COMPRESSIVE STRENGTH ANALYSIS OF A STEEL BOLTED CONNECTION UNDER BOLT LOSS CONDITIONS

Rafał Grzejda [1,*], Rafał Perz [2]

[1]Faculty of Mechanical Engineering and Mechatronics, West Pomeranian University of Technology in Szczecin, Szczecin, Poland
[2]Institute of Aeronautics and Applied Mechanics, Warsaw University of Technology, Warsaw, Poland

*E-mail of corresponding author: rafal.grzejda@zut.edu.pl

Resume
The aim of the study is the numerical analysis of a bolted connection under the conditions of loss of bearing capacity of some fasteners in this connection. The joined plates in the connection were made of the 3D finite elements, while the fasteners were treated as hybrid models consisting of rigid heads and nuts and flexible beams between them. A model of unilateral contact with friction was used between the joined plates. The bolted connection was first preloaded according to three different tensioning sequences and with a normalised force. After all the bolts were tensioned, the selected bolts were removed, simulating bolt damage under connection loading conditions. The connection was tested for external compressive loads up to 210 kN. The effect of the loosening of the connection on the load in the remaining bolts at the stage of the connection operation was investigated.

Article info
Received 11 July 2022
Accepted 5 October 2022
Online 24 October 2022

Keywords:
structural health monitoring
bolted connection
preload
fastener damage
finite element method

Available online: https://doi.org/10.26552/com.C.2022.4.B319-B327

ISSN 1335-4205 (print version)
ISSN 2585-7878 (online version)

1 Introduction

In the current literature, much attention is paid to monitoring the technical condition of various engineering structures. This applies especially to systems with structural nodes such as: bolted [1], riveted [2], adhesively bonded [3] or welded connections [4]. These issues are generally referred to as structural health monitoring (SHM). An overview of the methods used in this area is presented, inter alia, in [5].

Structural condition assessment can be carried out on the existing system in real time. Sometimes, however, it is justified to carry out such an assessment numerically, for example in the case of large-size systems or in the case of simulating gradual structural damage in a complex process involving geometric nonlinearity, nonlinear material performance, damage evolution and dynamics [6].

There are two main issues in structural health monitoring of bolted connections and bolts. The first is their analysis of the loss of bearing capacity of some load-bearing elements, such as a column. If one or more of these columns fails under abnormal loads, the vertical load transfer paths are cut off and internal forces would be transferred to adjacent structural members. In this case, there is a need for solidity of the remaining structure in order to evenly and effectively distribute the loads. Otherwise, local damage may cause a chain of damage that results in disproportionate damage or even collapse of the entire structure, which is termed progressive collapse. Consequently, numerous studies on progressive collapse have been carried out using numerical simulations. The most frequently used method in this case was the finite element method (FEM), which is implemented in many analyses of various structures [7-10].

Sadek et al. [11] have conducted a computational study of simple composite shear connections in the column loss scenario. The analyses showed that the composite floor system designed in accordance with the current guidelines is susceptible to collapse due to a loss of the middle column. Kim and Kim [12] have developed a finite element model of a steel frame resistant to bending. A nonlinear dynamic analysis of the FEM-based model under the column loss conditions has been performed. The numerical results showed that the location of the column removal had a significant impact on the behaviour of the panel zone. Lu et al.

[13] have proposed the coupled finite element-discrete element method to account for the influence and heaping of fragments in the progressive collapse analysis. Kwasniewski [14] has developed a detailed 3D model with a large number of finite elements for an existing multi-story structure. Based on the numerical results, modelling parameters that affect the potential for progressive collapse have been identified. Sasani et al. [15] have concluded that a method ignoring the effects of the bending moment and the axial force in the beams would underestimate the anti-collapse resistance of the structure. Fu [16] has built a 3D finite element model of a tall building that can represent the performance of a frame structure to prevent collapse in a column loss scenario. Helmy et al. [17] have performed a dynamic analysis of the gradual collapse of the structure using the applied-element method. The results showed that ignoring the floors in the gradual collapse analysis can lead to wasteful design. Gu et al. [18] have developed a progressive discrete element based collapse simulation system. With the help of this system, the collapse mode and the decomposition of debris after the collapse can be obtained. Based on the experimental results, Gao et al. [19] have carried out a numerical analysis taking into account the material fracture in order to predict the ultimate behaviour of the composite frame under column loss. Tang et al. [20] have conducted research on the progressive collapse of fully bolted beam-to-column connections. Wang et al. [21] have performed similar tests for different types of connections. Rodriguez et al. [22] have carried out an analysis of the fragility and sensitivity of steel frames with bolted-angle connections in conditions of progressive collapse.

The second main issue, related to the structural health monitoring of bolted connections and bolts, is their analysis of the loss of bearing capacity of some fasteners in the connection. However, there are only a few papers devoted to FE-modelling of phenomena occurring in bolted connections due to damage of fasteners. Rucka et al. [23] have applied the wave propagation in diagnostics of the steel bolted bridge parts. Qin and Chu [24] and Qin et al. [25] have performed a quasi-static finite element analysis of a typical disc-drum connection used in rotors of large rotating machines, provided that some bolts were removed from the connection model. Blachowski and Gutkowski [26] have investigated the variability of the connection stiffness, caused by the damage of several bolts and its effect on the displacements in the case of a selected tele-communications tower. Patil et al. [27] have presented the results of a transient analysis of a frame with bolted connections after removing one of the bolts, while Hasni et al. [28] have described the structural health monitoring of a steel frame, in which the damage was simulated by loosening the bolts and creating cracks on its members. The above-mentioned papers concerned the FEM analysis of connections with symmetrical bolt distribution.

Due to the fact that a small number of published papers related to the assessment of the health condition of bolted connections on the basis of modelling was noticed, this subject was taken up in the presented paper. The established numerical finite element model of the selected bolted connection made it possible to provide some assessments about the drop of the bearing capacity of the damaged connection system owing to the loss of one or two of fasteners. The paper is concerned with the bolted connection of plates with a ground contact surface, the experimental studies of which have been described in [29-30]. The scope of the paper covers two connection stages: preload and operation. The novelty, in relation to the above-mentioned articles, is that in this paper an asymmetric connection was modelled. The subject addressed in this paper is worthy of investigation both from a scientific point of view and for practical applications. All the calculations were performed using the Midas NFX 2020 R2 finite element commercial software.

The remainder of this paper is organised as follows: Section 2 briefly presents the models of the bolted connection selected for calculations. Section 3 describes the research procedure including the ways of tensioning of the bolts and their damage. Section 4 provides and discusses the experimental results. Section 5 concludes the paper.

2 Models of the bolted connection

2.1 3D model

The subject of research and analysis is a bolted connection, which is a pair of plates joined with i fasteners, shown in Figure 1 (for i = 1, 2, …, 7). The fasteners are of the M10 × 1.25 type. Each of the bolt-nut pair is treated as one part without creating threads, as existing studies [31] have shown that threadless bolt models can reproduce most of the mechanical response of threaded bolt models and effectively reduce computational time. This approach to fasteners modelling is often used by other researchers, as well [26, 32-33].

The joined plates are fastened to the upper and lower bases. The thickness of all the joined elements is equal to 28 mm. The connection is sloped horizontally at 60 degrees to introduce coexistence of compressive and shear stresses (for comparison, see [34]). The total height of the structure is approximately 266 mm. The plates and bases are made of 1.0577 steel [35]. The bolts are made in the class of mechanical properties 8.8 and the nuts in the class of mechanical properties 8.

The area of the contact surface between the joined plates and the established numbering of the bolts are presented in Figure 2. This area is within a circle with a radius of 90 mm and its size does not exceed 9×10^3 mm^2.

a) b)

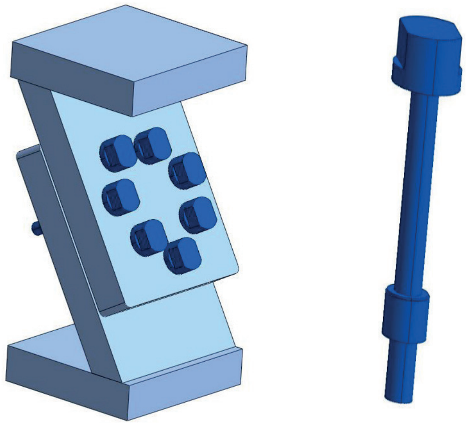


Figure 1 The 3D model of the bolted connection (a) and 3D model of the single fastener (b)

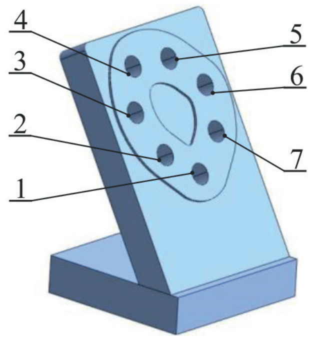


Figure 2 Contact surface between the joined plates and the established bolt numbering

a) b) c)

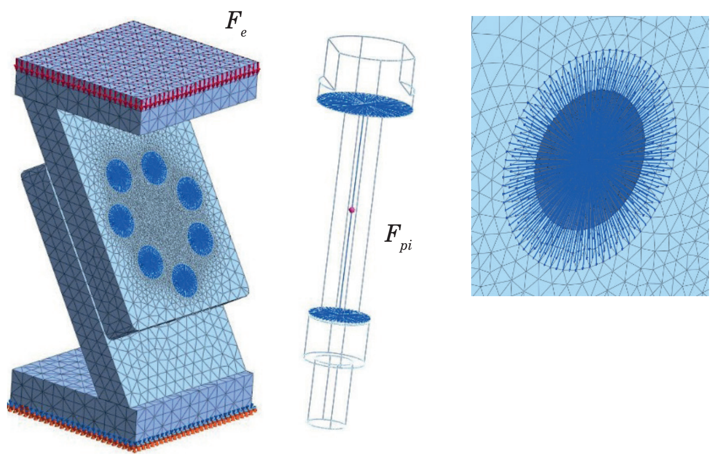


Figure 3 The FEM-based model of the bolted connection (a), FEM-based model of the single fastener (b) and bolt to plate connection (c)

Table 1 Parameters of materials used in the model of the bolted connection

Parameter	Joined elements	Fasteners
Elastic modulus, GPa	210	210
Poisson's ratio	0.30	0.28

2.2 FEM-based model

Using the Midas NFX 2020 R2 finite element system tools, a model of the bolted connection was made, shown in Figure 3. The joined plates were divided into 3D tetragonal finite elements, while the fasteners were modelled as flexible beams with rigid heads and nuts. In particular, the fastener models were obtained by connecting with rigid links the nodes of the beams and the nodes in the mesh of the joined plates lying within the heads of the bolts and nuts (for comparison, see [36-37]).

The individual parts of the bolted connection were assigned linear materials suitable for the steels listed in Section 2.1. Details on the parameters of these materials are given in Table 1.

General surface-to-surface contact elements were applied between the joined plates. They allow for the nonlinear analysis taking into consideration the possibility of separating the joined plates in the vertical direction and the occurrence of sliding in the horizontal direction. The following values of the contact layer parameters were adopted, appropriate for joining ground surfaces [38-39]:

- normal stiffness factor equal to 10,
- tangential stiffness factor equal to 1,
- coefficient of static friction equal to 0.14.

Welded type contact elements were applied between the plates and the bases to prevent the elements from moving relative to each other, in any direction.

The whole model of the bolted connection was built with 78750 elements and 133162 nodes. The model was constrained by taking away all degrees of freedom at the bottom of the lower base (Figure 3a). The preload of the bolts F_{pi} was applied using the "pretension" function available in the Midas NFX 2020 R2 system (marked by a red dot in Figure 3b). The external compressive load F_e was applied perpendicularly to the top surface of the upper base and its value increased from 0 to 210 kN (Figure 3a).

3 Research procedure

The research was divided into the following stages:

1. Preloading the bolted connection in succession in three tensioning sequences in one pass. (Details of the assembly are provided in Table 2.)
2. Entering the damage state by removing the selected bolt according to the diagram shown in Table 3 (after each method of tensioning the bolted connection). Characterisation of changes in the value of forces in the bolts remaining in the bolted connection.
3. Loading the bolted connection in the operating condition. Comparison of the bolt forces values for a healthy and damaged connection.

The value of the preload of bolts F_{pi} of 22 kN was calculated based on the PN-EN 1993-1-8 standard [40] and the analysis of the maximum surface pressure values between fasteners and joined plates was performed.

4 Research results and discussion

The graphical presentation of the calculation results for sequences A, B and C, respectively, is shown in Figures 4 to 6. The values of the operating forces in the selected bolts, related to the preload of the bolts, were compared for a healthy and damaged connection (after each state of damage). It is clear from the graphs that the drops in operating forces in the damaged connection occur faster than in the healthy connection. The analysis of this phenomenon can be performed based on the Z_1 indicator in the form:

$$Z_1 = \left| \frac{F_{bi}^h - F_{bi}^f}{F_{bi}^h} \right| \cdot 100 \,, \tag{1}$$

where: F_{bi}^h is the operating force in the i-th bolt in the considered distribution of forces at the end of the loading process of the healthy connection and F_{bi}^f is an analogous force in the i-th bolt in the case of the damaged connection.

The greatest drop in operating force occurred in bolt No. 3 and it did not exceed 3% in the first damaged state and 10% in the second damaged state, for all the method of tensioning the bolted connection (Table 4). The bolt tensioning method has a slight effect on differences in these drops.

The total bolts tension at the end of the connection loading process was also compared. For this purpose, the Z_2 indicator was introduced by the formula:

$$Z_2 = \left| \frac{F_t^h - F_t^f}{F_t^h} \right| \cdot 100 \,, \tag{2}$$

where: F_t^h is the total force in the bolts in the considered distribution of forces at the end of the process of loading the healthy connection and F_t^f is an analogous force in the case of the damaged connection.

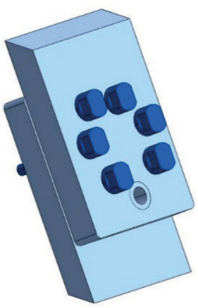
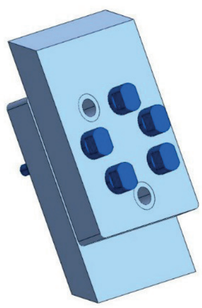
The greatest drops in total force do not exceed 1% in the first damaged state and 4% in the second damaged state, for all the methods of tensioning the bolted connection (Table 5). The bolt tensioning method has a slight effect on the differences in these drops.

The last comparisons of the graphs, shown in

Table 2 *Sequences of tensioning of the bolted connection*

Path type	Sequence (see Figure 2)
A	1-3-5-7-2-4-6
B	1-4-7-3-6-2-5
C	1-5-2-6-3-7-4

Table 3 *Simulation of the damage of the bolted connection*

State 1	State 2
	

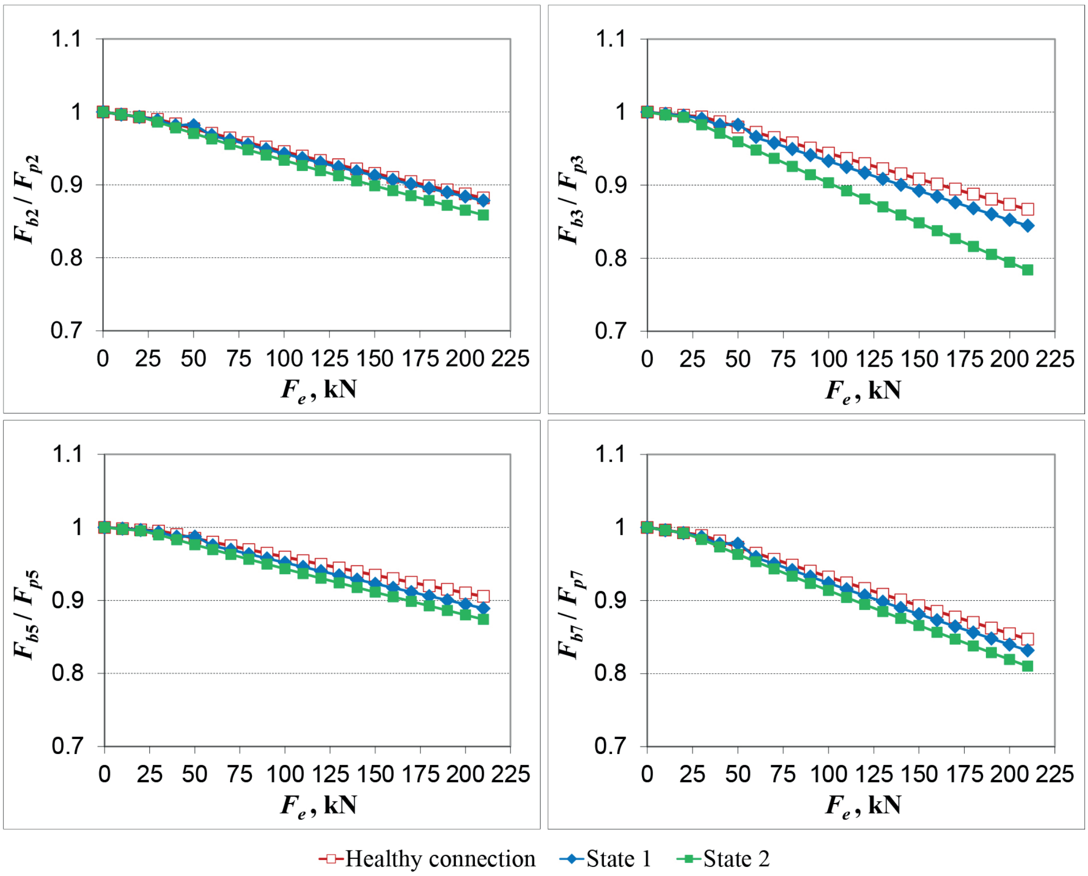


Figure 4 *Bolt forces in the connection tensioned according to the sequence of type A*

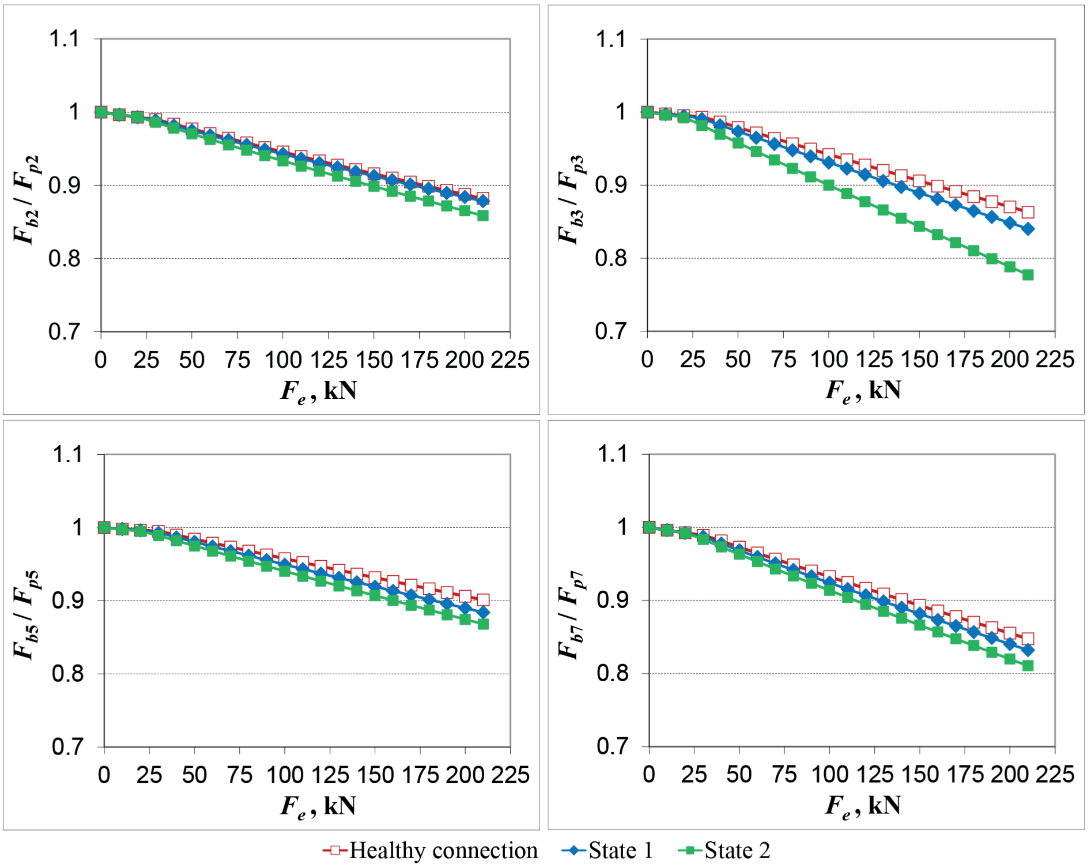


Figure 5 *Bolt forces in the connection tensioned according to the sequence of type B*

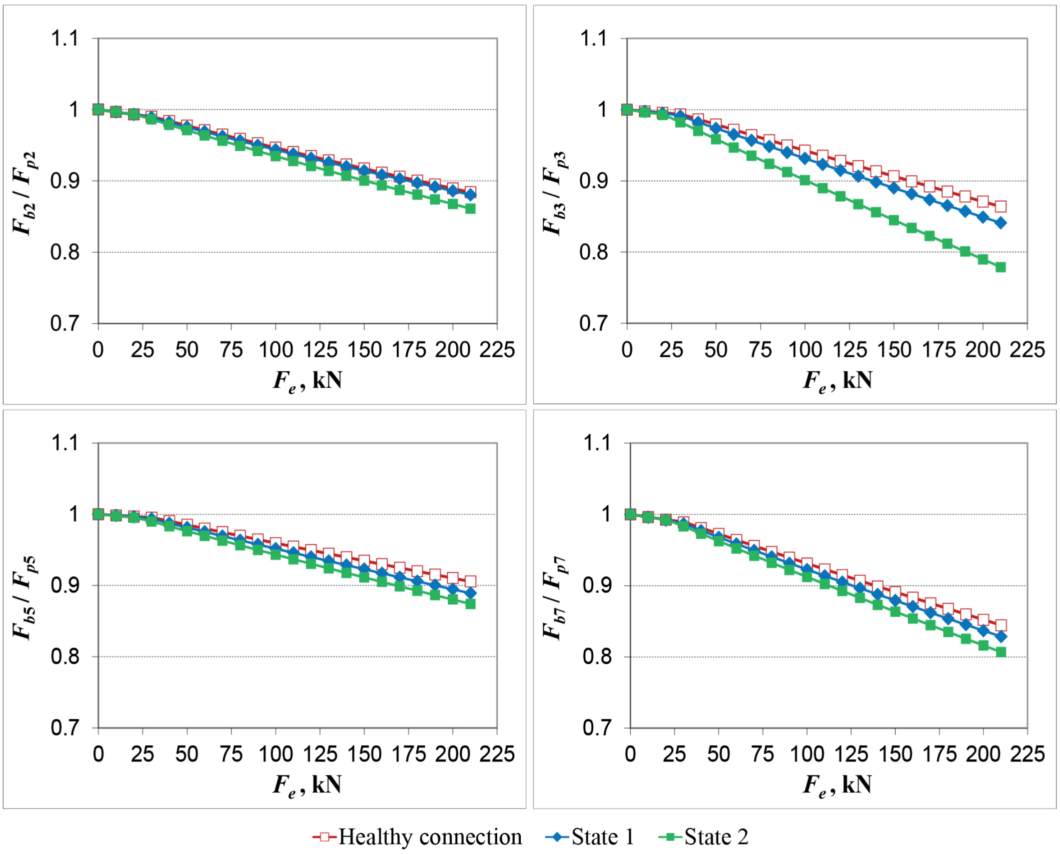


***Figure 6** Bolt forces in the connection tensioned according to the sequence of type C*

***Table 4** Z_1 indicator values (%)*

State 1				
Path type	Bolt number			
	2	3	5	7
A	0.41	2.58	1.82	1.83
B	0.41	2.65	1.91	1.82
C	0.40	2.64	1.82	1.87
State 2				
Path type	Bolt number			
	2	3	5	7
A	2.65	9.58	3.48	4.37
B	2.66	9.94	3.69	4.36
C	2.60	9.83	3.48	4.45

***Table 5** Z_2 indicator values (%)*

Path type	State 1	State 2
A	0.87	3.27
B	0.87	3.33
C	0.87	3.28

Figures 4 to 6, were aimed at determining the value of the external load F_e at which the operating forces in the bolts in the damaged connection reach the values corresponding to the final load condition in the healthy connection. The results of these analyses are summarised in Table 6. Based on that, it can be concluded that the bearing capacity of the connection in the first damage state decreased by approximately 14% and in the second damage state by approximately 37%. The bolt tensioning method has a slight effect on the

Table 6 *External load values (kN)*

State 1				
Path type	Bolt number			
	2	3	5	7
A	203.6	181.9	180.5	191.1
B	203.5	181.9	180.6	191.1
C	203.5	181.9	180.5	191.1
State 2				
Path type	Bolt number			
	2	3	5	7
A	174.8	133.1	159.1	170.1
B	174.6	132.6	158.7	170.0
C	174.7	133.0	159.1	170.1

value of the bearing capacity.

In the literature cited in the introduction, the differences in the displacements of the joined elements, as a result of the removal of selected bolts, were studied rather than the differences in the values of forces in the bolts not removed from the connection. However, similar to the results of the other researchers, is the fact that the stiffness of the bolted connection decreases after its damage, i.e. after removing a bolt or a few bolts [24-26].

5 Conclusions

The paper presents an example of modelling the preloaded asymmetric bolted connections under damage and external force load conditions. Consideration of the connection with an arbitrary bolt system is original in relation to the works carried out so far. The results of the study lead to the following conclusions:

1. The drops in operating forces in a damaged connection loaded with external force occur faster than in a healthy connection. The differences in the values of the operating forces can be as high as 10% (in the case of the two out of seven bolts failure).
2. The bearing capacity of a damaged connection (caused by the failure of two out of seven bolts) may be reduced by approximately 37%.
3. The method of tensioning the connection has a slight effect on the magnitude of drops in the values of bolt forces and the bearing capacity of the connection in its damage state.
4. It is possible to carry out experimental tests verifying the presented bolted connection model using the stand described in [29-30].
5. The presented method can be used in assessing the health of bolted connections.

References

[1] GRZEJDA, R., PARUS, A. Health assessment of a multi-bolted connection due to removing selected bolts. *FME Transactions* [online]. 2021, **49**(3), p. 634-642 [accessed 2022-07-11]. ISSN 1451-2092. Available from: https://doi.org/10.5937/fme2103634G

[2] DEMETGUL, M., SENYUREK, V. Y., UYANDIK, R., TANSEL, I. N., YAZICIOGLU, O. Evaluation of the health of riveted joints with active and passive structural health monitoring techniques. *Measurement* [online]. 2015, **69**, p. 42-51 [accessed 2022-07-11]. ISSN 0263-2241. Available from: https://doi.org/10.1016/j.measurement.2015.03.032

[3] MEDEIROS, R., SOUZA, G. S. C., MARQUES, D. E. T., FLOR, F. R., TITA, V. Vibration-based structural monitoring of bi-clamped metal-composite bonded joint: experimental and numerical analyses. *The Journal of Adhesion* [online]. 2021, **97**(10), p. 891-917 [accessed 2022-07-11]. ISSN 0021-8464. Available from: https://doi.org/10.1080/00218464.2020.1711742

[4] IJAZ, M., QAYYUM, F., ELAHI, H., ULLAH, M., EUGENI, M., BADSHAH, S., GAUDENZI, P. Effect of natural aging and fatigue crack propagation rate on welded and non-welded aluminum alloy (AA2219-T87). *Advances in Science and Technology - Research Journal* [online]. 2019, **13**(3), p. 129-143 [accessed 2022-07-11]. ISSN 2080-4075. Available from: https://doi.org/10.12913/22998624/110737

[5] BARSKI, M., KEDZIORA, P., MUC, A., ROMANOWICZ, P. Structural health monitoring (SHM) methods in machine design and operation. *Archive of Mechanical Engineering* [online]. 2014, **61**(4), p. 653-677 [accessed 2022-07-11]. ISSN 0004-0738. Available from: https://doi.org/10.2478/meceng-2014-0037

[6] GAO, S. Nonlinear finite element failure analysis of bolted steel-concrete composite frame under column-loss. *Journal of Constructional Steel Research* [online]. 2019, **155**, p. 62-76 [accessed 2022-07-11]. ISSN 0143-974X. Available from: https://doi.org/10.1016/j.jcsr.2018.12.020

[7] MAZURKIEWICZ, L., MALACHOWSKI, J., DAMAZIAK, K., TOMASZEWSKI, M. Evaluation of the response of fibre reinforced composite repair of steel pipeline subjected to puncture from excavator tooth. *Composite Structures* [online]. 2018, **202**, p. 1126-1135 [accessed 2022-07-11]. ISSN 0263-8223. Available from: https://doi.org/10.1016/j.compstruct.2018.05.065

[8] MIELOSZYK, J., TARNOWSKI, A., KOWALIK, M., PERZ, R., RZADKOWSKI, W. Preliminary design of 3D printed fittings for UAV. *Aircraft Engineering and Aerospace Technology* [online]. 2019, **91**(5), p. 756-760 [accessed 2022-07-11]. ISSN 1748-8842. Available from: https://doi.org/10.1108/AEAT-07-2018-0182

[9] GRZYWINSKI, M., SELEJDAK, J., DEDE, T. Shape and size optimization of trusses with dynamic constraints using a metaheuristic algorithm. *Steel and Composite Structures*. 2019, **33**(5), p. 747-753. ISSN 1229-9367.

[10] WYSMULSKI, P., DEBSKI, H., FALKOWICZ, K. Sensitivity of compressed composite channel columns to eccentric loading. *Materials* [online]. 2022, **15**(19), 6938 [accessed 2022-10-13]. ISSN 1996-1944. Available from: https://doi.org/10.3390/ma15196938

[11] SADEK, F., EL-TAWIL, S., LEW, H. S. Robustness of composite floor systems with shear connections: modeling, simulation and evaluation. *Journal of Structural Engineering*. 2008, **134**(11), p. 1717-1725. ISSN 0733-9445.

[12] KIM, T., KIM, J. Progressive collapse-resisting capacity of steel moment frames considering panel zone deformation. *Advances in Structural Engineering*. 2009, **12**(2), p. 231-240. ISSN 1369-4332.

[13] LU, X., LIN, X., YE, L. Simulation of structural collapse with coupled finite element-discrete element method. In: *Computational structural engineering*. 1. ed. Dordrecht: Springer, 2009, p. 127-135. ISBN 978-90-481-2822-8.

[14] KWASNIEWSKI, L. Nonlinear dynamic simulations of progressive collapse for a multistory building. *Engineering Structures* [online]. 2010, **32**(5), p. 1223-1235 [accessed 2022-07-11]. ISSN 0141-0296. Available from: https://doi.org/10.1016/j.engstruct.2009.12.048

[15] SASANI, M., KAZEMI, A., SAGIROGLU, S., FOREST, S. Progressive collapse resistance of an actual 11-story structure subjected to severe initial damage. *Journal of Structural Engineering*. 2011, **137**(9), p. 893-902. ISSN 0733-9445.

[16] FU, F. 3-D nonlinear dynamic progressive collapse analysis of multi-storey steel composite frame buildings - parametric study. *Engineering Structures* [online]. 2011, **32**(12), p. 3974-3980 [accessed 2022-07-11]. ISSN 0141-0296. Available from: https://doi.org/10.1016/j.engstruct.2010.09.008

[17] HELMY, H., SALEM, H., MOURAD, S. Computer-aided assessment of progressive collapse of reinforced concrete structures according to GSA code. *Journal of Performance of Constructed Facilities*. 2013, **27**(5), p. 529-539. ISSN 0887-3828.

[18] GU, X., WANG, X., YIN, X., LIN, F., HOU, J. Collapse simulation of reinforced concrete moment frames considering impact actions among blocks. *Engineering Structures* [online]. 2014, **65**, p. 30-41 [accessed 2022-07-11]. ISSN 0141-0296. Available from: https://doi.org/10.1016/j.engstruct.2014.01.046

[19] GAO, S., GUO, L., FU, F., ZHANG, S. Capacity of semi-rigid composite joints in accommodating columns loss. *Journal of Constructional Steel Research* [online]. 2017, **139**, p. 288-301 [accessed 2022-07-11]. ISSN 0143-974X. Available from: https://doi.org/10.1016/j.jcsr.2017.09.029

[20] TANG, H., DENG, X., JIA, Y., XIONG, J., PENG, C. Study on the progressive collapse behavior of fully bolted RCS beam-to-column connections. *Engineering Structures* [online]. 2019, **199**, 109618 [accessed 2022-07-11]. ISSN 0141-0296. Available from: https://doi.org/10.1016/j.engstruct.2019.109618

[21] WANG, F., YANG, J., PAN, Z. Progressive collapse behaviour of steel framed substructures with various beam-column connections. *Engineering Failure Analysis* [online]. 2020, **109**, 104399 [accessed 2022-07-11]. ISSN 1350-6307. Available from: https://doi.org/10.1016/j.engfailanal.2020.104399

[22] RODRIGUEZ, D., BRUNESI, E., NASCIMBENE, R. Fragility and sensitivity analysis of steel frames with bolted-angle connections under progressive collapse. *Engineering Structures* [online]. 2021, **228**, 111508 [accessed 2022-07-11]. ISSN 0141-0296. Available from: https://doi.org/10.1016/j.engstruct.2020.111508

[23] RUCKA, M., ZIMA, B., KEDRA, R. Application of guided wave propagation in diagnostics of steel bridge components. *Archives of Civil Engineering* [online]. 2014, **60**(4), p. 493-515 [accessed 2022-07-11]. ISSN 1230-2945. Available from: https://doi.org/10.2478/ace-2014-0033

[24] QIN, Z., CHU, F. Numerical studies on time-varying stiffness of disk-drum type rotor with bolt loosening. *Journal of Physics: Conference Series* [online]. 2015, **628**, 012076 [accessed 2022-07-11]. ISSN 1742-6588. Available from: https://doi.org/10.1088/1742-6596/628/1/012076

[25] QIN, Z., HAN, Q., CHU, F. Bolt loosening at rotating joint interface and its influence on rotor dynamics. *Engineering Failure Analysis* [online]. 2016, **59**, p. 456-466 [accessed 2022-07-11]. ISSN 1350-6307. Available from: https://doi.org/10.1016/j.engfailanal.2015.11.002

[26] BLACHOWSKI, B., GUTKOWSKI, W. Effect of damaged circular flange-bolted connections on behaviour of tall towers, modelled by multilevel substructuring. *Engineering Structures* [online]. 2016, **111**, p. 93-103 [accessed 2022-07-11]. ISSN 0141-0296. Available from: https://doi.org/10.1016/j.engstruct.2015.12.018

[27] PATIL, C. S., ROY, S., JAGTAP, K. R. Damage detection in frame structure using piezoelectric actuator. *Materials Today: Proceedings* [online]. 2017, **4**(2), Part A, p. 687-692 [accessed 2022-07-11]. ISSN 2214-7853. Available from: https://doi.org/10.1016/j.matpr.2017.01.073

[28] HASNI, H., JIAO, P., ALAVI, A. H., LAJNEF, N., MASRI, S. F. Structural health monitoring of steel frames using a network of self-powered strain and acceleration sensors: A numerical study. *Automation in Construction* [online]. 2018, **85**, p. 344-357 [accessed 2022-07-11]. ISSN 0926-5805. Available from: https://doi.org/10.1016/j.autcon.2017.10.022

[29] GRZEJDA, R., PARUS, A. Experimental studies of the process of tightening an asymmetric multi-bolted connection. *IEEE Access* [online]. 2021, **9**, p. 47372-47379 [accessed 2022-07-11]. ISSN 2169-3536. Available from: https://doi.org/10.1109/ACCESS.2021.3067956

[30] GRZEJDA, R., PARUS, A., KWIATKOWSKI, K. Experimental studies of an asymmetric multi-bolted connection under monotonic loads. *Materials* [online]. 2021, **14**(9), 2353 [accessed 2022-07-11]. ISSN 1996-1944. Available from: https://doi.org/10.3390/ma14092353

[31] CAO, Z., BRAKE, M. R. W., ZHANG, D. The failure mechanisms of fasteners under multi-axial loading. *Engineering Failure Analysis* [online]. 2019, **105**, p. 708-726 [accessed 2022-07-11]. ISSN 1350-6307. Available from: https://doi.org/10.1016/j.engfailanal.2019.06.100

[32] WALCZAK, R., PAWLICKI, J., ZAGORSKI, A. Tightness and material aspects of bolted flange connections with gaskets of nonlinear properties exposed to variable loads. *Archives of Metallurgy and Materials* [online]. 2016, **61**(3), p. 1409-1416 [accessed 2022-07-11]. ISSN 1733-3490. Available from: https://doi.org/10.1515/amm-2016-0231

[33] JASZAK, P. Prediction of the durability of a gasket operating in a bolted-flange-joint subjected to cyclic bending. *Engineering Failure Analysis* [online]. 2021, **120**, 105027 [accessed 2022-07-11]. ISSN 1350-6307. Available from: https://doi.org/10.1016/j.engfailanal.2020.105027

[34] CHAN, J. L. Y., LO, S. H. Direct analysis of steel frames with asymmetrical semi-rigid joints. *Steel and Composite Structures*. 2019, **31**(1), p. 99-112. ISSN 1229-9367.

[35] PN-EN 10025-1, Hot rolled products of structural steels, Part 1: General technical delivery conditions. Warsaw: Polish Committee for Standardization, 2007.

[36] GRZEJDA, R. FE-modelling of a contact layer between elements joined in preloaded bolted connections for the operational condition. *Advances in Science and Technology - Research Journal* [online]. 2014, **8**(24), p. 19-23 [accessed 2022-07-11]. ISSN 2080-4075. Available from: https://doi.org/10.12913/22998624/561

[37] PALENICA, P., POWALKA, B., GRZEJDA, R. Assessment of modal parameters of a building structure model. *Springer Proceedings in Mathematics and Statistics*. 2016, **181**, p. 319-325. ISSN 2194-1009.

[38] GRZESIK, W. Effect of the machine parts surface topography features on the machine service (in Polish). *Mechanik* [online]. 2015, **88**(8-9), p. 587-593 [accessed 2022-07-11]. ISSN 0025-6552. Available from: https://doi.org/10.17814/mechanik.2015.8-9.493

[39] GRZEJDA, R., WARZECHA, M., URBANOWICZ, K. Determination of pretension in bolts for structural health monitoring of multi-bolted connection: FEM approach. *Lubricants* [online]. 2022, **10**(5), 75 [accessed 2022-07-11]. ISSN 2075-4442. Available from: https://doi.org/10.3390/lubricants10050075

[40] PN-EN 1993-1-8, Eurocode 3: Design of steel structures, Part 1-8: Design of joints. Warsaw: Polish Committee for Standardization, 2006.