The effect of fire to the steel frame structure

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***Abstract*—**The paper describes experimental, numerical and analytical analysis of the statically indeterminate steel frame structure loaded by static load in case of fire situation. There is solved the effect of non-uniformly distributed temperature over the section of statically indeterminate structure. In the work there are compared results from the experiment realised in the thermal technical chamber of VSB-TU Ostrava, numerical modelling using the finite element method in the ANSYS software and analytical approach, where the geometric and physical nonlinearity is respected.

***Keywords*—**Steel frame structure, fire, experiment, numerical modeling, physical nonlinearity, geometric nonlinearity.

I. Introduction

The research in the field of structures exposed to high temperatures has its place among up to date topics of engineering science and research. Especially structures under fire loading are of particular interest. Increased scientific focus results from stronger accent on the structural and public safety. Main reason for the research within this field is the effort to find a behaviour prognosis of a structure under fire loading according to the fire scenario in order to prevent accidents. At assessment of fire loaded structures the comparison of computational results with experimental testing is very important.

The fire resistance of not protected steel structures is quite low and directly dependent on dimensions of particular carrying sections. The rigidity and strength of steel materials decrease with high temperatures. At statically indeterminate structures exposed to high temperature there is a thermal dilatation constrained by reactions in supports and subsequently internal forces occur within the structure [1], [2]. It is a non-stationary spread of heat during fire. Some thermal and also mechanical properties of steel change in dependence on temperature (yield limit, Young's modulus of elasticity, thermal expansion) [3]. Mechanical properties have an influence on a change of internal forces in case of statically indeterminate structures.

It is emphasised in [1]-[3] that Eurocodes relating to the fire design situations are valid for all steel section types, however it holds for elements of structures only. The whole construction functions as a system depend on a stress-strain state of particular members. At design of parts or the whole structures the methods upon basic principles of mechanics must be applied while respecting the growing temperature influence [4]. At the same time it may be taken into account the physical nonlinearity caused by variable values of material properties in time of fire and the geometric nonlinearity due to bending and compression combination in the structure.

The main aim of this work can be defined this way:

- experimental and computational verification of behaviour of a selected type of a steel frame under fire load,
- statically indeterminate frame behaviour modelling with the effect of inserting of plastic hinges in the structure until complete loss of carrying capacity and the formation of mechanism on the structure [4].

II. Heat transfer into the structure

A. General

The calculation of the temperature development inside structural members exposed to fire involves solving general Fourier´s partial differential equation for a three-dimensional body [3]

$$\rho\, c(\theta)\frac{\partial\theta}{\partial t}=\frac{\partial}{\partial x}\left(\lambda(\theta)\frac{\partial\theta}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda(\theta)\frac{\partial\theta}{\partial y}\right)+\frac{\partial}{\partial z}\left(\lambda(\theta)\frac{\partial\theta}{\partial z}\right), \quad (1)$$

where

- θ is temperature dependent on time and coordinates in [°C],
- $\lambda(\theta)$ heat conductivity depending on temperature in $[\mathrm{W.m^{-1}K^{-1}}]$,
- ρ steel density (ρ = 7850 $[\mathrm{kg.m^{-3}}]$),
- $c(\theta)$ specific heat depending on temperature $[\mathrm{J.kg^{-1}K^{-1}}]$.

To resolve the general differential equation (1) physical properties of the body must be known (ρ, $c(\theta)$, $\lambda(\theta)$). The graph of dependence of heat conductivity on temperature is illustrated on Fig. 1 and specific heat on Fig. 2, these graphs are constructed after the relationships from [3].

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The equation (1) must be completed with the initial conditions including a shape and dimensions of the body, initial temperature heat distribution within the body and limit

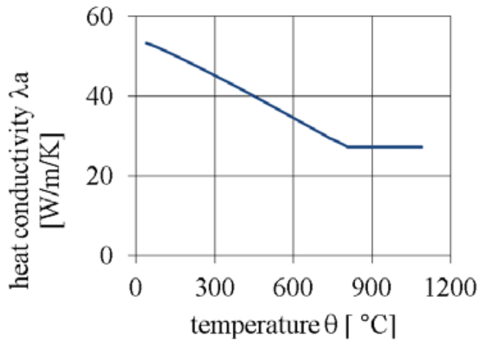

Fig. 1 dependence of heat conductivity of steel on

conditions characterising the body mutual reaction with its environment.

The left side of the equation expresses time change of the material elementary volume heat capacity, the right one total heat addition to the elementary volume due to thermal

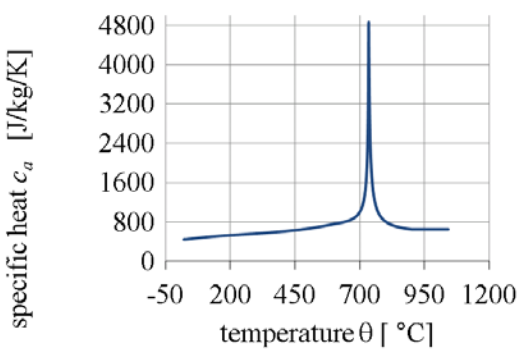

Fig. 2 dependence of specific heat of steel on temperature

conductivity. The equation can be solved analytically, by the differentiation method or using the finite element method as well.

Simple models for the calculations of the temperature field in the cross section of a structural member are based on the hypothesis of a uniform temperature distribution in the global cross section or in the parts of the cross section as presented in the Eurocodes relating to the fire situation [1].

Outside of these assumptions, advanced calculation models have to be used for the determination of the temperature distribution within structural members. In this case the thermal response model has to consider the realistic thermal action caused with high temperature and mechanical properties of steel in function of the temperature [5]-[8].

B. Boundary conditions of heat transfer equation

The correct setting of boundary condition by which the equation (1) is completed is essential for the numerical solution. Most frequently there are the following three types of boundary conditions:

- set temperature on body surface (Dirichlet condition),
- set heat flux on body surface (Neumann condition),
- heat transfer by convection (Newton condition) - set surrounding temperature and heat transfer coefficient.

III. SOLUTION OF STATICALLY INDETERMINATE STRUCTURES

Mechanical properties have an influence on a change of internal forces in case of statically indeterminate structures. Fig. 3 illustrates dependence of thermal expansion on the growing temperature and Fig. 4 shows reduction coefficients for the Yield limit (k_y) and for the Young´s modulus (k_E).

For the solution of statically indeterminate structures during fire the analytical approach according to the Eurocodes can be used or numerical modelling, for example by finite element method [9]. The verification of calculation results by experimental testing is essential for confirmation of theoretical assumptions and computing procedures [10]. There are processed experimental results focussed on a behaviour verification of the statically indeterminate steel frame exposed to high temperature in this paper. The results of the realised experiment are evaluated in time of fire and compared with the numerical model.

At the calculation of statically indeterminate structures it is necessary to monitor thermal load and at the same time its

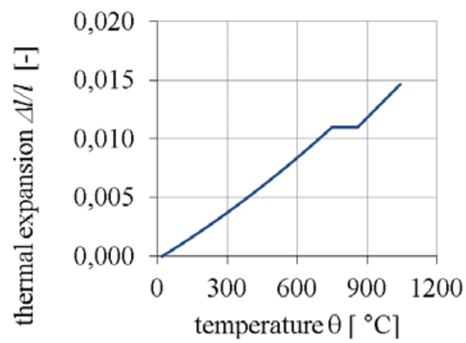

Fig. 3 dependence of thermal expansion on temperature

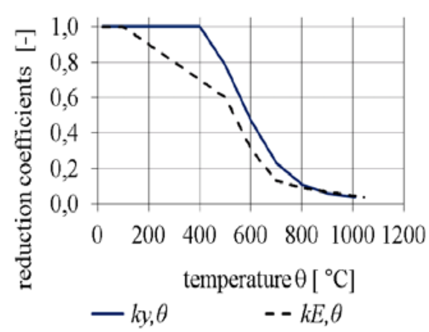

Fig. 4 reduction coefficients for Yield limit and Young´s modulus

influence on stress-strain state mainly at first minutes of fire [1]. With statically indeterminate structures the non-uniformly distributed temperature along the section height cause additional bending moments which influence the stress-strain state of the complete structure [5].

A. Experiment

The results from experimental testing, especially the fire testing, are irreplaceable [10]-[13]. In the thermal technical chamber of VŠB-TU Ostrava in the Faculty of Security Engineering thermal measurements and also measurements of strain of statically indeterminate frame structure exposed to high temperature were carried out. Steel frame scheme is shown on Fig. 5 and preparation of the experiment is on Fig. 6. Aims of the experiments were the following:

- evaluation of the stress-strain condition of statically indeterminate not protected steel structure under growing temperature,
- verification of calculation method of the statically indeterminate steel frame structure during fire.

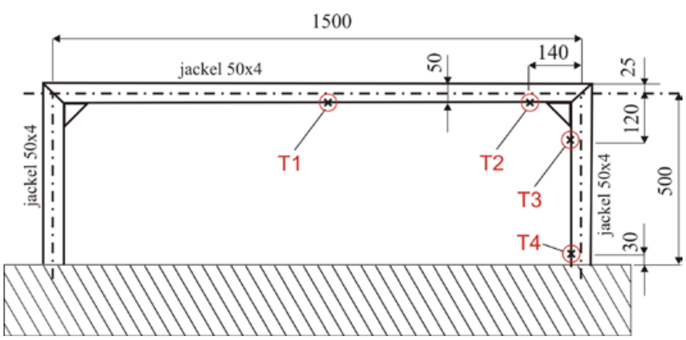

Fig. 5 steel frame scheme

B. Experimental measurement

Within the realised experiment the statically indeterminate


Fig. 6 preparation of steel frame for the experiment

steel frame with fixed ends in concrete basement was tested [6]. As a section of the frame the JACKEL 50/4, material Fe360/S235 was selected. The frame was loaded together with temperature also by a concrete beam from above (Fig. 2). This load type was selected from the reason to cause non-uniform temperature over the rung sectional height. The concrete beam (g = 0,6 kNm^{-1}) was placed in a way to avoid the beam and frame interaction. Strain was measured at two places T2 and T4 acc. to Fig. 5 and Fig. 7.

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

The strain was scanned by four special strain gauges LZE-NC-W250G-120/2M, which are intended for measurement of strain up to 1200 °C. These strain gauges were attached to the structure always in pairs in perpendicular direction to one measuring place using a special point device. Strain ε_x in longitudinal direction from force effects and from the thermal load are the measurement results.

All the obtained values of strain from the experiment are compared with numerical modelling using the finite element method in the ANSYS software environment [7]. The frame is

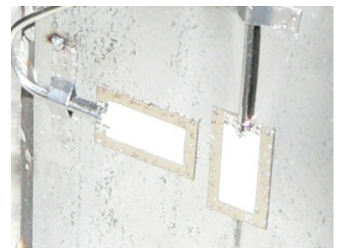
Fig. 7 strain gauges LZE-NC-W250G-120/2M

evaluated up to 700 °C upon physical and geometrical nonlinear solution.

During the experiment the temperatures were scanned using K-type sheathed thermometers with 1 mm diameter located on the structure and in chamber space as well. So there were measured the gas temperature in the chamber, the temperatures on the selected points of the frame including the temperature on the frame rung under the concrete beam. This temperature was measured for determination of the non-uniform temperature along the rung height.

C. Determination of temperature

Gas temperature and temperatures at selected places T1-T4 of the frame are shown on the graph in Fig. 8. It is obvious from the graph that during the experiment an approximate uniform temperature distribution was obtained over the structure.

It is clear from the graph that the temperature in upper side of the rung was lower than 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 measured temperature at bottom rung edge is lower compared to the temperature at columns which is caused by cooling of the whole rung by the ceiling and concrete beam. However this temperature difference is not as significant as the difference between temperatures in upper and bottom parts of the rung. It is stated in [8] that the difference between upper and lower flanges can make even 120 °C, in this case the difference was in first five minutes of the experiment almost 140 °C, which heavily influenced the stress-strain condition of the structure. According to [2] it is important to record the complete course of the experiment at the statically indeterminate structures because mainly in early phases of the fire plastic hinges may incur.

IV. Numerical solution

The obtained values from the measurement are compared with the results from numerical modeling. The heat conduction analysis is one of the most frequent task in the sphere of engineering computations using FEM [3]. By numerical

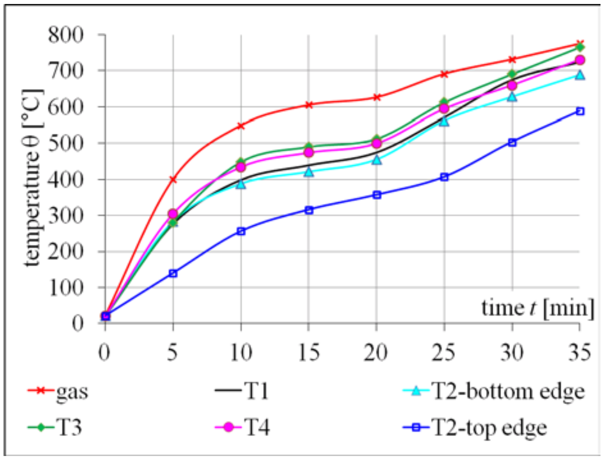

Fig. 8 Measured temperatures on the frame

modelling the temperature field distribution within the structure can be determined either as a result of unsettled time process or of a stationary time independent process (transient analysis). In case of continuity of the stress-strain and thermal task it is so called combined task when the temperature field must be first determined in the given area and afterwards the corresponding stress caused by constrained thermal dilatations.

A. numerical model

For numerical modelling of structure thermal behaviour at fire the numerical modelling using the finite element method within the ANSYS environment was applied in this work [14]. The frame model is created using the 3D finite elements of SOLID45 type and shell finite elements SHELL63. The elements of the type SOLID45 are eight-node isoparametric finite elements with three degrees of freedom (displacements) at each node. The four-node elements of SHELL63 type are intended for modelling of thin shells. At each node they have six degrees of freedom (three displacements and three rotations). At the thermal analysis responded elements are SOLID70 and SHELL57, with a single degree of freedom, temperature, at each node.. The detail of numerical model is shown in Fig. 9.

B. Material characteristics

The thermal and mechanical characteristics of the material were included in the computations as a temperature function [8] , graphs are seen on the Fig. 1-4.

C. Initial and boundary conditions of the solved task

The initial temperature of the frame was 21 °C. Surface temperatures of the structure are set directly on the nodes according to the measured values (Fig. 8) – Dirichlet boundary conditions. Other boundary conditions in static solution result from the supports of the frame.

The stress-strain state of the structure at fire situation can be influenced more by temperature than other external mechanical load and therefore it is very important to know exact thermal distribution in the section for the solution. On that ground also monitoring of the temperature field in the structure which formed ceiling of the thermal technical chamber was part of the test experiment.

The ceiling structure was made from several material layers,

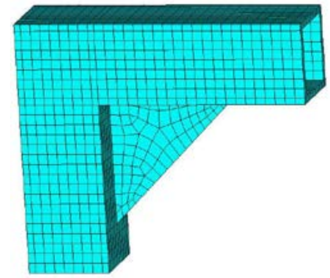

Fig. 9 numerical model of the frame

see Fig. 10, the numerical model can be seen on the Fig. 11. The upper part consisted of two pieces of fireproof plasterboards SDK GKF with thickness 2 x 12,5 mm, mineral fibre board (Rockwool thermal insulation) with thickness 50 mm, which was laid on PZD concrete beam with thickness 90 mm situated on the upper flange of the steel frame. The thermocouple sensors were placed in two sections of the ceiling structure – at place of the steel frame and beside the steel section (see Fig. 10).

Subsequently solved by ANSYS and measured temperature

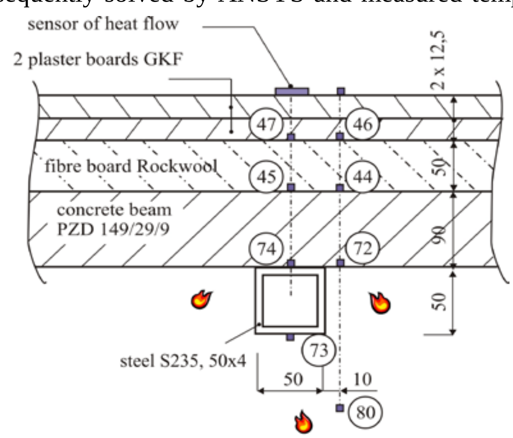

Fig. 10 ceiling structure section detail

values in both transversal sections of the construction were compared. The temperature field distribution at 3[rd] and 33[rd] minutes of the experiment is shown in Fig. 12.

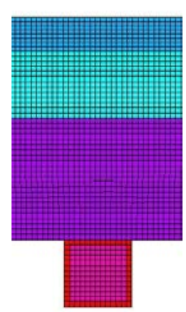

Fig. 11 numerical model of the ceiling structure

In Fig. 13 there is shown the temperature distribution in section at place of the frame obtained by measurement and numerical solution at 33rd minute. Conformity in measured and calculated temperatures is evident from the image. The higher measured temperatures are at connection point of concrete

Fig. 12 heat field at 3rd (left) and 33rd (right) minute

beam and thermal insulation which could be caused by untightness between layers which enabled access of hot gas into the structure. On the Fig. 14 there is shown a detail of a heat field at place T4, where the concrete basement was cooling down the frame at the fixed end.

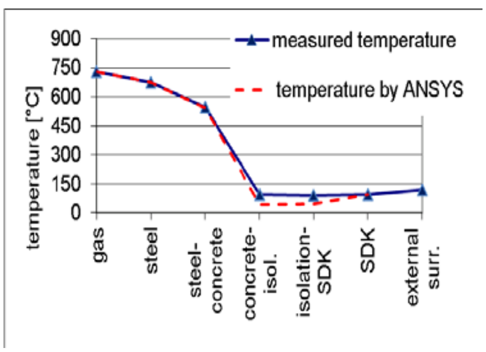

Fig. 13 measured and calculated temperatures in section 1 at 33rd minute of experiment duration

D. Solution – combined analysis

For the case that structure is loaded by non-uniform

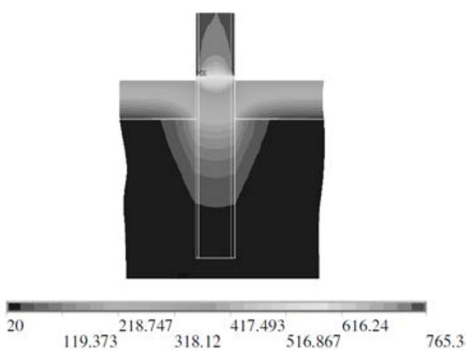

Fig. 14 detail of the heat field at place T4

temperature change the task was solved as a combined one in thermal and static analysis in the ANSYS software. In the thermal analysis the temperature distribution is obtained in the section and in static analysis the stress-strain state of the structure is solved in time of growing temperature.

In the first step of the solution the mechanical load by dead weight and by the concrete plate is set in the same way as it is in reality. Then the structure is loaded by temperature from the first time step in the thermal analysis. Once the temperature distribution in section is defined the structure is loaded by this thermal field and solved in static analysis. Other steps of thermal and static analysis follow. In the thermal analysis the construction is always loaded with total temperature in the given time, because it is necessary to calculate with material reductions for the given temperature. For obtaining of only the temperature increase to the static solution of the structure a reference temperature is set in the static analysis to obtain difference between the total temperature and temperature increase. This reference temperature is changed at each step. In this way the result of physically and geometrically nonlinear behaviour of structure is obtained. The thermal loads are set in steps on the deformed state of construction from the previous step at simultaneous change of all necessary thermal and mechanical properties of the material due to total temperature in section.

E. Results

The values of strain, normal stresses, nodal displacements and rotations of numerical model from temperature and mechanical loads in time of the experiment are result of the solution of this combined analysis by numerical modelling in ANSYS.

F. Evaluation of the results

The assessment of the experiment consists in comparison of measured relative strain with the relative deformations

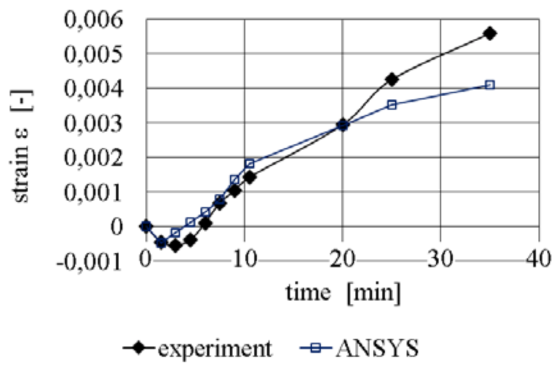

Fig. 15 measured strain and strain by ANSYS at T2 point

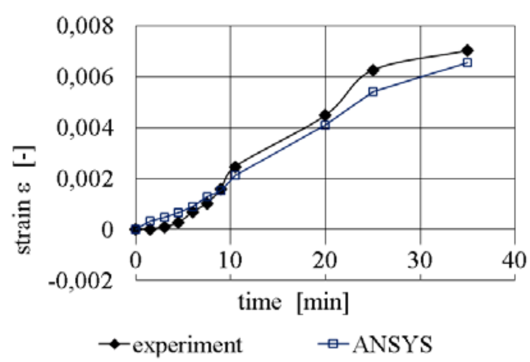

Fig. 16 measured strain and strain by ANSYS at T4 point

obtained from ANSYS. The comparison of measured relative deformation with numerical model at points T2 and T4 is shown on Fig. 15 and Fig. 16.

The numerical modelling results show a good conformity with the measured relative deformations at measuring point of the frame corner T2 see Fig. 15. At the beginning of the experiment negative relative deformations were measured at T2 and in 4th minute of the experiment turned into positive ones. At the second measuring point T4 the relative deformations grew gradually during the experiment (Fig. 16), to obtain slow growth of the deformations is used thermal analysis for determination of temperature distribution in the section at point of insulated concrete basement (Fig. 14).

The deformed condition of the construction and normal stress from the course of the experiment are shown in Fig. 17

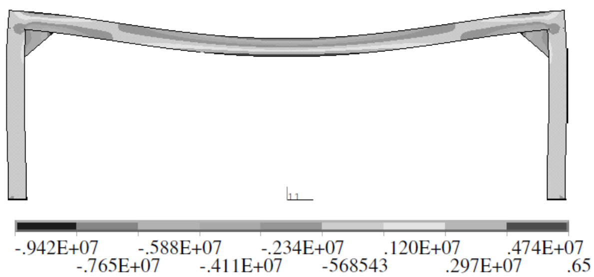

Fig. 17 normal stress σ_x from permanent load

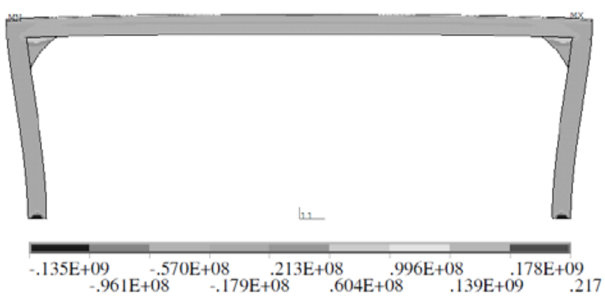

Fig. 18 normal stress σ_x at 1st minute of the experiment

to 20. Fig. 17 shows normal stress of the frame due to permanent load without temperature load. Fig. 18 shows deformed condition and normal stress of the structure at 1st minute of fire duration, Fig. 19 at 3rd minute and Fig.20 at 10th minute of the experiment.

Development of relative deformation courses (and also normal stress) at T2 (Fig. 19) is probably caused by a very quick heating of the frame during first five minutes of the experiment and also by big difference of temperatures between upper and bottom side of the rung section at simultaneously low value of uniform temperature. The measurement and also the numerical model confirm this behaviour of the steel frame, as well as according to [2] just in fire early stages the plastic joints may be formed (in this case at place T2 and at symmetric place of the frame).

V. Analytical Solution

For the analytical solution there are used the basic principles of mechanics with respecting physical and geometric nonlinerities. Physical nelinearity is caused by the variability of material properties in dependence on temperature and these are determinated after the Eurocodes. Geometric nonlinearity is caused by the effect of the combination bending and compression in the structure. Normal stress was computed with this assumptions:

- non-stationary distribution of temperature in the section of the frame, after the graf on the Fig. 8,
- there was used plastical section modulus,
- in the calculations there was used the theory of the second order for the combination of compression and bending.

After the Eurocodes and the combination rule for the

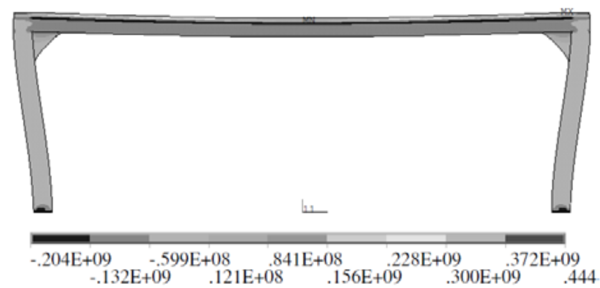

Fig. 19 normal stress σ_x at 3rd minute of the experiment

extraordinary combination the permanent load is taken into the calculations with the whole value g = 0,6 kNm^{-1}.

Statical scheme of the structure is ilustrated on the Fig. 21.

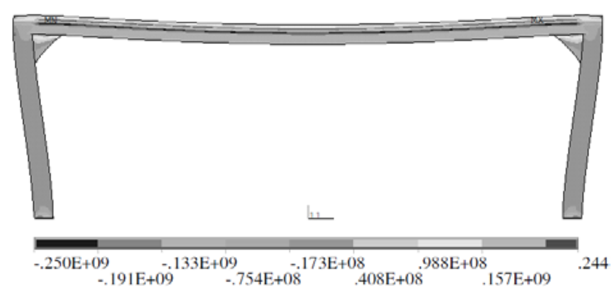

Fig. 20 normal stress σ_x at 10th minute of the experiment

On the structure there became aditional bending moments due to the non-stationary temperature on the frame rung. Theirs distribution can be different and depend on the value of the temperature of the top and the bottom edge and also on the participation of the uniform temperature at sections. At

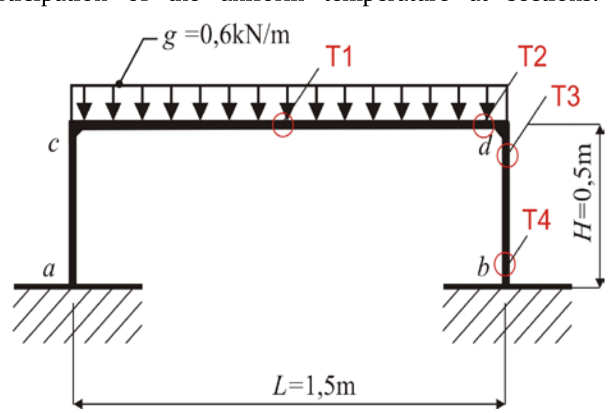

Fig. 21 statical scheme of the frame

statically indeterminated structures we cannot use the incremental method [3], because it is suitable only for uniformly distributed temperature. At analytical solution the tempearature was given in steps after the graf in Fig. 8. In

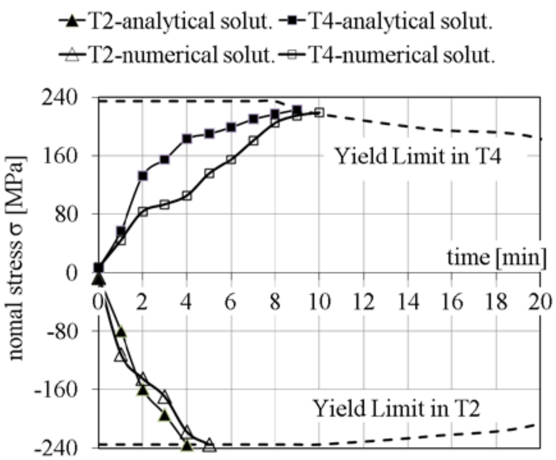

Fig. 22 strain at T2 point

these calculations there is supposed a linear distribution of the temperature over the hight of the section.

Normal stress obtained from the analytical solution is compared with the numerical solution on the Fig. 22. In the Table 1 there is shown a comparison of the analytical and numerical solutions results. In the analytical solution there was used the Method of subsequent development of plastic hinges [4] into the places of structures where there was reached the Yield limint in the whole section. There can be seen that from these calculations the plastic joints would become in the 4th minute of the experiment in the measuring place T2. Theoretically mechanism would become at the 10th minute of the experiment with the use of the plasticity of the material. The comparisson of the both approaches shows satisfying results. The difference in the point T4 can be caused by using results from the thermal analysis in the numerical solution, in which there was obtained heat field in that place influenced by cooling from the concrete basement.

VI. Conclusion

The assessment of the problem related to the behaviour of the indeterminate steel frame exposed to high temperature obtained from this paper can be formulated by the following points:

- mutual cooperation between the two approaches (experimental and mathematical) is necessary for the verification of calculation results,
- the results of the numerical simulations using the finite element method in the ANSYS software for the transient analysis proved a satisfying similarity with the experiment,
- at statically indeterminate structures it is necessary to monitor thermal load and at the same time its influence on stress-strain state mainly at first minutes of the fire,
- at statically indeterminate structures the non-uniformly distributed temperature along the section height causes additional bending moments which influence the stress-strain state of the complete structure,

Tab. I normal stress σ by analytical and numerical solution

time [min]	T4					T2				
	temp θ [°C]	$\Delta\theta$ [°C]	σ anal [MPa]	σ numer [MPa]	f_y [MPa]	temp θ [°C]	$\Delta\theta$ [°C]	σ anal [MPa]	σ numer [MPa]	f_y [MPa]
0	21	0	7	7	235	21	0	-7	-7	235
1	63	42	57	44	235	80	59	-80	-112	235
2	163	143	132	83	235	168	147	-159	-145	235
3	183	162	155	93	235	184	163	-194	-170	235
4	272	252	183	105	235	272	251	-235	-218	235
5	305	284	190	135	235	284	263		-235	235
6	330	309	199	155	235	304	283			235
7	359	338	210	181	235	329	308			235
8	367	346	217	205	235	351	330			235
9	422	401	223	215	224	372	351			235
10	434	413	231	219	217	388	367			235
15	474	453			197	422	401			224
20	499	478			184	456	435			206
25	594	574			115	562	541			138
30	659	639			77	628	607			95
35	730	709			46	688	667			60

- the influence of non-uniform heating of the section at simultaneous relatively low total temperature at the beginning of the experiment may decide on further course of strain (stress respectively),
- in following minutes this influence does not show itself as much as in the beginning because with growing temperature the share of non-uniform temperature distribution loses its importance and also by influence of the temperature the Young's modulus of elasticity decreases and thus also the normal stress drops down,
- in comparison numerical and analytical calculations there were reached satisfied results, so in this case the analytical solution would be a sufficient method to use.
- further evaluation of computations with even more detailed setting of particular time steps at first minutes of fire will have to be carried out under assumption of the elastic-plastic behaviour of the material.

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