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ANALYSIS OF A FIRE IN AN APARTMENT OF TIMBER BUILDING DEPENDING ON THE VENTILATION PARAMETER

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Abstract

In modern buildings are also currently used the wooden-based construction systems. A wide range of uses the timber constructions in apartment buildings is a vision of the countries of the EU. The use of timber and the other recyclable materials in apartment buildings creates the precondition for the implementation, operation and disposal of environmental impacts of the EU 2020 Strategy. In the long term is important to transform the construction of buildings to a sustainable standard, which the application of wood in construction supports. Currently, the fire height of timber-based residential construction in most EU countries is limited to 5 storeys, provided that the timber structures are fire-protected. This paper deals with the influence of the ventilation parameter in the time and the intensity of the gas temperature during a fire in a model of an apartment building with a timber load-bearing structure. The load-bearing structure is made of CLT panels, with a mixed structural unit, i.e. with fire-resistant cladding of all load-bearing and fire-dividing structures. FDS (Fire Dynamics Simulator - PyroSim software) is used for dynamic simulations of fire in the model apartment.

Keywords:

Fire safety;
Timber building;
FDS;
Fire;
Parametric fire.

1 Introduction

A limiting parameter in the design and realization of apartment buildings with load-bearing and fire-separating timber constructions is their flammability. Although, the fire test methods for the classification of individual construction products are harmonized in the EU, individual member states are responsible for building regulations covering the entire building structure - including fire safety requirements. Each state determines its own level of fire safety and the use of construction products, which differ according to the flammability of the structural unit, the function of the building and fire height.

Nowadays in European Union brings harmonization in evaluated of standards into each European country and try to make one concept of evaluated the flammability properties [1]. The category with the strictest requirements for fire safety of buildings in the Slovak Republic includes buildings with combustible structural unit - timber buildings, and the other buildings with a large concentration of persons, a large fire load and a high fire height. Fire safety of buildings is proposed in the STN 1992:2:01 part 1-4 in connection with Decree 94/2004 and its amendments. Requirements for the fire safety of timber apartment buildings are directly dependent on the number of their storeys and the flammability of the structural unit of the building. The definition of the structural unit of the building depends on the flammability of the load-bearing structures of the building, the flammability and the method of installation insulating and cladding materials, which are built into the load-bearing and fire dividing constructions. The fire height of the building depends on the number of fire floors of the building above ground level. The requirement for the minimum fire resistance of the load-bearing and fire dividing elements is subsequently determined, in depending on these two parameters. Modelling and dynamic fire simulation is an important tool in the design and assessment of fire safety of buildings. The computer models are most often used in estimating the risk of fire, predicting the course of the intensity of heat radiation in time depending on the size and distribution of the fire load, the time

course of smoke, and the speed of fuel burning. The outputs from the simulation are used for detailed analyses of the design of passive and active fire protection of building structures, protection of persons during evacuation and fire intervention during its liquidation. They are also used in the reconstruction of real fires using forensic evidence, so it was e.g. analysed the nightclub fire in Gothenburg by Yan et al. [2], or a fire with the consequent structural collapse of the World Trade Center Towers of McGrattan et al. [3].

Forensic evidence in fire reconstruction clarifies the real fire environment and then provides data to verify the results of fire models in simulation models. Three main numerical approaches are used to simulate fires in buildings [4]. The simplest are simulations with the creation of an analytical model of fire development. They use only the basic relationships describing the physicochemical reactions and processes that occur during combustion. Examples of this simulation methodology are the analyses of Lawson and Quintier [5] and Alvares and Fernandez-Pell [6]. Analytical fire models are quick and easy to use. Their accuracy is limited by the description of the fire environment. They usually serve as a basis for computer modelling in zone and dynamic simulations.

Zone models are a more comprehensive approach to fire simulations [7]. Their solution is based on the assumption that the fire space is composed of two gaseous layers that interact through the control equations. Zone modelling is implemented e.g. in the software simulation programs FIRST [8] and CFAST [9]. Their main ad-vantage is the speed of calculation, which allows to carry out extensive parametric studies of larger structures. Because these simulations take into account several physical mechanisms arising from a fire, they have a higher potential to provide more realistic results than analytical models [10]. However, the smaller number of simplifications implies the need to know a larger number of basic parameters that need to be extracted from experiments or from forensic evidence.

The results of simulations with zone models are often associated with considerable uncertainties. The most complete approach is dynamic simulations [6], which numerically solve 3D control equations for fire-controlled flow in their differential form with different levels of complexity. JASMINE [11], SOFIE [12] and FDS [13] software are most often used in their implementation. Dynamic simulations require more effort to set the boundary conditions of the model and longer computational time. Dynamic fire simulations are closest to the real course of the fire with optimally selected parameters of the fire load environment, including the source of fire initiation. [14, 15].

Some attempts to directly compare results from different models are available in the literature [16 - 18].

The aim of this paper is to investigate the heat release rate, gas temperature evolution and fire length in a model residential timber building made of fire-protected CLT panels. The apartment options have a variable ventilation parameter depending on the window area in the external walls. The FDS-PyroSim model is used to simulate the fire scenario in the apartment of the model.

2 Simulation methodology

Fire Dynamics Simulator (FDS) software works with a fluid dynamics calculation model. It was design by NIST and SMARTFIRE. In FDS simulation, three-dimensional space is divided into small rectangular volumes. Within each volume, the gas variables are considered uniform but change over time. To maintain momentum, FDS solves Navier-Stokes equations using large eddy simulation (LES) to simulating turbulent flows. For combustion reactions is used model with mixed stream [10]. There is heat transfer to solid surfaces and fluid flow. The radiation transport equation for the absorption emitting and scattering medium is solved [19]. An important step in setting up the model mesh. In the proposed solution, the mesh is in a grid of 0.25 x 0.25 x 0.25 m.

The main advantage of this method is that it provides variations of fire parameters and provides information of the thermal smoke load.

The most important limitations of the method are:

- validation of transport equations is needed for special scenarios,
- the mixed stream means a potential excess of combusted pyrolysis gas,
- convergence may not be more detailed grid size.

CFD models are able to model fire and its effects, the interaction of fire with several types of safety systems (such as fire ventilation, electrical signaling and fire extinguishing systems) and the impact of fire effects on the movement of persons within the area [20].

The bases of the mathematical model of FDS are 4 equations, of which 3 are partial differential equations:

Conservation of mass:

$$\frac{\partial_\rho}{\partial_t} + \nabla \cdot \rho_u = \dot{m_b^m} \ . \tag{1}$$

Conservation of angular momentum:

$$\frac{\partial}{\partial_t} \cdot (\rho_u) + \nabla \cdot \rho_{uu} + \nabla_p = p_g + f_b + \nabla \cdot \tau_{ij} \ . \tag{2}$$

Conservation of energy:

$$\frac{\partial}{\partial_t} \cdot (\rho_{hs}) + \nabla \cdot \rho_{hs} \cdot u = \frac{D_p}{D_t} + \dot{q^m} - \dot{q_b^m} - \nabla \cdot \dot{q^n} + \varepsilon \ . \tag{3}$$

Equation of state:

$$p = \frac{\rho R T}{\bar{W}} \ . \tag{4}$$

Where: ρ - density [kg·m^{-3}], u - (u, v, w) vector in three dimensions, p - pressure [N·m^{-2}], f_b - external force vector, τ_{ij} - the electromagnetic tensor, h_s - enthalpy density, $\dot{q}_b^{'''}$ - heat transfer processes inside the droplet, $\dot{q}^{'''}$ - heat release rate per unit volume, $\dot{q}^{''}$ - conduction heat transfer flow, R - universal gas constant, T - temperature, $\bar{W}$ - molecular weight, t - time, g - gravitational acceleration, $\mathcal{E}$ - velocity of kinetic energy during transformation into thermal energy.

The model solution is created by Fire Dynamics Simulator (FDS) computer software. The spatial model was created in the PyroSim 2020 software system, which is a graphical interface of the FDS software and is used to modify and control input data.

3 Description of the apartment model in FDS

The residential building has five floors. Five storeys is the maximum number of storeys allowed for timber buildings with passive fire protection in Slovakia. Numerical simulation is a time-consuming process; we limited the investigation of the fire progression in a confined space to one dwelling unit. The apartment consists of five rooms - entrance hall, bathroom, bedroom, kitchen connected with living room and pantry, it is located on the second floor, the perimeter construction is on two sides of the apartment.

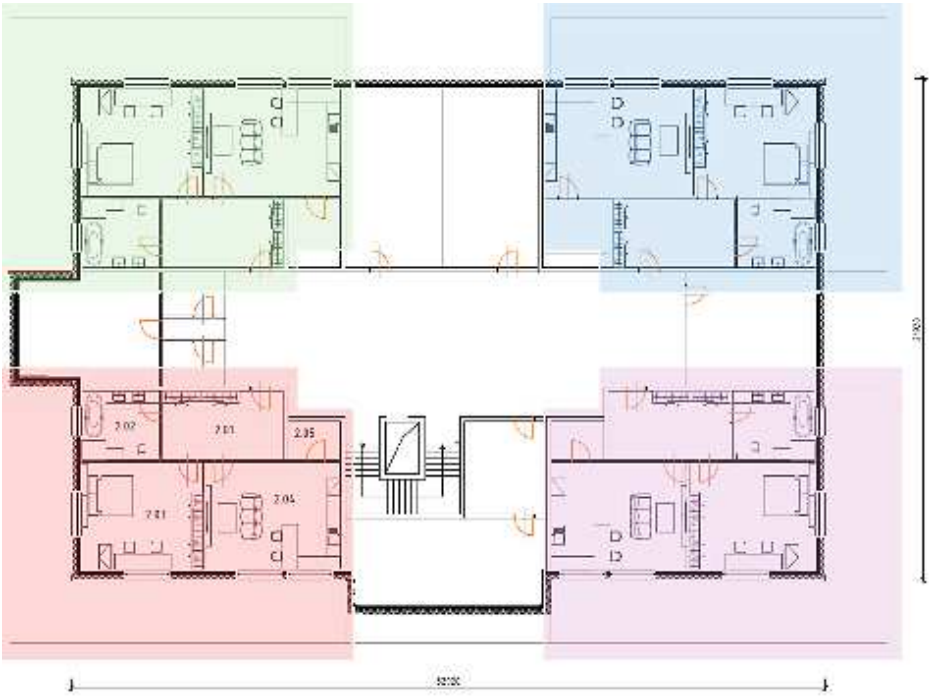


Fig.1: Floor plan of the apartment building.



Fig. 2: 3D model of the apartment building, PyroSim.

The load-bearing structural system of the apartment building is made of a system of vertical and horizontal CLT panels. The building is made of timber structures, which are protected from the interior by fire-resistant plasterboard cladding of 15 mm thickness. The entrance door to the apartment is fire rated, with a fire resistance rating of 30 minutes. A structural unit of building type D2 is defined as mixed according to STN 920201-2 if its structural elements do not increase the fire intensity because they have a reaction to fire class B or less. Structures having a higher reaction to fire class than A1, A2 s1d0 or B are completely enclosed within structures of reaction to fire class B or less. All cavities in the envelope - installation walls shall be filled with thermal insulation materials of reaction to fire class A1, A2 with a melting point of 1000 °C and shall be in a fixed position to prevent deformation and displacement in the structure during use. Combustible materials in structural element D2 shall not reach the flash point during the minimum required fire resistance period. This category includes lightweight sandwich construction with a load-bearing timber structure and cladding on both sides with non-combustible boards, e.g. plasterboard, provided that mineral wool or other non-combustible thermal insulation is placed in a fixed position in the sealed air gaps throughout the use of the building [21]. The flammability and combustibility of timber structures is defined by calorimetric measurements [10, 22, 23]. In the model solution, all internal partitions are made of CLT panels of 100 mm thickness. The perimeter wall consists of CLT panels 150 mm thick, which is on the interior side with plasterboard cladding, on the exterior side with a full-surface insulation of mineral wool with thin-layer plaster. Internal load-bearing and fire partition walls are made of CLT panels 150 mm thick and plasterboard cladding on both sides. Physical characteristics of the fire separating construction materials used in the simulations of the model solution, seen in Table1. The model solution considers a fire in the apartment indicated in Fig. 2. The method of fire design or assessment of the fire barrier comprises the choice of the model fire scenario, determination of model fire, calculation of the temperature development in structural members and calculation of the mechanical behaviour of a structure exposed to fire [24].

3.1 Fire scenario

A burning candle on a table in the living room was considered as the source of the fire in the simulation, which ignited the sofa and subsequently developed a fire in the room and the apartment.

In parametric fire simulations, we consider the following boundary conditions:

- The average fire load density in the apartment is about 970 MJ/m².
- The oxygen supply is provided by windows in the perimeter walls, and their integrity was considered to be compromised within 3 minutes after the fire started.

The dynamics of a parametric fire is directly dependent on the variable boundary conditions, which in this case are the ventilation parameter.

In variant A, the fire simulation considers the ventilation of the apartment by windows, which are 30 % of the area of the envelope. The height of the windows is 1.5 m, widths according to the location in the plan, see Fig. 3.

In variant B, the fire simulation considers the ventilation of the apartment with French windows, the height of which is 2.4 m, which is about 60 % of the total area of the perimeter walls. The dimensions of the apartment are approximately 8.5 m x 12 m with height of 2.6 m.

The aim of the analysis is to determine the time history of fire in a dynamic simulation of an apartment with a standard fire load as a function of the ventilation parameter. The load-bearing system

of the timber building, including the partitions, is made of CLT panels, which are protected by fire-rated plasterboard cladding. The compositions of the boundary structures of the apartment are shown in Table 1.

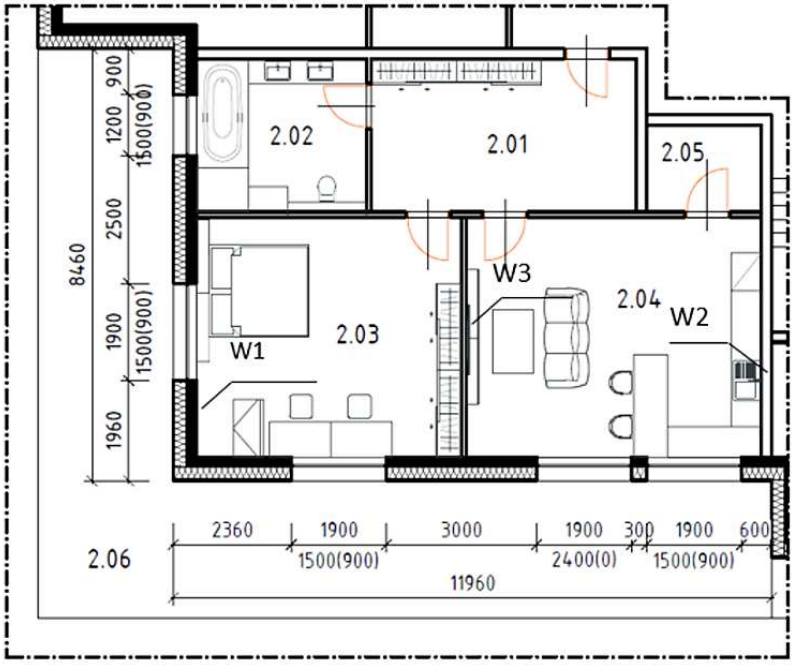


Fig. 3: Floor plan of the apartment building.

Table 1: Thermal properties of non-combustible materials used in computational simulations.

Construction	Type of a layer	Thickness [mm]	ρ [kg/m^3]	λ [W/mK]	Specific heat [kJ/kgK]	Emissivity
Wall 1	Gypsum plasterboard	15	750	0.22	1.06	0.9
	CLT panels	150	470	0.11	1,6	0.9
	Mineral wool	180	120	0.040	1.74	0.9
	Silicate plaster	10	1800	0.8	0.01	0.9
Wall 2	Gypsum plasterboard	15	750	0.22	1.06	0.9
	Wooden CLT panels	150	470	0.11	1.6	0.9
	Gypsum plasterboard	15	750	0.22	1.06	0.9
Wall 3	Gypsum plasterboard	15	750	0.22	1.06	0.9
	Wooden CLT panels	100	470	0.11	1.6	0.9
	Gypsum plasterboard	15	750	0.22	1.06	0.9
Celing C1	Gypsum plasterboard	15	750	0.22	1.06	0.9
	Wooden CLT panels	200	470	0.11	1.6	0.9
Floor F1	Wooden parquet	12	600	0.18	2.51	0.9
	Mineral wool	40	180	0.050	1.74	0.9
	CLT panels	200	470	0.11	1.6	0.9
	Gypsum plasterboard	15	750	0.22	1.06	0.9

The aim of the analysis is to determine the time history of fire in a dynamic simulation of an apartment with a standard fire load as a function of the ventilation parameter. The load-bearing system, including the partitions, is made of CLT panels.

The parametric simulations in the graphs are:

• **Variant 1A** - the external walls are on the exterior side with full insulation of mineral wool with thin layer plaster. The window area is 30 % of the envelope area. All walls are on the interior side with plasterboard 15 mm thick with fire protection function.

• **Variant 1B** – the external walls are on the exterior side with full mineral wool insulation with thin-layer plaster. The window area is 60 % of the envelope area. All walls are on the interior side with plasterboard 15 mm thick with fire protection function.

In the simulations, the activation of sprinklers and alarms was not considered. For this type of building, active fire-technical devices are not considered under Slovak legislation.

4 Results of parametric simulations

4.1 Variant 1A

The apartment is of mixed construction unit with fire-protected timber structure on the interior side plasterboard thickness of 15 mm. The dynamics of the fire progression in the apartment is shown in time sequences in Fig. 4.

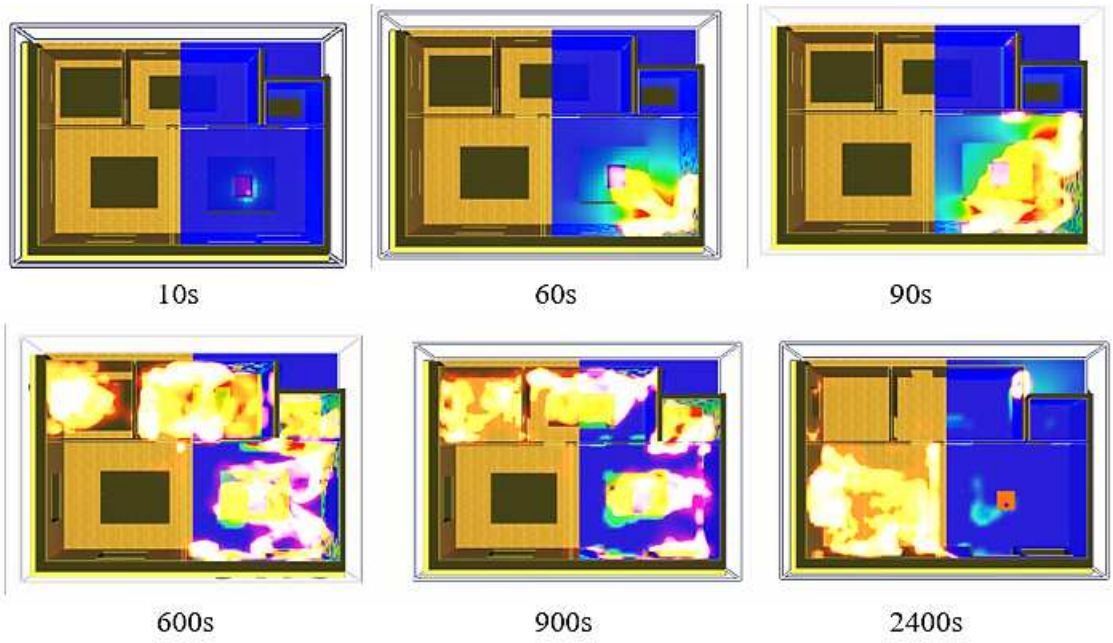


Fig. 4: Dynamics of the course of fire in apartment - Variant 1A.

From the ignition of the source, after approximately 90 seconds, the accidental fire load burns throughout the room. The accidental fire load from furniture and equipment is simulated in the rooms by a wood dump - in the simulation these are dark rectangles with a resulting fire load density of approximately 970 MJ/m^2. After 180 minutes, the fire intensity increases significantly, due to deformation of windows and cracking of glazing. This causes an increase in the temperature of the gases and, after the integrity of the door has been broken, it spreads to the three rooms of the flat which are connected to the room with the source of combustion by the door. Subsequently, the heat release rate increases with the destruction of the windows in these rooms, as can be seen in the graph - a step increase in the heat release rate. The rooms are burnt out by random and steady fire loads. The peak temperature of the gases in the burning apartment is about 500 seconds after the start. Burning out of combustible materials - accidental and continuous fire load occurs after about 1800 seconds. By this time, the adjacent room has not been involved in the burning process with its fire load. The ignition process of the accidental fire load in this room occurs at about 2000 seconds, at about 700 seconds its fire load burns out. After 2700 seconds the cooling process occurs.

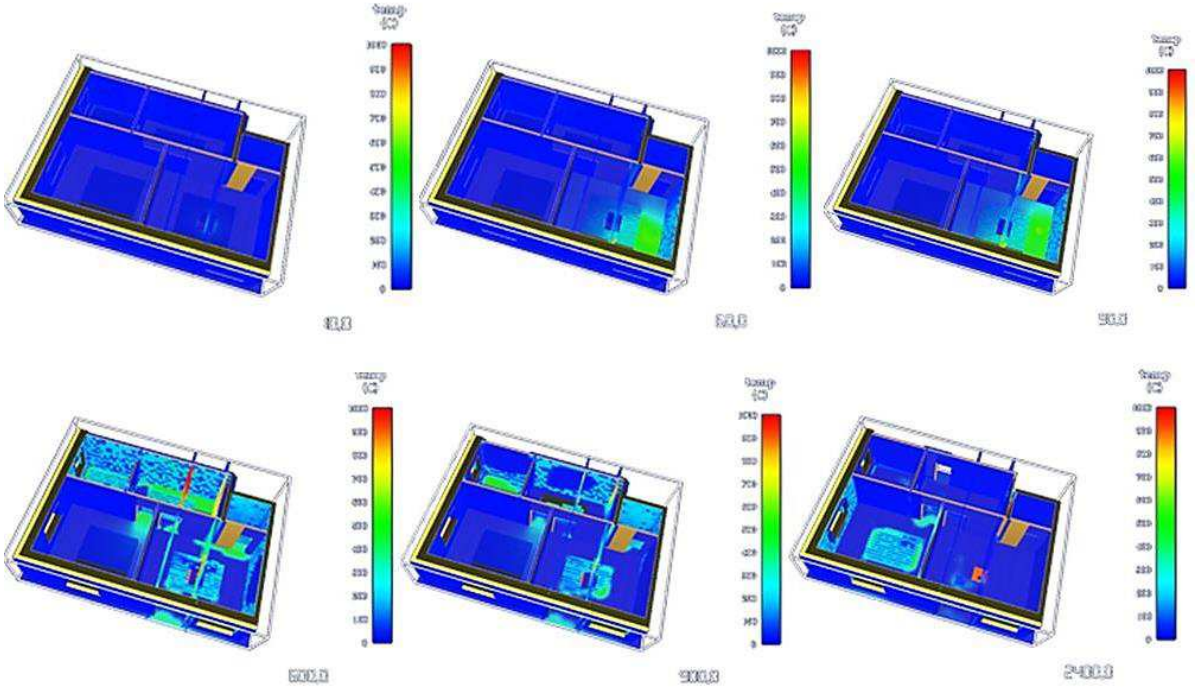


Fig. 5: Dynamics of thermal stresses on fire-divisible and load-bearing structures by fire in the apartment - Variant 1A.

Protected timber elements were not involved in the combustion process. When designing the anchorage and connections, it is important to protect the connecting elements so that they do not melt due to surface temperatures and consequently the possible loss of the fire protection integrity of the timber elements. The maximum heat release rate is about 68 MW.

4.2 Variant 1B

The apartment is of mixed construction with fire protected timber construction. The dynamics of the fire progression in the apartment is shown in time sequences in Fig. 7

From the ignition of the source, after approximately 90 seconds, the accidental fire load burns throughout the room. After 180 minutes, the fire intensity increases significantly, due to deformation of windows and cracking of glazing. This causes an increase in the temperature of the gases and, after the integrity of the door has been broken, it spreads to the three rooms of the flat which are connected to the room with the source of combustion by the door. Subsequently, the heat release rate increases with the destruction of the windows in these rooms, as can be seen in the graph - a step increase in the heat release rate. The peak temperature of the gases in the burning apartment is about 300 seconds after the start. Burning out of combustible materials - accidental and permanent fire load in the greater part of the apartment occurs after about 1500 seconds. By this time the adjacent room has not been involved in the burning process with its fire load. The ignition process of the accidental fire load in this room occurs at about 2000 seconds, at about 500 seconds its fire load burns out. After 2700 seconds the cooling process occurs. The maximum heat release rate is about 58 MW. The temperature on the surfaces of the structure ranges from 300 to 550 °C, see Fig. 8.

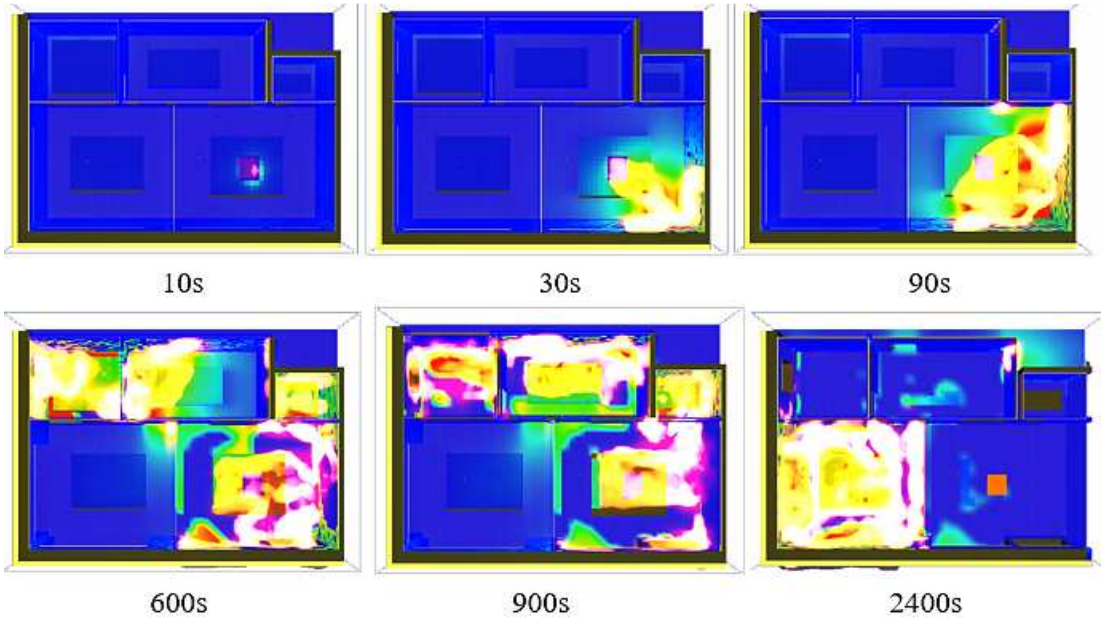


Fig. 6: Dynamics of the course of fire in apartment - Variant 1B.

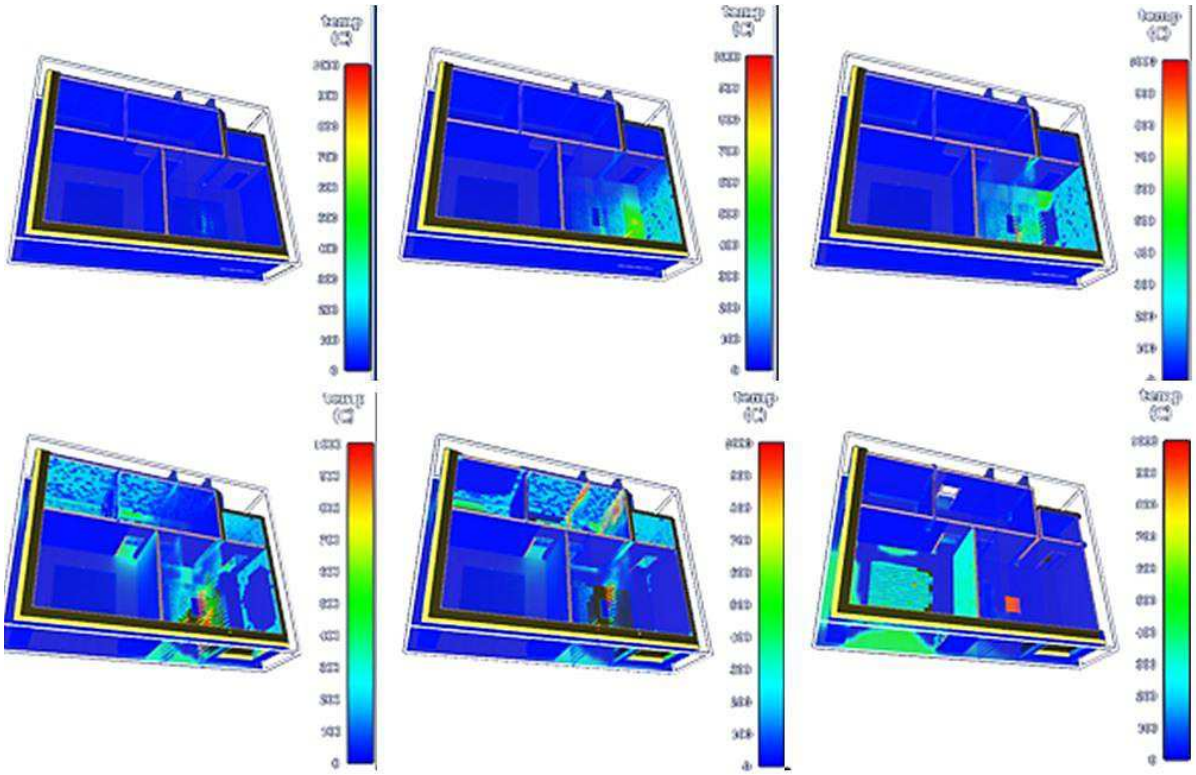


Fig. 7: Dynamics of thermal stresses on fire-divisible and load-bearing structures by fire in the apartment - Variant 1B.

4 Conclusion

In the computer simulation carried out using FDS software, we found that for a mixed structural unit, the fire dynamics varies depending on the ventilation parameter. The comparison of the combustion dynamics in the apartment in variants 1A, 1B can be seen in the Fig. 8.

As the venting parameter increases, the heat release rate decreases and the whole combustion process shortens. The heat load time as well as the surface temperature of the fire bearing and fire dividing structures is reduced. With decreasing window area in the envelope wall, which has an impact on the ventilation parameter, the heat load on the building structures as well as the fire duration increases.

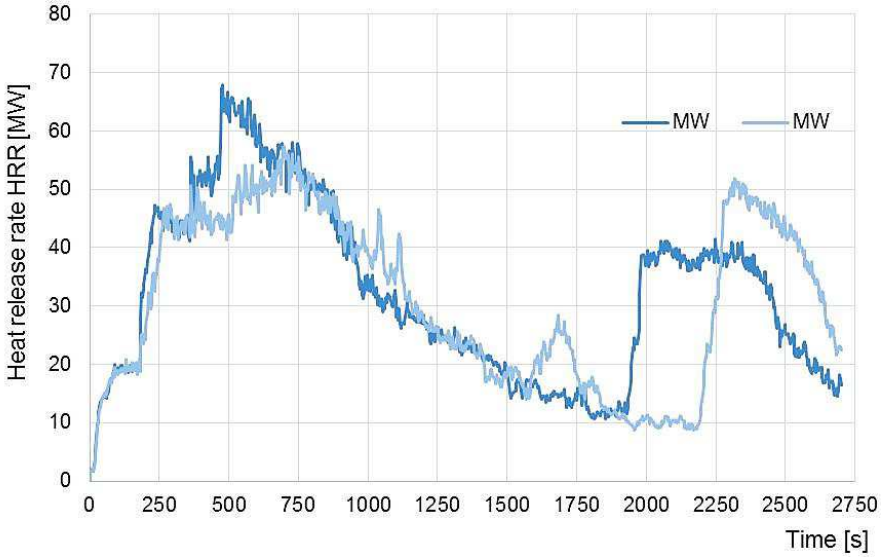


Fig. 8: Heat release rate in fire - Variant 1B.

Protected timber elements were not involved in the burning process. When designing anchorages and connections, it is important to protect the connecting elements so that they do not melt due to the surface temperatures and consequently the possible loss of the fire protection integrity of the timber elements.

The requirement for fire resistance according to the standard fire according to the calculation methodology STN 920201-1 is for fire dividing structures REI 60, for the perimeter wall from the interior side REW 60, for load-bearing structures located in the fire section R60. In terms of the simulation for the boundary conditions of a parametric fire controlled by ventilation, the time of exposure to thermal loads is significantly lower than the minimum required value of fire resistance in terms of the standard requirements. It follows that their sizing in practice is significantly on the side of safety. The methods of anchoring and protection against high temperatures are decisive for maintaining the integrity of protective cladding systems.

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