Numerical Investigation of the Variability of Bolt Forces in a Preloaded Asymmetric Multi-Bolted Connection under Cyclical Loading

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Abstract: - A numerical study of a seven-bolt connection with an asymmetric contact surface between the components to be joined is reported. The investigations were organised into two steps. Firstly, the connection was preloaded in a three-pass cycle. Then, the connection was subjected to the cyclically varying force imposed at an angle of 30 degrees to the joined components' contact surfaces to produce both compressive and shear loads in the connection. The connection modelling was performed in the finite element method convention. The joined components were discretized using three-dimensional finite elements and the fasteners were modelled as special elements consisting of flexible beams, stiff heads, and stiff nuts. The article is concluded by analysing selected computational outcomes.

Key-Words: - multi-bolted connection, preload, cyclical loading, FE analysis

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1 Introduction

Steel and aluminum multi-bolted connections with preloaded bolts are one of the most widely applied nodes in various engineering fields. Their proper functioning depends mainly on the behaviour of the bolt forces. With cyclical loads applied to both single-bolted connections and multi-bolted connections, the variability of these forces can be noticed, [1], [2], [3], [4]. Lack of adequate mechanical protection may even lead to self-loosening of the connections, [5], [6]. An overview of the reasons and mechanisms of rotational and non-rotational bolt loosening was reported by [7]. Actions to prevent loosening of multi-bolted connections under dynamic loads include, but are not limited to, coating the bolts, [8]. Furthermore, the cyclical tensile behaviour of preloaded bolts made in class 10.9, widely adopted in engineering structures, was discussed by [9].

Testing of cyclically loaded multi-bolted connections usually consists in observing the deformation of the components of these connections during their operation. It leads to the determination of hysteretic stiffness curves and the formulation of conclusions regarding the considered connection. Selected numerical studies on this subject include the following articles. In [10], the authors depicted the results of testing the behaviour of a semi-rigid frame specimen loaded cyclically. In [11], the authors analysed a hollow section beam-to-column connection in order to determine their ultimate behaviour. In [12], the authors described the research of the innovative double-split tee (DST) connection subjected to cyclical loading. Based on the research results, they have demonstrated the possibility of using DST connections with friction shock absorbers in structures subjected to seismic action. In [13], the authors observed the behaviour of extended end-plate bolted connections under monotonical and cyclical loads. They noted that cyclical loading reduces both the bending and rotational resistance of such connections.

Testing of cyclically loaded multi-bolted connections less frequently relies on the observation of changes in bolt forces during the operation of the connections. In [14], the authors determined the bolt preload degeneration in the reinforced legs of a retrofitted transmission tower under cyclical loading. They performed experimental tests on a section of the selected leg and then validated the results using a simplified model consisting of non-linear springs and rigid links, created using the finite element method (FEM), [15], [16]. In [17], the authors investigated the variability of the bolt preload in a double-shear lap connection under cyclical loads. They carried out the analysis for half of the connection model, due to its symmetry, and using three-dimensional finite elements. In [18], the author predicted the operating life of a gasket in a bolted flange connection under cyclical bending, while observing changes in forces in the bolts. He conducted the analysis for a full flange connection model built from three-dimensional finite elements.

There are also articles focusing on the observation of bolt failure mechanisms in cyclically loaded bolted connections, [19], [20].

The publications cited above are concerned with typical multi-bolted connections, usually symmetrical, or single-bolted connections. So far, less attention has been paid to multi-bolted connections with asymmetrical bolt arrangements, [21], [22]. This gap is filled by the present article, which analyses an asymmetric connection loaded cyclically by forces inducing both normal and tangential stresses in the connection. The objective set in the article is to investigate the variability of bolt forces in such a loaded connection using finite element modelling. An analysis of the variability of bolt forces in the multi-bolted connection was carried out both at the preloading step of the connection in a three-pass cycle and after loading with a cyclically varying external force. It was shown that, as a result of applying this force, the bolt forces also change in a cyclical manner, and that this variability depends on the position of the bolt in the asymmetrical bolt arrangement in the connection. This has not yet been shown in other papers, as demonstrated above.

2 Problem Formulation

The multi-bolted connection investigated in this study is illustrated in Figure 1 and consists of a pair of components connected by i fasteners with M10×1.25 threads ($i \in \{1, 2, 3, \ldots, 7\}$).

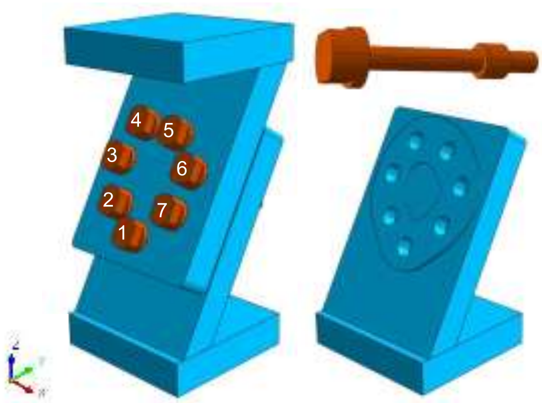


Fig. 1: Details of the physical multi-bolted connection model

Each component to be joined in a connection consists of two plates. One of them is inclined and is the main connection plate while the other, referred to as the base plate, is located in the XOY plane (indicated in Figure 1). The components were formed from 1.0577 steel, while the bolts were made in class 8.8 and the nuts in class 8. In order to minimise the number of contact joints, no washers were used in the connection. The contact surface of the joined main plates is angled at 60 degrees from the horizontal so that the connection can be subjected to compressive and shear loads simultaneously, [23]. The contact surface shape between the joined main plates is asymmetrical.

As demonstrated in the first section of the article, FEM is at present the most common way for modelling multi-bolted connections. In the models developed using this method, the components to be connected are generally modelled using three-dimensional elements, [24], [25]. Fasteners, on the other hand, are modelled in several different ways, which are mentioned in [26], among others. After assessing the existing bolt models in the literature, in this article, a flexible beam model with a stiff head and a stiff nut was chosen to model the fasteners, [27], [28]. A multi-bolted connection model structured in the convention of the finite element method is shown in Figure 2.

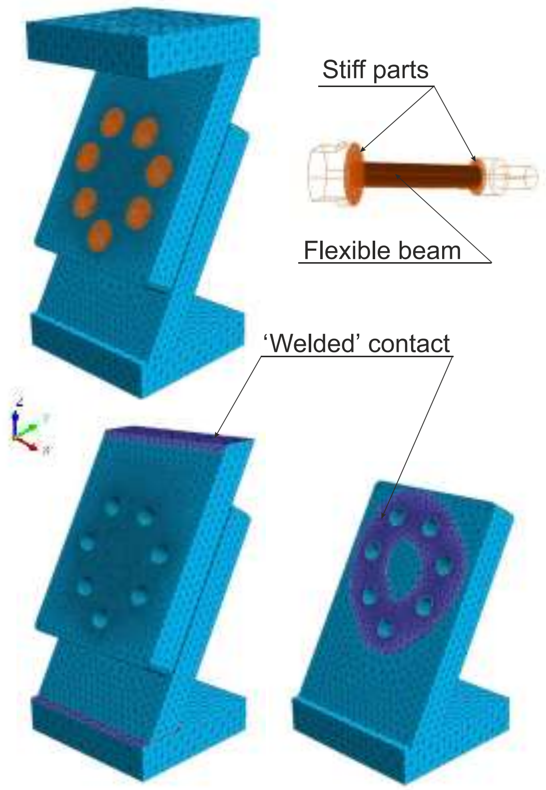


Fig. 2: Details of the discrete multi-bolted connection model

All parts of the connection were attributed to the properties of linear isotropic steel materials. The constitutive relations, in this case, can be characterised by Hooke's law, [29]. The constants for the materials used in the discrete connection model, including Elastic modulus E and Poisson's ratio n, are summarised in Table 1. They correspond to the steels with the characteristics given at the beginning of Section 2.

Table 1. Characteristics of the materials used in the discrete multi-bolted connection model.

Components	E, GPa	ν
Fasteners	210	0.28
Main plates	210	0.3
Base plates	210	0.3

'Welded' contact elements were inserted between the main connection plates and the base plates to avoid them moving in any direction relative to each other (Figure 2), in accordance with the real implementation of the connection. 'Welded' contact elements were also applied between the main connection plates. This procedure in numerical simulations is common practice for preloaded connections, [30], [31], [32].

The FE-based multi-bolted connection model was generated with a total of 93,283 elements and 157,559 nodes. The maximum side dimension of the finite element in the mesh is less than 10 mm. The mesh was considerably thickened at the interface between the main plates and at the interface between the fasteners and the main plates (compare with [33]).

The connection was fully restrained at all nodes on the bottom surface of the lower base plate.

The test procedure was organised into two steps. Firstly, the multi-bolted connection was preloaded in accordance with the tightening method and order established experimentally beforehand as the most favourable with regard to the end distribution of bolt forces after the tightening process, [34]. The bolt preload value F_{p0} was set to be equal to 22 kN based on an analysis of the allowable pressure values between the nuts and the lower main plate in the multi-bolted connection. The connection was preloaded in a three-pass cycle, sequentially tightening bolts with numbers: 1, 4, 7, 3, 6, 2, and 5 (the adopted bolt numbering is provided in Figure 1). In the first pass, the bolts were preloaded to $0.2{\cdot}F_{p0}$, in the second pass to $0.6{\cdot}F_{p0}$, and in the third pass to F_{p0}.

In the second step, the preloaded connection was subjected to an external F_e cyclical force, the variability of which is depicted in Figure 3. The direction of this load changed repeatedly from top to bottom and vice versa (for comparison see, [13]).

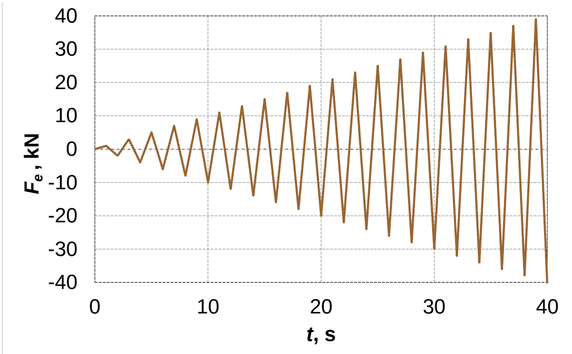


Fig. 3: Operating load variability

The external load was imposed in the Z direction uniformly across the top surface of the upper base plate. The maximum for the F_e force was chosen so that the shear loads it induced were less than the frictional forces acting at the contact of the joined main plates.

3 Problem Solution

The calculations were performed in Midas NFX 2020 R2 using a sequential non-linear module.

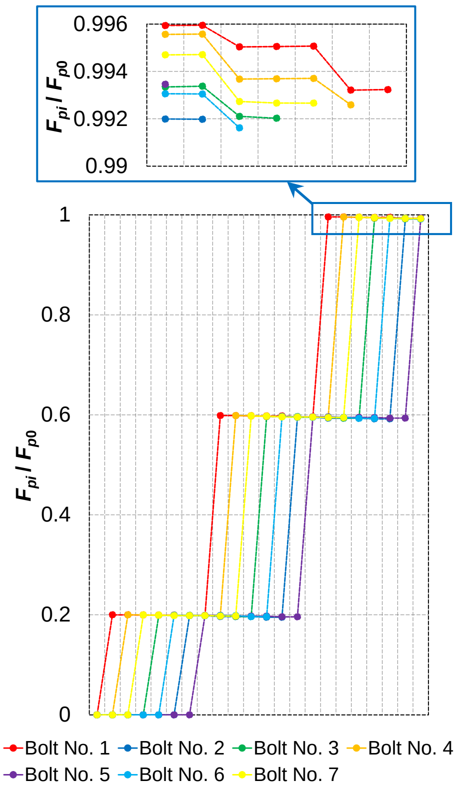


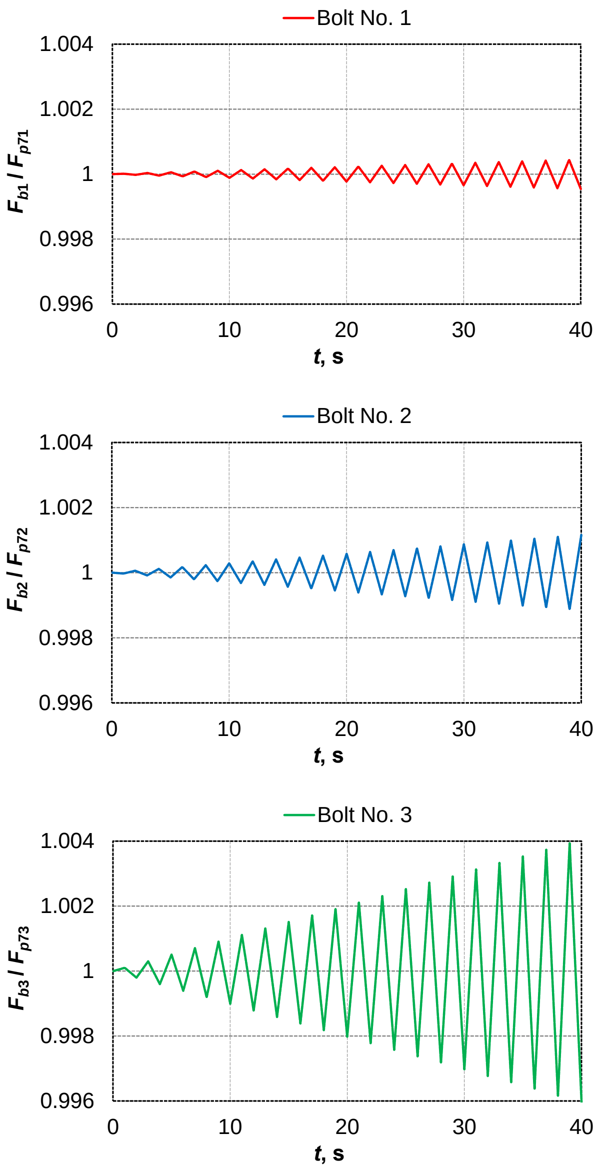
Fig. 4: Bolt force distribution during connection preloading

The module includes a non-linear static analysis for the bolt preloading phase as well as a non-linear implicit transient analysis, [35], for the connection operating phase.

The distribution of forces in the bolts during the preloading of the connection is shown in Figure 4. The graph shows the unified values of the bolt preload forces F_{pi} related to the base value F_{p0}.

The values of the bolt forces after preloading decrease as the tightening of the connection progress. A quantitative assessment of this variability can be made based on the W_1 indicator given by the formula:

$$W_1 = \frac{F_{p0} - F_{pi}}{F_{p0}} \tag{1}$$



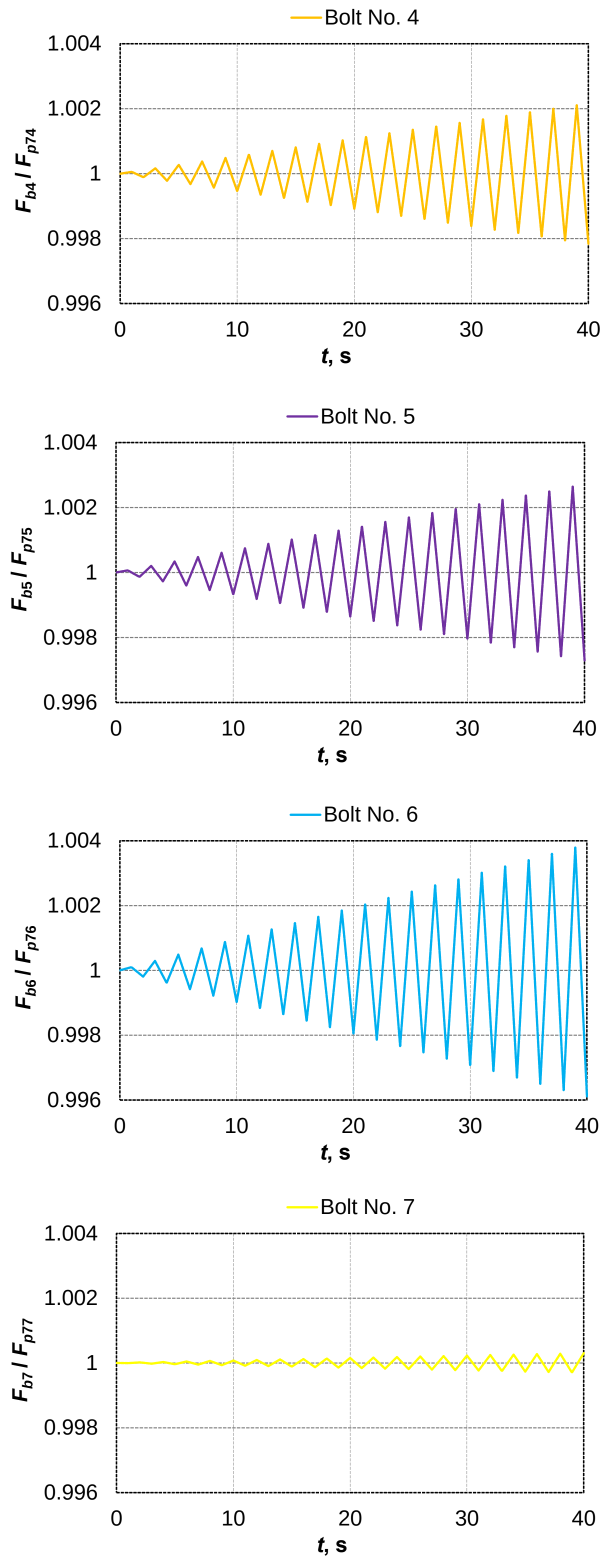


Fig. 5: Bolt force distributions during operational loading of the connection

The values of the W_1 indicator as a function of bolt number i are listed in Table 2.

Table 2. W_1 indicator values.

i	W_1, %
1	0.68
2	0.80
3	0.80
4	0.74
5	0.65
6	0.84
7	0.73

The noticeable only slight reduction in force in a particular bolt under preloading of subsequent bolts is due to the adoption of a rigid type of contact joint (i.e. 'welded' contact) between the main connection plates. The negligible discrepancy in bolt preload values in relation to its base value is also influenced by the way the tightening process is carried out, i.e. its implementation in three passes.

The bolt force distributions in relation to the operating load obtained from the calculations are shown in Figure 5. The graphs show the unified values of the bolt forces F_{bi} related to the bolt forces at the end of the tightening process F_{p7i}.

The values of the bolt forces after external loading change as the loading of the connection progress. A quantitative assessment of this variability can be made on the basis of the W_2 indicator given by the formula:

$$W_2 = \frac{F_{p7i} - F_{bi}}{F_{p7i}} \tag{2}$$

The values of the W_2 indicator as a function of bolt number i are listed in Table 3.

Table 3. W_2 indicator values.

i	W_2, %
1	0.05
2	-0.12
3	0.40
4	0.22
5	0.27
6	0.39
7	-0.03

The forces in the bolts located above the centre of gravity of the contact surface between the main connection plates (i.e. with numbers 3, 4, 5, and 6) show more variability than for the other bolts. It is also noticeable that not in all bolts the force changes analogously to the operational force. In the case of bolts numbered 2 and 7, these changes occur in the opposite phase. However, the observed variations in bolt forces are only minor and do not cause a loss of load-bearing capacity of the multi-bolted connection.

4 Conclusion

This article presents a numerical investigation of an asymmetric multi-bolted connection successively preloaded and then cyclically exposed to normal and tangential loads. The following findings can be extracted from the test outcomes:

1. Conducting the tightening process of a multi-bolted connection in a series of passes results in a relatively uniform distribution of preload force in the bolts at the process end.
2. The forces in the individual bolts vary due to the alternating external load on the multi-bolted connection. In the considered case, the decrease in bolt forces at the end of the operating process is only minor and does not cause a loss of load-bearing capacity of the multi-bolted connection.
3. For preloaded multi-bolted connections, which are loaded operationally with cyclical force, it is advisable to model the contact between the components to be joined as a rigid type of contact (for example, as the 'welded' contact proposed in Midas NFX 2020 R2). This simplification significantly reduces the numerical calculation time.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

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Conflict of Interest

The author has no conflicts of interest to declare.