CHIMNEYS' INFLUENCE ON FIRE RISK OF SOLID WOOD STRUCTURES IN RESIDENTIAL BUILDINGS IN RURAL BALKAN SETTLEMENTS

by

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According to official fire statistics, chimney fires account for almost 20% of all fires that occur in family residential buildings every year in the Balkan region. The high temperature from the chimneys may have an influence on fire spreading to the wooden girders. The objective of the study was to gather and analyse data on timber structure fire incidents occurring in family residential buildings in lowland rural settlements in Serbia (2010-2014) and a mountain settlement in Montenegro (2007-2013) in order to determine the extent to which existing data can be used in fire risk assessment. Additionally, the chimney-timber floor heat transfer mechanism was investigated, namely, the time dependent temperature distribution in the cross-section of few types of mostly used chimneys and floor structures were analysed. This research illustrates how the lack of chimney maintenance and social vulnerability of the settlements (aged rural population with low incomes, living in many cases alone in old houses in areas with limited access to distance heating systems or piped gas) could influence the fire risk in timber structures in rural lowland and mountain areas. It is shown that significant differences exist with respect to fire causation over time and the type of wooden structural elements – due to different temperature distribution in the cross-sections of the floor structure, both in lowland and mountain settlements.

Key words*: chimneys, fire statistics, timber structures, heat transfer, residential buildings, risk analysis*

Introduction

Fire safety is widely considered as one of the most significant obstacles to the increase of use of wood in construction. Most fire regulations in Europe have traditionally been very prescriptive and based on experiences from large city fires. Combustibility of wood, unlike of other structural materials commonly used (*e.g.* concrete, steel or masonry), is the main reason why most building codes strictly limit the use of timber as building material. In North Macedonia, timber structures are limited to low-rise buildings up to two storeys. Although in Serbia, since

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2009, the Fire Protection Law [1] allows the use of performance based design and risk analysis, it is still not frequently in use, as is the situation with the other Balkan and European countries [2]. In fire risk classification and analysis, the Serbian building codes do not treat differently timber or timber based structures based on the applied type of wood or wood based product, cross-sectional area of elements or applied structural system and type of structural connections. The number of storeys is not strictly limited by the fire safety codes, but buildings with a principal timber structure are generally constructed as low rise buildings with maximum two storeys. The official statistics of both Serbia and North Macedonia show that wooden houses account for about 1% of the total housing (residential homes) construction, while concrete, steel and masonry (clay products) dominate in residential and public buildings. The situation in Montenegro is similar [3]. However, the entire Balkan building heritage includes wooden churches and monasteries as well as numerous historical buildings in rural and central urban areas that are completely or partially (only roofs and ceilings) made of wood [4]. Traditional buildings constructed of local poplar wood and mud mixed with straw, covered and reinforced by reed, are present in the north region of Serbia, *i.e.* Vojvodina plain. Prefabricated wooden elements such as light-frame trusses connected by punched metal plates are frequently used for rehabilitation of flat roofs in urban areas. Other prefabricates such as LVL, I joists and beams*, etc.*, are not present due to a lack of domestic production. Residential prefabricated modular houses made of timber frame panel walls finished by timber boards (OSB, particle, veneer, plywood*, etc.*) have recently (after a severe earthquake in 2010) achieved a significant progress because of the rapid construction and good performance in case of seismic events [5]. Glulam products are usually used for sport halls, swimming pools, hotels, small bridges and other public representative buildings or special canopies. Technologically advanced products, such as cross laminated timber are not present in modern construction sector in Serbia, North Macedonia and Montenegro [3, 6, 7]. Although not a dominant building material, the use of wood is inevitable: traditional roof structures made of solid timber are still dominantly used in residential buildings.

Fire statistics database and analysis represent the basis for fire risk identification, analysis and assessment. Temporal analyses of timber structure fire incidents occurring in rural lowland settlements in Serbia (Žabalj and Žitište, from 2010-2014) and a mountain settlement in Montenegro (Pljevlja) are carried out. Statistical data is provided by fire-brigades, meaning that they are based on field experience, not experts' investigation. Fire inspectors and court officials are obliged to conduct investigations and provide detailed reports for official legal use, which are not accessible without a special legal approval, often resulting in a very long and difficult procedure.

According to official Serbian fire statistics, chimney fires account for almost 20% of all fires occurring in family residential buildings. Fire-brigades classify the burning accumulated soot and tar inside the chimney as chimney fire. High temperature from the chimneys may have an influence on fire spreading to wooden girders. However, the applied structural systems or used cross-sections of elements behave differently in case of fire [8]. Emissions of heat or sparks through the cracks in the chimneys, or open or faulty door for cleaning the flue gas duct may lead to ignition of flammable material around the chimney in the attics. If the chimney is not maintained, it may cause inflammation of accumulated soot and tar within the channel. Many fires occur because of a damaged stove or failure of the tubes that connect the stove and the chimney, or due to poorly executed connection or overloading of the chimney. If the potential risk pertaining to fire occurrence is higher for wooden buildings than for other buildings, special methods, materials and practical skills are needed [8].

In normal regime, the temperatures inside the chimney may differ, depending on the type of the heating system and the fuel. Nowadays, the testing of chimneys is standardized

[9] and the temperature class is indicated in the CE marking of fireplaces, as T80 up to T600 (T indicates the maximum nominal operating temperature). In the highest temperature classes, *e.g.* T400, T450, and T600, the hot gas temperature used in testing the chimney is 100 °C higher than the indicated temperature class. However, the standardized tests do not provide temperature data required for dimensioning chimneys. The tests conducted by Peacock in 1987 [10] showed that the evolvement of fireplaces over the years had resulted in higher flue gas temperatures being developed. For the possible operational conditions of a metal chimney, Neri and Pilotelli [11] conducted extensive measuring tests at the chimney-roof penetration, considering real operating conditions [12] and the conditions considered in the chimney certification procedure [13]. The main differences between these two conditions were compared in [14]. In [15] a 2-D and a 3-D numerical models for the estimation of the steady temperature at the chimney-roof penetration were defined. In [16] it was shown that the smouldering combustion within mineral wool usually installed at the chimney-roof penetration may cause an increase in temperature up to 100 °C.

For the commercial room heaters that use wood as fuel, the mean flue gas temperature indicated in the CE marking is usually T250 °C. However, in the temperature safety tests, intended to ensure the fire safety of the area around the fireplace, studies conducted by Leppanen [17] have shown that the measured flue gas temperatures were 124-381 °C higher than those of the CE markings. According to CICIND report [18] the temperatures in normal regime are between 200 °C and 400 °C.

When wood is exposed to constant heating over a period of time, it may undergo chemical change resulting in a much lower ignition temperature and increased potential for self-ignition. From that reason a very important factor in preventing fire in wooden houses is limiting the temperature rise in timber and other surrounding flammable elements. When wood burns slowly and makes a smoky fire, the smoke can condense on the cool inner surface of the chimney producing creosote deposits. Creosote is a highly-flammable material. If it ignites at the base of the chimney, it can produce a raging fire that travels up the chimney causing extremely high temperatures as it spreads. In case when coal is used as a fuel, the chimney fire may reach 1000 °C, while in case of a wooden fuel, it may even reach 1200 °C [19]. In such a case the chimney may become hot enough to ignite nearby building materials and start a house fire. Because of that, according to Standards EN 1856 and EN 1859, chimneys designated as soot-fire resistant have to be subjected to a chimney fire test. In the test, hot gas temperature must be 1000 °C (–20 °C/+ 50 °C) for 30 minutes after which the hot gas generator has to be turned off. The influence of the materials between chimney and roof, studied in [20, 21] showed that installing a conductive material in the clearance between chimney and roof delays the peak temperature on the roof and the maximum temperature remains much lower than in case with insulating material only.

Fires in floor and roof structural elements occur due to damage of chimney walls, chimneys in contact with wooden girders or walls and other poorly insulated or non-insulated wooden structural elements, tab. 1, according to [22].

Table 1. Chimney fire causes in Serbia in the period 2002-2013

Year *	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	Total
Structural defects	45	53	48	81	226	43	30	38	69	52	46	17	748
Fireplace malfunction	295	338	394	368	315	213	247	385	414	603	547	174	4293

* Data from 2002 to 2009 are based on preventive protection inspector's survey, while data from 2010 to 2013 are based on fire rescue units' intervention records

The main objective of this study was to gather and analyse data on various causes of fires in order to determine the extent to which existing data can be used in fire risk assessment. This research illustrates how the patterns of timber structural fire incidents vary, showing significant differences existing in respect to fire causation over time and the types of heating systems in buildings. The other objective was to show that the materials used for the chimney and the construction details are important factors for preventing fires in traditional wooden houses. In the Balkan countries, chimneys are usually made of brick work, with or without rendering from outside, with wooden girders in floor and roof structures made of oak and pine and often placed close to the chimney. The temperature development in case of chimney fire and the impact on the surrounding elements is studied numerically using heat transfer analysis. To quantify the fire resistance of the floor assemblies in contact with chimney, standard ISO 834 [23, 24] fire curve is adopted, starting from 250 °C, up to 1200 °C, as it is recommended for room heaters and wooden fuel [17, 19].

Methods of fire risk analysis

The following study consists mainly of the two kinds of research. First, a literature review is made, reporting statistical data on fire occurances in a lowland and mountain settlements in Serbia and Montenegro, pointing the problem of interest, followed by the numerical research on the heat transfer occuring in case of a chimney fire.

Fire statistics

Fire statistics on the history of fire occurrences (specific place/room, season, month, time of day) is valuable for fire risk assessment in terms of probability calculation. Spatiotemporal analysis of fire incidents could provide useful information for planning of fire prevention and response activities in terms of risk identification, resource targeting and routing of fire personnel and equipment, allocation of preventative measures, and policy evaluation [25, 26].

To improve the risk analysis and assessment, it is important to research specific types of settlements (buildings, dwellings, inhabitants). The knowledge on the age and quality of dwellings or the type of installation and equipment, as well as the habits of the residents could be helpful in risk identification. Relations between the characteristics of the settlements and fire occurrences could also contribute to the creation of better fire prevention plans and measures, which would contribute to mitigation of social vulnerability of analysed settlements. The elderly and/or single households, with low incomes and limited access to distance heating system or piped gas, are not able to provide stoves of good quality or proper maintenance of their homes and chimneys, often using lower quality coal and wood for heating, which contribute to faster forming of soot and tar layers in the chimneys.

Modelling of heat transfer at chimney-roof penetration

The non-linear and transient temperature distribution can be calculated by use of the Theory of Heat Transfer [27, 28].

The governing differential equation for conductive heat transfer:

$$\frac{\partial}{\partial x}\left(\lambda_x \frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda_y \frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(\lambda_z \frac{\partial T}{\partial z}\right)=\rho c\frac{\partial T}{\partial t} \tag{1}$$

where $\lambda_{x,y,z}$ is the thermal conductivity in all three directions (temperature dependent), ρ – the density of the material (temperature dependent), c – the specific heat (temperature dependent), T – the temperature, and t – is the time parameter.

The temperature distribution in the cross-section of the timber floor structure which is in contact with the chimney depends on: the position and distance of the timber elements from the chimney, the geometry and thermal properties of the chimney elements and timber, the thermal properties of eventual protective layers and the temperature inside the chimney.

The boundary conditions can be modelled in terms of both heat transfer mechanisms: convection and radiation.

The heat flux caused by convection:

$$q_{\mathrm{c}} = h_{\mathrm{c}}\left(T_{\mathrm{z}} - T_{\mathrm{f}}\right) \tag{2}$$

where h_{c} is the coefficient of convection (for wall in room at ambient temperature the recommended value is $h_{\mathrm{c}} = 4$ W/m^{2}K, while in case of room fire, or in case of air-flow through the chimney (chimney fire) its recommended value is $h_{\mathrm{c}} \geq 25$ W/m^{2}K) [27, 29, 30], T_{z} – the temperature at the boundary of the element, and T_{f} – the temperature of the fluid around the element.

The heat flux caused by radiation:

$$q_{\mathrm{r}} = V\varepsilon\sigma_{\mathrm{c}}\left(T_{\mathrm{z,a}}^4 - T_{\mathrm{f,a}}^4\right) = h_{\mathrm{r}}\left(T_{\mathrm{z}} - T_{\mathrm{f}}\right) \tag{3}$$

$$h_{\mathrm{r}} = V\varepsilon\sigma_{\mathrm{c}}\left(T_{\mathrm{z,a}}^2 + T_{\mathrm{f,a}}^2\right)\left(T_{\mathrm{z,a}} + T_{\mathrm{f,a}}\right) \tag{4}$$

where h_{z} is the coefficient of radiation (temperature dependent), V – the radiation view factor (usually, $V = 1.0$), ε – the resultant coefficient of emission $\varepsilon = \varepsilon_{\mathrm{f}}\varepsilon_{\mathrm{z}}$, and $\varepsilon_{\mathrm{f}} = 1.0$ is the coefficient of emission for the surrounding fluid, ε_{z} – the coefficient of emission for the surface of the element for brick elements $\varepsilon_{\mathrm{z}} = 0.9$, $\sigma_{\mathrm{c}} = 5.67$ W/m^{2}K^4 – the Stefan-Boltzmann constant, $T_{\mathrm{z,a}}$ – the absolute temperature of the surface, and $T_{\mathrm{f,a}}$ – the absolute temperature of the fluid.

In case of chimney fire analysis, $T_{\mathrm{f,a}}$ is the room air temperature or the flue gas temperature.

The solution of a differential eq. (1) with defined initial and boundary conditions, which takes into account the temperature-dependent thermal characteristics of the materials, is only possible by using numerical methods, such as the finite element method (FEM). The computer program FIRE [28], which was used for the analysis, is based on FEM and originally was developed at the Faculty of Civil Engineering in Skopje, North Macedonia. The program FIRE was verified through a few case studies [28, 31-34] by comparing the numerically achieved results with the experimental ones and with the results obtained by use of the SAFIR program [35].

Results and discussion

Risk analysis of settlements' population, quality of dwellings and fire events

The statistical data on fires for the analysed settlements were provided by the local firefighting brigades (Serbia: 2010-2014, Montenegro: 2007-2013), while data on the dwellings and the population were obtained from the 2011 Census on Population, Households and Dwellings in Serbia and Montenegro.

Žabalj and Žitište are typical lowland settlements in Vojvodina region in Serbia, with family housing and agriculture oriented economy. The municipality of Pljevlja is located in the north of the Montenegro area, between Tara and Lim rivers. It is situated in the valley at an altitude of 700 m and is surrounded by low hills. Such geographical position makes the municipality of Pljevlja particularly vulnerable to toxic gasses in the air which consequently increases the risk of casualties in the case of fire events. It covers an area of 1346 km^2 and it is the third largest municipality in the state. The statistical data covering the two lowland and one mountain settlements is presented in tab. 2.

Table 2. Statistical data on the analysed settlements according to the 2011 census

Municipality	Žabalj	Žitište	Pljevlja
Type of settlement	lowland	lowland	mountain
Residents	26134	16841	31060
Occupied dwellings	7354	6138	10627
Temporarily unoccupied or abandoned dwellings	2527	164	
Occupied dwellings older than 25 years	6260	5382	9458
Dwellings with outer walls made of weak material*	444	3725	n/a
Average population age	39.7	43.4	41.8
Average members per households	3.12	2.67	2.92
Percentage of households having one or two members	42	54	n/a

* Outer walls built solely or predominantly of soil cement, adobe, wattle dam, boards, with pitched roof structure and attic floor predominantly made of wood

In both Žabalj and Žitište settlements, in the case of buildings made of a hard material (the outer walls are built solely or predominantly of brick, hollow clay block, gas concrete, and other contemporary construction materials and elements), the pitched roof structure is made of solid wood. These types of family houses are also predominant in city outskirts. Most of the buildings built before 1946 in the city downtown areas are also built with a pitched roof structure constructed of solid wood.

The city centre of Pljevlja comprises residential and commercial buildings. Certain parts of the city (Moćevac and Ševari) are overcrowded by illegally constructed facilities which limit the access of firefighting vehicles. There are two types of settlements in the rural area: compact and dispersed.

Significant problems of villages in the municipality of Pljevlja are: the prevalent population are elderly people, lack of water supply system and a long distance from the firefighting unit. This indicates an increased social vulnerability to fire.

A preliminary analysis indicated that most of the fires started from the chimneys [22]. These findings encouraged research of data on the type of heating installations available in Žabalj and Žitište. According to the 2011 Census, only 8.7% of the dwellings in Serbia have the availability of piped gas heating. However, the situation in Vojvodina region is better (28%), namely, piped gas is in use for heating in 39% and 51%, while district or central heating installations are available in 33% and 16% of the dwellings in Žabalj and Žitište, respectively.

There were 110 fire events in residential buildings registered by local firefighting brigades in Žabalj and Žitište municipalities in the period 2010-2014. The results of the fire statistics indicate that most of the fires occurred in the winter season, in the course of the working days of the week and during nights, fig. 1.

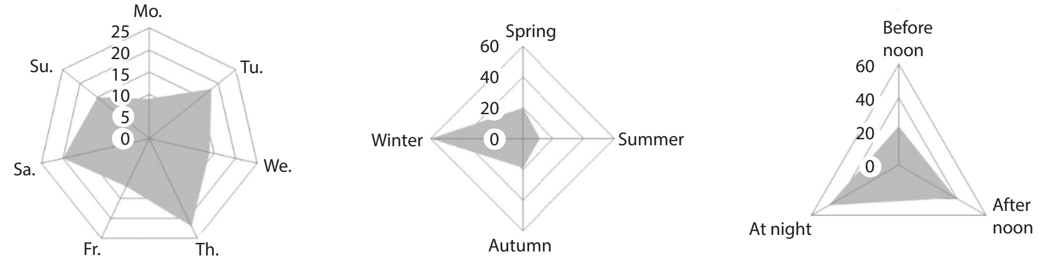


Figure 1. Daily, seasonally and period-of-the-day distribution of total fire incidents in Žabalj and Žitište municipalities, in the period 2010-2014

Since roof structures are predominantly made of wood and the fire in the chimneys may, in certain circumstances, easily spread to the roof, chimney fires increase the risk of fire in the attics or the roofs. In many cases, it only depends on the time of the fire brigade arrival whether the chimney fire will be spread further through the house. The number of chimney fires represents almost half of the number of residential building fires that broke out in the researched rural areas (47.3% or 52 out of total 110 fires) in the analysed time period. The share of roof fires is 10.9% of the total number of residential building fires (or 12 out of total 110 fires). The records in the fire-brigades' fire reports show that most of the roof fires started near the chimneys. In terms of potential risk, based on the acquired data, this may indicate the possibility that 23.1% of the chimney fires will spread to the wooden roof structures. Also, there is no fire alarm in any home in analysed area.

Having in mind that there are very limited possibilities for fire extinguishing in this type of households, an additional risk factor contributing to fire spreading is the distance to the fire-brigade station. The travelling speed of the firefighting vehicles is 1 km per minute (60 km/h). It is an adopted parameter for the calculations in Serbia. There is no time limitation for the time of arrival to the fire accident. Both municipalities have one firefighting brigade each, located in Žabalj and Žitište. The most distant settlement from the firefighting brigade is Hetin (33.7 km) in Žitište municipality and Čurug (10.8 km) in Žabalj municipality, which means that the fire has enough time to spread through the whole house, before the firefighters arrive.

District heating installations in Pljevlja are available for only 11% of dwellings. According to the data obtained from the protection and rescue services of the municipality of Pljevlja [36], there were 3662 fires in the period from 1990 to 2014, fig. 2. A significant increase in the number of fires is evident in the period from 2007-2013, fig. 3. The year 2007 is known for the large number of fires, mostly forest fires, which lasted for several days at some locations. Fires related to residential facilities were also present, but less frequent, and these were mainly auxiliary facilities. In this period, the registered number of fire-brigade interventions was 2001, out of which 1662 were related to fire events: 339 fires occurred in residential facilities, accounting for 20% of the total number of fires.

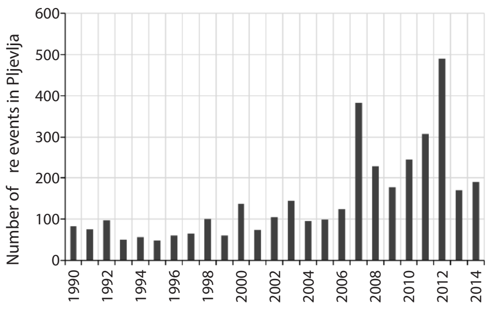


Figure 2. Number of all fire events in Pljevlja, in the period 1990-2014

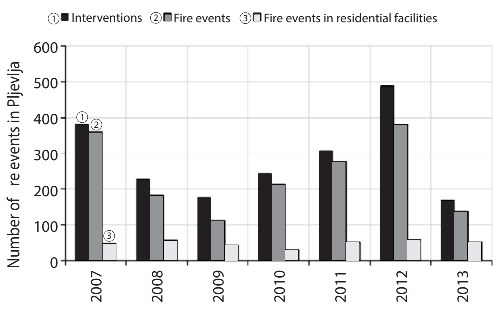


Figure 3. Number of all fire events and interventions, in the period 2007-2013

The majority of fires in residential buildings in Pljevlja broke out in winter, during heating season, fig. 4, and only 20% occurred in summer. A large number of fires in the municipality of Pljevlja were seasonal fires that occurred in summer, *i.e.* from May to September. These fires destroyed large areas of meadows, undergrowth areas and large complexes of forests of high quality wood for industrial processing. Most of the fire events in residential buildings occurred during working days of the week, with a peak on Wednesdays and Thursdays. The least number of fire incidents took place during the weekends. As to the time of the day, the fires mostly broke out at night and before noon. The most deadly fires occurred at home when people were sleeping. The most common causes of fires at night were carelessly thrown cigarettes, sparks from fireplaces without spark screens or glass doors, and heating appliances left too close to furniture or other combustibles. These fires can be particularly dangerous since they may smoulder for a long period before being discovered by sleeping residents. The same as in analysed lowland settlements in Serbia, there are no fire alarms in family residential houses in Pljevlja. Except the old and damaged electrical installations that pose a threat throughout the year, in the winter months, additional threats are the unattended lanterns and decorative candles or drying clothes on heaters.

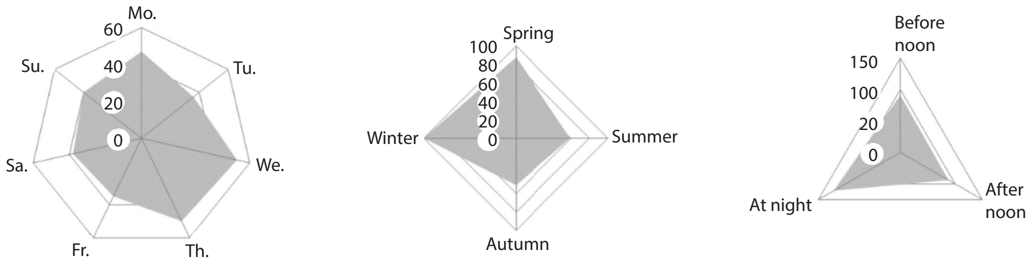


Figure 4. Daily, seasonally and period-of-the-day distribution of total fire incidents in residential facilities in Pljevlja, in the period 2007-2013

A relatively low percentage (20%) of fires in the buildings in Pljevlja occurred in the analysed period. However, a very large percentage (64%) of these fires was related to chimneys because of the dominant number of homes heated by stoves (wood and coal) and little attention paid to chimney inspection and maintenance. There are approximately 15-30 chimney fires per year in Pljevlja, making them the most frequent place of fire occurrence in housing facilities. The share of roof fires in the total number of residential building fires is 5%. According to the fire-brigades' reports, most of the roof fires started near the chimneys. In terms of potential risk, this may indicate the possibility that 7.5% of chimney fires will spread to the wooden roof structures, fig. 5.

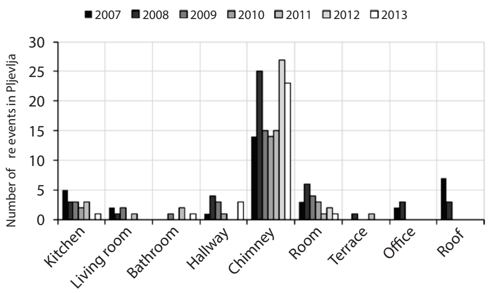


Figure 5. Fire events distribution in Pljevlja municipality, according to place of origin

Case study – Timber frame member in contact with chimney

Most of fires in rural settlements are due to inadequate chimney maintenance. In case of chimney fire, high temperatures inside the chimney (up to 1200 °C) are transferred from the chimney shaft to the surrounding elements, and if the wooden elements are located in the vicinity of the chimney, self-ignition may occur. For this reason, the influence of the chimney structure on the risk of fire is analysed in this paper. Three cases of floor structure in contact with a chimney are presented in fig. 6. In many cases, especially when it is built of decorative bricks, the chimney shaft is not rendered from the outside, fig. 6(a). In other case a mortar or gypsum plaster board is placed over the chimney shaft, fig. 6(b), but very often this layer is missing at the contact between the chimney and the wooden elements. Often, because of the

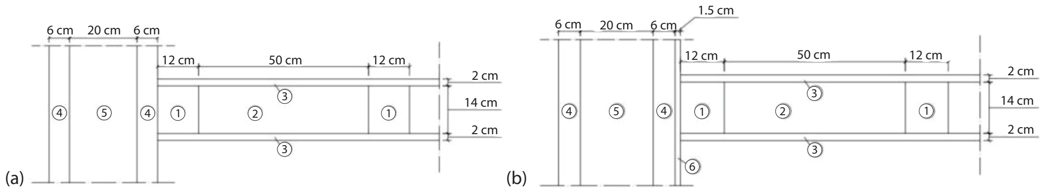
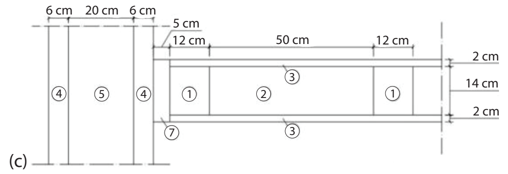


Figure 6. Characteristic detailing of a timber floor structure in rural houses; (a) without thermal insulation, (b) with insulation of mortar or gypsum board, and (c) with stone wool insulation at the contact with the chimney;
1 – timber frame element, 2 – void cavity, 3 – timber solid panels as floor covering or ceiling, 4 – chimney shaft, 5 – chimney flue, 6 – mortar or gypsum plasterboard, 7 – stone wool



heating effects, there is no insulating protective layer along the shaft, or insulation is used only at the contact between the chimney and the wooden elements, fig. 6(c).

This case study demonstrates the risk of spontaneous ignition of structural timber elements in contact with a chimney, in which, in normal regime, the flue gas temperature is assumed to be 250 °C, while in case of a chimney fire (for wooden fuel) it is assumed to rise up to 1200 °C.

Three different case studies were analysed:

– Case I – the timber frame member (beam) is in direct contact with the chimney, fig. 6(a),
– Case II – an insulation of 1.5 cm gypsum plasterboard is placed between the timber frame member (beam element) and the chimney, fig. 6(b),
– Case III – an insulation of 5 cm stone wool is placed between the timber frame member (beam element) and the chimney, fig. 6(c).

The chimney is built of bricks, d = 6 cm. The coefficient of thermal conductivity for the brick is assumed to be constant. The thermal properties of all other constitutive materials (wood, stone wool and gypsum) are temperature dependent, fig. 7, as recommended in [30, 37], and incorporated in the computer program FIRE [28] which is used for the numerical analysis. Material properties at room temperature (20 °C) are given in tab. 3.

Table 3. Thermal properties of materials at room temperature (20 °C)

Layer (see fig. 6)	Material	Thermal conductivity, λ [Wm^{-1}K^{-1}]	Specific heat, c [Jkg^{-1}K^{-1}]	Density, ρ [kgm^{-3}]
1, 3	Wood (pine) 12% moisture *	0.120	1530	580
2	Air cavity	0.026	1005	1.205
4	Brick	0.760	920	1800
6	Gypsum plasterboard **	0.400	960	950
6	Mortar	0.990	1050	1900
7	Stone wool **	0.036	880	50

* The values are recommended in EN 1995-1-2 [30] ** Nominal values at 20 °C, temperature dependency according to [37]

While defining the non-linear and transient temperature field in the cross-section of the timber floor structure, which is close to the chimney, the problem is treated as 2-D and the flue gas temperature in the chimney appears to be a unique thermal load. The air temperature in

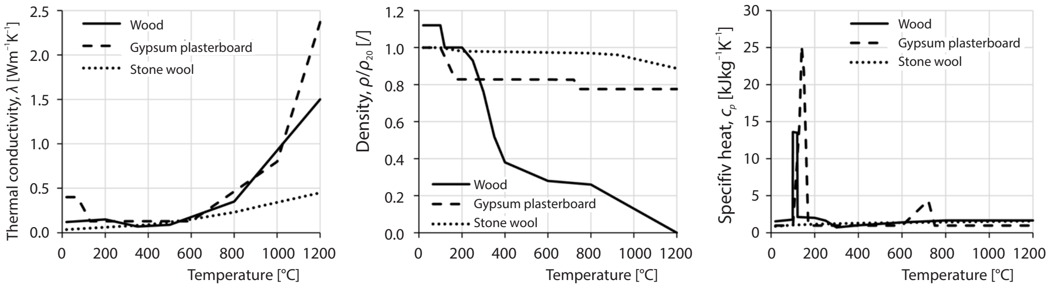
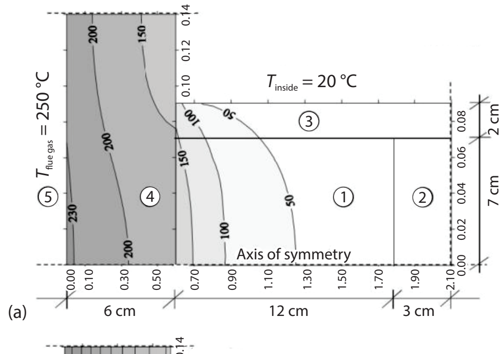


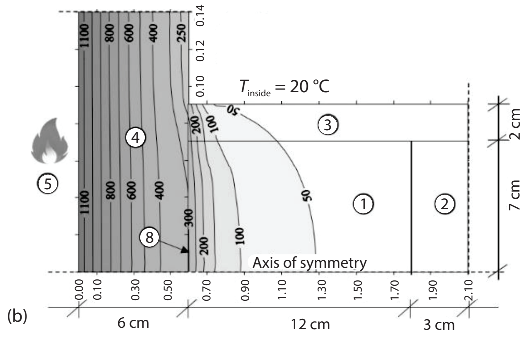
Figure 7. Temperature dependent properties of wood [30], gypsum plasterboard and stone wool [37]

the room is assumed as 20 °C. The convection coefficient for the outer surface of the chimney shaft (on the side of the room) is assumed to be 4 W/m^{2}K^1, while for the inner surface of the shaft the lowest recommended value of 25 W/m^{2}K^1 is assumed [29, 30].

A 2-D heat transfer analysis is conducted using the program FIRE. Because of the horizontal axis symmetry, only upper half parts of the assemblies are analysed. The cross-sections of the floor assembly and the brick wall chimney shaft are discretized by 1056 four node isoparametric finite elements (5 × 5 mm). The time step is 0.01 hours = 36 seconds. The time dependent temperature field in the cross-section of the timber floor assembly for the three analysed cases (with and without thermal insulation at the contact with the chimney) is presented in figs. 8-10.

In case I, the timber frame member (beam element) is in direct contact with the chimney. The isotherms in the timber floor cross-section after five hours of normal regime are presented in fig. 8(a). Within a short time after the start of the chimney fire (t = 24 minutes), the temperature in the inner part of the beam cross-section reaches 300 °C, fig. 8(b). At that moment, the charring process starts and after 12 minutes (t = 36 minutes), the whole contact sur-





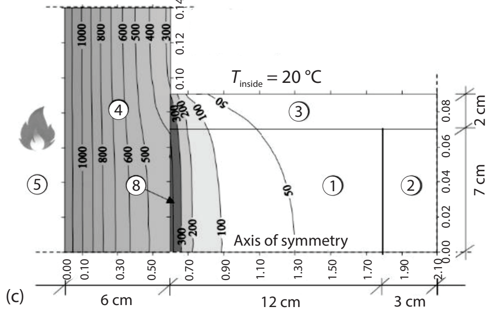
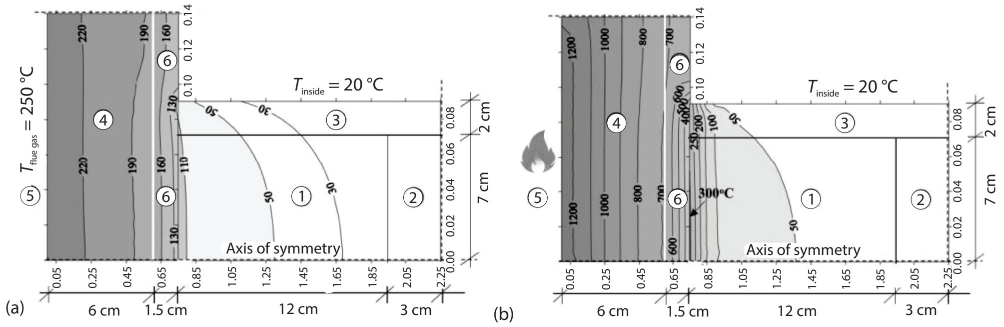


Figure 8. Isotherms after five hours of normal regime of the chimney (250 °C); (a) prior to fire, (b) followed by 24 minutes fire action (ISO 834), and (c) followed by 36 minutes fire action (ISO 834); *1 – timber frame element, 2 – void cavity, 3 – timber dolid panel, 4 – chimney shaft, 5 – chimney flue, 8 – chair layer* T_{inside} *= 20 °C*

face reaches 300 °C, fig. 8(c). This moment may be assumed as the moment when spontaneous ignition of the wooden elements starts. The charring rate in this case is 0.83 mm/min (after 6 minutes, the char layer is 5 mm).

In Case II, an insulation of 1.5 cm gypsum plasterboard is placed between the timber frame member (beam element) and the chimney, fig. 6(b). In this case, the moment of spontaneous ignition is postponed. The isotherms in the timber floor cross-section after five hours of normal regime are presented in fig. 9(a). After one hour of fire action, the temperature at the timber beam surface reaches 300 °C, fig. 9(b). After two hours, fig. 9(c), as a result of the insulating layer, the char layer thickness is only 25 mm, resulting in the charring rate of 0.416 mm per minute.

In case III, an insulation of 5 cm stone wool is placed between the timber frame member (beam element) and the chimney, fig. 6(c). In this case, the moment of spontaneous ignition is much more postponed. After 2.3 hours of fire action, the temperature reaches 300 °C, fig. 10 at some points of the cross-section. Normally, chimney fires do not last so long [38].



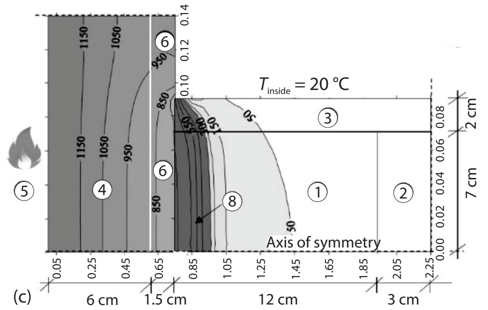


Figure 9. Isotherms in case of gypsum plasterboard insulation, after five hours of normal regime of the chimney (250 °C); (a) prior to fire, (b) followed by 1 hour fire action (ISO 834), and (c) followed by two hours fire action (ISO 834); *1 – timber frame element, 2 – void cavity, 3 – timber solid panel, 4 – chimney shaft, 5 – chimney flue, 6 – gypsum plasterboard, 8 – chair layer T_{inside} = 20 °C*

Based on the analysis it can be concluded that in case the chimney is not insulated and the wooden elements are in direct contact with the duct, self-ignition can occur in less than half an hour after the chimney fire occurs. If only one gypsum cardboard is placed between these two elements, the time is delayed by double, and in case 5 cm stone wool insulation is installed, self-ignition will not occur because chimney fires do not last more than two hours. In this case, after 2.3 hours only in one contact point a char layer (layer 8, fig. 10) is formed. By proper construction of the chimney shaft and the surrounding timber elements, the problem of room fires caused by chimney fires may be avoided.

Conclusions

Roof fires are the predominant type of fires analysed in residential family buildings, most frequently occurring in winter, during heating season, in houses without district heating or

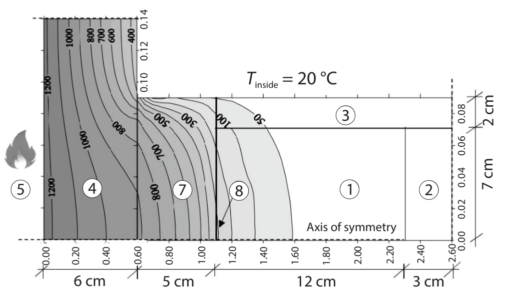


Figure 10. Isotherms in case of a 5 cm stone wool insulation between the chimney and the wooden beam element, after five hours of normal regime of the chimney, followed by 2.3 hours fire action (ISO 834); *1 – timber frame element, 2 – void cavity, 3 – timber solid panel, 4 – chimney shaft, 5 – chimney flue, 7 – stone wool, 8 – chair layer* T_{inside} *= 20 °C*

piped gas. A large percentage of fires is related to chimneys due to lack of maintenance. In most cases, fire starts in chimneys (inflamed soot and tar layers) and spreads to the timber roof construction in the attic. The risk increases with the age of the house (cracks in the chimney walls) and the lack of maintenance (chimneys are not controlled and cleaned regularly). Additional risk factors are the age of inhabitants and the distance to a fire-brigade station. The combination of all these factors may cause extensive damage, injuries and even loss of life. Since the analysed fire risks originate primarily from social vulnerability, preventive fire risk measures should contribute to increasing the resilience of local rural communities to fire hazards.

In case of chimney fires, the flue gas temperatures are very high (around 1200 °C) and may cause damage to the chimney structure and the nearby combustible parts of the building. When a chimney fire occurs in a masonry chimney, high temperatures can melt the mortar and crack the tiles. These effects provide a pathway for the flames to reach the combustible timber frame elements of the house, but adequate measures may prevent these negative effects and stop the spread of fire to the entire building. Often, because of the heating effects, there is no insulating protective layer along the chimney shaft, or insulation is used only at the contact between the chimney and the wooden elements. The results from the analyses of the three different case studies show that the moment of spontaneous ignition of the wooden elements can be significantly postponed by using insulating layers of gypsum plasterboard or stone wool between the chimney wall and the timber elements. A thin layer of 1.5 cm gypsum plasterboard delays the ignition for 2.5 times and decreases the charring rate up to 50%.

Regular chimney maintenance and control, as well as additional insulation of chimney, should be provided by local governments for vulnerable groups. Since most of the fires occur during the night, the most effective measure to prevent people's death under such circumstances is smoke alarm that would warn residents about the presence of noxious carbon monoxide fumes. It would also decrease the time needed for evacuation from the fire endangered area.

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