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EXPERIMENTAL AND NUMERICAL ANALYSIS OF STEEL FRAME STRUCTURE EXPOSED TO HIGH TEMPERATURE

Abstract

Structures exposed to fire loading, where supports prevent thermal expansions, must be calculated according to the basic principles of mechanics while respecting the effect of rising temperature on the structure and its effect on the value of variable material properties at the time of fire. The paper analyzed and compared results of the experiment aimed to verify the behavior of statically indeterminate steel frame exposed to high temperature and numerical modelling using finite element method in the ANSYS software.

Keywords

Steel frame structure, fire, thermal analysis, experiment, numerical modelling.

1 INTRODUCTION

The paper deals with the effect of non-uniform temperature over the cross-section in the steel frame structure under fire loading. The unequal temperature distribution causes additional bending moments in statically indeterminate structures. Numerical results of thermal and structural analysis from the commercial computer software ANSYS are compared with the experimental measurements on the steel frame exposed to high temperature.

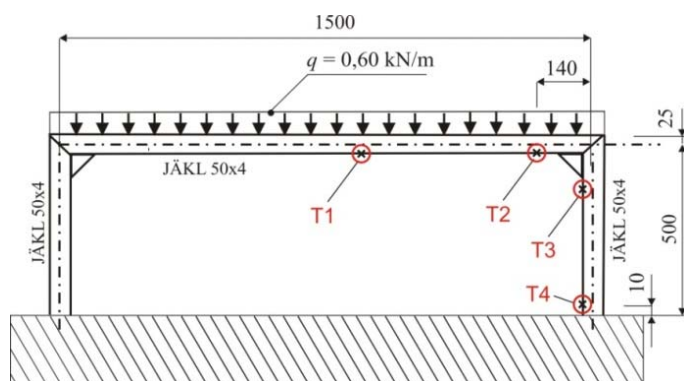


Fig. 1: Scheme of tested frame

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2 EXPERIMENT

Thermal and strain measurements of a statically indeterminate steel frame structure exposed to high temperature were carried out in the thermal technical chamber of VSB-TU Ostrava in 2012 [6]. Aims of the experiments were the following:

- evaluation of stress-strain state of a statically indeterminate not protected steel structure exposed to fire with non-uniform temperature distribution over the cross section,
- comparison of experimental results and results from numerical simulation by FEM.

There was tested a steel frame with fixed ends in the concrete basement of a section JACKEL 50/4 and material Fe360/S235, scheme is shown in Fig. 1. The frame was loaded together with temperature by a concrete beam from above (Fig. 2). This type of load was selected in order to cause non-uniform temperature over the beam height.



Fig. 2: Preparation of the model for experiment

2.1 Temperature measurement

The temperature was measured using K-type sheathed thermometers located on the frame structure, and also inside of the structure which formed ceiling of the thermal technical chamber. The ceiling structure was made from several material layers (Fig. 2 (right) and Fig. 3 (right)). Gas temperature and temperatures at selected places on the frame are shown on the graph in Fig. 3 (left). It is clear from the graph that the temperature in the upper side of the beam was lower than temperature in other measured places on the structure, which was intentionally caused by thermal loss on upper surface of the cross section into the relatively colder concrete beam. The difference between temperature of upper and lower flanges was in first five minutes of the experiment almost 140 °C, which heavily influenced the stress-strain state of the structure.

2.2 Strain measurement

Strain was monitoring at two places T2 and T4 acc. to Fig. 1:

- measuring place T2 – frame corner, measured at bottom edge of the rung,
- measuring place T4 – internal side of the column at the place of support.

There were used special temperature resistant strain gauges LZE-NC-W250G-120/2M, which are intended for measurement of strain up to 1200 °C. Results are shown in the graphs on Fig. 5.

3 NUMERICAL SOLUTION

The obtained values from the measurement were compared with the results of FEM numerical modelling in the ANSYS software. The frame model was created using 3D finite elements of SOLID45 type and shell finite elements SHELL63.

The task was solved as a combined one in thermal and static analysis in the ANSYS software. In the thermal analysis the temperature distribution was obtained in the section. In the static analysis

the corresponding stress-strain state of the structure caused by constrained thermal dilatation was solved in the steps of temperature change.

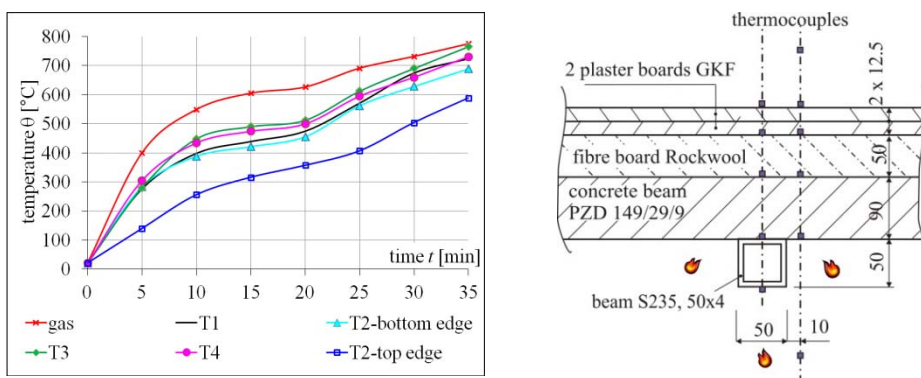


Fig. 3: Measured temperature at points T1-T4 (left), detail of the ceiling structure (right)

3.1 Thermal analysis

The thermal and mechanical characteristics of the material were set as a function of temperature [1, 3, 4]. The initial temperature of the frame was 21 °C. There were used Dirichlet boundary conditions, it means that surface temperatures of the structure were set directly on the nodes according to the measured values [5, 7, 8].

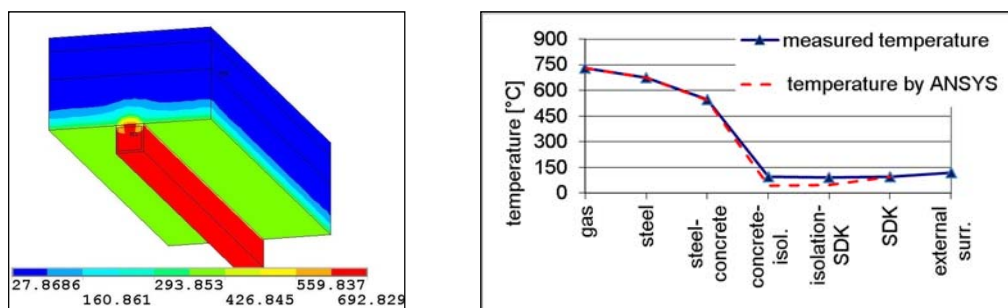


Fig. 4: Thermal field in 33th minute (left), temperature in the ceiling structure in 33th minute (right)

Fig. 4 (left) shows temperature distribution in 33th minute of the experiment, which is the result of the numerical simulation. Fig. 4 (right) shows temperature distribution in the ceiling structure in 33th minute obtained from experiment measuring and from numerical simulation in ANSYS. The difference between measured temperature and calculated temperature can be caused by the gap between the concrete beam and deformed steel beam of the frame in time of experiment.

3.2 Structural analysis

The thermal loading was set in steps on the deformed state of construction at simultaneous change of all necessary thermal and mechanical properties of the material related to total temperature in structure. Results of the static analysis were the values of strain, normal stresses, nodal displacements and rotations of numerical model from temperature and mechanical loads in time of the experiment.

3.3 Results

The assessment of the experiment consists of a comparison of measured relative strain with strain obtained from ANSYS. The comparison of measured strain with numerical model at points T2 and T4 is shown in graphs in Fig. 5.

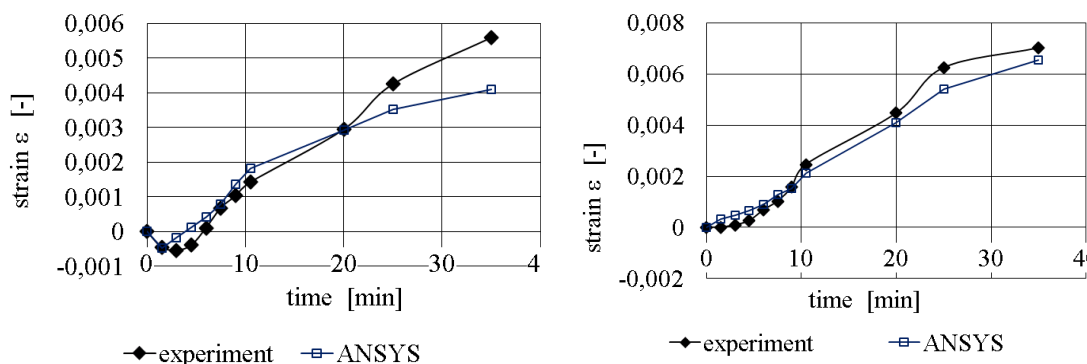


Fig. 5: Measured and calculated strain in T2 point (left), b) T4 point (right)

Development of strain (resp. normal stress) at T2 (Fig. 5 (left)) is probably caused by a very quick heating of the frame during first minutes of the experiment. It caused big difference of temperatures between upper and bottom side of the beam section at simultaneously low value of uniform temperature. The measurement and also the numerical model confirm this behaviour of the steel frame. The research in agreement with [2, 3, 4] revealed that the plastic joints may be formed in early stages of the fire (in this case at place T2 and at symmetric place).

At the second measuring point T4, strain grew gradually during the experiment (Fig. 5 (right)). To obtain slow growth of the deformations, there was used thermal analysis for determination of temperature distribution at the place of insulated concrete basement.

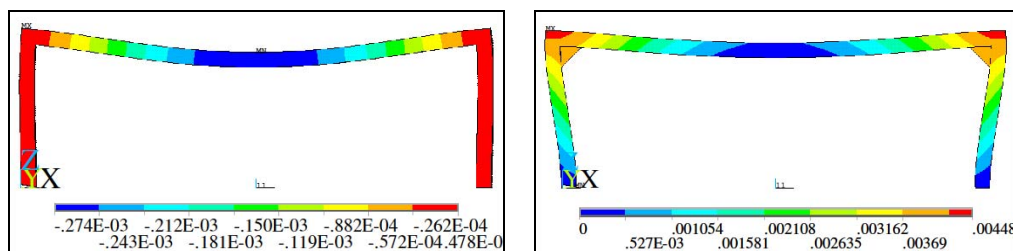


Fig. 6: Deformation of structure without temperature load (left), 7th minute of the experiment (right)

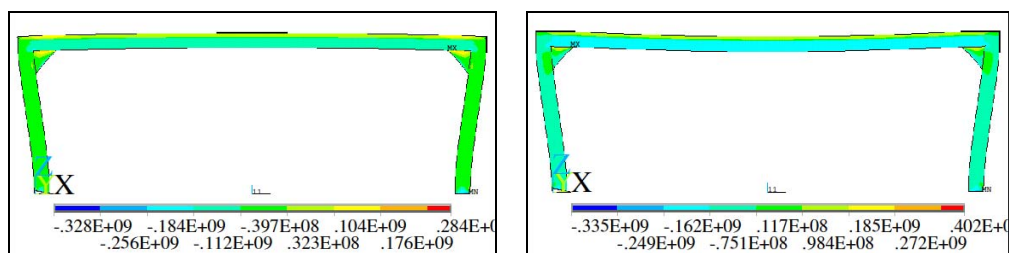


Fig. 7: Normal stress σ_x in 4th minute (left), 7th minute of the experiment (right)

The numerical modelling results showed a good conformity with the measured strain at measuring points. At the beginning of the experiment negative relative deformations were measured at T2, which at about 4th minute turned into positive ones. These results corresponded with the deformation state of the structure from numerical modelling. Difference in a deformed state and normal stress of the frame structure in time of experiment could be seen in Fig. 6 and Fig. 7.

4 CONCLUSION

The influence of non-uniform temperature distribution over the section with relatively low total temperature at the beginning of fire at statically indeterminate structures may decide on further progression of stress-strain state. In following minutes this influence does not show itself as much as in the beginning. The participation of non-uniform temperature distribution with the growing temperature loses its importance and also by influence of the rising temperature the Young's modulus of elasticity decreases and thus also the normal stress drops down. Results presented in this article confirmed the assumption of necessity to monitor temperature distribution and stress-strain state of the structure at the beginning of the fire.

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