Analysis of the Tightening Process of an Asymmetrical Multi-Bolted Connection

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Abstract
The paper deals with modelling and calculations of a multi-bolted connection characterized by an asymmetric arrangement of bolts. Equations of system equilibrium on the preloading stage of the connection are described. The iterative algorithm of the computational process is presented, which is related to both nonlinearity of spring elements used for modelling of the contact layer between joined elements and one-sidedness of constraints imposed on the connection. Results of calculations of the selected multi-bolted connection are presented.

Keywords: multi-bolted connection, FE-modelling, tightening process, preload analysis.

1 Introduction
In many practical purposes multi-bolted connections are designed as preloaded systems (Bai et al., 2015; Crocco et al., 2011). Therefore, in calculating this type of connections, it should be considered two different load conditions caused respectively during their assembly and operational states. In traditional methods of calculations presented in books on the fundamentals of machine design (Osiński et al., 2010; Skoć et al., 2012; Szopa, 2013), this fact is omitted assuming an equal force in all of the bolts and uniform clamping of joined elements after the preloading process. However, the final pretension of the connection at the end of its assembly operation is not uniform and depends on taken into consideration sequence of bolt tightening (He and Wang, 2015; Kumakura and Saito, 2003). A varied load of the contact surface between joined elements is also affected by both geometric imperfection of joined elements (Feldmann et al., 2011; Lener and Schweigkofler, 2011) and specificity of the way of creating the connection, through which the greatest load contact surfaces of joined elements occurs around the bolt head (Chakherlou et al., 2008; Marshall et al., 2006; Williams et al., 2009). On the other hand, a common cause of bolted connection leakage is improperly chosen value of the preload. This has been given in (Mag-
nucki and Sekulski (2005), where through example of a two-dimensional symmetrical bolted flange connection model, boundary conditions which ensure leaktightness of the joint have been derived.

Analysis of the multi-bolted connection model on the preloading stage, taking into account nonlinear properties of the contact layer between joined elements, is presented in (Grzejda, 2013). The current study is the continuation of theoretical research on this model. Their aim is to determine the optimum sequence of bolt tightening that provides the smallest scatter of normal pressure on the contact surface of joined elements and hence the best uniformity of adherence of these elements. The study was realized using the finite element method (FEM) in the Midas NFX 2014 program.

2 Model of the multi-bolted connection

A general structure of the multi-bolted connection model results from an idea described in (Grzejda, 2013). The model is based on a flexible flange element that is fastened to a rigid support by means of $k$ spider bolt models (Grzejda, 2014). Spring properties of the $i$-th model of the bolt ($i = 1, 2, \ldots, k$) are described by the linear stiffness coefficient $c_{yi}$ (Fig. 1). A contact layer between the flange element and the support is modeled as the Winkler elastic foundation (Szmidla and Jurczyńska, 2014), which is described by means of $l$ one-sided nonlinear spring elements (Fig. 1).
The equation of system equilibrium can be represented as:

$$ \mathbf{K} \cdot \mathbf{q} = \mathbf{p} $$  \hspace{1cm} (1)

where:
- $\mathbf{K}$ – stiffness matrix,
- $\mathbf{q}$ – displacements vector,
- $\mathbf{p}$ – loads vector.

**Fig 1.** Multi-bolted connection: a) scheme, b) description of spring properties, c) FEM-model
It can be distinguished the following three different subsystems in the analyzed multi-bolted connection:
- subsystem B – the bolts,
- subsystem F – the flexible flange element,
- subsystem C – the conventional contact layer.

Having regard to the division of the system into listed subsystems, Eq. (1) can be converted to the formula:
\[
\begin{bmatrix}
K_{BB} & K_{BF} & 0 \\
K_{FB} & K_{FF} & K_{FC} \\
0 & K_{CF} & K_{CC}
\end{bmatrix}
\begin{bmatrix}
q_B \\
q_F \\
q_C
\end{bmatrix}
=
\begin{bmatrix}
p_B \\
p_F \\
p_C
\end{bmatrix}
\] (2)

where:

- \(K_{BB}, K_{FF}, K_{CC}\) – stiffness matrices of subsystems B, F, C;
- \(K_{BF}, K_{FB}, K_{FC}, K_{CF}\) – matrices of elastic couplings among subsystems B, F, C;
- \(q_B, q_F, q_C\) – displacements vectors of elements of subsystems B, F, C;
- \(p_B, p_F, p_C\) – loads vector of elements of subsystems B, F, C.

The defined model of the multi-bolted connection allows to determine the bolt forces both during the tightening process and after it has been completed.

3 Tightening process of the multi-bolted connection model

The method of introducing the preload of bolts into the model of the multi-bolted connection has been specified in [Grzejda, 2013]. In this work, the tightening process is extended with the ability to analyze values of current normal pressure on the contact surface of joined elements in order to shape their best distribution through the appropriate selection of the bolt tensioning sequence. In every step of the iterative process of solving Eq. (2), the values of components of the displacements vector of nonlinear springs \(q_C\):

\[
q_C = col(q_{C1}, q_{C2}, ..., q_{Cl})
\] (3)

are analyzed for each of the \(j\)-th nonlinear spring \((j = 1, 2, ..., l)\), describing the properties of the contact layer between joined elements.

Based on the received values of the nonlinear spring displacement \(q_{Cj}\), normal contact pressure \(p_j\) on the \(j\)-th elementary contact surface can be determined according to the relationship:

\[
p_j = \frac{c_{zj} \cdot q_{Cj}}{A_j}
\] (4)

where:
- \(c_{zj}\) – stiffness coefficient of the \(j\)-th spring’s model,
- \(A_j\) – area of the \(j\)-th elementary contact surface.

As the next bolt for tightening, the bolt lying in the area of the least average value of normal pressure on the contact surface of joined elements is selected.
4 Numerical example

As an example, computations of an asymmetrical bolted flange connection tightened by means of seven M10 bolts were performed (Fig. 2a). It is assumed that the flange thickness is equal to 20 mm and the bolt preload is equal to 20 kN. The characteristics of nonlinear springs are described as the power function determined experimentally (Grzejda and Cieloszyk 2014).

The optimum bolt tightening sequence designated for the adopted multi-bolted connection is specified in Table 1. In contrast, Fig. 3 shows distribution of normal contact pressure on elementary surfaces on the line joining the nodes defined in Fig. 2b, during the tightening process of the connection.

![Diagram](image)

**Fig 2.** Scheme of the calculated multi-bolted connection: a) distribution of bolts, b) nodes adopted to describe distribution of normal contact pressure.

**Table 1.** Optimum sequence of bolt tightening.

<table>
<thead>
<tr>
<th>Bolt's number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sequence of bolt tightening</td>
<td>1</td>
<td>4</td>
<td>6</td>
<td>2</td>
<td>5</td>
<td>7</td>
<td>3</td>
</tr>
</tbody>
</table>

The assessment of final values of normal contact pressure is conducted on the basis of the W index:

\[
W = \frac{p_n - p_{an}}{p_{an}} \cdot 100\% 
\]  

(5)

where:

- \(p_n\) – value of normal contact pressure on the \(n\)-th contact surface, linked to the \(n\)-th node (Fig. 2b, \(n = 1, 2, \ldots, 19\)),
- \(p_{an}\) – average value of normal contact pressure on the line joining the nodes shown in Fig. 2b.
The W index values are specified in Table 2. On their basis, high variability of normal contact pressure values on the analyzed surface of joined elements compared to their average value can be noted.

![Table 2. W index values](image)

**Fig 3.** Diagrams of normal contact pressure during the tightening process of the multi-bolted connection.

<table>
<thead>
<tr>
<th>Node’s number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>W [%]</td>
<td>-5.8</td>
<td>23.8</td>
<td>9.0</td>
<td>-2.1</td>
<td>3.8</td>
<td>-4.8</td>
<td>6.8</td>
<td>-0.8</td>
<td>-13.6</td>
<td>-4.3</td>
</tr>
<tr>
<td>Node’s number</td>
<td>11</td>
<td>12</td>
<td>13</td>
<td>14</td>
<td>15</td>
<td>16</td>
<td>17</td>
<td>18</td>
<td>19</td>
<td></td>
</tr>
<tr>
<td>W [%]</td>
<td>-5.1</td>
<td>0.5</td>
<td>10.0</td>
<td>-0.3</td>
<td>5.8</td>
<td>4.6</td>
<td>-7.8</td>
<td>-5.8</td>
<td>-14.1</td>
<td></td>
</tr>
</tbody>
</table>
5 Conclusions

The presented model of the multi-bolted connection can be effectively used in analysis of preload variation of bolts in the case of joints complying with adopted model assumptions. Its application enables control of the current value of normal contact pressure between joined elements and lets to select the optimum sequence of bolt tightening.

References


