Perspectives in Science (2016) 7, 247—252

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/pisc

# Thermal transient analysis of steel hollow sections exposed to fire☆

**Lenka Lausova***, **Iveta Skotnicova**, **Vladimira Michalcova**

*Faculty of Civil Engineering, VSB-Technical University of Ostrava, Ludvika Podeste 1875/17, Ostrava-Poruba 708 33, Czech Republic*

Received 23 October 2015; accepted 19 November 2015
Available online 12 December 2015

**KEYWORDS**
Fire loading;
Steel hollow section;
Non-uniform temperature distribution;
Statically indeterminate frame;
Experiment;
Numerical modelling

**Summary** The paper describes a study of non-uniform temperature distribution across the section of steel structures where elevated temperature causes additive internal forces due to restrained conditions. The work provides comparison of a heat field at the time of fire in the non-protected steel hollow cross-sections of different sizes. The study compares simplified calculations according to valid standard and numerical simulations in finite element analysis of steel structures exposed to fire loading from three sides. Numerical thermal analysis is also compared with results obtained from the fire testing in VSB-Technical University of Ostrava.


## Introduction

The valid standards for fire design situation allow simplified methods of calculation based on empirical formulae for thermal analysis of structures (Wald et al., 2005). These assumptions may result in conservative solutions, which can be suitable for structural element calculations, but they cannot be used e.g. for structures where elevated temperature causes additive internal forces due to restrained conditions.

The whole structural function as a system depends on a stress—strain state of particular elements. Methods based on elementary principles of mechanics while respecting the influence of growing temperature must be applied in structures design. Various analysis stages must be considered for calculation and the task has to be solved as a combined one both in thermal and structural analysis. The temperature distribution in a section is obtained in thermal analysis and the stress—strain state of a structure at the time of growing temperature is solved in static analysis. Furthermore, variable values of material properties, which depend on temperature, must be taken into account.

The paper evaluates hollow steel non-protected profiles exposed to elevated temperature with special attention to non-uniformly distributed temperature over the section. Moreover, results from experimental testing of a steel statically indeterminate frame in the technical chamber carried out in VSB-TU of Ostrava are presented and compared

☆ This article is part of a special issue entitled ''Proceedings of the 1st Czech-China Scientific Conference 2015''.

* Corresponding author.
*E-mail addresses:* lenka.lausova@vsb.cz (L. Lausova), iveta.skotnicova@vsb.cz (I. Skotnicova), vladimira.michalcova@vsb.cz (V. Michalcova).

http://dx.doi.org/10.1016/j.pisc.2015.11.040

with the results from numerical modelling in the ANSYS software.

## Standard solution

Temperature distribution can be calculated in the section for a given temperature load on the basis of Fourier equation (Wald et al., 2005) if there are known thermal characteristics of the materials from which the structure element is composed. The simplest way to determine the temperature of steel sections is the simplified method according to the valid standard EN 1993-1-2 by heat transfer from the gas temperature. Thus, the temperature can be determined in the open and hollow cross-sections, with or without fire protection, and also temperature rise at the beam heated on three sides.

Furthermore, it is possible to determine the temperature in the section numerically with the incremental method (Wald et al., 2005), which assesses the temperature change in the section for a given time period. Increment section temperature is calculated from the temperature of the gas through the heat flow and it is dependent on the so called section factor, specific heat and density of the material. Slowing rise of temperature at protected sections is influenced by thermal characteristics of the protective material and its thickness. The section factor may generally be determined by dividing of the circumference part exposed to fire and the cross-sectional area. The section factor at hollow sections where $t$ (thickness of the section) is much smaller than $b$ (width of the section) is determined by relation $1/t$ (Wald et al., 2005). Calculation of the section factor for all above mentioned cases of cross-sections can be found in valid standard with the exception of the hollow steel cross-section heated from three sides, which is the aim of this article.

Due to the high value of thermal conductivity of material the temperature distribution in steel cross-sections is more uniform than e.g. in concrete elements (Cajka and Mateckova, 2010, 2013; Handbook 5, 2005; Wald et al., 2005). To simplify the problem a uniform temperature distribution in the whole cross-section is assumed. At the section exposed to fire on three sides the temperature of the bottom flange and the web is almost identical. However, the temperature of the upper flange is lower. This is due to heat losses at the top surface of the upper flange to the relatively cold concrete slabs. Steel hollow sections show bigger differences in temperature distribution compared to open sections. As was mentioned above, according to standard the uniform temperature distribution can be considered in all steel sections. This uniform temperature in the whole section is derived from the temperature of the bottom flange exposed to fire. Under certain conditions it is useful to apply numerical methods for temperature field calculation (Delgado et al., 2015; Gardner and Ng, 2006; Lausova et al., 2014, 2015; Yin and Wang, 2003).

## Calculations of statically indeterminate structures exposed to elevated temperature

This paper is focused on the calculation of non-uniform temperature distribution across the section which causes additional bending moments in structures where the thermal expansion is prevented by restrained conditions. The assumption of necessity to monitor temperature and stress—strain state at the beginning of the fire at statically indeterminate structures is confirmed in (Lausova et al., 2014, 2015). The influence of non-uniform heating of the section at simultaneous relatively low total temperature at the beginning of fire may decide further progression of stress. During the following minutes this influence does not show itself as much as at the start from two reasons:

- participation of the total temperature increase becomes more significant than non-uniform temperature distribution
- at temperatures above 200 °C the Young's modulus decreases and thus internal forces drop down.

On the other hand, in steel structures at elevated temperatures above 400 °C the yield stress decreases (carrying capacity of the section). All these assumptions must be taken into account when calculating statically indeterminate structures under fire loading.

## Experimental results

In this paper the measured surface temperature from experimental testing are used as boundary conditions in numerical simulation. The fire test was realized in VSB-TU Ostrava in 2012 in the technical chamber of the Faculty of Safety Engineering (Lausova et al., 2014, 2015). The simple steel frame with fixed ends was tested. Both columns and beam of the frame were of the same hollow squared cross-section 50/4, the beam was exposed to fire load from three sides, the columns from all sides. Temperatures were measured on the frame and also in the component parts of ceiling, as seen in Fig. 1. The temperatures obtained from the testing are shown on the graph in Fig. 2.

Measuring points T1—T4 were placed on the frame parts exposed to fire load, the measuring point T2-top edge was placed on the upper edge of the beam under the ceiling structure cooling the steel (Fig. 1). On Fig. 2 there can be clearly seen that measured values of the temperature on the upper side of the beam are lower than temperatures on other sides of the beam cross-section as well as other parts of the structure.

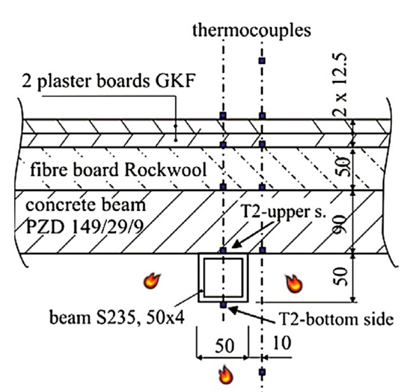


**Figure 1** Ceiling structure with the position of T2.

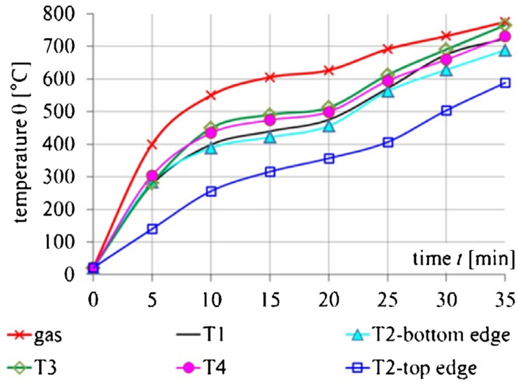


**Figure 2** Measured temperature at T1—T4.

The scope of this work does not include description of the experiment, as it was evaluated in (Lausova et al., 2014, 2015).

## Numerical solution

The aim of this article is a numerical analysis of the temperature distribution across the hollow sections exposed to elevated temperature on three sides. Thermal task is solved using FEM as a transient nonlinear thermal analysis in the ANSYS software and the temperature distribution is obtained in the cross-sections at the time of experimental testing. In this study four different types of the hollow squared cross-sections (50/4, 70/4, 100/4, 200/10) are evaluated numerically and also three squared hollow sections of the same size with different thicknesses (50/2, 50/3, 50/4) are evaluated and compared to the experimental results. The thermal loading is set in steps at simultaneous change of all necessary thermal characteristics of material (heat conductivity, specific heat) related to temperature in the structure.

### Boundary conditions

Dirichlet boundary conditions are in use, meaning that surface temperatures of the structure are set directly on the nodes according to the measured values from experiment. The initial temperature of the frame is 21 °C.

### Numerical model

The model is created using finite elements of PLANE55 type, element has four nodes with a single degree of freedom, temperature, at each node. The element is applicable to a two-dimensional, steady-state or transient thermal analysis. The investigated cross-sections are discretized and modelled as rectangular elements. The grids of finite elements are used to calculate the temperature distribution across each cross section considered. The mesh size is chosen to be 0.002 m.

## Results of the numerical study

### Profiles 50/4, 70/4, 100/4, 200/10

In Table 1 there are shown temperatures of the upper flanges at investigated squared hollow cross-sections exposed to elevated temperature from three sides obtained from numerical simulation and also calculated temperature differences of the upper and bottom side of the sections. These temperatures are evaluated for the first 15 min of the experiment. Thermal fields in the 4th minute in profiles 50/4, 70/4, 100/4, 200/10 are shown in the Fig. 3a—d. These thermal distributions relate to the values in Table 1. High temperature of the exposed side of the sections (taken from the experimental measurement, boundary condition) can be seen as well as investigated temperature on the upper side of the cross-sections. The temperature on sides exposed to fire is 284 °C, values of the temperature in the upper flange vary from 209 °C (profile 50/4) to 51 °C (profile 200/10). The

**Table 1** Temperature of the upper flange and temperature difference of the upper and bottom sides of the sections obtained by numerical simulation.

| Time [min] | Temperature [°C] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Fire exposure edges | Profile 50/4 | | Profile 70/4 | | Profile 100/4 | | Profile 200/10 | |
| | | Upper edge | Differences | Upper edge | Differences | Upper edge | Differences | Upper edge | Differences |
| 0 | 21 | 21 | 0 | 21 | 0 | 21 | 0 | 21 | 0 |
| 1 | 96 | 54 | 41 | 42 | 64 | 29 | 67 | 22 | 74 |
| 2 | 169 | 106 | 63 | 84 | 86 | 52 | 117 | 26 | 143 |
| 3 | 242 | 163 | 80 | 135 | 108 | 85 | 158 | 36 | 206 |
| 4 | 284 | 209 | 75 | 183 | 101 | 121 | 163 | 51 | 232 |
| 5 | 294 | 231 | 63 | 213 | 80 | 151 | 143 | 69 | 225 |
| 7 | 326 | 261 | 65 | 252 | 74 | 192 | 134 | 103 | 223 |
| 9 | 377 | 300 | 77 | 291 | 86 | 229 | 148 | 134 | 243 |
| 11 | 398 | 329 | 69 | 325 | 73 | 263 | 135 | 164 | 234 |
| 13 | 410 | 345 | 65 | 345 | 65 | 288 | 122 | 192 | 218 |
| 15 | 419 | 358 | 61 | 359 | 60 | 306 | 113 | 215 | 205 |

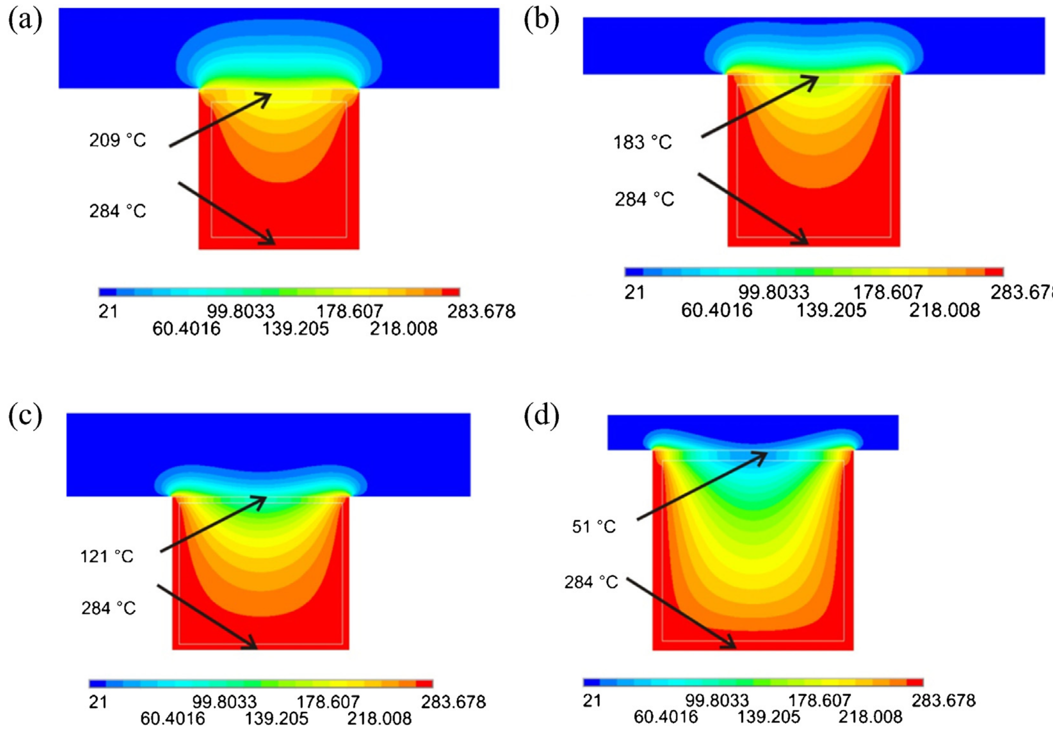


**Figure 3** Thermal field in the 4th minute: (a) profile 50/4, (b) 70/4, (c) 100/4, (d) 200/10.

differences between the upper and bottom part of the sections vary from 75 °C to 232 °C in the 4th minute of the time of the experiment (Table 1).

Fig. 4a graph shows growing temperature of the upper flange of the chosen sections at the time of the experiment and the temperature rise of the part exposed to fire. Fig. 4b graph illustrates the differences of the temperature between upper and bottom flanges of the calculated profiles.

From both graphs there can be clearly seen that the differences between the upper and the bottom flange vary for different dimensions of the hollow profiles, bigger profiles have bigger temperature difference between upper and bottom side of the section.

## Profiles 50/2, 50/3, 50/4

This study also compares the thermal field of the squared hollow cross-sections of the size 50 mm with different thicknesses: 2, 3, 4 mm. These profiles are compared with the experimental results of the frame beam section 50/4.

In Table 2 there are shown temperatures of the upper flanges at investigated cross-sections exposed to elevated temperature from three sides obtained from numerical simulation depending on the thickness of the section and also calculated temperature differences of the upper and bottom side of these sections. The temperatures are also evaluated for the first 15 min of the experiment.

The study shows that in the same sections with different thicknesses the difference of the temperature in the upper and bottom flange greatly vary. The profile with the smallest value of the thickness (2 mm) has the biggest temperature difference compared to the thicknesses 3 and 4 mm.

Fig. 5 a, b shows graphs which illustrate the comparison of numerical analysis results with the measured temperature of the upper flange under concrete ceiling structure. Fig. 5a graph shows growing temperature of the upper edge of the investigated sections during the experiment, the

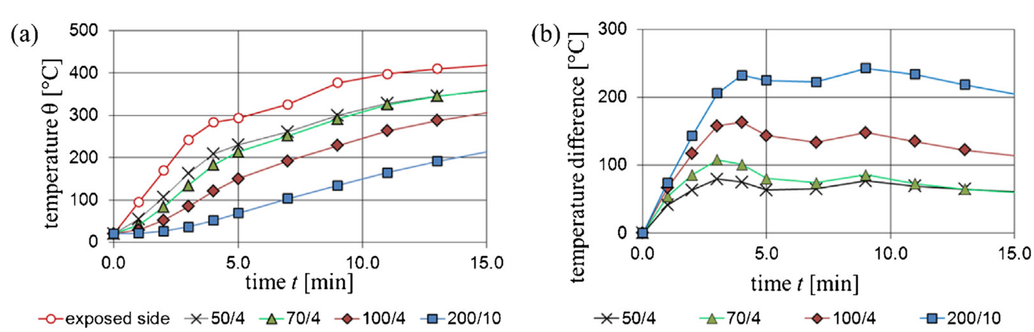


**Figure 4** (a) Temperature of the upper flange of the sections, (b) differences in temperature of the upper and bottom flanges of profiles.

**Table 2** Temperature of the upper flange of the hollow section depending on the thickness of the section obtained by numerical simulation.

| Time [min] | Temperature [°C] | | | | | | |
|---|---|---|---|---|---|---|---|
| | Fire exposure edges | Profile 50/2 | | Profile 50/3 | | Profile 50/4 | |
| | | Upper edge | Differences | Upper edge | Differences | Upper edge | Differences |
| 0 | 21 | 21 | 0 | 21 | 0 | 21 | 0 |
| 1 | 96 | 44 | 52 | 50 | 45 | 54 | 41 |
| 2 | 169 | 82 | 87 | 97 | 72 | 106 | 63 |
| 3 | 242 | 126 | 116 | 150 | 93 | 163 | 80 |
| 4 | 284 | 164 | 119 | 193 | 90 | 209 | 75 |
| 5 | 294 | 186 | 108 | 215 | 79 | 231 | 63 |
| 7 | 326 | 214 | 112 | 245 | 81 | 261 | 65 |
| 9 | 377 | 249 | 128 | 282 | 95 | 300 | 77 |
| 11 | 398 | 276 | 122 | 311 | 87 | 329 | 69 |
| 13 | 410 | 294 | 116 | 328 | 82 | 345 | 65 |
| 15 | 419 | 308 | 111 | 341 | 78 | 358 | 61 |

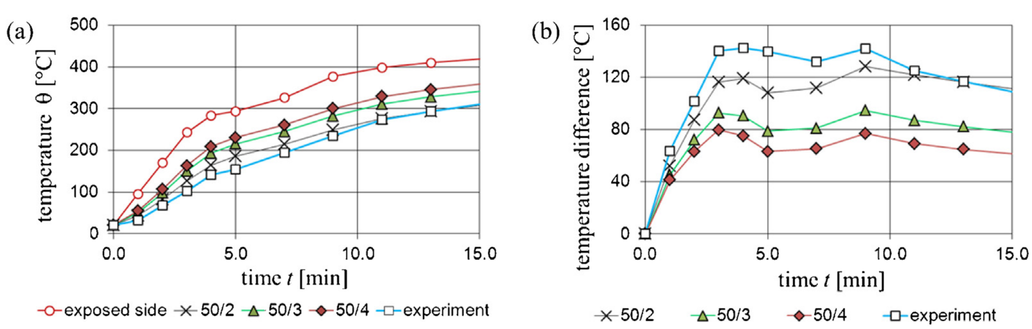


**Figure 5** (a) Temperature of the upper flange of the sections, (b) differences in temperature of the upper and bottom flanges of profiles obtained by numerical simulation.

temperature rise of the part exposed to fire and experimental measured temperature values of the upper flange. Fig. 5b graph illustrates differences of the temperature between upper and bottom flanges of calculated profiles and the experimental testing profile.

Measured temperatures of the upper flange (T2 — top edge in Fig. 3) are even of lower values than calculated (Fig. 5a). The differences between the measurement and results obtained from numerical model could have been caused by a large temperature increase at the start of the experiment.

## Conclusion

Based on the results of the study reported in this paper, the following conclusions can be drawn:

1. A numerical study of the heat field in the hollow cross-sections exposed to fire loading from three sides is presented, the finite element method in the commercial software ANSYS is used for calculations. The main focus is on determining the value of non-uniform temperature distribution in the section. Investigated hollow cross-sections loaded with elevated temperature show big differences between temperature of the upper protected flange and the fire exposed sides at the same boundary conditions depending on the size as well as on the thickness of the profile.
2. Some results of the numerical study are compared to the experimental results from the fire test realized in VSB-Technical university of Ostrava. Experimental measurement confirmed the assumptions of significant non-uniform temperature distribution in the steel hollow cross-section and it may be useful to make further experimental temperature measurements to verify other numerical results.
3. The exact knowledge of temperature distribution is important for advanced calculations especially in structures where the thermal expansion is prevented by restrained conditions and subsequently internal forces arise. The overall findings indicate that any general simplified procedure for calculations of temperature in the steel hollow sections exposed to fire from three sides is not applicable.

## Conflict of interest

The authors declare that there is no conflict of interest.

## Acknowledgements

The work was financially supported from the funds of the Ministry of Education, Youth and Sports of the Czech Republic allocated to the Conceptual development of science, research and innovation for 2015 at VSB-Technical University of Ostrava.

## References

Cajka, R., Mateckova, P., 2010. Different types of pre-stressed hollow core panels and their fire resistance according to Eurocodes. J. Struct. Fire Eng. 1 (4), Multi-Science Publishing, ISSN 2040-2317, http://dx.doi.org/10.1260/2040-2317.1.4.243.

Cajka, R., Mateckova, P., 2013. Fire resistance of ceiling slab concreted in trapezoidal sheet. In: Proceedings of Conference Concrete and Concrete Structures, Terchova, Slovak Republic. Elsevier, ISSN: 1877-7058. http://dx.doi:10.1016/j.proeng.2013.09.061.

Delgado, O.O., et al., 2015. Fire exposed steel columns with a thermal gradient over the cross-section. Thin-Walled Struct., http://dx.doi:10.1016/j.tws.2015.02.009.

Gardner, L., Ng, K.T., 2006. Temperature development in structural stainless steel sections exposed to fire. Fire Saf. J. 41 (3), 185—203, http://dxdoiorg/10.1016/jfiresaf.2005.11.009.

Handbook 5, Book by Leonardo da Vinci Pilot Project CZ/02/B/F/PP-134007 2005. Design of Buildings for the Fire Situation.

Lausova, L., Michalcova, V., Skotnicova, I., Konecny, P., 2015. Effect of non-uniform temperature distribution over the cross-section in steel frame structure. Appl. Mech. Mater. 769, http://dx.doi.org/10.4028/www.scientific.net/AMM.769.65.

Lausova, L., Skotnicova, I., Brozovsky, J., 2014. Numerical analysis of effects of fire to steel frame structures. In: The twelfth international conference on computational structures technology, Naples, Italy, pp. 1759—3433, http://dx.doi.org/10.4203/ccp.106.20, ISBN 978-1-905088-61-4.

Wald, F., et al., 2005. Calculation of Fire Resistance of Structures. CVUT, Prague.

Yin, Y.Z., Wang, Y.C., 2003. Numerical simulations of the effects of non-uniform temperature distributions on lateral torsional buckling resistance of steel I-beams. J. Constr. Steel Res., http://dx.doi.org/10.1016/S0143-974X(03)00003-8.