BOLTED JOINTS IN FIRE BY THE COMPONENT-BASED FINITE ELEMENT METHOD

Batuhan Der [1*], František Wald [2], Martin Vild [3], and Jaroslav Kabeláč [4]

[1,2] Czech Technical University in Prague, Czech Republic,
[3] Brno University of Technology, Czech Republic
[4] IDEA RS s.r.o., U Vodárny 3032/2a, Brno, Czech Republic
Email: [1] abhishek.ghimire@fsv.cvut.cz, [2] wald@fsv.cvut.cz,*
[3] vild.m@fce.vutbr.cz, [4] jaromir.kabelac@ideastatica.com
DOI: https://doi.org/10.59382/pro.intl.con-ibst.2023.ses1-4

ABSTRACT: This paper presents a study using the component-based finite element method (CBFEM) to analyse the behaviour bolted joints in fire. The model was verified and validated on analytical and experimental results at elevated temperature. In this work, the plates are modelled using shell elements and the bolt is represented by non-linear springs. The elements are analysed by geometrically and materially nonlinear analysis with imperfections (GMNIA). Consequently, the method used in this work can give reasonable results to predict the behaviour of joints at elevated temperature.

KEYWORDS: Numerical design calculation, regular inclined shell element model, high-strength steel, strength.

1. INTRODUCTION

Elevated temperatures usually cause degradation of the structural properties of commonly used construction materials, especially those of steel. Therefore, the resistance of structures to disproportionate collapse in fire needs to be given sufficient attention during their design stage. Bolted joints are commonly used in modern steel structures. The mechanical behaviour bolted joints at elevated temperature can be investigated by experiments, analytical and numerical models.

The component-based method has been standardized to analyse semi-rigid joints at ambient temperatures in EN 1993-1-8 [1]. Eurocode 3 Part 1.8 lists different joint components with stiffness and strength based on the literature review. The logic behind the component method is decomposing a joint into compression, tension and shear zones. Several basic components are used to describe the behaviour of each zone. The overall joint behaviour can be calculated from assembling the contributions of individual joint components which are represented by rigid links and translational springs with nonlinear force-displacement response, either in parallel or series where appropriate [2]. In order to evaluate the fire resistance of a steel connection, the behaviour of both the components such as plates, bolts and welds should be accurately predicted at elevated temperatures. For fire design of steel connections, EN 1993-1-2 [3] proposes reduction factors for carbon steel, bolts and welds.

Many authors [4-7] have developed the finite element models to determine the resistance of bolted connections at ambient and high temperatures. The finite element methods may use solid or shell elements to model the bolted connections. Wald et al. [8] describes that the solid elements are used for generating research-oriented finite element models which are numerical simulation (ROFEM), and the design-oriented finite element models (DOFEM), which can be defined as numerical calculation, include the shell elements. Several studies [9-11] indicated that shell elements are reliable models to predict the behaviour of bolted connections at ambient temperatures. Numerical calculations can be used replacing analytical models by engineers in the design level of structural fire engineering. The fire resistance of bolted connection may be determined by a numerical method.

CBFEM method is combination of the Finite Element Method (FEM) and Component Method (CM). The stresses and internal forces calculated on the accurate CBFEM model are used in checks of all components according to Eurocode EN 1993-1-8. The verification and validation procedure are an important integral part of any finite element analyses. The procedure checks the finite element models and their effective use by designer. The verification and validation procedure were based on the principles proposed by Wald et al. [8]. Validation compares the analytical and numerical solution with the experimental data whereas, verification uses comparison of computational solutions with highly accurate analytical or numerical solution. The CBFEM verified and validated by many benchmark studies [10].

The study presents CBFEM models for bolted lap joint and T-stub at different temperature level. Design resistances at high temperatures calculated by CBFEM are compared with results of analytical model and experiments. To investigate the different components of steel joints bolted lap joints and T-stubs are used for verification and validation of CBFEM model. Two different bolt grades are studied in shear and tension at elevated temperatures.

2. EXPERIMENTS

Bolted lap joints and T-stubs in fire were investigated since the main components of bolted joints are bolts in shear, tension and bearing.

2.1. Bolted lap joints

The experimental work [11] was performed on 9 double lap joints with two or four bolts positioned perpendicular to the loading direction. The experimental program was performed to measure the resistance of double lap joints at elevated temperature at the Czech Technical University in Prague. The tests on the bolted lap joints have been carried out by the Shimadzu Autograph AG-X plus machine under monotonic loading conditions. The loads have been applied under displacement control with a speed equal to 0.65 mm/min. Figure 1 shows the geometry of test specimens and heating setup.

The test specimens were designed for shear failure in bolt according to EN 1933-1-8 [1] at each temperature. As calculated in design level, the specimens failed due to bolts in shear as indicated in Figure 2. The important geometrical dimensions are shown in Figure 3.

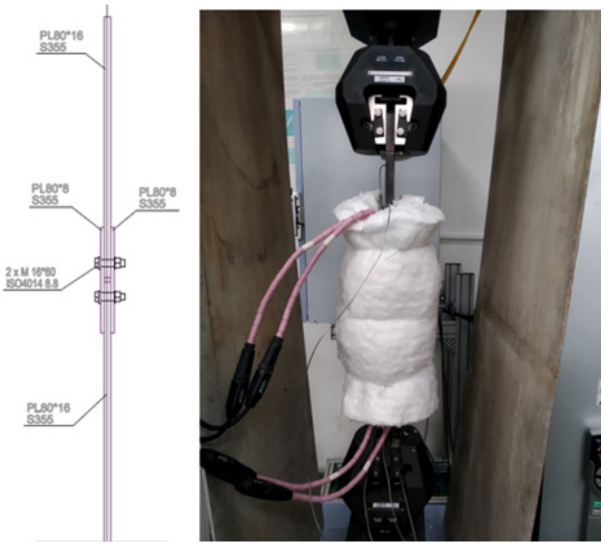


Figure 1. Test specimen and heating system

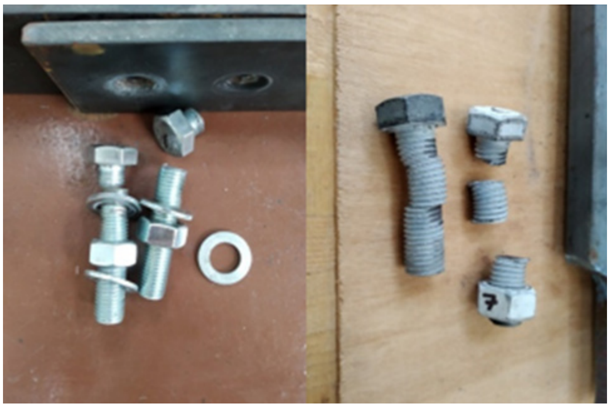


Figure 2. Failure modes at ambient and elevated temperature

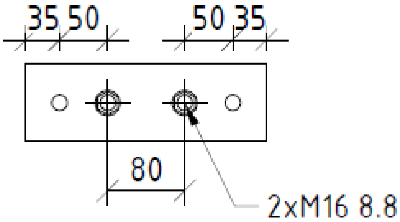


Figure 3. Top view of cover plate with nominal characteristics

2.2. T-stubs

The benchmark [10] study presented the experimental study [12] which comprising fifteen tests on welded T-stubs components with three different geometries (t_p = 10 mm, 15 mm and 20 mm) and three different temperatures (20ºC, 500ºC and 600ºC).

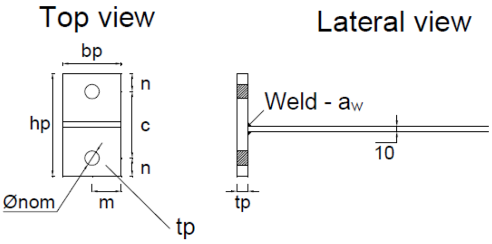


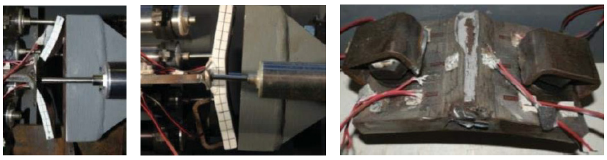
Figure 4. Top view and lateral view of the tested T-sub

The characterization of the tested T-sub specimens is shown in Figure 4 and the values are presented in Table 1.

Table 1. Characterization of the t-stub specimens [12]

Specimens	Dimensions [mm]					
	t_p	b_p	h_p	c	n	m
FL-10	10	105	170	110	30	52.5
FL-15	15	105	170	110	30	52.5
FL-20	20	105	185	120	32.5	52.5

Different types of failure were observed during tests. At ambient temperature FL-10 and FL-20 specimens indicated complete yielding of the flange before tension bolt fracture, whereas FL-15 specimen failed due to mode 2 according to Eurocode as shown in Figure 5. At elevated temperatures, the failure mode 2 was the dominant failure mode for each specimen.



a) b) c)

Figure 5. Failure modes [12] at ambient temperature: a) FL-10; b) FL-15; c) FL-20

3. CBFEM

The steel connection design software IDEA StatiCa [13] were used to model bolted lap joints and T-stubs at ambient and elevated temperatures.

3.1. General description

In the CBFEM, the bolt with its behaviour in tension, shear, and bearing is the component described by the dependent nonlinear springs. Bolt assembly consists of bolt, washer, and nut and is simulated by a nonlinear spring, rigid body elements and gap elements. Figure 6 shows the assembly and modelling of tested bolted lap joints and T-stubs. The plates are modelled using 4-node quadrangle shell elements.

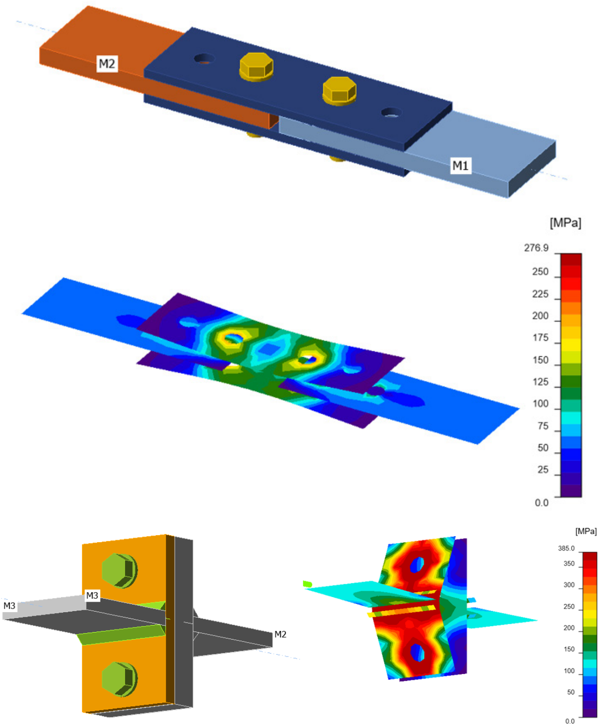


Figure 6. Assembly and modelling of T-stubs

3.2. Material Models

The plates in IDEA StatiCa ***are*** modelled with elastic-plastic material with a nominal yielding plateau slope according to EN1993-1-5 [14]. The material behaviour is based on the von Mises yield criterion. It is assumed to be elastic before reaching the design yield strength, f_{yd}. The ultimate limit state criterion for regions not susceptible to buckling is reaching the limiting value of the principal membrane strain. The value of 5% is recommended in EN1993-1-5 [14].

3.3. Contact

In the CBFEM the standard penalty method is recommended for modelling the contact between plates. According to this methodology, penetration of nodes between plates in contact is prevented, as the solver checks their nodes during every non-linear iteration. If penetration is detected, a penalty stiffness is added via the contact springs and the contact force is redistributed between the two surfaces.

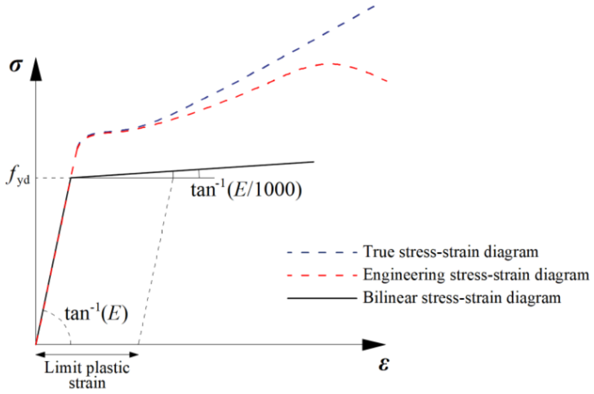


Figure 7. Material model used in the CBFEM

4. VALIDATION

In this section, CBFEM models are validated through experimental results. The load-deformation curves of bolted lap joints are presented obtaining from experimental study and CBFEM. The main parameters are resistance values and failure modes of T-stubs for validation of CBFEM.

4.1. Resistance

Figure 8-10 compare the numerical predictions (dashed lines) with the experimental results of bolted lap joints (solid lines) at 20°C, 400°C and 600°C. The design resistance of bolted lap joints is 10% less than measured resistance up to 600°C. The trend of load-deformation curve is similar to experimental study with lower yield strength. In Figure 11-13 it can be seen that CBFEM is also providing safer results comparing to experimental results of T-stubs. The difference between resistance results is increasing with higher flange thickness of T-stubs.

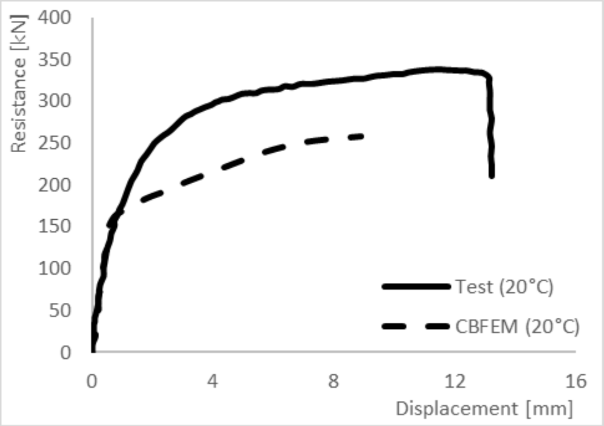


Figure 8. Load-deformation curves of bolted lap joints at ambient temperature

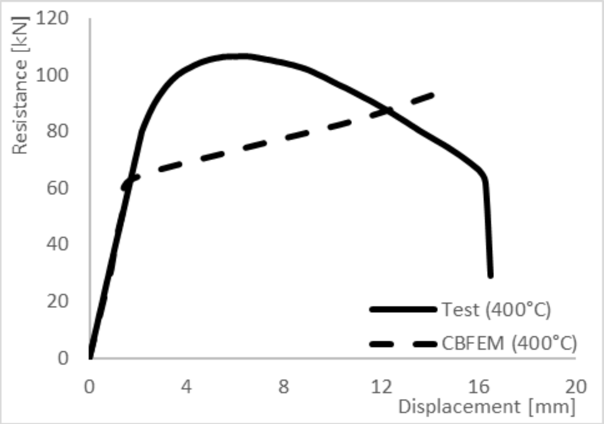


Figure 9. Load-deformation curves of bolted lap joints at 400℃

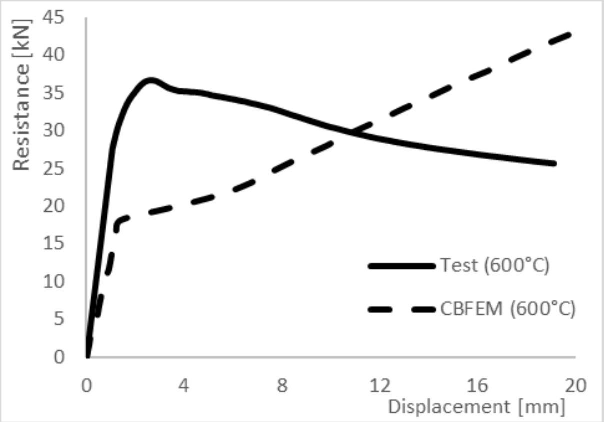


Figure 10. Load-deformation curves of bolted lap joints at 600℃

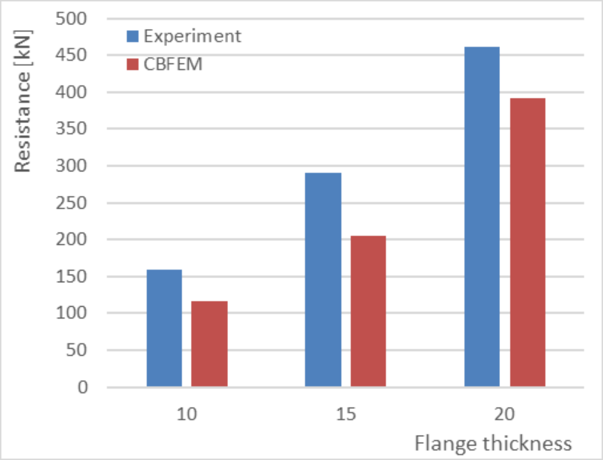


Figure 11. Comparison of T-stub resistance at ambient temperature

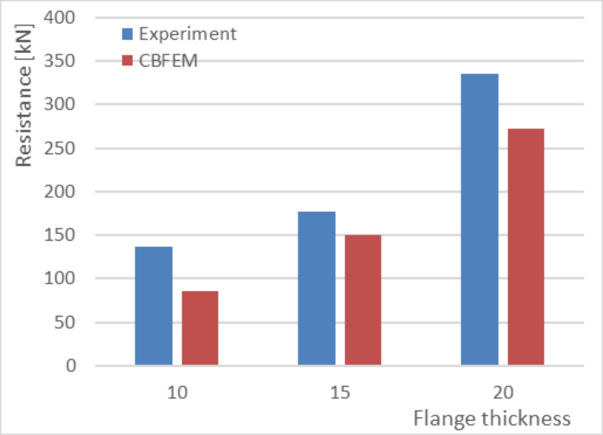


Figure 12. Comparison of T-stub resistance at 400°C

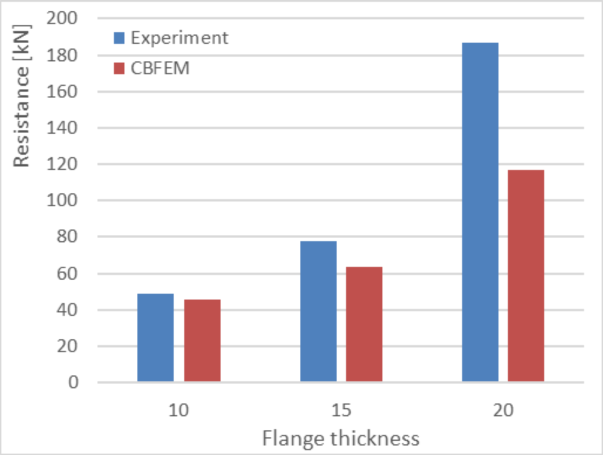


Figure 13. Comparison of T-stub resistance at 600°C

4.2. Failure Modes

CBFEM detected the bolt shear failure at each temperature as obtained in experimental study. Figure 14 shows that the bolt reaches to ultimate capacity before plates have 5% plastic strain. The experimental study of T-stubs indicated two different failure modes: Mode 1 and Mode 2. The definition of Mode 1 is complete flange yielding before bolt fracture according to EN 1993-1-8. failure. In Mode 2, the flange yields as bolts reach to ultimate stress.

As defined in Eurocode, when plate reaches to 5% plastic limit strain, the bolts also use 94.7% of its capacity in Figure 15. However, the bolts do not get close to its ultimate capacity in mode 2 as indicated in Figure 16.

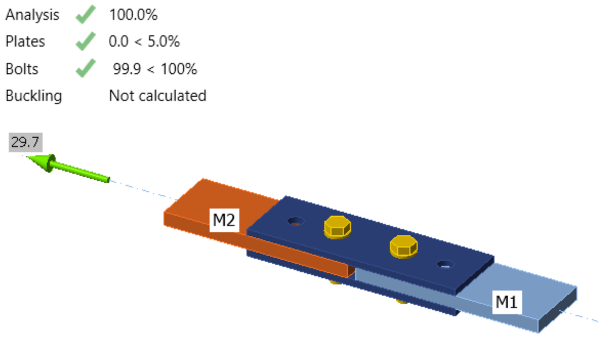


Figure 14. Bolts failure in CBFEM

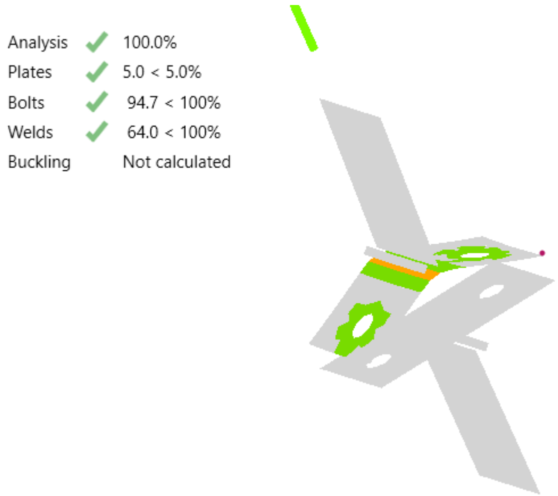


Figure 15. Failure mode 1 in CBFEM

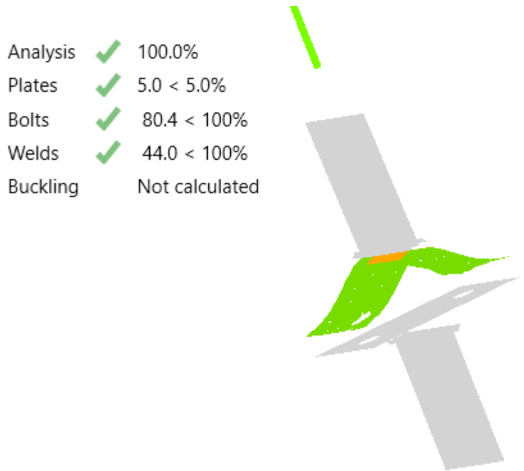


Figure 16. Failure mode 2 in CBFEM

5. VERIFICATION

A comparison between results from the component-based finite element method (CBFEM) and analytical methods presented in EN 1993-1-8 [1] for bolted lap joints and T-stub connections is presented in this study. The bolt resistance in shear and the plate resistance in bearing are designed according to EN 1993-1-8. Since the R-squared values are higher than 0.98 for both cases, the CBFEM can be considered reliable method in-stead of analytical models for structural fire designers.

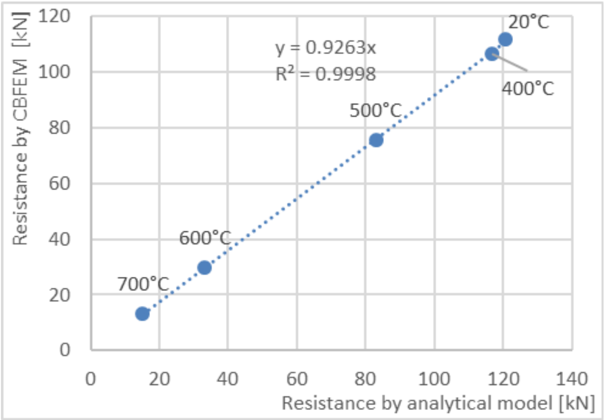


Figure 17. Comparison of analytical and CBFEM models

Table 2 presents the resistance values and types of failure modes obtaining from analytical and CBFEM models. The CBFEM generally gives similar results with analytical model in terms of resistance and failure mode. At 600°C, the models with 15 mm and 20 mm of flange thickness have different failure mode. The models in CBFEM fail due to failure mode 3 which is bolt fracture before flange yielding. However, the resistance values of Mode 2 and Mode 3 according to analytical model are really close to each other.

Table 2. Resistance values and failure modes of CBFEM by AM and CBFEM

Specimen	Resistance [kN]		Failure Modes	
	AM	CBFEM	AM	CBFEM
FL-10 (20)	114.6	117.1	1	1
FL-15 (20)	217.8	204.4	2	2
FL-20 (20)	413.6	391	2	2
FL-10 (500)	89.4	85.2	1	1
FL-15 (500)	134.8	150	2	2
FL-20 (500)	253.6	271.6	2	2
FL-10 (600)	45.5	45.5	2	2
FL-15 (600)	64.3	63.3	2	3
FL-20 (600)	119.4	117	2	3

6. SUMMARY

The CBFEM models for bolted lap joints and T-stubs were presented in this study at ambient and elevated temperatures. The CBFEM models were generated using IDEA StatiCa. The experimental studies were used to validate the CBFEM models in terms of resistance and failure modes. Then, the verification procedure was performed comparing the CBFEM results with the analytical models proposed in EN 1993-1-8. The CBFEM models provided lower resistance results than experimental results for each type of joint. Moreover, the CBFEM models were able to detect similar failure modes as obtained during experimental study. Design resistances calculated by CBFEM were compared with results of analytical model (AM). The logic behind the difference between analytical model and CBFEM of bolted lap joints is loading of bolts since the analytical model applies pure shear force to bolts and it neglects the tensile forces occurring due to plate deformation.

It can be concluded that CBFEM is a good alternative to analytical models for design of joints at elevated temperature because it uses advantages of FEM which are not considered by analytical models.

ACKNOWLEDGEMENTS

This research is supported by the grant SGS22/144/OHK1/3T/11 from CTU in Prague.

REFERENCE

[1] EN-1993-1-8. (2005). *Eurocode 3: Design of Steel Structures, Part 1.8: Design of joints*. European Committee for Standardisation. Brussels, Belgium: European Committee for Standardization.

[2] Jaspart, J. P. (2000). *General Report: session on connections*. Journal of Constructional Steel Research, 55, 69-89.

[3] EN-1993-1-2. (2005). *Eurocodes 3: Design of Steel Structures, Part 1.2: Structural Fire Design.* European Committee for Standardisation. Brussels, Belgium: European Committee for Standardization.

[4] Al-Jabri, K. S., Seibi, A., & Karrech, A. (2006). *Modelling of unstiffened flush endplate bolted connections in fire*. Journal of Constructional Steel Research, 62, 151-159.

[5] Sarraj, M., Burgess, I. W., Davison, J. B., & Plank, R. J. (2007). *Finite element modelling of steel fin plate connections in fire*. Fire Safety Journal, 42, 408-415.

[6] J. Kim, J. C. Yoon und B. S. Kang (2007). *Finite element analysis and modeling of structure with bolted join*ts, Applied Mathematical Modelling, Bd. 31, p. 895–911,

[7] Selamet, S., & Garlock, M. E. (2014). *Fire resistance of steel shear connections*. Fire Safety Journal, 68, 52-60.

[8] Wald, F.; Kwasniewski, L.; Gödrich, L.; Kurejková, M. (2014). *Validation and verification procedures for connection design in steel structures.* In 12th International Conference on Steel, Space and Composite Structures (pp. 111-120).

[9] N. Tanlak, F. O. Sonmez und E. Talay (2011). *Detailed and simplified models of bolted joints under impact loading*, The Journal of Strain Analysis and Engineering Design, Bd. 46, Nr. 3, pp. 213-225,

[10] Wald, F.; Šabatka, L.; Bajer, M.; Kozich M.; Vild M.; Gulubiatnikov K.; Kabelac J.; Kurikova M. (2021) *Component-based Finite Element Design of Steel Connections*, Czech Technical University Prague, ISBN 978-80-01-06862-5.

[11] Der, B.; Wald, F. (2022) *Experimental and Numerical Studies of Bolted Lap Joints at Elevated Temperature*. The International Colloqium on Stability and Ductility of Steel Structures, ce/papers 5, No. 4, pp. 204-209, https://doi.org/10.1002/cepa.1746

[12] Barata, P.; Riberio, J.; Rigueiro, C.; Santiago, A.; Rodrugues J, P. (2014) *Assessment of the T-stub joint component at ambient and elevated temperatures*, Fire Safety Journal 70, pp. 1-13, http://dx.doi.org/10.1016/j.firesaf.2014.08.0090379-7112.

[13] IDEA Connection, Version 22.1. Theoretical background (2022), IDEA StatiCa ®. Available at: https://www.ideastatica.com/support-center/general-theoretical-background.

[14] EN1993-1-5 (2006), *Eurocode 3: Design of steel structures - Part 1-5: General rules - Plated structural elements*, CEN, Brussels.