolts $q_{Bi}$ in the current step of joint tightening, are measured from the working points $W_i$ which defines tension of bolts in the previous step of calculations (Figure 3b). On the basis of so defined displacements $q_{Bi}$, the bolt forces $F_{mi}$ can be determined from the relation

$$F_{mi} = c_{yi} \cdot q_{Bi}$$  \hspace{1cm} (9)

As a result of solving the equation (5) one obtains the displacements vector of nonlinear springs $q_C$ too (which can be evaluated using the formula (7)). In order to determine displacements of nonlinear springs $q_{Ci}$ one achieves a linearization by means of the incremental-iterative method [5, 7]. In the case of the first bolt tightening, the linearization runs according to the way shown in Figure 3a. And in the case of the next bolt tightening, the linearization runs according to the way shown in Figure 3c starting from the working points $W_j$, which defines tension of nonlinear springs in the previous step of calculations. The linearization process in the current step of joint tightening is kept running in $\Gamma$ iterations (for $\Gamma = 1, 2, 3, ..., \gamma$) in which one looks for so load values for which the following condition has been qualified

$$\left| \Delta R_{ji}^{(\gamma)} - \Delta R_{ji}^{(\gamma - 1)} \right| / \Delta R_{ji}^{(\gamma - 1)} \leq \varepsilon$$  \hspace{1cm} (10)

where
\[
\Delta R_\gamma' = \begin{cases} 
R_{a1} & \text{for } \Gamma = 1 \\
R_{a\gamma} - R_{a(\gamma-1)} & \text{for } \Gamma = 2, 3, 4, \ldots, \gamma 
\end{cases}
\] (11)

\[
\Delta R_\gamma'^* = \begin{cases} 
R_{a1} & \text{for } \Gamma = 1 \\
R_{a\gamma}' - R_{a(\gamma-1)} & \text{for } \Gamma = 2, 3, 4, \ldots, \gamma 
\end{cases}
\] (12)

where: \( R_{\gamma}' \) is the force in the nonlinear spring No. \( j \) and in the step No. \( \Gamma \) obtained from the linearization by means of the incremental-iterative method [5, 7] (Figure 3a and Figure 3c), \( R_{\gamma}' \) is the real force in the nonlinear spring No. \( j \) and in the step No. \( \Gamma \), \( \varepsilon \) is the admissible error of the linearization and \( \alpha \) is the index dependent on the case of tightening (\( \alpha \in \{j, m\} \)).

Final displacements of nonlinear springs \( q_{Gj} \) are equal to \( q_{Gj}' \). On the basis of so defined displacements \( q_{Gj}' \), the forces \( R_{mj} \) can be determined from the relation (2) for \( u_j \) equal to \( q_{Gj} \).

Figure 4. Block diagram of iterative calculations of the bolted flange connection

The diagram of iterative calculations of the bolted flange connection at the assembly state is shown in Figure 4.
3. CALCULATIONS OF THE BOLTED FLANGE CONNECTION FOR THE ASSEMBLY CONDITION

According to the presented method, computations of an asymmetrical bolted flange connections were performed (Figure 5). The joint, assumed here, is an element of the special test stand designed to measurement of bolt forces in such a connection [6]. A simplified FEM-based model of the joint is shown in Figure 5a. A fragment of the cross-section of the joint with models of bolts and the contact layer is illustrated in Figure 5b. A contact surface between joined elements as well as the bolt’s arrangement nad their numeration are shown in Figure 5c. Calculations were carried out for two values of the joined element’s thickness \( h \) (for \( h \in \{20 \text{ mm, 40 mm}\} \)). Characteristics of nonlinear springs are described as the following power function [5]

\[
R_j = A_j \cdot (3.428 \cdot u_j^{1.657})
\]  

(13)

To fastening of the joint, the bolts M10x1.25 are used. The preload of bolts \( F_{ni} \) is equal to 20 kN and it is set down on the base of Polish Standard [13]. The tightening sequence taken here on, is parenthesized in Figure 5c.

![Figure 5](image)

Figure 5. Considered bolted flange connection: a) simplified FEM-based model, b) fragment of the cross-section, c) contact surface

Results of calculations were put together in graphs according as the individual thickness of the flange element. Owing to the fact that obtained graphs are qualitative similar, in the paper only results of calculations get in the case of \( h \) equal to 40 mm are presented. In Figure 6 variations of load in individual bolts during the preloading process are shown as follows:

- in the first row – force changes in the bolt No. 1 (tensioned as the first bolt),
- in the second row – force changes in bolts No. 4 and 5 (tensioned as the second and the seventh bolt, respectively),
- in the third row – force changes in bolts No. 7 and 2 (tensioned as the third and the sixth bolt, respectively),
Figure 6. Preload values during the assembly process

Figure 7. Preload values at the end of the assembly process
– in the fourth row – force changes in bolts No. 3 and 6 (tensioned as the fourth and the fifth bolt, respectively).

In Figure 7 scatter of bolt forces at the end of the preloading process is presented. In most of the cases, computed preload values in individual bolts during the assembly process and after it has been completed are higher than their experimental values [6]. Analysis of relative difference between obtained preloads is done on the basis of the $W$ index

$$ W = \frac{F_{mi}^{\text{FEM}} - F_{mi}^{\text{EXP}}}{F_{mi}^{\text{EXP}}} \times 100 \% $$

(14)

where: $F_{mi}^{\text{FEM}}$ is the force in the $i$-th bolt at the end of the preloading process according to the FEM model and $F_{mi}^{\text{EXP}}$ is the force in the $i$-th bolt at the end of the preloading process according to experimental research [6].

Depending on the joined element’s thickness, the assumption of the introduced model of the bolted flange connection can underrepresent preload values of bolts from 0.64 % to 3.18 %.

4. CONCLUSIONS

The presented model of the bolted flange connection can be successfully used in analysis of preload variations in the case of any joint in which a flexible flange element is connected with a rigid support. The model can allow to analyze how the tightening sequence affects the preload values in bolts before the preloaded joint is loaded by an external force.

REFERENCES


WYZNACZANIE SIŁ W ŚRUBACH
KOLNIERZOWEGO POŁĄCZENIA ŚRUBOWEGO W STANIE MONTAŻOWYM

S tre s z c e n i e

W artykule przedstawiono modelowanie i obliczenia asymetrycznego, kołnierzowego połączenia śrubowego na etapie napinania wstępnego. Fizyczny model połączenia utworzono jako złącze odkształcального elementu kołnierzowego i nieodkształcalnej ostoi z elementami hybrydowymi, zastępującymi śruby. Pomimo element kołnierzowy a ostoję wprowadzono nieliniowy model warstw stykowej typu winkerowskiego. Zaproponowano model obliczeniowy układu, dzięki któremu możliwe jest analizowanie wpływu kolejności napinania śrub na rozkład sił w śrubach w trakcie montażu połączenia i po jego zakończeniu. Wyniki obliczeń porównano z wynikami badań doświadczalnych [5].

Słowa kluczowe: kołnierzowe połączenie śrubowe, stan montażowy, napięcie wstępe

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