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Modelling of bolted joints in fire using the component-based finite element method

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Abstract

This paper presents a study using the component-based finite element method to analyze the behavior 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 analyzed by geometrically and materially nonlinear analysis with imperfections (GMNIA). Consequently, the method used in this work can give reasonable results to predict the behavior of joints at elevated temperature. It is predicting the resistance and the stiffness for design of steel structure at elevated temperature by 3D model with members represented by 1D or 2D elements.

Keywords

CBFEM, bolted joints, fire, shell element, validation, verification.

1 Introduction

The behaviour of the connections is required to be accurately analysed to predict the fire characteristics of a structure. The structural steel connections at elevated temperature can be designed by experimental, curve fitting, analytical and numerical models. Experimental fire tests are quite expensive to represent the behaviour of each type of joints and there are size limitations of existing furnaces to test the connections.

The analytical modelling of components of connections are well developed for all connectors, bolts, welds, anchor bolts etc. EN 1993-1-8:2006 [1] standardised the equations to predict the resistance and stiffness of components at ambient temperature. For fire design of steel connections, EN 1993-1-2:2005 [2] proposes reduction factors for carbon steel, bolts and welds.

Finite element model is a general method commonly used for connection analysis. The solid finite element models can simulate the behaviour of steel connections at high temperatures. However, the cost of simulation time and storage size make solid models improper to design steel connections in fire. Shell elements are good alternatives for modelling of steel connections.

The Component based Finite Element Method (CBFEM) is a n method to analyse and design connections of steel structures in fire. CBFEM model combines advantages of general finite elements method and standard method of components [3]. It is able to model most of joint types and provide structural engineers clear information about stress and strain of individual components at ambient temperature. It is simple and fast to predict safe results in time comparable to current solid finite element models. Wald et. al [4] presented benchmark cases for its validation and verification for various structural steel joints and connections at ambient temperature. Each benchmark case shows results from the analytical model according to design standards followed by references to laboratory experiments, validated models, and numerical experiments. However, the CBFEM is needed to be verified and validated in order to be sure if it is possible to use it to design steel connections at elevated temperature in fire.

The verification and validation procedure are an integral part of any finite element analyses. The procedure is checking the software and the use by designer. The verification and validation procedure were based on the principles proposed by Wald et al. [5]. 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 paper presents the results of the verification and validation of CBFEM for modelling of bolted steel joints at elevated temperatures. It compares the results of hand calculations according to EN1993-1-2:2005 with the results of CBFEM [6]. Then, experimental studies were used to validate bolted lap joints and T-stubs models created in shell model.

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2 CBFEM

2.1 General Description

CBFEM model decomposes the whole joint into separated components - steel plates, welds, bolts, anchors and concrete block. Each component has its own analysis model [6]:

- 2D shell elements for steel plates
- Nonlinear springs for bolts and anchors
- contact elements between plates in connections.

The model [6] performs two types of analysis: geometrically linear analysis with material and contact nonlinearities for stress and strain analysis and eigenvalue analysis to determine the possibility of buckling.

2.2 Material Model and Element Types

The plates in are modelled with elastic-plastic material with a nominal yielding plateau slope as $\tan^{-1}$ (E/1000) according to EN1993-1-5:2005 [7]. The material behaviour is based on the von Mises yield criterion. At elevated temperature, material degradation of steel plates, bolts and welds are available according to EN 1993-1-2:2005 [2].

The CBFEM model uses 4-node quadrangle shell elements to model the plates of steel connections. Every node considers 6 degrees of freedom that are 3 translations and rotations. The standard penalty method is used for modelling contact between plates. The penalty stiffness is controlled by a heuristic algorithm during the nonlinear iteration to get a better convergence.

2.3 Failure Types

In this study, bolted lap joints and T-stubs are modelled using CBFEM. The main failure modes of bolted lap joints are bolts in shear and bearing failure according to the standard EN 1993-1-8:2006 [1]. Three modes of collapse are considered: 1. mode with full yielding of the flange, 2. mode with two yield lines by web and fracture of the bolts, and 3. mode for fracture of the bolts.

The CBFEM model conducts checks for the following components:

- the plastic strain in plates,
- the bolts resistance in shear, tension, and a combination of tension and shear,
- the welds resistance.

The model proportionally increases all load components until one of the included failures is not reached. Strain is recommended to be limited to 5 % in EN 1993-1-5. The analysis stops when the plates reach to 5% plastic limit strain. Furthermore, the bolts and welds are checked individually according to EN1993-1-8:2006 and EN1993-1-3:2005 formulas. For bolt´s resistance is expected maximum allowed plastic strain $\varepsilon_{\mathrm{lim}}$ as 25 % of elongation to fracture of bolt according to EN ISO 898-1 [8].

3 Verification and Validation

The main components of bolted joints are bolts in tension bolts in shear and plate bearing. Therefore, bolted lap joints and T-stubs in tension were chosen for verification and validation. The experimental results were taken from following studies; bolted lap joint [9] and T-stubs [10] for validation of CBFEM. Individual components are checked according to EN 1993-1-8:2006 [1] and CBFEM results were compared for verification.

3.1 Bolted Lap Joints in Fire

In the study [9], the numerical and experimental study were carried out on bolted lap joints at elevated temperature. The cover and connected plated were fabricated from a single steel plate, grade S355. The specimens were tested at 3 different nominal temperature θ levels, namely, at ambient temperature 20 °C and elevated ones 400 °C and 600 °C. The details of test specimen and the model are shown in Figure 1. The thickness of inner and cover plates are 8 mm and 16 mm, respectively.

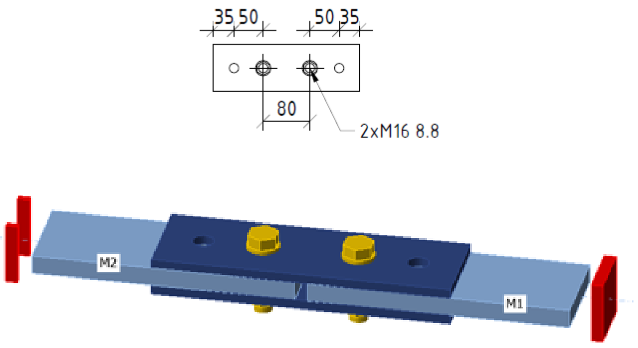

Figure 1. Details and modelling of the bolted lap joint

The analytical resistance of tested bolted lap joints were predicted previously in accordance with EN1993-1-8:2006, considering the reduction factors for carbon steel and bolts at elevated temperatures presented in EN1993-1-2:2005. To show the prediction of the CBFEM model, results of the studies are plotted in Figure 2 comparing resistances by CBFEM and analytical model. The results show that the difference of the two calculation methods is up to 10 %.

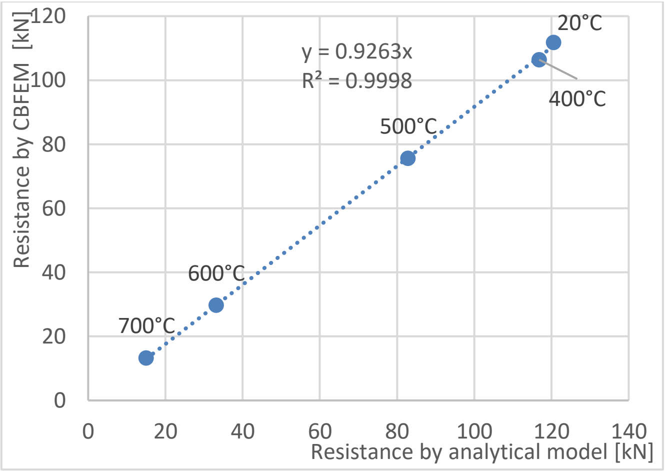

Figure 2. Verification of CBFEM model on analytical one – bolted lap joint

Figure 2. shows a comparison of the resistance values predicted by the CBFEM and experiments at 20°C, 400°C and 600°C. The CBFEM model is in very close agreement with the experimental results.

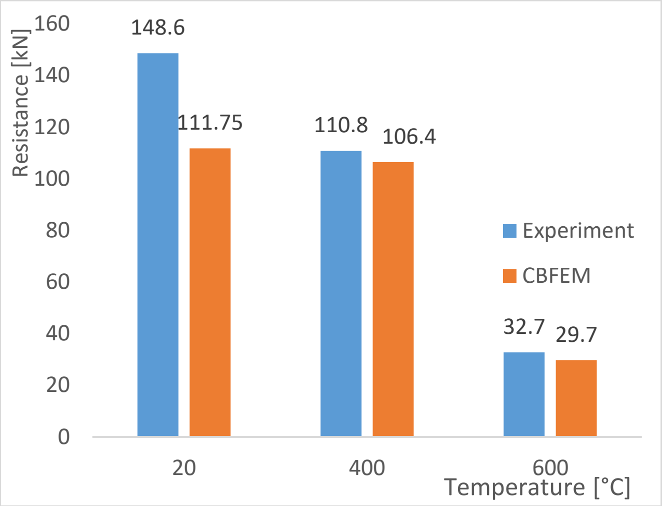

Figure 3. Validation of CBFEM model – bolted lap joint

The failure mode observed in experiments was bolts in shear at each temperature level. The CBFEM model obtained the same failure mode as shown in Figure 4. The bolts reached to shear ultimate capacity before the 5 % plastic strain occurs in the plates.

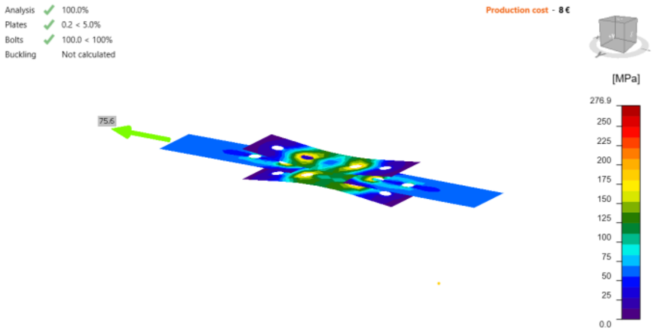

Figure 4. The plastic strain in bolted lap joint before the bolt failure in shear by CBFEM model at elevated temperature

3.2 T-stubs in fire

Barata et. al [10] study experimentally the behaviour of the welded T-stub specimen exposed to static loading, at ambient and elevated temperatures The study includs T-stub specimens with three different thicknesses of flange (t_f = 10 mm, 15 mm and 20 mm) at 20°C, 500°C and 600°C. M20 bolts, grade 8.8 was used to fasten T-stub specimens with the flanges (t_f = 10 mm and 15 mm), while the 20 mm flange is connected using M24, grade 10.9 bolts.

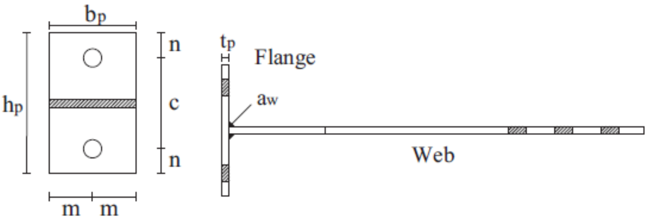

Figure 5. Details of the T-stub specimens

The details of test specimens and important dimensions are shown in Figure 5. The nominal values of major characteristics of specimens are summarised in Table 1.

Table 1 T-stubs geometrical characteristics

Specimen	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

Fire design resistances evaluated by CBFEM were compared with results of analytical models including three different failure modes proposed by EN 1993-1-8:2006 [1]. It can be seen that very good agreement observed between the CBFEM and analytical results in Figure 6. The difference is for all thickness and temperature less than 11 %.

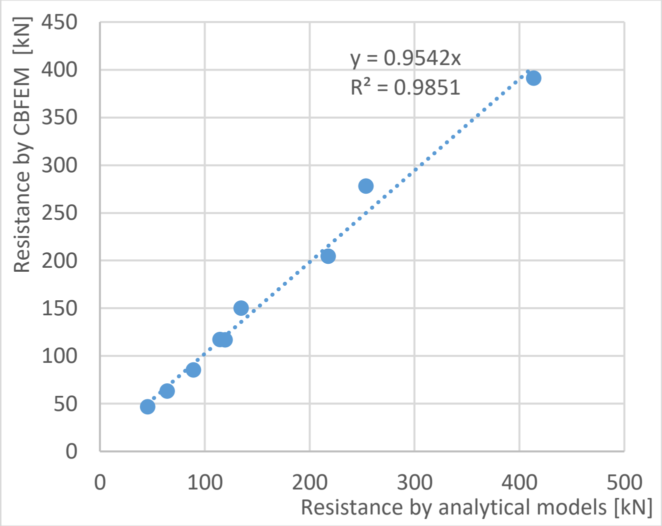

Figure 6. Verification of CBFEM model on component method - T-stubs at ambient and elevated temperatures

The comparison of the fire resistance of T-stubs with different flange thickness are shown graphically to see the difference between CBFEM results and test data in Figure 7. CBFEM results is sufficiently conservative in terms of measured fire resistance.

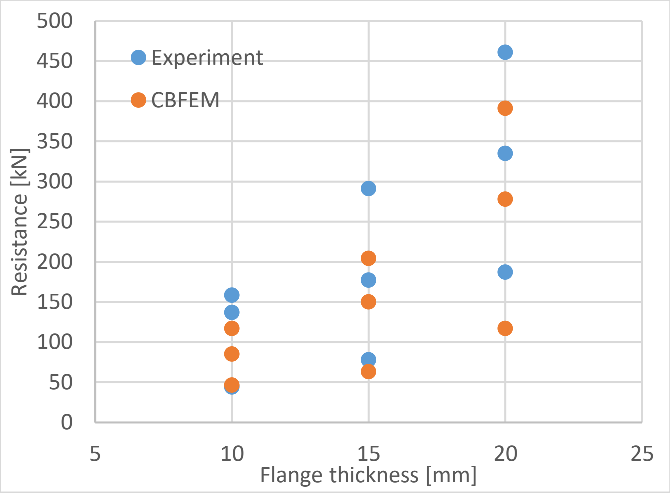

Figure 7. Validation of CBFEM model on experiments - T-stubs at ambient and elevated temperatures

Barata et al. [10] stated that the specimen with 15 mm of flange thickness failed due to the bolt fracture at 600°C. The CBFEM check was also ended up due to the bolt fracture when the plastic limit strain reaches to only 0.7 % as shown in Figure 8.

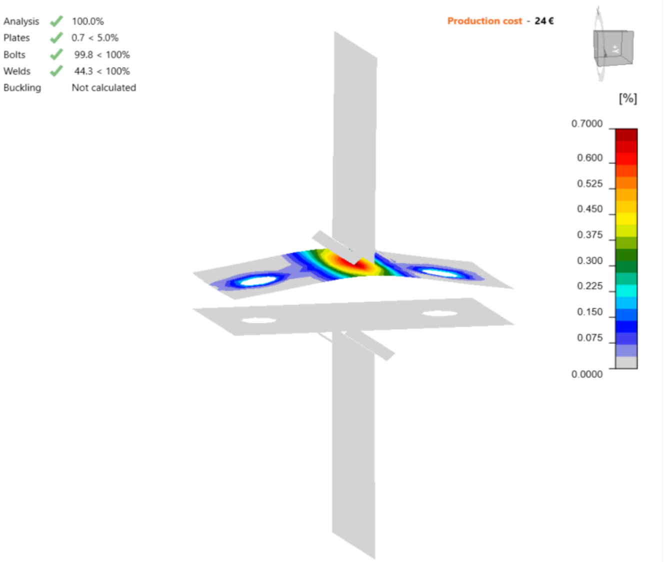

Figure 8. The plastic strain in T-stub (15 mm) at 600°C before the bolt failure by CBFEM model

The 10 mm thickness of specimens at 500°C and 600°C, the development of the plastic hinges was firstly observed during the tests [10]. As indicated in Figure 9, the flange reached to 5% plastic limit strain while the bolts still have 20% more capacity to resist the load. Furthermore, similar failure modes were observed for the specimens with 20 mm thickness and CBFEM captured the failure modes correctly.

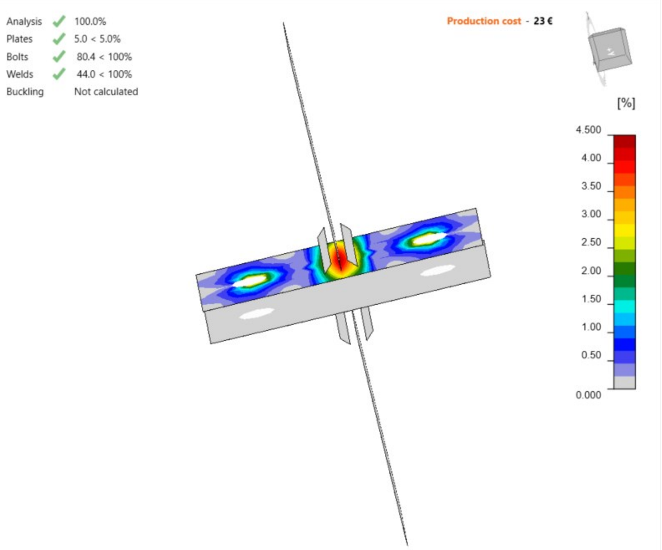

Figure 9. The limiting plastic strain in T-stub (10 mm) at 500°C by CBFEM model

4 Conclusion

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. The comparison of the resistances obtained by Eurocode and CBFEM indicated that the CBFEM provides safe resistance values at elevated temperatures design engineers. Since the R-squared values are higher than 0.98 for both cases, the CBFEM can be considered reliable method instead of analytical models for structural fire designers. Finally, the CBFEM models are validated by the experimental results. The experimental results are in very close agreement with the CBFEM results and the predicted failure mode closely resembled that observed in the experiments. It can be concluded that the CBFEM is well conditioned to calculate the fire resistance of bolted joints.

Acknowledgement

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