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TIMBER FRAME CONSTRUCTION FIRE RESISTANCE EVALUTION

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ABSTRACT

In timber frame construction, a longitudinal groove with a thermal insulation is placed between two pieces of solid construction timber. In terms of fire resistance, this contact of two massive elements must meet the required criteria. The aim of this paper is to evaluate the criteria of thermal insulation and integrity of the longitudinal groove. The fire resistance, thermal insulation and integrity criteria were assessed on the basis of a medium-scale test. The theoretical approach is based on thestandard STN EN 13501-2: 2016 and its follow-up standards. Some parts of the medium-scale test are different from the STN EN 1363-1 and STN 1365-1. Fire scenario of the medium-scale test is the standard time-temperature curve. Two timber frame constructions with different longitudinal groove, the longitudinal groove with polyurethane foam and the longitudinal groove with mineral wool insulation were subjected to thermal loading for 60 min. The integrity criterion was evaluated based on the visual inspection of the unexposed side of the test samples. The integrity criterion of the sample with mineral wool insulation and of the sample with polyurethane foam met the requirement for 60 min. The thermal insulation criterion was evaluated on the basis of the temperatures recorded by thermocouples. Tdhermal insulation met the requirement for 60 min.

Keywords: fire resistance, integrity, thermal insulation, timber frame construction.

INTRODUCTION

The wooden structure is a structure with construction elements made of wood (Záhradníček, Horák 2007). The external walls in the case of traditional log houses are constructed by the interposition of solid wooden elements (prisms or logs).

The above-mentioned construction is made up of one type of construction element, according to Kolb (2007), fulfills several functions - bearing, tiling and creating space.

Grossi *et al*. (2016) introduce in their paper, focusing the modern constructions that the logs are composed of squared solid wood or laminated beams and the logs are locked together with single or multiple tongue-and-groove connections that facilitate the assembly and improved the wall stability.

In designing the massive log constructions, it is therefore necessary to draw attention to the suitable material (suitable type of wood, the nature of insulating materials) and the construction design. Massive wood (also timber) is obtained by sawing of stems on edged construction elements of various sizes (Kuklík *et al*. 2008).

Wood, as a construction material, is a complex heterogeneous colloidal system consisting of the main (hemicelluloses, cellulose, and lignin) and the accompanying components. The thermal resistance of the basic building components of the wood is different. Hemicelluloses are the least resistant to thermal decomposition. They decompose in a temperature range of 170–240 °C. Cellulose is more resistant than hemicelluloses. At 250 °C, the cellulose decomposition is moderate. In the temperature range of 250-350 °C, there is an intense thermal decomposition of the cellulose. Lignin is the most durable component of wood in terms of thermal decomposition. Active lignin decomposition takes place at temperature interval of 300–400 °C. When wood is burning, the thermal decomposition of its basic components and the change of their chemical composition leads to the formation of many products. In addition to the chemical composition, the physical properties of wood and wood-based materials considerably influence the course of combustion. The structure of wood and the construction of wood-based materials directly affect their burning. Its effect is given by the size of the pores of micro and macro capillaries that affect the transport of oxygen to the mass and the release of volatile wood products. (ČABALOVÁ *et al*. 2013)

Timber is a flammable material and, as it was mentioned, prone to thermal degradation. In the fire conditions, timber structure is simultaneously subjected to the impact of excitations in the form of forces and thermal actions. Simultaneous action of these two factors influences the distribution of stresses in timber structure as well as limits load-bearing capacity of construction. (OGRODNIK *et al*. 2017)

According to RAMAGE *et al*. (2017), the use of timber in larger structures on fire engineering design to ensure that the building can retain its structural integrity for sufficient time either for building occupants to be evacuated, or for the fire to be extinguished and in construction using large cross-section timber features, this may be done by assuming rate at which the timber chars (BS EN 1995-1-2:2008. Eurocode 5), and therefore the cross-section of timber remaining after a given time (WELLS 2011). Research of fire resistance of wood construction according to Eurocode 5 has been realised by e.g. BELLOVÁ *et al*. (2010), KUKLÍK and KUKLÍKOVÁ (2010), LEŠKO and LOPUŠIAK (2015), LARSEN and ENJILY (2009), VAVRUŠKOVÁ and LOKAJ (2009), HOPKIN *et al*. (2011).

Design of timber structures, specifically structural fire design, is by STN EN 1995-1-2 (2008). Eurocode 5 (STN 1995-1-2 2008) includes passive methods of fire protection. In terms of mechanical resistance, at the external walls of the log cabins is determined effective cross-section.

Research of method of effective cross-section has been realised by e.g. OSVALD (2015), KUČERA *et al*. (2012), OLBŘÍMEK *et al*. (2010), LEŠKO and LOPUŠIAK (2015). Most of these authors assessed the load-bearing capacity of the ceiling structure under thermal loading. The introducted assessed the design on the basis of the large-scale test. VAVRUŠKOVÁ and LOKAJ (2009) study the adumbration of fire loaded timber structures design using normative and alternative methods.

STADE (2000) introduced the 16/20 and 20/20 cm as the smallest dimension of the edged wood beams. Among the wood element it is appropriate to place the bed joint (groove). This groove is needed wherever the wall separates the heated space from unheated or heated space from the outside (HOUDEK and KOUDELKA2011). According to BRANDEJSOVÁ *et al*. (2007), it is a weak site, quite often repeated on the area of the construction of external massive wooden wall.

This intersection of the two massive elements must be designed to ensure the most advanced and, above all, permanent barrier between the interior and the exterior of the building. The material for encapsulation of all joints must have thermal insulating properties (BRANDEJSOVÁ *et al*. 2007), bust also the required criteria of the fire resistance.

The aim of this work is therefore to assess design of the longitudinal groove of the timber frame construction, in terms of fire resistance.

EXPERIMENTAL

The core of the medium-scale test is to study the heat transfer or flame spread through a longitudinal groove in external log wall made of the solid prism. The evaluations focus exclusively on the two criteria of fire resistance, namely integrity and thermal insulation.

The general procedure for the classification of construction products in terms of fire resistance is set out in the STN EN 13501-2 (2016). The supporting elements, namely walls, are discussed in more detail in the STN EN 1365-1 (2013) and STN EN 1363-1 (2013).

The test samples were subjected to the medium-scale test. The theoretical approach is based on the above standards. Some parts of the medium-scale test are different from the STN EN 1363-1 and STN 1365-1. This is a model test, in which the test conditions are not endorsed with a medium-scale test in a certified testing facility.

The testing equipment for performing an medium-scale test to test the two criteria of fire resistance (thermal insulation and integrity) consists of the following components: a test chamber made of aerated concrete blocks, a construction to seal the sample, a device to simulate the thermal loading of the test sample (screw rods), a device used for thermal loading of the test sample − gas burners, a stand for a device designed for thermal loading of the test sample, a device for controlling the thermal loading (burner power) and hence for temperature control in the furnace, a temperature recorder, a voltage recording apparatus, an object used for evaluation of test sample integrity, timber.

The testing chamber is used to test the vertical components. It is made of aerated concrete blocks. This is a space with a bright dimension of 400 x 600 mm. Clean air can also be fed to the combustion chamber through the bottom of the opening located on the front of the testing chamber. The combustion products from the testing chamber are discharged to the free atmosphere through the upper part of the opening located on the front the testing chamber. The gas exchange during the test is based on difference in gas pressure in the testing chamber and ambient air pressure.

The thermal loading of the test sample is carried out by two propane-butane burners operating on the principle of the Bunsen burner. The sample subjected to the medium- scale test is thermally loaded according to the fire scenario - the standard time-temperature curve. The temperature on the exposed side is recorded by a thermocouple placed at the top of the testing chamber. The temperature at specific locations is scanned every 10 s for 60 min. The thermocouples are placed directly into the sample into the longitudinal groove between the two prisms. The position of the individual thermocouples is shown in Figure 1.

By the medium- scale test to test the fire resistance, the fire resistance of a log wall made of a massive prism without surface treatment was evaluated. The individual solid structural elements were made of spruce wood. Between two pieces of prism a layer of insulating material was applied. The dimensions of one prism were of 260 × 180 × 400 mm. At a distance of 50 mm from the sides of the sample, a 20 × 20 × 5 mm washer was placed between the prisms. Individual pieces of massif were joined by two twist rods that were located 50 mm from the side edges of the test sample. This way, the required voltage was generated in the test sample.

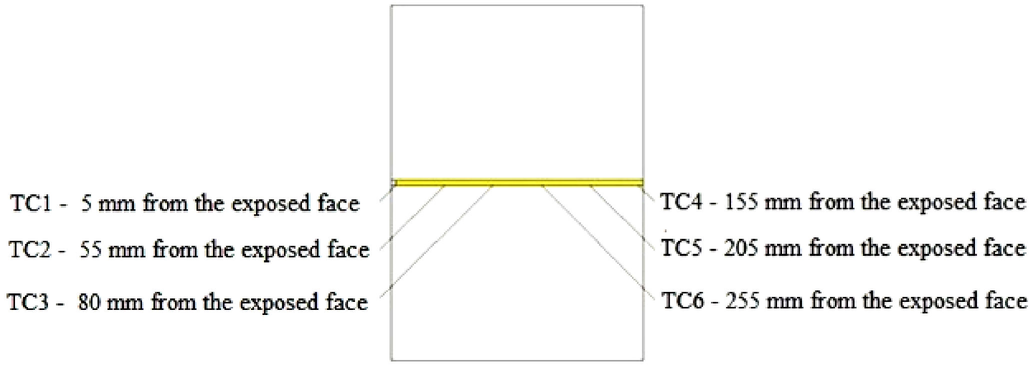

Fig. 1 Placing the thermocouples in the longitudinal groove.

On the thermally loaded side, in the longitudinal groove of the tightly insulating material, a layer of 5 mm thick fire protection sealant is applied produced based on acrylate dispersion, according to MŰLLEROVÁ and MICHALOVIČ (2012).

The differences in the individual alternatives lie in the type of insulating material that is applied to the longitudinal groove. The longitudinal groove is as follows:

- Alternative 1 – mineral wool insulation;
- Alternative 2 – mounting polyurethane (PUR) foam.

Two test samples from each alternative are subjected to the medium-scale test. Based on an input condition (simulation of thermal loading according to the standard time-temperature curve), the output values (measured by thermocouples) are divided into relevant and secondary for each alternative. Relevant results have been evaluated in this paper.

Integrity criterion

In the medium-scale test, the integrity of the individual alternatives is evaluated partially as described in the STN EN 1363-1 (2013).

The procedure for evaluating the integrity criterion is as follows:

- During the medium-scale test, the integrity of the surface of the unexposed side was visually checked at 10 min, 20 min, 30 min, 40 min, 50 min and 60 min time intervals.
- After completion of the medium-scale test, the chinks and joints on the unexposed side shall be evaluated, and the final visual inspection of the unexposed side.
- In case of the chinks and cracks occurrence:
  - Using a scale of 6 mm in diameter, it is observed their passing through a test sample;
  - The dimensions of chinks and craks are measured.
- In case of absence of chinks and cracks, the integrity criterion is retained.

Thermal insulation criterion

In the medium-scale test, the insulation criterion is evaluated based on the temperature recorded by the thermocouples.

The insulation criterion is retained if the increase in the average temperature relative to the initial average temperature is not greater than 140 °C on the unexposed side, according to the STN EN 1363-1 (2013).

RESULTS AND DISCUSSION

As the above, evaluation was subjected to one test sample of each alternative. It is always the test sample that has been able to simulate the input condition to a greater extent.

When simulating the thermal loading of the test samples, it was not possible to achieve the thermal loading of the individual test samples identical to the standard time-temperature curve (Fig. 2).

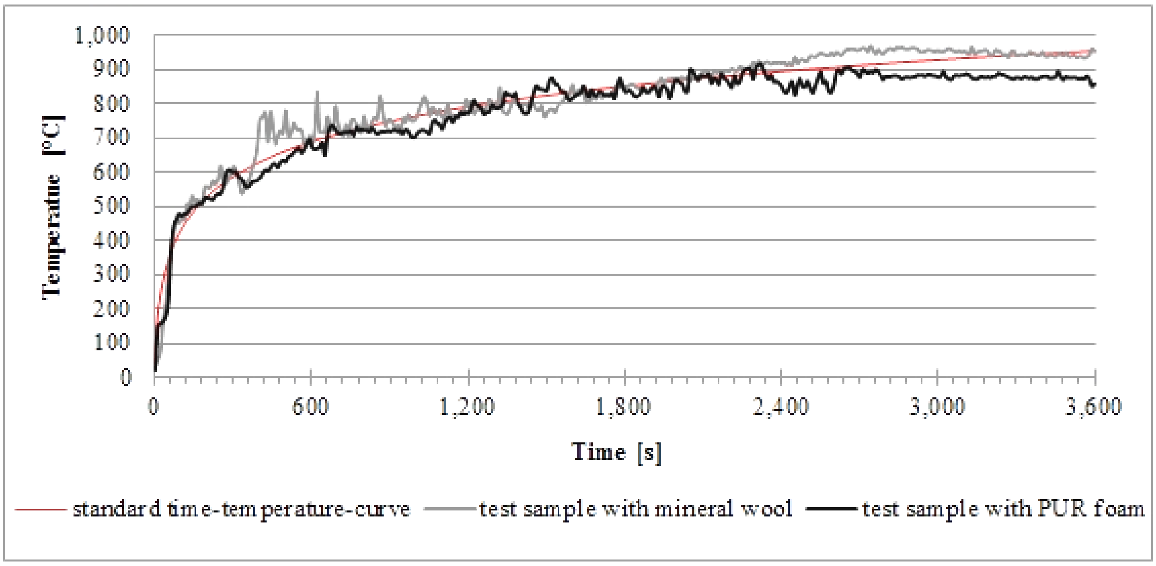

Fig. 2 Thermal loading of the test samples.

Temperature course recorded with thermocouples TC1, TC2 (at distance of 5 to 55 mm from the exposed side) – mineral wool insulation test sample (Figure 3)
The test sample was made of a 255 mm strip of stone wool and a 5 mm layer of fireproof cement, which burst in 40 s. The foamed layer of fireproof cement ceased to insulate in 80 s. Applied mineral wool insulation, specifically stone wool, consisted of two components - stone fiber and binder. Stone fibers are made from components of this test, meeting the criterion to remain stable up to temperature at least of 1,000 °C. Based on the initial condition this temperature was not reached (Figure 2).

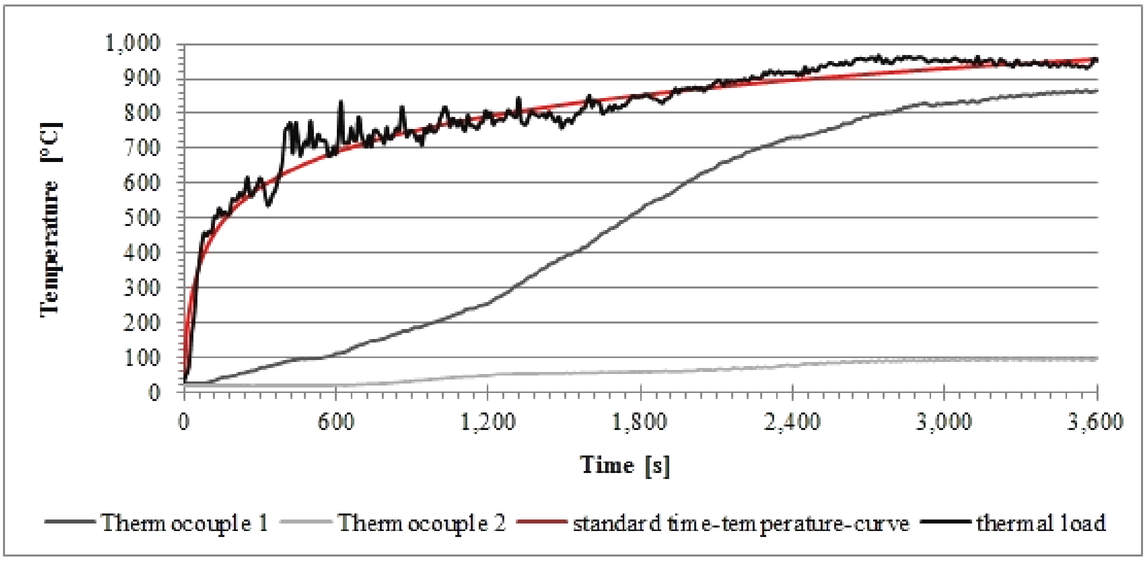

Fig. 3 TC 1 and TC2 temperature course -mineral wool insulation test sample.

According to the material technical documentation it can be stated that, during the thermal loading, a non-flammable CO_2 gas was released from a stone wool binder. Subsequent heat supply to the sample resulted in the heating of those gases.

Temperature course recorded with thermocouples TC1, TC2 (at distance of 5–55 mm from the exposed side) - test sample with PUR foam (Figure 4)

Expansion of the fireproof cement layer occurred in 40 s, when a temperature of 22.1 °C was recorded on the TC1 thermocouple. Its effectiveness has been declining from70s, with a slight increase in temperature from 75 s.

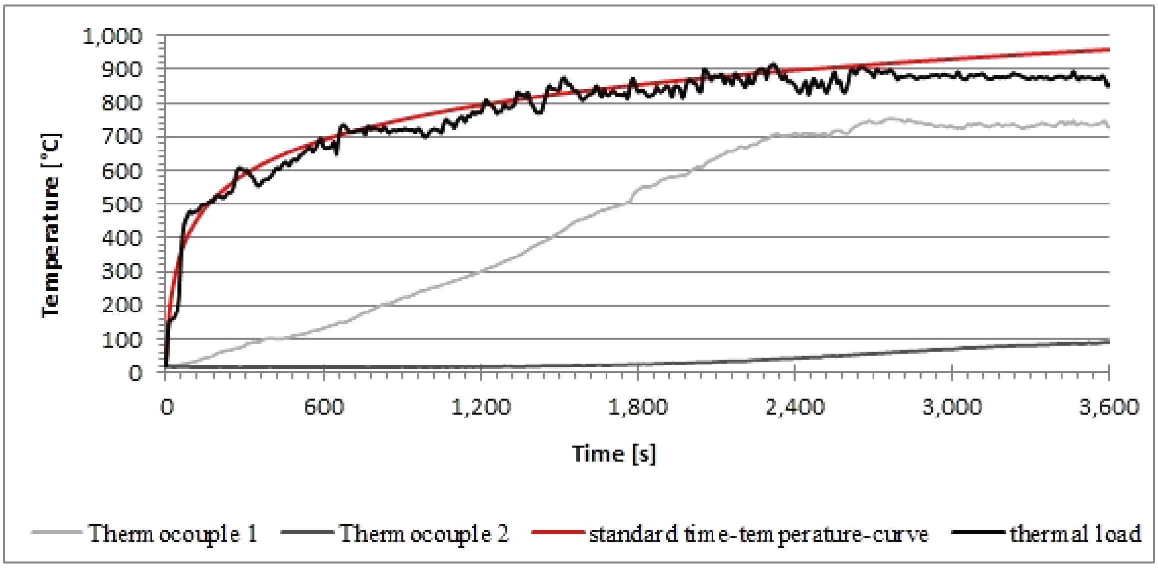

Fig. 4 TC 1 and TC2 temperature course - PUR foam test sample.

Between 420 s and 700 s the thermal decomposition of the PUR foam occurred. In the case of pyrolysis, part of the heat energy was consumed to heat the solid, which was reflected by a lower increase in temperature.

According to KOŠÍK (1986), the thermolysis of most carbonaceous polymers is carried out by a chain mechanism as a radical reaction. In addition, author states, in the thermolysis process, acetaldehyde, formaldehyde, NO, NO_2, HCN, CO, CO_2 was been released.

The flammable gases released have oxidized to the surface and, in 870 s, the flammable set has reached a lower flammability limit. In the presence of a radiant source, the PUR foam has been ignited.

The fact that the PUR foam was ignited confirms the secondary results (Figure 5), when the thermocouple TC1 recorded higher temperatures than the thermal loading itself. The difference was caused by the burning of the insulation material, which was accompanied by the release of heat from the insulating material to the environment (directly to the thermocouple TC1).

This was a burning controlled by an oxidizing agent. From the pyrolysis zone, more flammable gases were fed to the surface of the substance than was capable of oxidizing. It was revealed by the amount of unoxidized gaseous fuel, carbon residue and a slow burning process.

In 2,310 s, the values on the TC1 thermocouple dropped slightly and temperature of c.a. 150 °C stagnated. Within a given time range, the thermal loading has decreased. A smaller amount of heat was brought into the pyrolysis zone, most of which was consumed for thermal decomposition of the material.

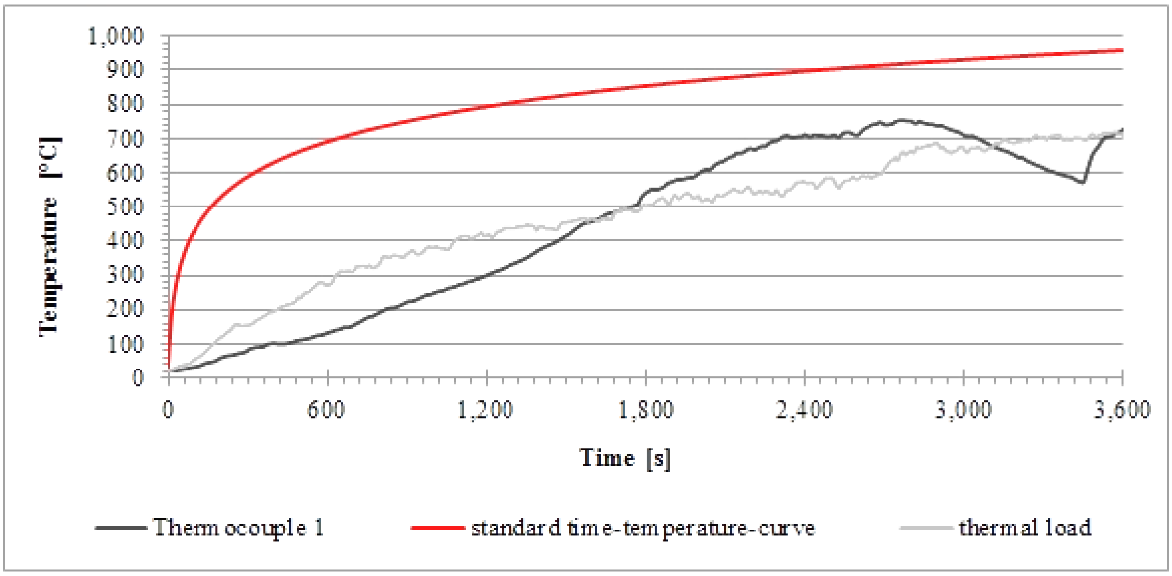

Fig. 5 Test sample with the flammable PUR foam (secondary result).

Temperature course recorded with thermocouple TC2 (at distance of 55 mm from the exposed side)

A comparison of the temperatures recorded by the TC2 thermocouple, which depended on the behaviour of the materials under thermal loading and the thermal conductivity coefficient, is shown in Figure 6.

In the 5 mm to 55 mm layer of the mineral wool, namely from the binder of the stone fibres, began $CO_2$to release. The nonflamable gas released was heated by the thermal energy from the radiant source. This resulted in an increase in temperature. The heat was guided by mineral wool insulation to the layers distal to the exposed side to the greatest extent (Figures 7 and 8).

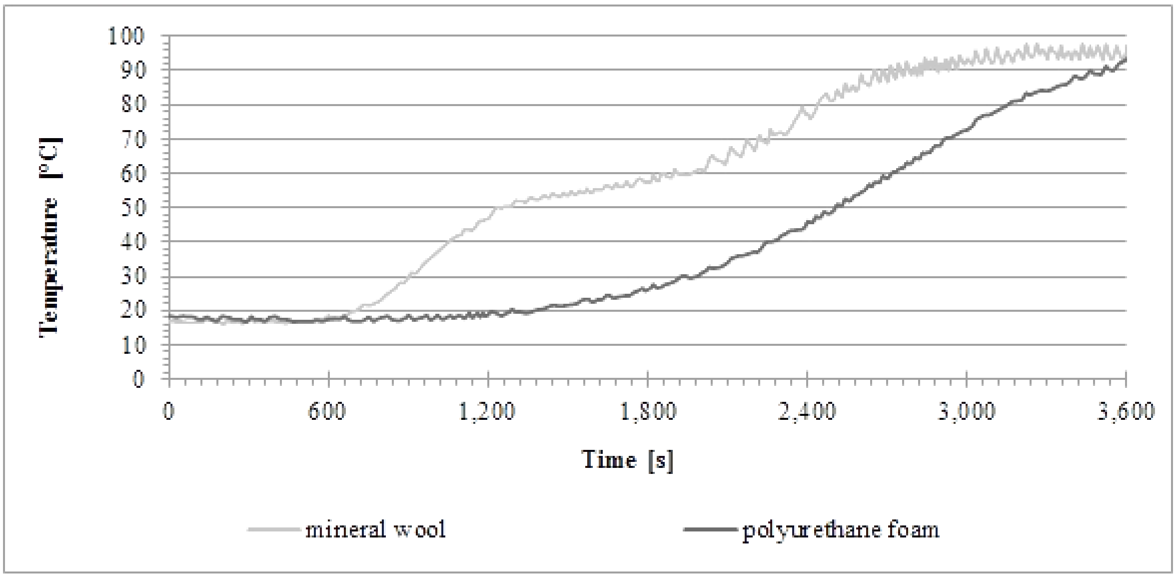

Fig. 6 Comparison of the temperature course in distance of 55 mm from the exposed side of the sample (TC 2).

The mounting PUR foam is a very easy flammable material. In the pyrolysis, there were released flammable gases, which have oxidized and ignited on the surface. This is the process, in which the insulation material has given the heat to the environment. This alternative did not result in the accumulation of hot gases as in the case of mineral wool insulation. Part of the heat was released in the exothermic reaction of the combustion, and part of the heat was led through the insulating material.

The test samples with insulating materials, the temperature courses recorded by the thermocouples at a distance of 55 mm from the exposed side depend on:

- the chemical composition of the individual insulating materials, which determines their behaviour in fire by controlled exhaust (whether an exothermic reaction of combustion occurred),
- the amount and nature of the released gaseous products (whether the accumulation of hot non-flammable gases occurred or the burning of hot flammable gases are oxidised and ignited),
- the heat conductivity coefficient.

Temperature course recorded with thermocouple TC3 (at distance of 80 mm from the exposed side)

Figure 7 shows the temperature courses recorded by the thermocouple wires, which were located 80 mm from the edge of the exposed side.

The test sample with mineral wool insulation recorded temperature of 83 °C after 60 min of the medium-scale test. The test sample, which groove was filled with PUR foam, recorded an increase in temperature by 31.5 °C after 60 min of testing.

It can be stated that the temperature course at a distance of 80 mm from the edge loaded by the fire is primarily dependent on the coefficient of thermal conductivity.

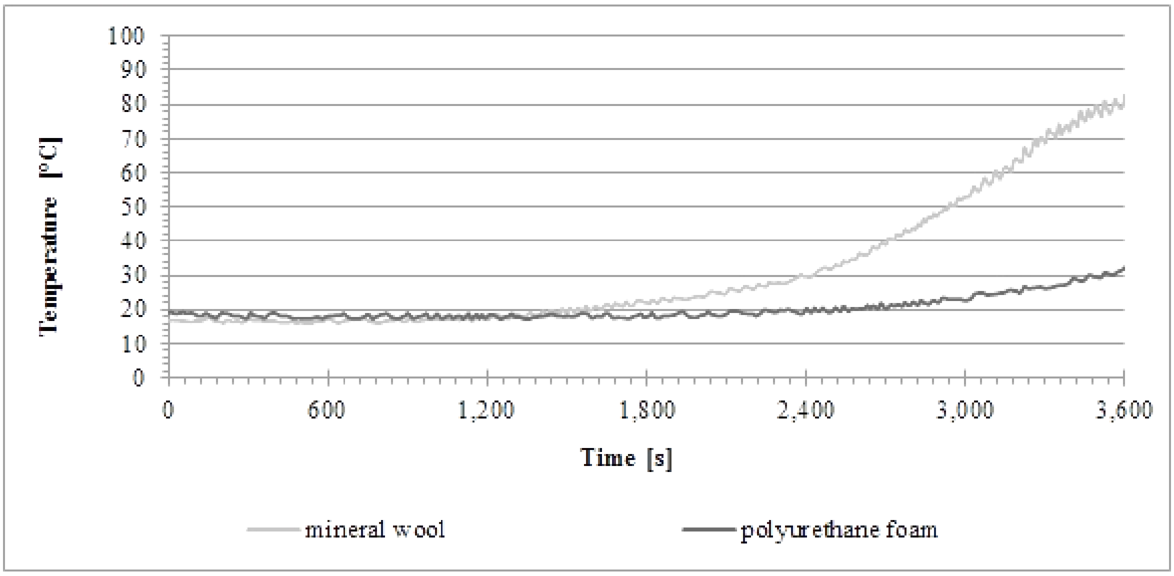

Fig. 7 Comparison of the temperature course recorded by the thermocouple TC3.

Temperature course recorded with thermocouple TC4 (at distance of 155 mm from the exposed side)

At a distance of 155 mm from the exposed side, the temperature course was recorded by the TC4 thermocouple (Figure 8). A slight increase occurred from 2,830 s in a mineral wool insulation test sample on the TC4 thermocouple. From this time to the end of the medium-scale test, the temperature increased from 19.1 °C to 28.3 °C.

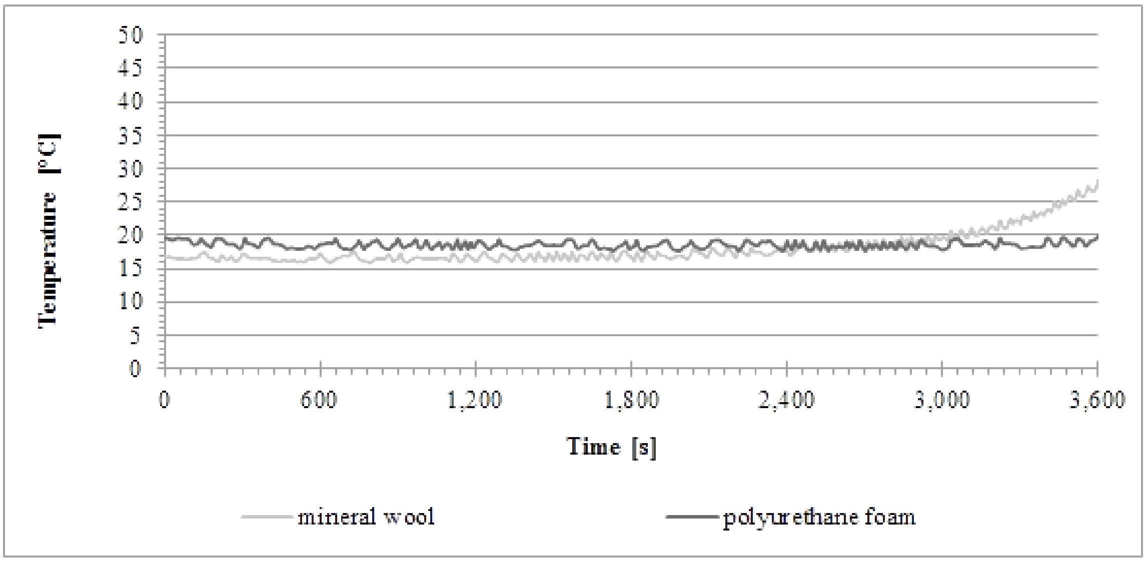

Fig. 8 Comparison of the temperature course in distance of 155 mm from the exposed side of the sample (TC 4).

Temperature course recorded with thermocouple TC5 (at distance of 205 mm from the exposed side) and thermocouple TC6 (at distance of 255 mm)

At a distance of 250 and 255 mm from the thermal loaded side, there was no temperature increase after 60 min. The temperature courses for each alternative are shown in Figures 9 and 10.

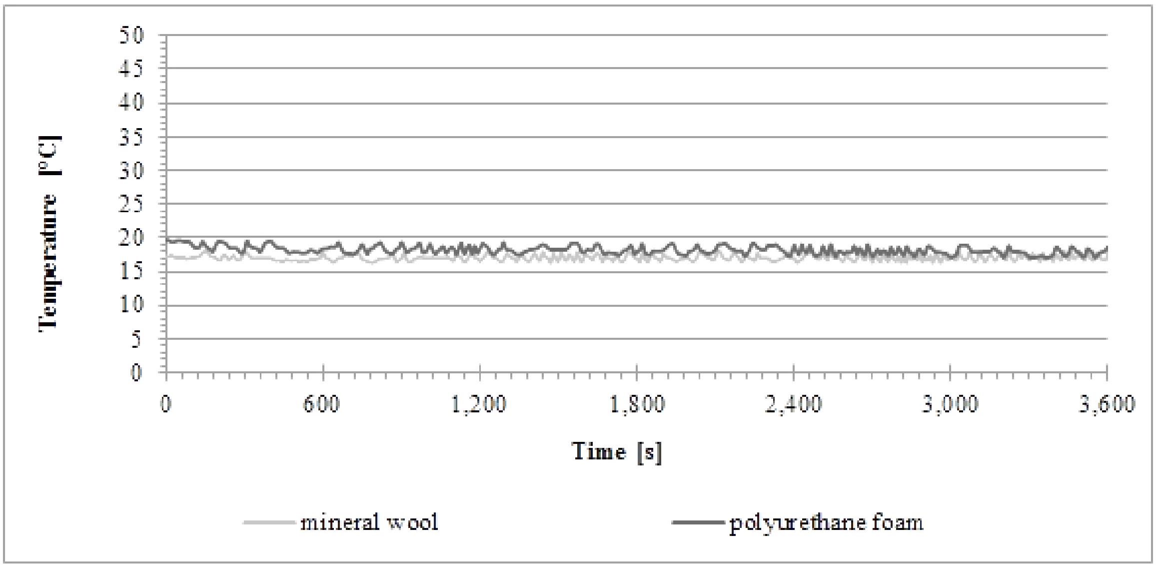

Fig. 9 Comparison of the temperature course in distance of 205 mm from the exposed side of the sample (TC 5).

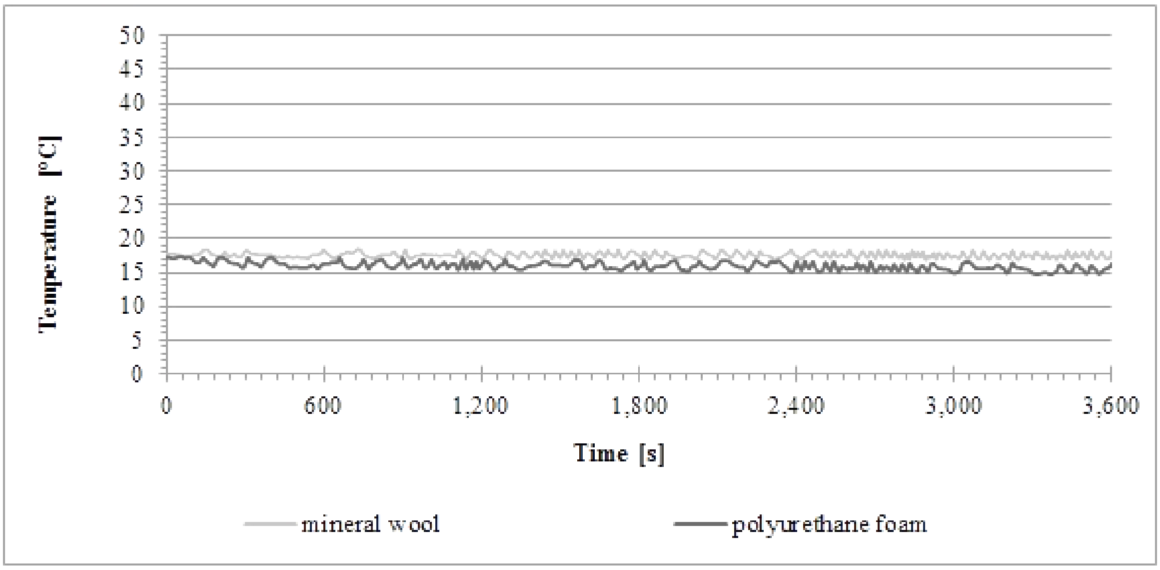

Fig. 10 Comparison of the temperature course in distance of 255 mm from the exposed side of the sample (TC 6).

Integrity criterion evaluation according to the medium-scale test results

Compliance with the integrity criterion was evaluated by visual inspection during the medium-scale test and comprehensive post-test control.

During the medium-scale test, the integrity of the unexposed side was visually checked at time intervals of 10 min, 20 min, 30 min, 40 min, 50 min and 60 min. The results from the preliminary evaluation are showed in Table 1.

According to the continuous evaluation results, it was expected that the integrity criterion will be retained.

Tab. 1 Continuous evaluation of integrity.

Test sample / Time(min)	10	20	30	40	50	60
With mineral wool insulation	X	X	X	X	X	X
With flammable PUR foam	X	X	X	X	X	X
X – intact surface; √ - formation of chinks and cracks						

After cooling down the test samples, the final visualin spection of the unexposed side was repeated for:

- Test sample with mineral wool insulation (Figure 11);
- Test sample with flammable PUR foam (Figure 12).

Based on the visual final inspection, it was concluded that no chinks and cracks were formed on the unexposed side of the test sample during and after the medium-scale test.

After the visual inspection of the test samples, no further controls were made in the determination of the integrity criterion retaining - passing of the scale from the exposed side to the unexposed was not checked.

In the medium-scale test, in which the test sample was thermal loaded for 60 min, the integrity criterion was retained for:

- Test sample with flammable PUR foam;
- Test sample with mineral wool insulation.

Fig. 11 Unexposed side of ther test sample with the mineral wool insulation after thermal loading for 60 min.

Fig. 12 Unexposed side of ther test sample with the flammable PUR foam after thermal loading for 60 min.

Thermal insulation criterion evaluation according to the medium-scale test results

The construction of the longitudinal groove located in the log wall has been partially evaluated for insulation according to the STN EN 1363-1 (2013). In this standard (STN EN 1363-1 2013), it is introduced that an increase in the mean temperature on the unexposed side during the test may not be more than 140 °C, and the rise in temperature relative to the initial temperature must not be greater than 180 °C anywhere.

In the medium-scale testing of the test samples for insulation, an increase in the temperature by 140 °C on the unexposed side was estimated.

The increase in the mean temperature on the unexposed side was not evaluated for the test samples. In the medium-scale test, six thermocouple wires (5mm, 55mm, 80mm, 155mm, 205mm, and 255mm from the exposed side) were applied, which were placed across the sample at different distances. Therefore, there was only one temperature course recorded on the unexposed side. So it was not possible to average the values recorded for one test sample.

When evaluating the thermal insulation criterion, the temperature measured by the TC6 thermocouple, which was located 5 mm from the edge of the unexposed side of the construction feature, was evaluated. At the same time, the temperatures on the exposed side are recorded as well as the heat dissipation across the longitudinal groove.

The main criterion for evaluation the insulation limit was determined by the fact that the temperature on the unexposed side could not reach 140 °C. The thermal insulation criterion was retained in both alternatives. In the case of a mineral wool insulation test sample, the temperature rise on the unexposed side was not more than 0.8 °C in comparison to the initial temperature. The specified insulation condition was retainedeven at a distance of 55 mm from the exposed side after 60 min of thermal loading, while the maximum temperature rise was of 80.4 °C.

In the case of a mineral wool insulation test sample on the unexposed side, the temperature rise was not more than 0.8 °C in comparison to the initial temperature. The specified insulation condition was maintained at a distance of 55 mm from the exposed side after 60 minutes of thermal load where the maximum temperature rise was 80.4 ° C.

There was no increase in temperature on the exposed side by the test sample with flammable PUR foam. Temperatures were not changed even at distance of 205 mm from the exposed side. The specified insulation condition was retained after 60 min of thermal loading, even at distance of 55 mm from the exposed side, where the maximum temperature rise was of 75.2 °C.

WAKEFIELD *et al*. (2009) assessed the solid timber external wall. The samples were made from the white cypress round logs and in different variations. The sample subjected to this test was thermally loaded according to the fire scenario – simulated bushfire attack. Authors summarized the performance criteria: formation of through gaps greater than 3 mm, sustained flaming for 10 s on the non-fire side, flaming on the fire-exposed surface at the end of the 60 min test period, radiant heat flux of 365 mm from the non-fire side exceeding 15 $kW.m^{-2}$, mean and maximum temperature rises greater than 140 °C and 180 °C, radiant heat flux 250 mm from the specimen, greater than 3 $kW.m^{-2}$ between 20 and 60 min, mean and maximum temperature of internal (unexposed) faces exceed 250 °C and 300 °C respectively between 20 and 60 min after commencement of test. At the 52^{th}, test sample without surface conditioning was ignition. This sample was significant charring. According to WAKEFIELD *et al*. (2009), this sample pass the criteria.

Tereňová and Jochim (2005) studied the behavior of the timber frame construction during the thermal loading. The sample was made of wood elements and thermal insulation. Thermal insulation was placed on the surface of the unexposed side. Test sample was exposed to thermal radiation field produced by a gas-fired radiation panel. At the 30^{th} min, temperature of the surface of the exposed side was of 497.6 °C. At the point of contact of the wood elements and thermal insulation, the temperature did not increase during the entire test.

CONSLUSIONS

The paper is focused on influence of specific insulating materials for the propagation of heat (or fire) by a longitudinal groove, when loading the test sample by fire. Thermal loading was applied to two alternatives of the longitudinal groove. The difference was in the type of insulating material - alternative 1 had a groove filled with mineral wool insulation material, and alternative 2 was filled with polyurethane foam. The individual test samples were fire loaded for 60 minutes, according to the fire scenario - the standard time-temperature curve.

The temperature course at a distance of 5 mm was determined by the thermal loading on the exposed side and the same time, it was also influenced by the processes that took place in the insulation material. This argument was confirmed in the case of the test sample with PUR foam. In the case flammable PUR foam, the thermocouple TC1 detected heat released during burning.

The temperature course at a distance of 55 mm from the exposed side was subjected to the chemical compositions of individual insulating materials, the amounts of gases released and the thermal conductivity coefficient of the material. Temperature course from the TC3 thermocouple was dependent on the thermal conductivity coefficient.

The main criterion in evaluating the thermal insulation was the temperature rise of 140 ° C on the unexposed side. This temperature rise did not even occur in one of the test samples.

From the building thermal protection point of view, the mineral wool insulation is a material that shows better heat transfer than PUR foam. However, PUR foam has a reaction to fire class F according to the STN EN 13501-1. At the thermal loading of this alternative, flammable gases have started to be released from the test sample, which have oxidized on the surface and were subsequently ignited. For this reason, it represents a higher risk from the point of view of fire safety.

During the medium-scale test and after the test, a visualin spection on was carried out, concluding that the other procedures for determining the integrity would not be considered to be examined – passing of the scale from the exposed side to the unexposed. Unexposed side of the test samples was intact and criterion of integrity was retained for samples.

Test samples, which were compared by a comparative method, retained their integrity and thermal insulation during the medium-scale test with duration of 60 min.

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