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Thermal analysis of fire effects on fire doors using the finite element method

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Abstract

The goal of this paper is to use the finite element method and computer simulation to prove the effectiveness in assessing the fire resistance of building construction elements, specifically on the example of the fire resistance of fire doors. For that purpose, data from the building where fire doors with defined characteristics were installed were used. For simulation purposes, numerical modelling with thermal and structural analysis will be used. In this way, the parameters of the temperature distribution on the fire door and the contact material due to fire will be obtained, as well as the distribution of strain and stresses, which will indicate the fire resistance of the used structure. Computer simulation with numerical modelling offers a number of advantages both in the speed of providing results of a larger number of variants of the simulation model and in the accuracy of the results obtained once the model is calibrated. Also, the mentioned type of predicting the effect of fire can be applied to other elements of the structure of the construction object, which can significantly influence the decision-making that will prevent the negative consequences of the occurrence of a possible fire.

Keywords: Thermal analysis, Finite element method, Fire, Fire door, Building, Computer simulation, Numerical modelling, Stress, Strain

Introduction

By applying reliable engineering methods, significant progress has been made in understanding the behaviour of structures in a fire. Intensive research has led to the development of numerous design methods that provide good engineering solutions for buildings in a fire. These can be simpler elementary methods or advanced methods of fire engineering. Fire engineering, which combines reliability engineering with finite element modelling, can predict the real behaviour of a structure during a fire and, based on that, determine fire protection measures.

Nowadays, we are aware that, despite the constant progress in technique and technology, as well as the materials used in the construction of buildings, great attention must be paid to fire prevention measures in order to anticipate undesirable situations during the construction and future use of buildings. This is especially pronounced in high-rise buildings, where teams of people are formed who take care of the application of standards and compliance with fire regulations. There are numerous examples of catastrophic consequences of fire in high-rise buildings as a reminder of the necessity of constant consideration and analysis of the possibility of improving the fire protection process. In addition to the strict implementation of prescribed rules and compliance with standards in the field of fire protection in high-rise buildings, it is necessary for each specific situation to use a scientific and professional approach to the analysis and consideration of individual influential factors that would lead to the improvement of the level of fire protection of the building [1].

Simulation of temperature and thermal stress using computer-aided design systems has a long history of successful application to structures. This type of analysis is used to determine the temperature and other heat quantities in the body due to various thermal loads. Thermal loads applied to structures are time dependent. In order to obtain reliable results, the model should include the thermal behaviour of the wall and door. All factors such as changes in model geometry, boundary conditions and incremental procedure must be included. If the temperature variation is large enough, these stresses can reach levels that can lead to structural failure, especially in brittle materials. Therefore, for many problems involving high-temperature variations, knowledge of thermal stress analysis can be very important. Analytical techniques in solving such problems have serious limitations due to the difficulty in deriving closed solutions of nonlinear differential equations. That is why the finite element method was used to analyse the problem.

The subject of research in this paper is the analysis of temperature distribution, stresses and strain for specific conditions will be analysed, i.e. for the selected type of fire door and the type of material of the surrounding physical system, and the defined dimensions of the fire sector as well as the predicted developed temperatures in case of fire. In order to carry out the research effectively, the finite element method was chosen as a mathematical methodology for calculating defined parameters. The finite element method is the most commonly used methodology for calculating not only the stress-strain states of structures but also for thermal and fluid analysis. This methodology, as already proven and applicable in many areas of engineering research, has been implemented in software for simulation and provides satisfactory results as an input in the final decision-making process. The temperature distribution in the section is obtained by thermal analysis, and the stress-strain state of the structure at the time of temperature rise is solved by static structure analysis.

The aim of the article is to analyse the obtained results of numerical modelling and computer simulation both in the fire door itself and in the surrounding material (walls around the built-in door). Also, it is necessary to determine the justification of the selected materials in the construction of the building in case of fire. In order to carry out the subject analysis, it is necessary to collect all relevant parameters for the purposes of modelling and simulation and harmonise the initial conditions with the existing regulations in the field of fire protection in high-rise buildings.

Methods

Basics of fire protection in high-rise buildings

High-rise buildings mean buildings with rooms for people to stay, residential and commercial in nature, with the highest floor located at least 22 m above the lowest ground level [2]. Uncontrolled burning that endangers human life and health or results in material damage can be defined as a fire. A fire occurs due to the combination of a combustible substance with oxygen from the air in the presence of a heat source. The type of building material of a certain building affects not only the speed of fire spread and the type and amount of combustion products but also the fire resistance of the building structure and the size of the fire load. The behaviour of building materials in a fire is influenced by the following: type, shape, geometric dimensions, method of workability and connections with other elements [1, 3, 4].

The spread of fire inside the building can be horizontal and vertical. They can spread by direct flame or heat transfer. The fire resistance of the fire sector is the time during which the fire will not spread to the surrounding fire sectors or from the surrounding area to the observed fire sector [2, 5]. The fire sector can be one room, several rooms or an entire building. The formation of fire sectors depends on the purpose of the building, the height of the fire load, the fire resistance of the building, the height of the building and the installed stable extinguishing systems. In a residential building, one apartment should be one fire sector. According to the requirements, firewalls have the highest fire resistance at the borders of the fire sector, followed by mezzanine structures, and doors and flaps at openings in walls or mezzanine structures have the lowest [6–8].

Behaviour of building materials due to fire

In addition to changes in the mechanical and thermal properties of concrete, due to exposure to fire, there are also changes in its surface appearance, manifested as peeling of the surface and the appearance of cracks. Due to exposure to high temperatures, concrete and reinforcement begin to stretch differently. The reinforcement stretches faster, which creates additional stresses and eventually cracks appear. The existence of cracks enables the passage of high temperatures into the interior of the concrete and its further damage [9]. With steel, in addition to thermal elongation at high temperatures, there are changes in specific heat capacity and thermal conductivity. The protection of the steel should be performed so that the temperature of 300 °C, to which the reinforcement is heated, is not exceeded [1, 10, 11].

Applied methodology for computer modelling and simulation

When we want to perform computer modelling, it is necessary to simplify a given physical problem through the creation of a graphic model, without violating the basic laws of the existence of that problem. This is followed by its translation into mathematical form, i.e. creating a matrix of properties, loads and unknowns. A simulation is an imitation of certain real things, conditions or processes. The strength of simulation lies in the fact that it can be applied to a number of different systems and another important aspect of the simulation technique is that once the simulation model is built, it can be replicated on actual systems. Computer simulation is the discipline of designing a model of a real system, executing the model on a computer and analysing the obtained output. The reality of the simulation and people's trust in the simulation depends on the verification and validation of the simulation model. Computer graphics can be used to display the results of a computer simulation. The finite element method is a numerical method that seeks an approximate solution to the distribution of variables in the problem field, which is difficult to obtain analytically [12].

The final result is a complete numerical process implemented on a computer, i.e. formulation of finite element matrices, numerical integration for the development of matrices into matric corresponding to a complete system of finite elements and numerical solution of a system of equations. The finite element method can be applied to inhomogeneous materials, nonlinear problems of high elasticity and plasticity, problems of fluid mechanics, etc. In order to describe the reaction of a body to a given system of forces to which it is subjected, it is necessary to know the equations that can be used to describe the reaction, as well as the corresponding boundary conditions [12].

Thermal analysis by the finite element method

There are three types of heat transfer: conduction, convection and radiation. For heat transfer to occur there must be a difference in temperature and it is transferred in the direction of decreasing temperature. Temperature is a scalar, but heat flow is a vector quantity. Conduction takes place within the boundaries of the body by the diffusion of its internal energy [6, 13].

The finite element method creates a set of algebraic equations using an equivalent governing integral form that is integrated over a mesh that approximates the volume and surface area of the body of interest. A network consists of elements connected to nodes. In thermal analysis, there will be one simultaneous equation for each node. The unknown at each node is the temperature. The finite element model considers fire exposure as a time-temperature variation boundary condition, and material properties at elevated temperature are included in the model to achieve accurate results [7, 14, 15].

For conductive heat transfer the governing differential equation is as follows:

$$\frac{\partial}{\partial x}\left(\lambda_x \bullet \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda_y \bullet \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(\lambda_z \bullet \frac{\partial T}{\partial z}\right) = \rho \bullet c \bullet \frac{\partial T}{\partial t}$$

$l_{x,y,z}$, thermal conductivity in all three directions (temperature dependent);

ρ, material density (depending on temperature);

c, specific heat (temperature dependent);

T, temperature;

t, time parameter.

Boundary conditions can be modelled in terms of both heat transfer mechanisms: convection and radiation [15, 16].

The heat flow caused by convection is:

$q_c = h_c(T_z – T_f)$

h_c, convection coefficient (for a wall in a room at ambient temperature, the recommended value is $h_c = 4$ [Wm^{-2} K^{-1}], whilst in the event of a fire in the room, the value is recommended $h_c \geq 25$ [Wm^{-2} K^{-1}]);

Tz, element boundary temperature;

T_f, temperature of the fluid around the element.

Heat flow caused by radiation [15, 16]:

$$q_Y = V \bullet \varepsilon \bullet \sigma_c \bullet \left(T_{z,a}^4 - T_{f,a}^4\right) = h_Y \bullet \left(T_z - T_f\right)$$

$$h_Y = V \bullet \varepsilon \bullet \sigma_c \bullet \left(T_{z,a}^2 - T_{f,a}^2\right) \bullet \left(T_{z,a} - T_{f,a}\right)$$

hy, radiation coefficient (depending on temperature);

V, radiation factor, $V = 1.0$;

ε, resultant emission coefficient, $\varepsilon_f = 1$ emission coefficient for the surrounding fluid, ε_z emission coefficient for the surface of the element, depending on the materialisation (can be obtained from the relevant Eurocode standards);

$\sigma_c = 5.67\ 10^{-8}$ [$\mathrm{Wm^{-2}\ K^{-4}}$] Stefan–Boltzmann constant;

$T_{z,a}$, absolute surface temperature;

$T_{f,a}$, absolute fluid temperature.

The total strain vector is the sum of the thermal strain vector and the elastic strain vector [15].

$$\alpha(\mathrm{T}) = \frac{\mathrm{l(T) - l(T_{ref})}}{\mathrm{(T - T_{ref}) \bullet l(T_{ref})}} = \frac{\Delta \mathrm{l}}{\mathrm{l} \bullet \Delta \mathrm{T}} = \frac{\varepsilon(\mathrm{T})}{\Delta \mathrm{T}}$$

$$\{\varepsilon\} = \{\varepsilon\}_{\mathrm{T}} + \{\varepsilon\}_{\mathrm{s}}$$

$$\begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \gamma_{xy} \\ \gamma_{yz} \\ \gamma_{xz} \end{Bmatrix} = \begin{Bmatrix} \alpha_x \Delta \mathrm{T} \\ \alpha_y \Delta \mathrm{T} \\ \alpha_z \Delta \mathrm{T} \\ 0 \\ 0 \\ 0 \end{Bmatrix}_{\mathrm{T}} + \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \gamma_{xy} \\ \gamma_{yz} \\ \gamma_{xz} \end{Bmatrix}_{\mathrm{s}}$$

A partial differential equation that describes the transient flow of heat through the body (law of conservation of energy):

$$\rho \bullet c \bullet \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda_x \bullet \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda_y \bullet \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(\lambda_z \bullet \frac{\partial T}{\partial z}\right) + q_v(x, y, z, t)$$

$$\frac{\partial T}{\partial t} = a_d \bullet \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) + q_v = a_d \bullet \nabla^2 T + q_v$$

Calculation of the stress-deformation-temperature state parameters of the fire sector

The geometric model for the calculation was prepared on the basis of the actual parameters of the built-in anti-fire doors in the building, and it is presented in Fig. 1, and the finite element model for the given construction is shown in Fig. 2.

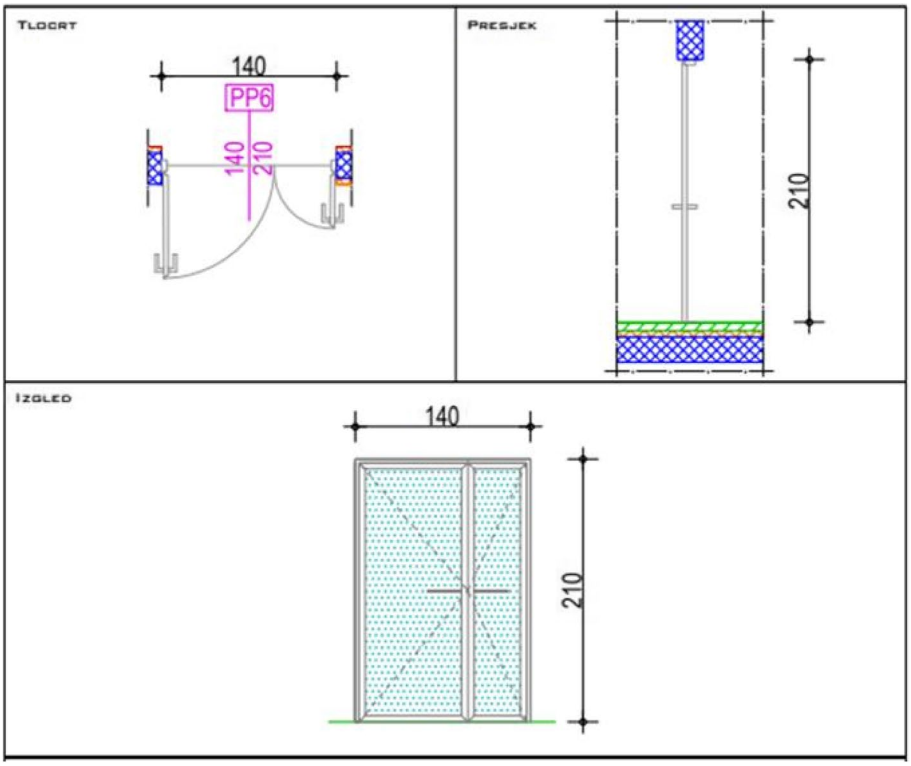

Fig. 1 Fire door model

A computer simulation was performed for the thermal load of the model in the ADINA software—thermal module. The obtained temperature loads of the model were used as input parameters for the structural analysis in the ADINA structure module. The model contains a total of 275 finite elements and 961 nodes in thermal analysis where 6 groups of elements were used:

- Element group 1: 200 axisymmetric conduction elements,
- Element group 3: 25 axisymmetric conduction elements,
- Element group 4: 20 axisymmetric line boundary convection elements,
- Element group 6: 5 axisymmetric line boundary convection elements,
- Element group 7: 20 axisymmetric line boundary radiation elements,
- Element group 9: 5 axisymmetric line boundary radiation elements.

For this model, 2D solid elements were used for structural analysis, with a total of 225 elements and 961 nodes:

- Element group 1: 200 axisymmetric solid elements,
- Element group 2: 25 axisymmetric solid elements

The article deals with the analysis of the resistance of fire doors in ideal conditions of application of exclusively defined materials during the construction of the building, without additional influential parameters such as human action in the sense of

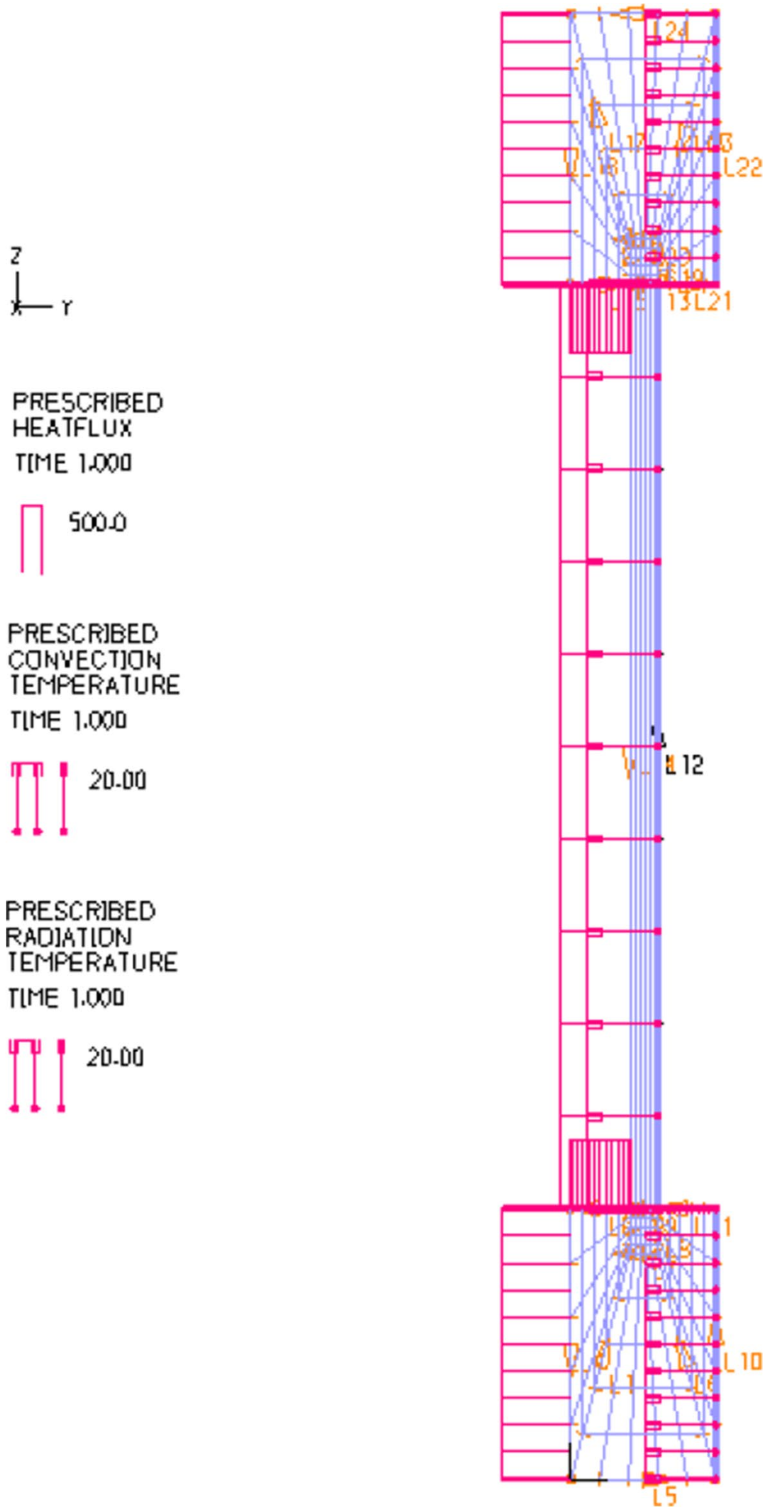

Fig. 2 Numerical model of the fire door cross section

installation, and leaving equipment and objects that could additionally affect the development, flow and intensity of the fire. Also, the conditions and properties of the materials in the newly built building were considered, and there was no fatigue of the materials nor any additional changes to the door or the surrounding material. For the simulation, the properties of the materials that were incorporated in the specifically considered case were used, i.e. concrete for surrounding material, aluminium and glass for fire doors. The main influencing factor on the accuracy of the simulation results is the accuracy of the input parameters. Through the classification report issued by the Institute IGH, Zagreb, the materials used for the production of doors were confirmed. The material properties necessary for the analysis were taken from the study (elaboration) for the construction of the building, and no additional laboratory confirmations of the accuracy of the specified characteristics were made. As it is a serious construction project of a tall building for which all building permits have been issued, it can be considered that the mentioned parameters for the analysis are valid.

For the models, the simulation of the assumed fire development was considered according to the following principle (Table 1): A total of 20 time steps were defined, one step simulated 5 min. The maximum fire development temperature of 1200 °C is assumed. The output values of the structural analysis are displacements, strains and stresses.

Table 1 Time function 1 of temperature development due to fire

Time step	Load magnitude (percentages)	Heat load magnitude (°C)
0	0.02	24
1	0.2	240
2	0.4	480
3	0.6	720
4	0.8	960
5	1	1200
6	1	1200
7	1	1200
8	1	1200
9	0.8	960
10	0.6	720
11	0.4	480
12	0.3	360
13	0.25	300
14	0.2	240
15	0.15	180
16	0.1	120
17	0.1	120
18	0.1	120
19	0.05	60
20	0.02	24

Results and discussion

By analysing the obtained simulation results, it can be determined that the maximum temperature on the model of 213 °C was registered on the side of the open flame (Fig. 3). No significant increase in temperature was registered on the opposite side of the fire door.

The distribution of the heat flux (Fig. 4) indicates the critical points of the model, namely the glass surfaces of the door as well as the concrete part of the connection of the door with the surrounding structure, which is also confirmed with the temperature distribution on the model.

Tensile stresses in critical time steps (Fig. 5) indicate and confirm the fact that the weak point of the structure is the junction of concrete and fire doors, and the stresses are significantly expressed in these places and a possible source of fire transmission to the next fire sector.

Table 2 presents the values of thermal deformations on the model for certain time steps. Taking into account the distribution of thermal deformations, deformations in the y–z plane, as well as deformation vectors, and obtained stress values, it can be concluded that the deformations are pronounced in the concrete parts, especially in the upper block. Deformations are also transmitted to the structure of the protected fire sector, but they do not exceed the permitted values, so the structure does not break, and especially it does not break and disintegrate.

The changes in y displacement (Fig. 6) also confirm the earlier conclusions, and the maximum displacement on the concrete block structure above the fire door is 0.0003 m.

Physical fire tests on real fire doors were carried out by Istituto Giordano S.p.A., Italy, as well as by the IGH Institute, a joint-stock company, Building Physics Laboratory, Zagreb Croatia. The institute issued a report on the fire resistance of UNIFORM EI2 120 doors

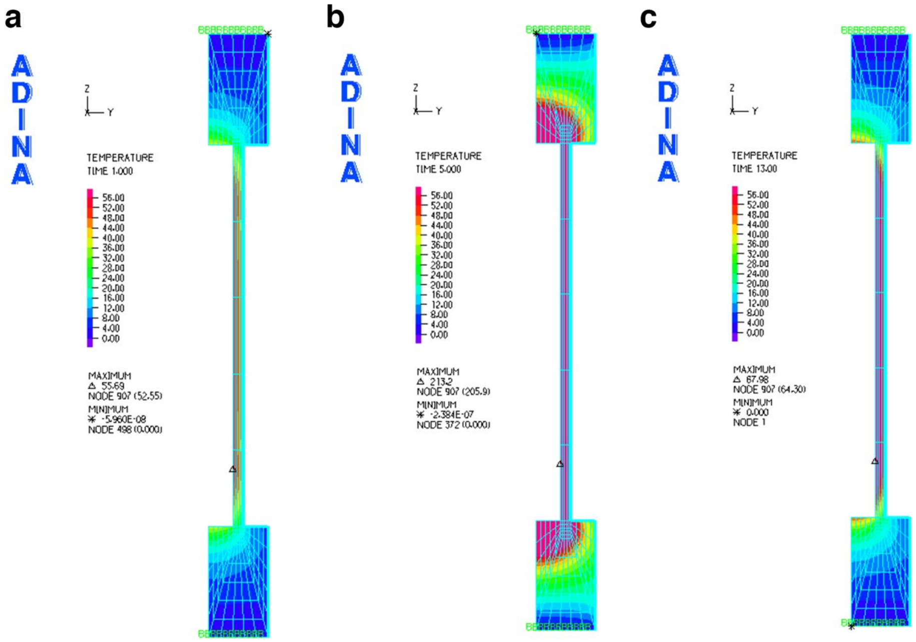

Fig. 3 **a**–**c** Temperature distributions on the model for time steps 1, 5, and 13

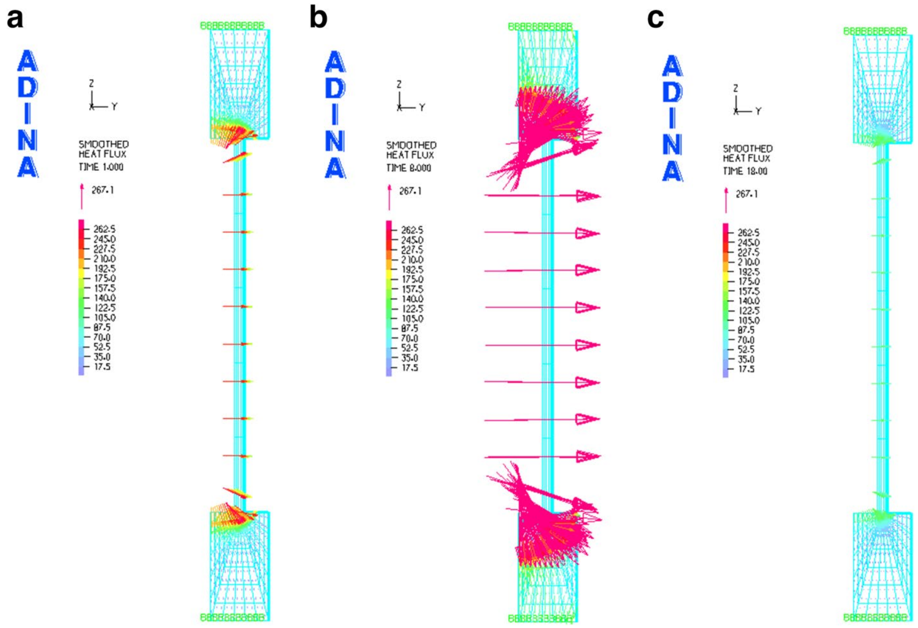

Fig. 4 **a**–**c** Heat flux distribution on the model for time steps 1, 8, and 18

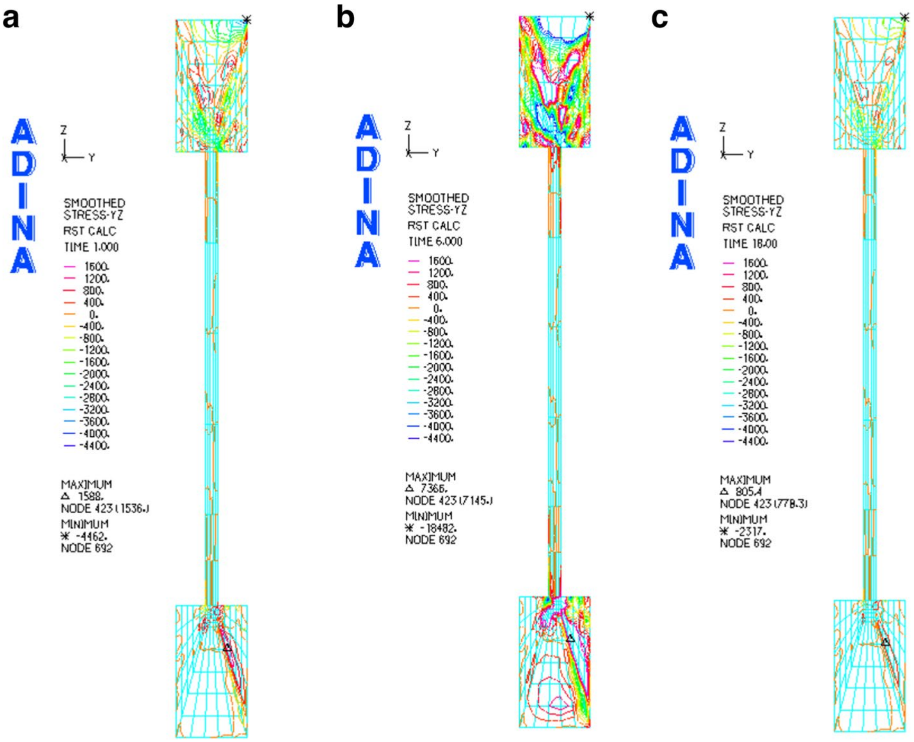

Fig. 5 **a**–**c** Stress distributions in the y–z plane on the model for time steps 1, 6, and 18

according to the HRN EN 13501-2:2016 classification standard (classification report number 72570/160/16-168/16 dated 07.10.2016). The report stated that the said door has the property of resisting the transmission of fire by the passage of flames or hot gases on the

Table 2 Value of maximum and minimum thermal deformations (TD)

Time step	Maximum TD	Minimal TD
1	$5.9\ 10^{-4}$	$-2.2\ 10^{-5}$
5	$2.2\ 10^{-4}$	$-9.7\ 10^{-5}$
9	$1.9\ 10^{-3}$	$-7.9\ 10^{-5}$
11	$1.1\ 10^{-3}$	$-4.3\ 10^{-5}$
13	$7.2\ 10^{-4}$	$-2.8\ 10^{-5}$
15	$4.6\ 10^{-4}$	$-1.7\ 10^{-5}$
18	$3.1\ 10^{-4}$	$-1.1\ 10^{-5}$

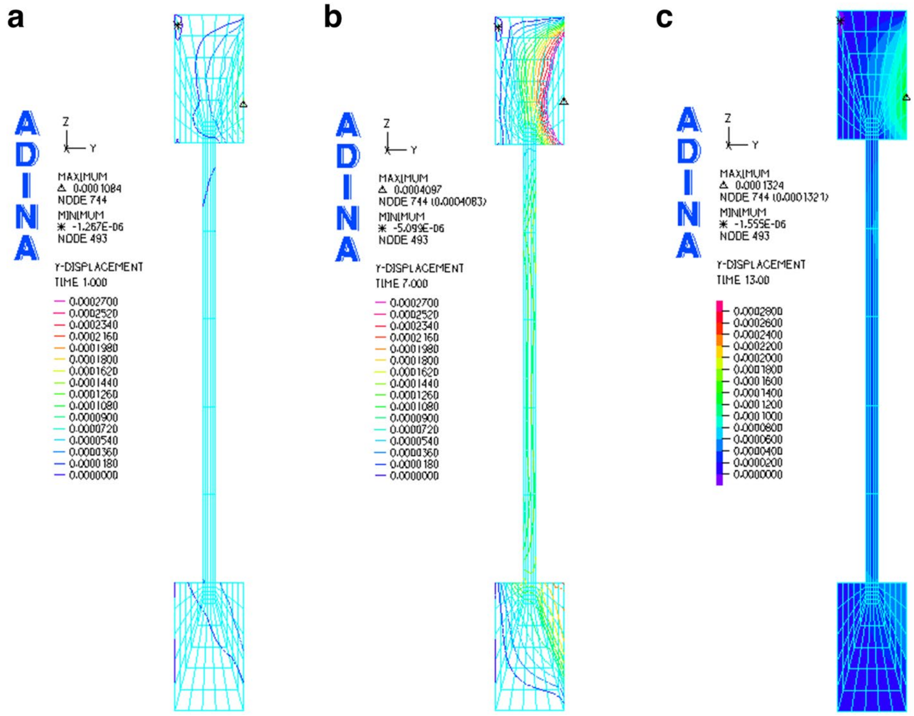

Fig. 6 **a**–**c** Distribution of y displacements for time steps 1, 7, and 13

non-exposed side, so that there is no ignition of non-exposed surfaces, nor materials near those non-exposed surfaces, and to protect people in their vicinity. The properties of integrity E and insulation I of the door are in the direction when the door leaves are opened towards the fire and when the door leaves are opened away from the fire. Two full-size insulating single-wing hinged metal doors were tested, installed in a standard (200 ± 50) mm thick support structure of solid high-density brick, one with the door leaf opening outside the test furnace and one with the door leaf opening into the test furnace. A test report has been attached, confirming the classification to EI_2 120.

Conclusions

The subject of research in this work was the analysis of load and temperature distribution on fire doors and the surrounding material of a fire sector on a high-rise building in the event of an extreme situation, i.e. fire development. The distribution of temperatures, stresses and deformations for specific conditions was analysed. In order to carry out the research effectively, the finite element method was chosen as a mathematical methodology for calculating defined parameters.

Through the overall analysis of the results obtained for the model with the fire development variant defined by time function 1, it can be concluded that there are certain changes in the structure of the model, especially on the side exposed to the fire, but that the calculated displacements, stresses and deformations indicate the stability of the structure, i.e. that there was no disintegration in the concrete or glass elements and that the fire doors and the concrete elements in which the doors are embedded fulfil their function of protecting the fire sector and preventing the transfer of fire to the next sector. The existence of certain deformations on both the door and the concrete elements was determined but that is to be expected due to exposure to the maximum temperature during the duration of the fire.

Based on everything presented, it can be concluded that the predicted fire with a maximum temperature of 1200 °C leads to deformation of the fire doors but not to the collapse of the structure, i.e. fracture or permanent plastic deformation. The numerical model not only gives a clearer idea that there will be no transfer of the fire to the next fire sector but also indicates the weak points of the model that should be paid attention to when installing the fire doors, both due to the geometry and the type of material that will be used in the implementation phase.

The obtained simulation results were compared with the reports from the certificate on the installed door. On the basis of the certificate, i.e. Declaration of conformity made by Mr. Locher Gebhard (as a representative of the company LOCHER and door manufacturer) number 174/2, which confirmed that the doors are certified according to the European standard UNI EN 1634-1 and that they are in line with homologated doors. Also, with the certificate issued by Istituto Giordano S.p.A., Italy, it is confirmed that all the provisions related to the assessment and verification of the constancy of the properties are according to system 1 for the EN 16034:2014 standards, and that the product meets all the prescribed requirements, and that it is included in the range standards EN 14351-1:2006+A2:2016. With the mentioned certificates, the properties of the materials used in the description of the fire doors in the mentioned fire development conditions were verified. Furthermore, the Statement of Properties issued (in accordance with EC Regulation No. 305/2011–EC Delegated Regulation No. 574/2014) no. 6 for the UNIFORM EI_2 120 fire door, the product type is identified, and the intended use for fire protection and exit routes, with the specified manufacturer Locher Gebhrad, and compliance with the EC 16034:2014 standard by the notified body Istituto Giordano S.p.A certificate 0407-CPR-1565 (IG-177-2019) that the fire resistance is EI_2 120 and that it has smoke control Sa/Sm, sound insulation 37 dB and automatic closing C5/200000 cycles. Of the stated declared properties for the analysed parameters, the important parameter for the article is fire resistance EI_2 120. The certificate confirms that, i.e. the results of the analysis were verified that the door has resistance to fire even after 120 min and for temperatures over 1000 °C. In the article, the development of the fire was assumed according to one of the variants where the maximum temperature of 1200 °C is reached in 25 min and that maximum lasts for the next 15 min, so one of the less favourable variants was analysed and the stability of the installed fire doors in the specific considered building was shown.

However, for the long-term use of fire doors and the analysis of the state of stability of the system after a certain period of time, the changed characteristics of the material that occur not only due to fatigue but also possibly due to other conditions that can affect the change in the properties of the material (subsidence of the building, earthquakes, etc.) should be taken into account. So that additional analyses and simulations could be made, predicting new conditions and new input parameters, and using the results of such analysis in the further decision-making process.

For the purpose of researching the fire resistance of fire doors, in addition to the mentioned experiment (numerical model), three more variants of the experiment were performed. The second variant refers to the same transverse profile of the door, but with a different dynamic of fire development over time, where the maximum is expected in 35 min. The third variant refers to the longitudinal profile with the first fire development dynamics, and the fourth model is the longitudinal profile with the second fire development variant. The fire resistance of the installed doors has been confirmed for the remaining three variants as well.

Even more reliable output data can be obtained if it were possible to use high-quality and verified data on the changed material properties during the effect of temperature, which could be applied in the simulation process through restart analysis, so that changes in temperature and material properties would be defined at the same time, and not only stress changes and deformations in structural elements due to temperature effects as initial parameters for each subsequent time step.

Abbreviations

TD	Termal deformation

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Not applicable

Authors' contributions
AN performed, analysed and interpreted the obtained results of the computer simulation. AV collected and presented the data for thermal analysis and for regulations in the field of buildings and fire protection. SN collected and presented data for the finite element method and input data for the numerical simulation. All authors read and approved the final manuscript.

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Availability of data and materials
The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interest
The authors declare that they have no competing interests.

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