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A Comparison of the Rise of the Temperature of an Unprotected Steel Column Subjected to the Standard Fire Curve ISO 834 and to a Natural Fire Model in the Office[1)]

Maciej SZUMIGAŁA, Łukasz POLUS

Poznań University of Technology
Faculty of Civil and Environmental Engineering
Institute of Structural Engineering
Piotrowo 5, 60-965 Poznań, Poland
e-mail: lukasz.polus@put.poznan.pl

This paper presents a comparison of the changes in the temperature of a steel HEB 300 section column in a standard fire curve and in a natural fire. The EN 1991-1-2 standard and the fire dynamics simulator (FDS) were used to calculate the temperature of the steel column in a fire situation. The temperature of the steel column based on Eurocodes using the ISO 834 curve was different from the temperature obtained from the fire dynamics simulator, modeling a natural fire.

Key words: fire safety, fire dynamics simulator, natural fire model, standard fire curve.

1. Introduction

Fire safety is very important. All the structural elements of a building should have a fire resistance degree ensuring a safe evacuation of people. Fire resistance requirements for buildings are regulated by the national law. Thermal action can be analysed using different methods [1] that include the temperature-time curve and the natural fire model [2]. The first method presents the evolution of the temperature of the gases surrounding the element as a function of time. This temperature determines the heat flux transmitted from the hot gases to the steel element [2]. The second method focuses on the heat flux affecting the element. The temperature of the steel element is determined using the combination of the heat flux affecting the element and the flux reemitted by the element [2].

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The ISO 834 curve is used to determine the fire resistance of construction elements. Natural fire models are rarely used in the design process, because they need special software and are more time-consuming. The existing regulations provide for the use of the standard ISO curve to verify the fire resistance of structural elements. The question is whether it is possible to use a natural fire model to verify the fire resistance of structural elements. In Poland, the commander of the provincial fire brigade may grant an authorization to use natural fire models to verify the durability of the elements of a particular building fire.

There are a lot of papers on natural fire models. Some of them are about designing buildings in fire conditions using natural fire models [3]. Rzeszut and Polus [4] observed that the results obtained based on time-temperature relationships may be significantly different from the results based on a natural fire model. The authors [4] analysed a steel beam in a fire situation. The temperature of the beam in a natural fire of a city bus was lower than the temperature obtained in the procedure according to the standard time-temperature ISO curve [4]. The fire dynamics simulator is a program which can be used to simulate a fire. It is a computational fluid dynamic (CFD) model of a fire-driven fluid flow [5]. The results of an FDS simulation may be displayed in a separate visualization program called Smokeview [6]. Models of buildings may be prepared in the PyroSim program, which is a graphic user interface for the fire dynamics simulator [7]. In many cases, a design using the ISO 834 temperature-time curve results in an increased spending on fire protection measures [8]. A design based on a natural fire takes into account the size of the fire zone, the construction of the room, the number of vents, the furnishing, the amount of combustible material, the size of the fire load, the speed of heat and the ventilation rate. A report should contain the following details of the model: name and version of the program, details of sub-models, input data, assumptions, number of cells, evidence that convergence was achieved throughout the simulation, evidence that the result is insensitive to the number of cells, demonstration of sensitivity to other variable parameters, e.g., an open window vs. a closed window [9, 10]. The full-scale experiments conducted by the State Key Laboratory of Fire Science in China show the difference between the rise of the temperature of a space truss according to the ISO 834 curve and a large-space building fire [11]. In 2002, the National Institute of Standards and Technology recommended the improvement of "*the century-old standard for the testing of building components, assemblies and systems*" [12]. Natural fire curves can be used instead of the ISO 834 curve. The ISO curve and natural fire curves are not identical, which is presented in Fig. 1.

The purpose of this paper is to describe the difference in temperature calculations using the ISO curve and in a natural office fire. The rise of the temperature of the steel HEB 300 section column was calculated over a period of 30 minutes.

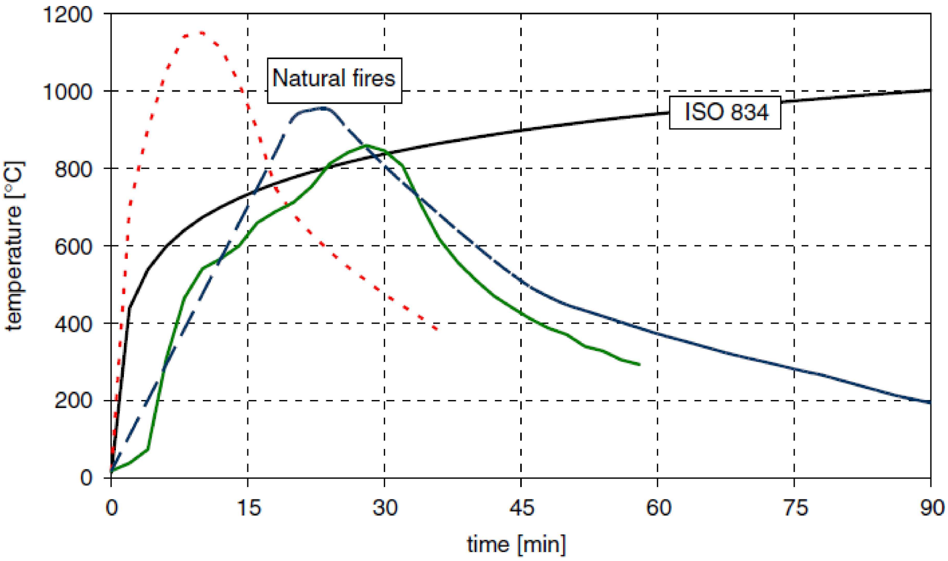

FIG. 1. A comparison between natural fire curves and the ISO 834 curve [8].

This is enough time to achieve high temperature which may be critical for the unprotected steel column.

2. Materials and methods

2.1. The temperature of the steel column the standard fire

The temperature of the steel column in a fire situation may be calculated using the iterative method [4]. The standard temperature-time curve is specified in EN 1991-1-2 [1] as

$$\Theta_g = 20 + 345 \log_{10}(8t + 1), \tag{2.1}$$

where Θ_g – the temperature of the gas in the fire compartment [°C], t – the time [min].

The curve represents a fully developed fire. It is an analytical function of temperature over time [2]. The equation describes the heating conditions of the structural element [13]. What is important, the standard ISO 834 temperature-time curve does not represent a real fire [2]. It is used to calculate the temperature of the gas in the fire, which can be used to calculate the temperature of an unprotected steel element exposed to the fire. The input data for calculating the rise of the temperature of the steel column constructed from a HEB 300 section are presented in Table 1.

Table 1. Input data [14].

Parameter	Symbol	Value	Unit
unit mass of steel	ρ_a	7850	kg/m^3
correction factor for the shadow effect	k_{sh}	0.62	–
section factor for the unprotected steel member	A_m/V	116.1	m^{-1}
box value of the section factor	$[A_m/V]_b$	80.5	m^{-1}
time interval	Δt	4.0	s
coefficient of heat transfer by convection	α_c	25.0	W/m^{2}K
configuration ration factor	Φ	1.0	–
surface emissivity of the member	ε_m	0.7	–
emissivity of the fire	ε_f	1.0	–
Stephan Boltzmann constant	σ	$5.67{\cdot}10^{-8}$	W/m^{2}K^4
temperature of the gas in the fire in 0 s	$\theta_{g,0}$	20.0	°C
surface temperature of the steel member in 0 s	$\theta_{m,0}$	20.0	°C
specific heat of steel in 0 s	$c_{a,0}$	439.8	J/kgK

2.2. The temperature of the steel column in the natural fire

In this paper, the rise of the temperature of the steel column constructed from a HEB 300 section in the office room was calculated using the fire dynamics simulator. The model of the room was prepared using PyroSim. The office room is presented in Fig. 2.

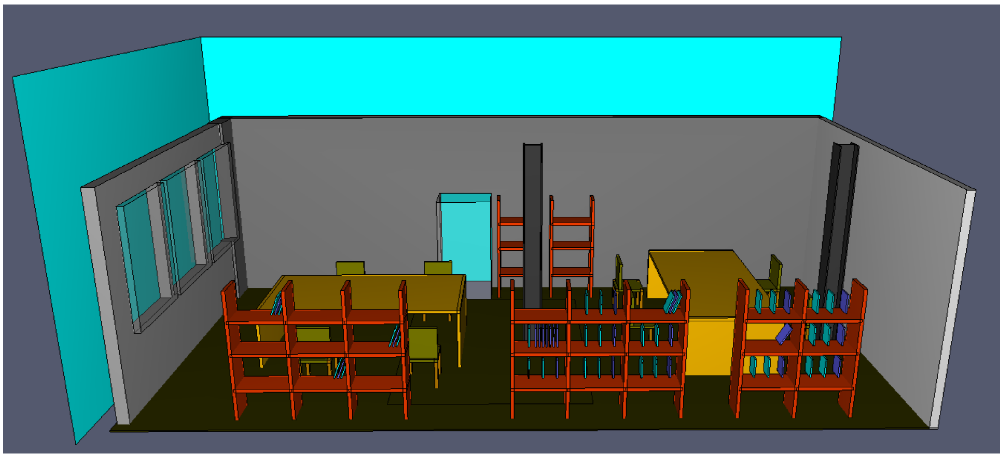

Fig. 2. The office room prepared in PyroSim.

An office room has a medium fire growth rate and a heat release density rate of 250 kW/m^2. The maximum power released by a fire can be calculated using the following formula [2]:

$$Q = A_{fi}\mathrm{RHR}_f, \tag{2.2}$$

where A_{fi} – the maximum reach of the fire [m^2], RHR_f – the heat release density rate [kW/m^2].

The maximum area that a fire can spread over in an office room without sprinklers is 47 m^2, if it is not fully developed, or the entire area of the room, if it is fully developed [15]. Figure 3 presents the evolution of the heat release rate (HRR).

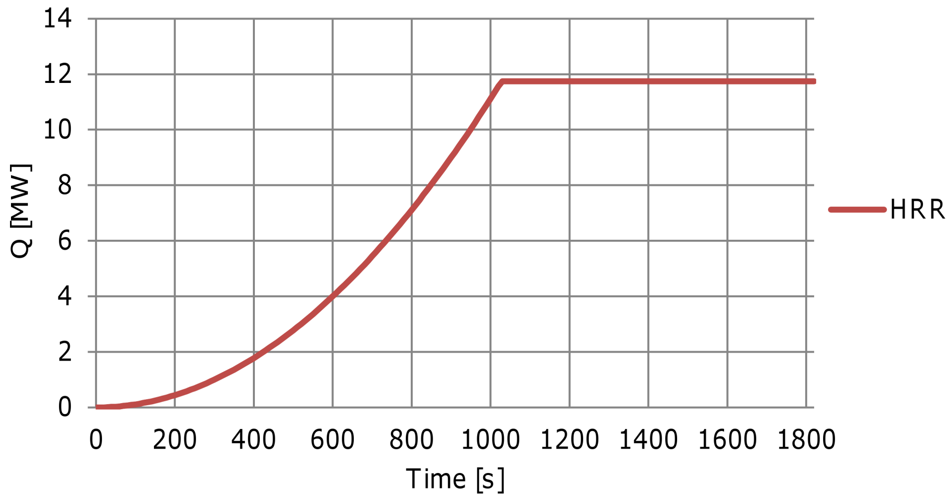

Fig. 3. The evolution of the rate of heat release (RHR).

A mesh should be carefully chosen to obtain accurate results [16]. The mesh size depends on the size of the compartment and the power released by the fire. It may be calculated using the FDS mesh size calculator [17]. The model should be verified. Evidence should be provided that mathematical models are properly implemented and that the numerical solution is correct with respect to the mathematical model [18]. The input data are presented in Table 2. Different meshes were used to verify the model.

The most severe fire is a result of the largest possible fuel load [19]. The fire scenario is presented in Table 3.

The model was verified using different meshes and cells sizes. The meshes are presented in Table 4.

Table 2. Input data in the natural fire model.

Parameter	Symbol	Value	Unit
area of the room	A	57.6	m^2
maximum reach of the fire	A_{fi}	47.0	m^2
maximum power released by the fire	Q	11.75	MW
height of the room	h	3.5	m
width of the room	s	5.16	m
length of the room	l	11.17	m
number of doors	–	1	–
width of the door	–	1.0	m
height of the door	–	2.0	m
number of windows	–	3	–
width of the window	–	1.3	m
height of the window	–	1.9	m
surface of walls	–	concrete	–
surface of the floor	–	felt	–
surface of desks	–	pine	–
surface of chairs	–	pine	–
surface of books	–	paper	–
surface of bookstands	–	oak	–
surface of columns	–	steel	–
time needed to reach 11.75 MW	–	1028	s

Table 3. The fire scenario.

Time	Action
0 s	ignition, the door and two windows are open
when the detector of smoke is activated	the door is closed
when the detector of temperature is activated	the third window is open
1028 s	the power released by the fire reaches its maximum value

Table 4. The meshes.

Variant	Number of meshes	Size of cells
1	6	0.1×0.1×0.1 m for five meshes 0.05×0.05×0.05 m for one mesh
2	6	0.25×0.25×0.25 m
3	2	0.1×0.1×0.1 m
4	2	0.25×0.25×0.25 m

Figure 4 shows the model with the first and the second mesh variant.

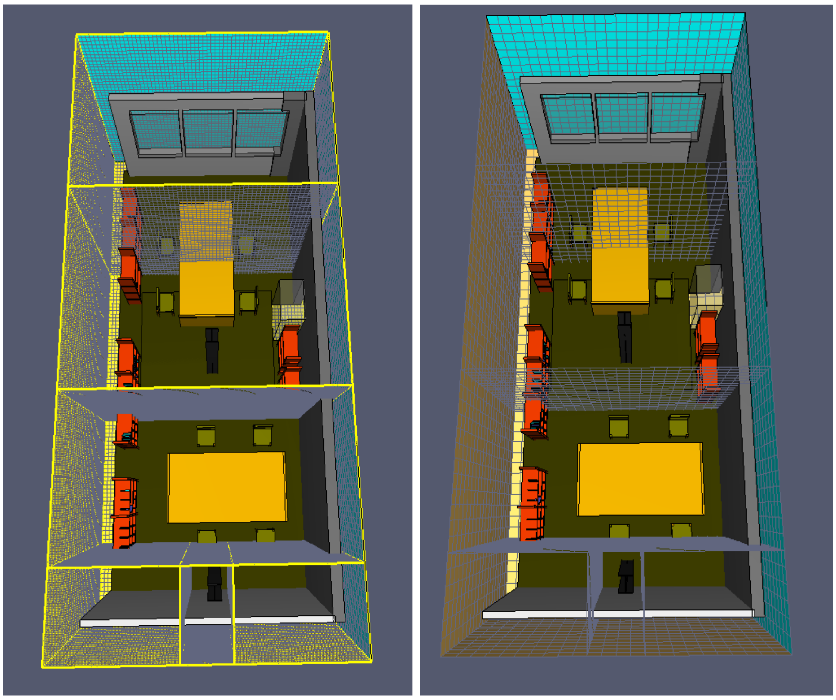

FIG. 4. The first and the second mesh variant.

Figure 5 shows the model with the third and the fourth mesh variant.

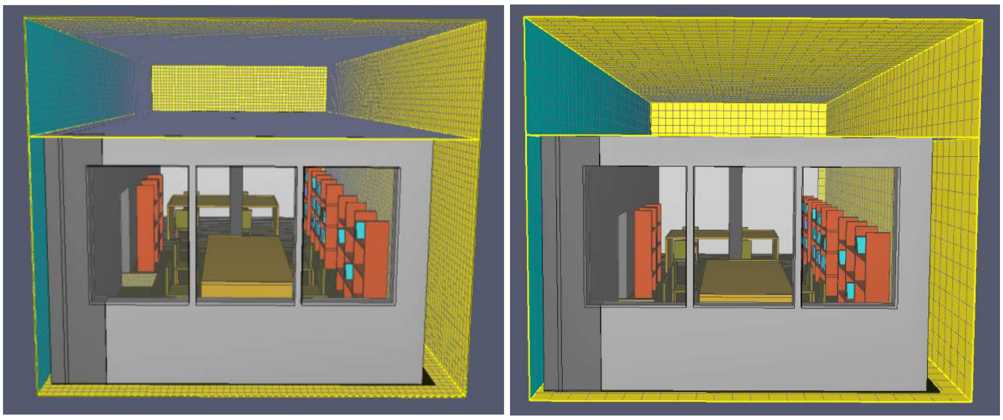

FIG. 5. The third and the fourth mesh variant.

In the first variant, the cell size of the mesh is different from the cell size in other meshes. A smaller cell size was intentionally used near the column. There are two steel columns in the model. The first one is located near the wall, whereas the second one is in the center of the room. The burner surface covers the part of the floor where the second column is located. There are a lot of detectors in the model. The smoke detector is located in the center of the room, 2.2 m above the floor. The device is activated when the obscuration threshold reaches 3.28%/m. A temperature detector is located near the window that is activated when the gas reaches the temperature of 300°C. The columns are equipped with wall temperature detectors. They are located at a 0.1 m distance from one another.

3. Results

3.1. The temperature of the steel column in the standard fire

The increase in the temperature of the unprotected steel column was calculated over 30 minutes of fire. The final seconds are presented in Table 5.

Table 5. The final seconds of the 30-minute analysis.

Time [s]	Θ_g [°C]	$h_{\mathrm{net},r}$ [W/m^2]	$h_{\mathrm{net},c}$ [W/m^2]	$h_{\mathrm{net},d}$ [W/m^2]	$c_{a,i}$ [J/kgK]	$\Delta\theta_{a,t}$ [°C]	$\theta_{a,t}$ [°C]
1780	840.13	20 047.78	2641.88	22 689.66	4332.34	0.20	734.45
1784	840.46	20 089.95	2645.45	22 735.40	4542.315	0.19	734.65
1788	840.80	20 133.40	2649.21	22 782.61	4766.762	0.18	734.83
1792	841.13	20 178.07	2653.16	22 831.24	4994.80	0.18	735.00
1796	841.46	20 223.88	2657.29	22 881.17	4815.99	0.17	735.17
1800	841.80	20 268.50	2661.23	22 929.73	4644.76	0.17	735.35

The temperature of the unprotected steel column reached 735.35°C after 30 minutes.

3.2. The temperature of the steel column in the natural fire

The temperature of the gas near the windows was lower than in the center of the room. There was fresh air near the windows. The comparison between the temperatures of the gas near the windows in all variants is presented in Fig. 6.

The comparison between the temperatures of the gas in the center of the room in all variants is presented in Fig. 7.

The column 1 had the maximum temperature at 2.9 m above the ground whether the column 2 had it at 1.0 m. The column 1 had the maximum temperature at 2.9 m, because it contained the hottest gases. The column 2 had the

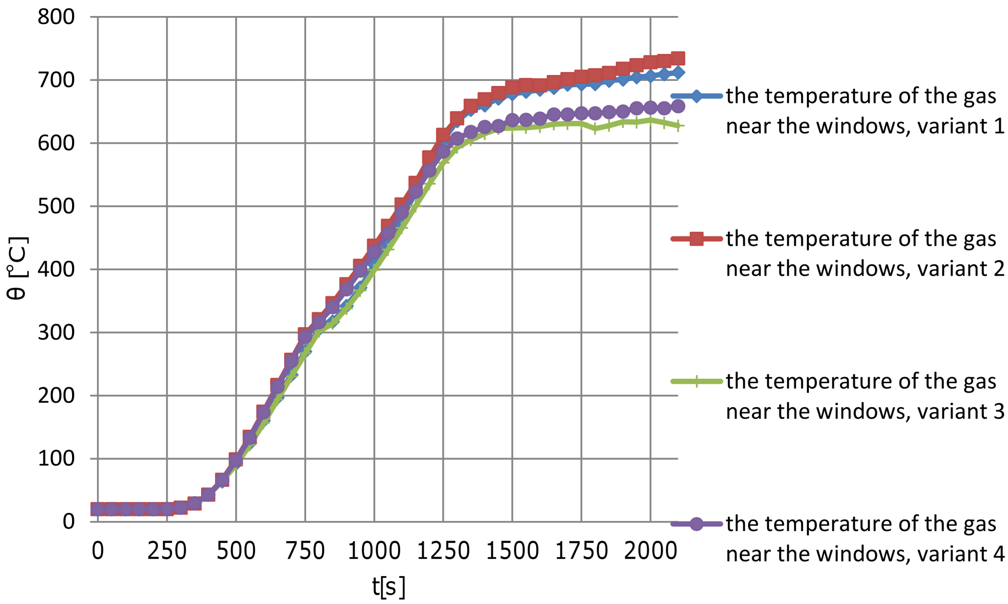

FIG. 6. The temperatures of the gas near the windows in all variants.

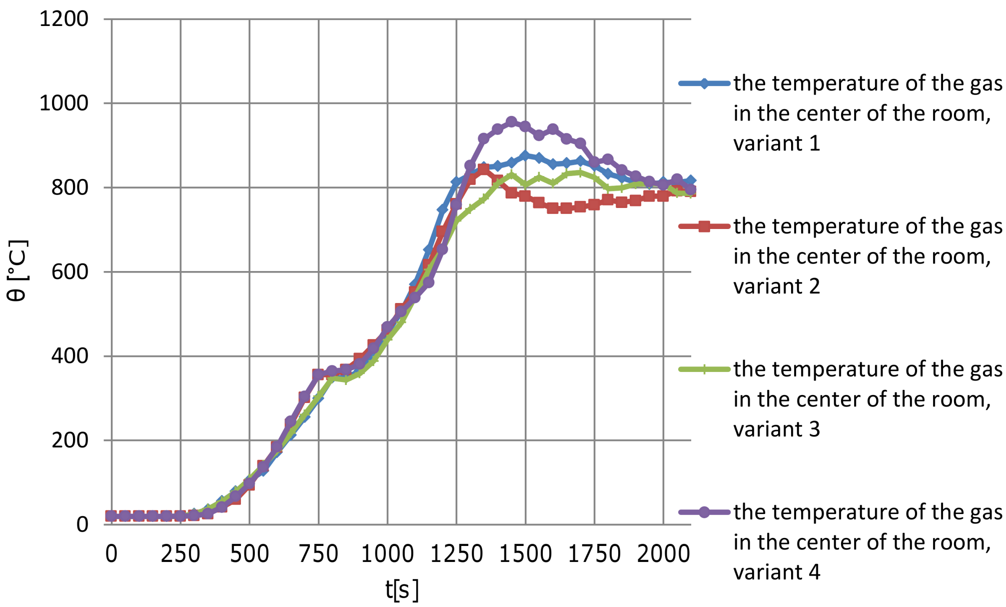

FIG. 7. The temperatures of the gas in the center of the room in all variants.

maximum temperature at low height, because it was specially located on the burner surface. The comparison between the temperatures of column 1 at 1.0 m above the ground in all variants is presented in Fig. 8.

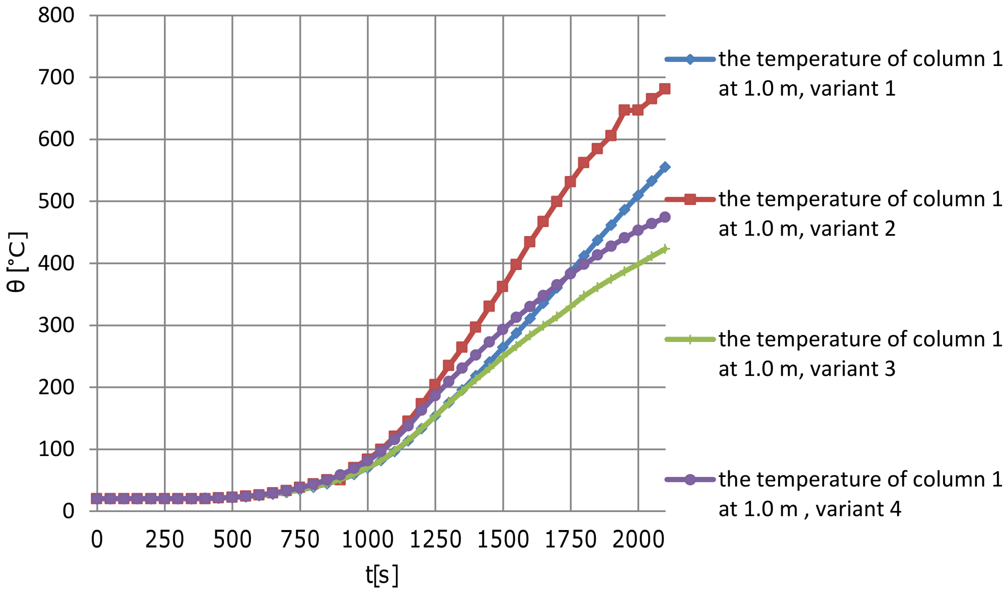

FIG. 8. The temperatures of column 1 at 1.0 m above the ground.

The comparison between the temperatures of column 1 at 2.9 m above the ground in all variants is presented in Fig. 9.

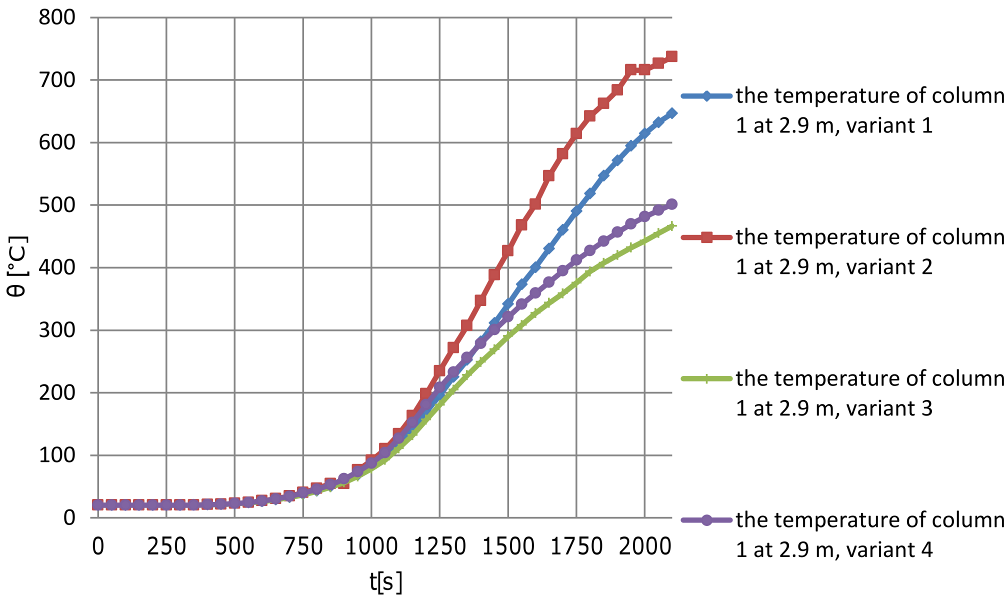

FIG. 9. The temperatures of column 1 at 2.9 m above the ground in all variants.

The comparison between the temperatures of column 2 at 1.0 m above the ground in all variants is presented in Fig. 10.

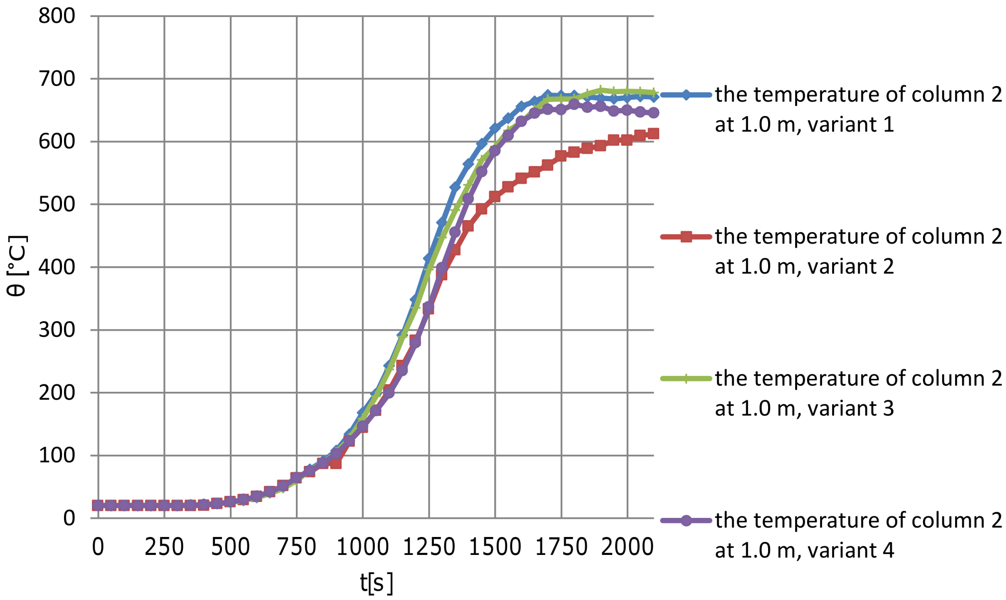

Fig. 10. The temperatures of column 2 at 1.0 m above the ground in all variants.

The comparison between the temperatures of column 2 at 2.9 m above the ground in all variants is presented in Fig. 11.

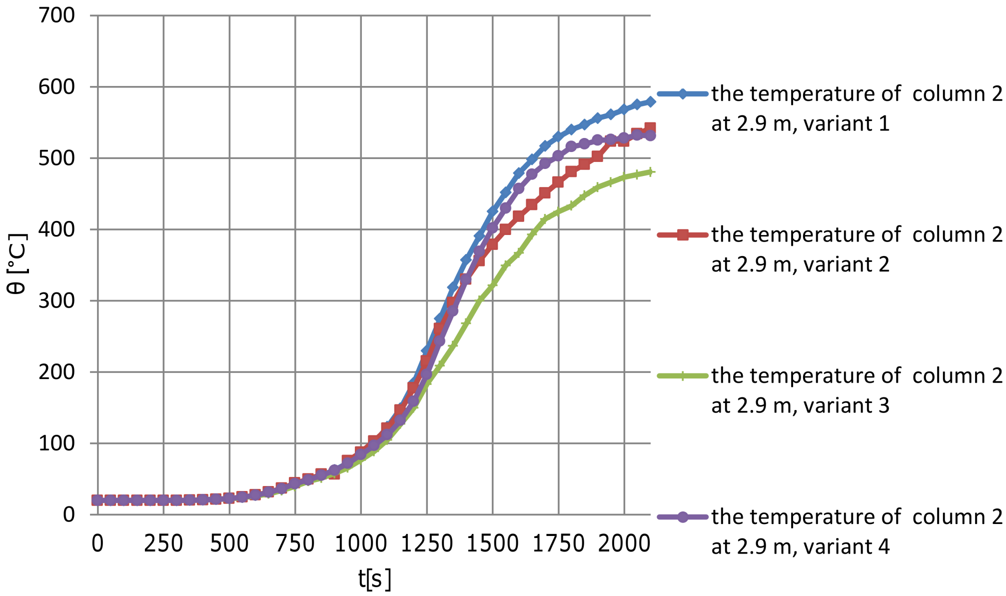

Fig. 11. The temperatures of column 2 at 2.9 m above the ground in all variants.

Figure 12 shows the evolution of the rate of heat release obtained in the fire dynamics simulator.

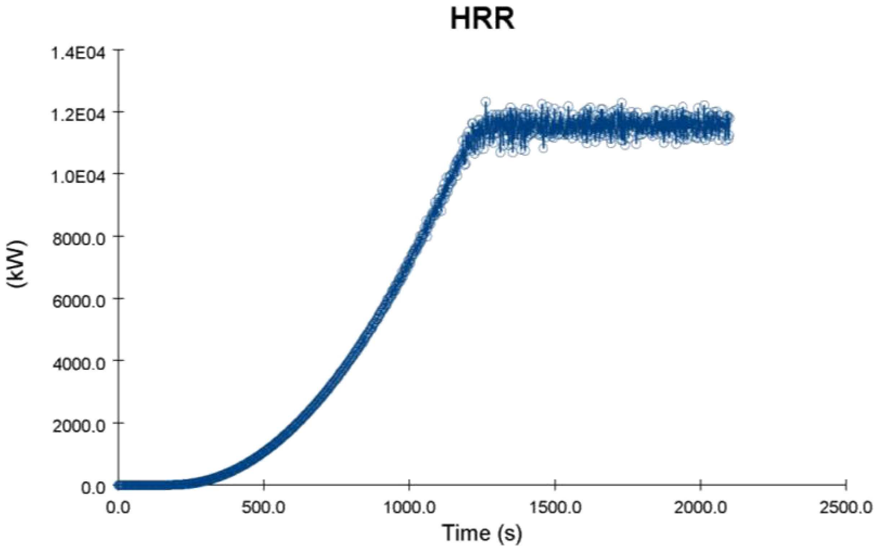

Fig. 12. The evolution of the rate of heat release obtained in the fire dynamics simulator.

Figure 12 shows that the fire did not have enough air after reaching the maximum rate of heat release. The RHR line is unstable. It may be one of the reasons for the differences between the results in 1028 s obtained in all variants. The other reason is the accuracy of the meshes.

4. Discussion

A comparison between the rise of the temperature of the unprotected steel column subjected to the standard fire curve ISO 834 and to the natural office fire model is presented in Fig. 13.

The temperature of the column in the standard fire was higher than in the natural fire. The result obtained based on the time-temperature relationships is significantly different from the result based on the natural fire model in the first 1500 seconds. From 1500 s to 2000 s, the temperature of the column in the ISO fire is similar to the temperature of the column in the natural fire. The rise of temperature in the standard fire curve ISO 834 is faster than in the natural fire model, which is similar to the results presented in [2] and in Fig. 1. The temperature of the gases in the natural fire model does not exceed the temperature of the gases in the ISO fire, which is different from the results presented in Fig. 1. This difference is because of the small size of the room and the small maximum power released by the fire.

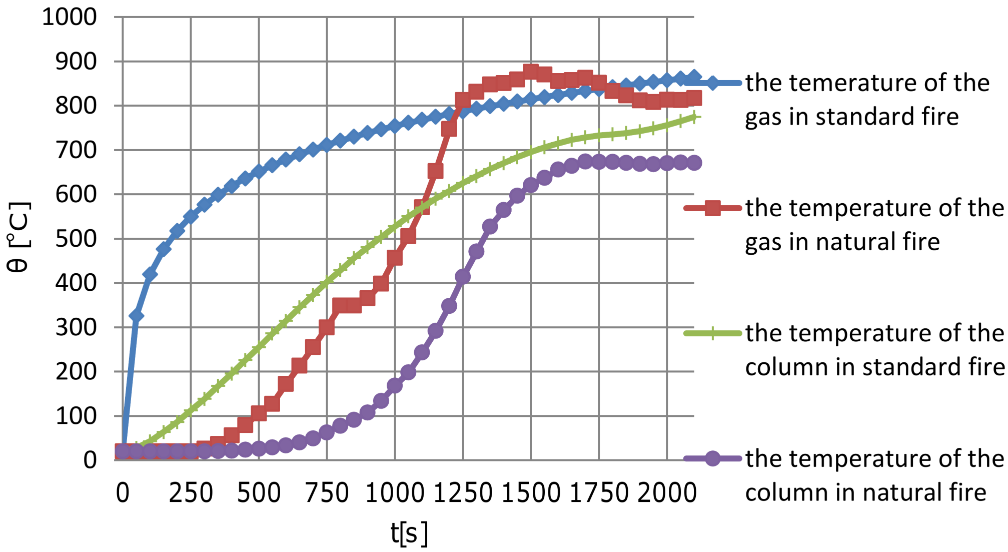

Fig. 13. The rise of the temperature of the unprotected steel column subjected to the standard fire curve ISO 834 and to the natural office fire model.

5. Conclusions

The temperature of the column in the standard fire was higher than in the natural office fire. The standard temperature-time curve does not take into account the parameters of the model. The use of natural fire models in the design process may reduce the costs of fire protection materials, especially in small rooms where the rate of heat release density is low. In simulations of natural fires the size of the mesh has a significant impact on the results. It is more visible in situations where the fire has not enough oxygen, which was the case in this paper.

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