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SIMULATION OF A COMPARTMENT FIRE EFFECT ON A LOAD-BEARING WALL MADE OF STRAW

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ABSTRACT

Natural materials, including straw, are increasingly becoming more popular in the construction industry. Load-bearing external walls made of straw bales demonstrated remarkable fire resistance results according to tests carried out abroad. The aim of the paper was to determine the ability of a representative sample of a load-bearing external wall made of straw to withstand the effects of a compartment fully developed fire by simulation using the ANSYS modeling program. The program primarily uses mathematical modeling methods for a virtually created model. The simulation results showed that under the stress of a compartment fully developed fire, a charred layer is gradually formed on the surface of a straw structure, which protects the remaining construction for an expected fire resistance of 120 minutes. The ANSYS program simulation results were comparable to the test performed in an authorized test laboratory.

Keywords: load-bearing wall made of straw; compartment fully developed fire; simulation; fire resistance.

INTRODUCTION

Current lifestyle trends, especially in housing, indicate a preferred return to natural housing (Loučanová *et al.,* 2023). Straw as a building material deserves considerable attention in the modern era of building sustainable creation as a natural, energetically, and environmentally sustainable material. (Džidic and Milíčić, 2017). By insulating houses with straw bales, passive house standards can be achieved.

Straw walls are generally made of straw bales with subsequent treatment that may include clay, cement, and hardwood as an additional thermal insulation layer (Tlaiji *et al.*, 2022). The requirements for mechanical and physical properties are determined by the density of the materials (Konečný *et al.*, 2013). The density of straw bales has an influence on the thermal insulation properties of the external walls. This means that as the density increases, the coefficient of thermal conductivity also increases, which has the effect of reducing the thermal insulation properties of the structure. The same relationship exists between humidity and thermal insulation properties, which change over the course of the year.

The density of straw bales used as building material depends on the function they perform. There are two different construction systems for straw bale walls. The first system is presented by a load-bearing wall made of straw bales, which directly transfers the roof's weight through the straw bales to the foundations. Such a wall is also called a load-bearing straw wall. If the structure is made of bales that perform a load-bearing function, the recommended bulk density is 90-120 kg.m^{-3} (Konečný *et al.*, 2013). King (2006) gives a more specific value of 130 kg.m^{-3}. The second construction system is a skeleton construction, usually made of wood, filled with straw bales, or made with an extended shell made of straw bales. If straw bales are used as filling material, i.e., they do not perform a load-bearing function, their volume density is around 70 kg.m^{-3} (King, 2006).

Straw bales are used to construct self-standing straw houses or as the main insulating and filling material of wooden constructions. Like all other buildings, buildings made of straw bales must also meet the fire safety requirement. Research in the field of straw construction shows that straw bale walls can meet the required fire resistance requirements.

Fire resistance is an unexpected property of straw bales because straw is highly flammable, whereas straw bales can provide fire resistance comparable to traditional building materials (Cascone *et al.*, 2019).

This fact is also confirmed by Teslík (2021), who describes fire tests performed on non-plastered straw bales with a density of 90 kg.m^{-3} to 150 kg/m^{-3}. It was concluded that the bale of straw would be classified in fire reaction class E according to STN EN 13501-1:2019.

However, if the structure made of straw bales is plastered, it achieves more favorable results compared with non-plastered construction. Such a construction was tested in an authorized PAVUS testing laboratory and, as stated by Růžička (2021), based on the tests performed, the construction reached a fire resistance of REI 120 min.

Cascone *et al.* (2019) claim that the increased fire resistance of straw bales is attributed to the plaster applied to the structure, as it provides an insulating barrier against the heat source and oxygen access to the straw. As the reason for the thermal stability of straw bales, Marković and Milić (2018) point out the lack of oxygen in the bale, which prevents the straw from ignition. The amount of oxygen can also be reduced by suitable compression of the stalks. The more the stalks are compressed in a bale, the less space is left for air (Theis, 2003; and Džidic and Milíčić, 2017).

The aim of the contribution is to point out the temperature behavior in different layers of the building construction made of load-bearing straw when loaded with the effects of an internal fire. Temperature curves are obtained from the simulation in the ANSYS program (ANSYS, Inc., Canonsburg, Pennsylvania, U.S.). The validity of the simulation results will be confirmed by comparison with those obtained in the authorized PAVUS test room.

MATERIAL AND METHODS

Modelling methodology

The subject of the investigation is the assessment of the requirements for fire resistance of a structural element of the external wall made of load-bearing straw. The structural element is made of straw bales, on which clay plaster is applied. The time during which the sample can withstand a compartment fully developed fire following STN EN 13 501-2:2023 is assessed. The sample is loaded with temperature according to the standard temperature curve, representing the conditions of a fully developed fire inside a building. The course of this curve is determined according to the equation:

$$T = 345 \log 10\,(8t + 1) + 20 \tag{1}$$

Where: *t* is the time from the start of the test, which is expressed in minutes (STN EN 13 501-2, 2023).

Simulation in the program ANSYS (ANSYS, Inc., Canonsburg, Pennsylvania, U.S.) can help us verify the behavior of a real or imaginary object. The ANSYS program primarily uses mathematical modeling methods for a virtually created model.
The subject of the test is a load-bearing wall sample made of wheat straw bales laid flat. The sample has dimensions of 1600 mm x 1200 mm x 600 mm (width x height x thickness) and has the following composition:
• multi-layer clay plaster with a total thickness of approximately 50 mm,
• A load-bearing layer of straw bales with a thickness of 500 mm is placed on top of each other in three layers. The bales are placed on the lower bond beam and mounted on four guiding rods with a thickness of 40 mm. After the third layer, the upper bond beam is installed, and the wall is tightened with tightening belts. In the upper bond beam, there are four holes for inserting rods with a thickness of 40 mm and a length of 800 mm in the axis of the straw wall.
• external earthen plaster of 50 mm thickness with the addition of horse dung, shredded hay, and sand.
Cross and Longitudinal sections of the examined sample are shown in Fig. 1.

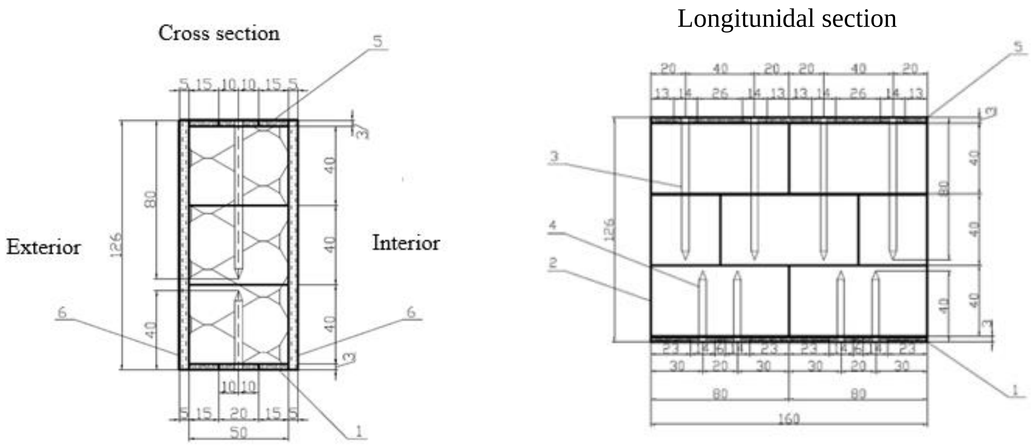

Fig. 1 Cross section and Longitudinal section through a straw bale wall.
1 – lower bond beam, 2 – straw bale, 3 – vertical rod in the axis of the wall, 4 – guiding pin, 5 – upper bond beam, 6 – earthen/clay plaster

The data needed for modeling

To verify if fire resistance requirements were met, the input data on the materials forming the construction and their properties are necessary. Tab. 1 shows the properties of materials that compose a straw bale wall; their characteristics include thickness, specific heat capacity, thermal conductivity, and density.

Tab. 1 Properties of the constituent building materials (Růžička and Pokorný, 2021).

	Material	Thickness (mm)	Specific heat capacity (kJ.kg^{-1}.K^{-1})	Heat conductivity (W.m^{-1}.K^{-1})	Density (kg.m^{-3})
1	Earthen plaster (exterior)	50	0.24	0.53	1300
2	Straw bale (flat laid)	500	2.74	0.12-1.5	120
3	Clay plaster (interior)	50	0.24	0.53	1300

Geometry and discrete modeling

The finite element model (FEM) was created in the "SpaceClaim" environment (ANSYS, Inc., Canonsburg, Pennsylvania, U.S.) and was simplified to the straw bale wall model and simple radiation panel without small structures and the environment. Their absence did not affect the simulation results and speeded up the calculations. "Patch Conforming Method" was applied to create the straw bale wall and radiation panel mesh. The hexahedral mesh with an element size of 20 mm was created for the wall, while the hexahedral mesh with an element size of 10 mm was created for the radiation panel. A total number of 62,179 elements and 274,358 nodes for the straw bale wall were generated. The connection area in the model was created manually, representing the thermal connection between the radiation panel and the thermally loaded surface of the straw bale wall. Fig. 2 shows an automatically generated finite element mesh.

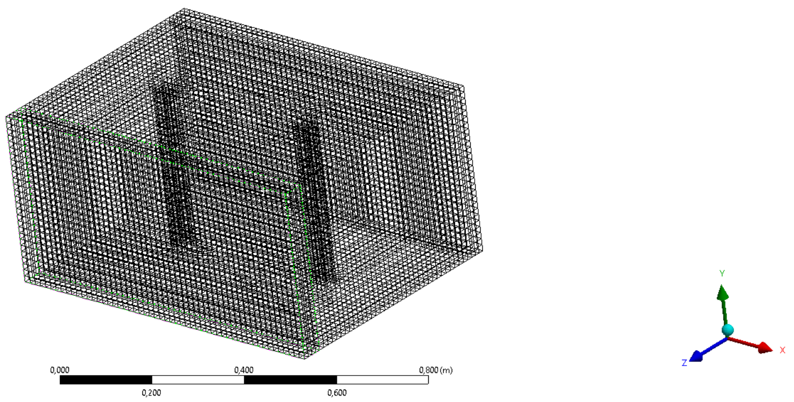

Fig. 2 The mesh of finite elements.

Validation of the model

The designed FEM of the load-bearing straw wall plastered with clay plaster was verified using data from the test that took place in the Czech Republic in the fire test room in Veselí nad Lužnicí PAVUS, Plc., which is accredited by the Czech Institute for Accreditation, where a similar fire resistance test of a load-bearing wall made of straw bales (thickness 500 mm) plastered with clay plaster from the inside (thickness 50 mm) and the outside (thickness 30 mm) was performed. The temperature in the furnace increased according to the standard temperature curve, identically to the development in our model.

Fig. 9 compares the temperatures measured in PAVUS and the temperatures recorded during the simulation in the section behind the internal clay plaster.

RESULTS AND DISCUSSION

A simulation of the fire load of a structure was carried out. The temperature of which increased using a standard temperature curve. The temperature curves were evaluated at several layers - on the surface of the clay plaster on the exposed side, in the layer between the clay plaster and the straw bale, and at one-third of the thickness from the clay plaster. The behavior of the materials and load-bearing elements in the structure was observed. Fig. 3 illustrates the temperature profile of the straw wall sample in the ANSYS program from the beginning of the simulation for 150 minutes. The temperature profile of the simulated fire load shows that the temperature on the unexposed side of the sample did not rise.

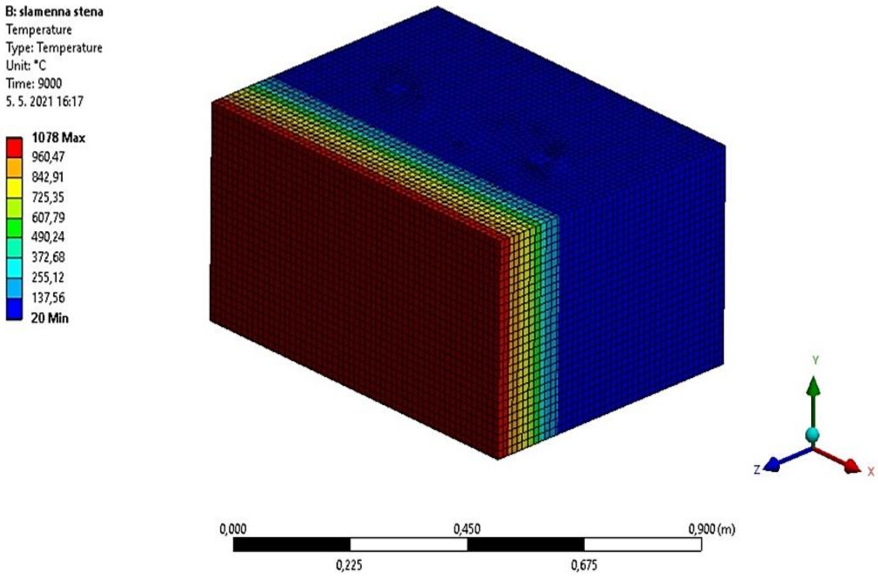

Fig. 3 Temperature profile of a straw bale wall sample in ANSYS program.

Results for the clay plaster surface on the exposed side

The first layer of the straw wall was created by clay plaster, whose temperature reached 1078°C in the 150th minute of the test (Fig. 4). We can assume that as the temperature rose, the clay plaster burned and cracked, creating cracks through which air could penetrate under the plaster. This fact is also reported by Janowska-Renkas et al. (2022), who state that firing the clay plaster changes its structure, which creates cracks in it. Garas *et al.* (2009) observed the behavior of straw samples stressed by fire, plastered with cement, lime, and sand plaster; in the 25th min., they noted the formation of cracks on the exposed side of the sample from which visible smoke was escaping. During the simulation, it was observed that the clay plaster turned into ceramic and formed a non-combustible layer. The plaster represented a certain insulating barrier (Růžička, 2021; Cascon *et al.,* 2019; Theis, 2003; Li *et al*., 2023) against the heat source and oxygen access to the straw.

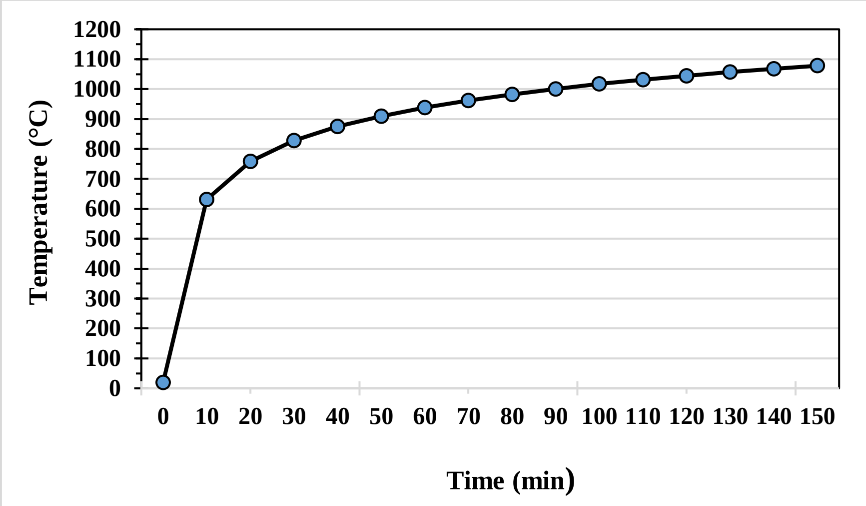

Fig. 4 Temperature development on the clay plaster surface depending on time.

Results for the layer between the clay plaster and the straw bale

The temperature rise between the clay plaster layer and the straw bale is recorded in Fig. 5. After the end of the simulation, the temperature at this point reached a value of 869.96°C.

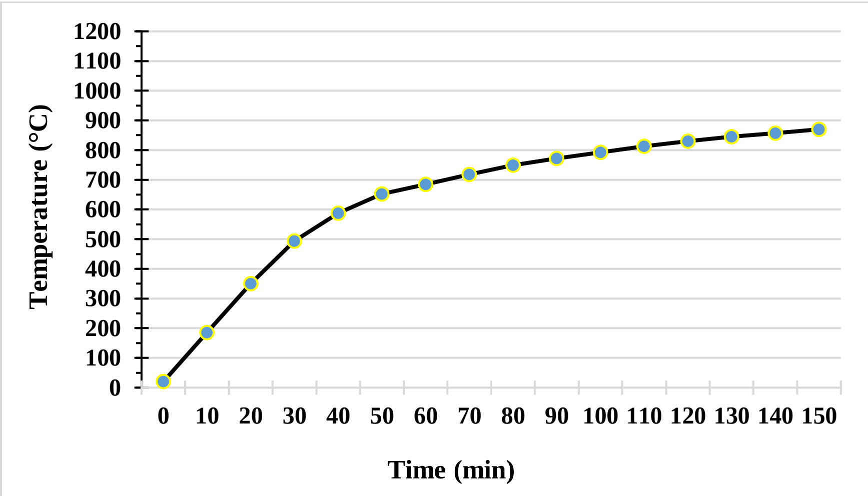

Fig. 5 Temperature development in the layer between the clay plaster and the straw bale.

At the same time, we can state that up to the 20th minute, the structure of the external wall behaved as a structural element of type D2 (the combustible material inside the sample must not reach the ignition temperature). Since the temperature in this layer has reached the flash point of the straw, i.e., more than 310°C, we can consider this composition only as a structural element of type D3. If burning occurs, the straw undergoes pyrolysis or combustion reactions. The pyrolysis of wood materials is equivalent to the sum of the pyrolysis reactions of each component in the order of hemicellulose, celluloses, and lignin (Aleń et al., 1996). The main reaction temperatures are 210–320 °C, 310–390 °C, and 480–510 °C (Greenhal et al., 2012; Wu et al., 2009). The reaction sequence of straw combustion is the same as that of wood pyrolysis (Li, 2023).

Figure 6 shows the temperature profile between the clay plaster and the straw bale.

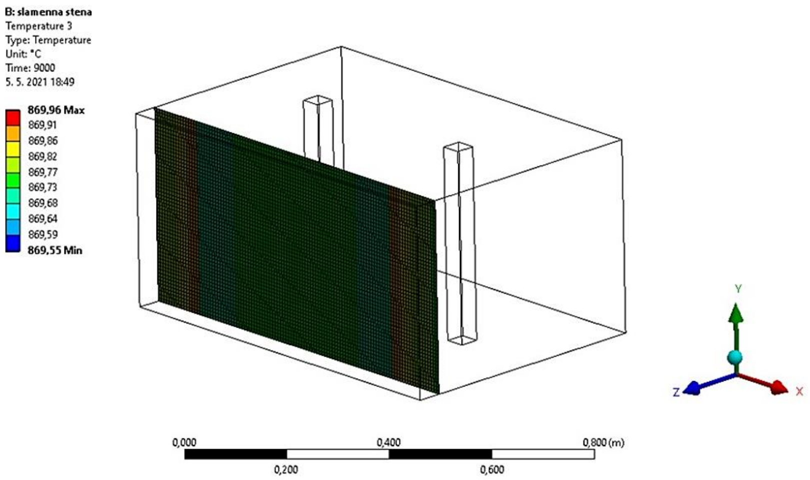

Fig. 6 Temperature profile between the clay plaster and the straw bale.

Results for the 1/3 of thickness from the clay plaster

In one-third of the thickness of the straw bale from the clay plaster, the temperature reached 161.51°C in the 150th minute, i.e., approximately half of the ignition temperature of the straw. Fig. 7 shows the temperature profile for a distance of 1/3 of the thickness from the clay plaster.

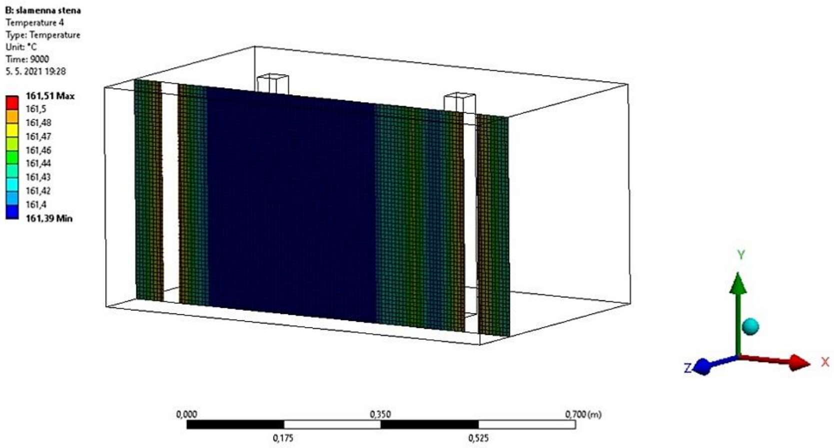

Fig. 7 Temperature profile for one-third from the clay plaster.

As mentioned above, in addition to the plaster as an insulating barrier, the compression of the straw into the bale affects the fire resistance. Compressing the straw into the block significantly reduces the amount of oxygen, thus limiting one of the components of the burning triangle (Theis, 2003). The mentioned aspects are the reasons for the low-temperature values (Fig. 8) measured in one-third of the thickness of the straw bale from the clay plaster exposed to the fire's effects.

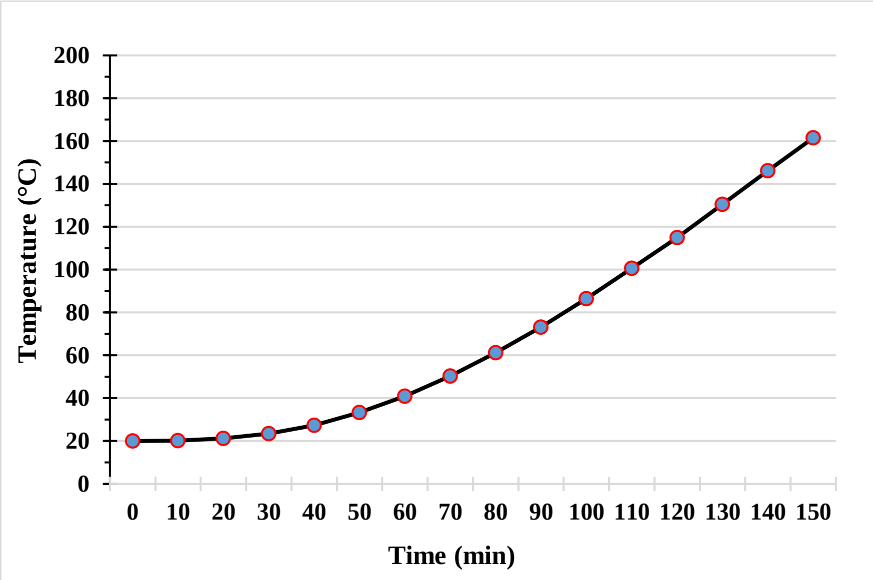

Fig. 8 Temperature development in one-third from the clay plaster.

The difference in temperature behavior in the individual examined layers of the test composition of the load-bearing straw wall is recorded in Fig. 9. The highest temperature on the surface of the plaster reached 1078°C; 870°C in the layer between the plaster and the straw bale, and just under 162°C in one-third of the thickness of the clay plaster.

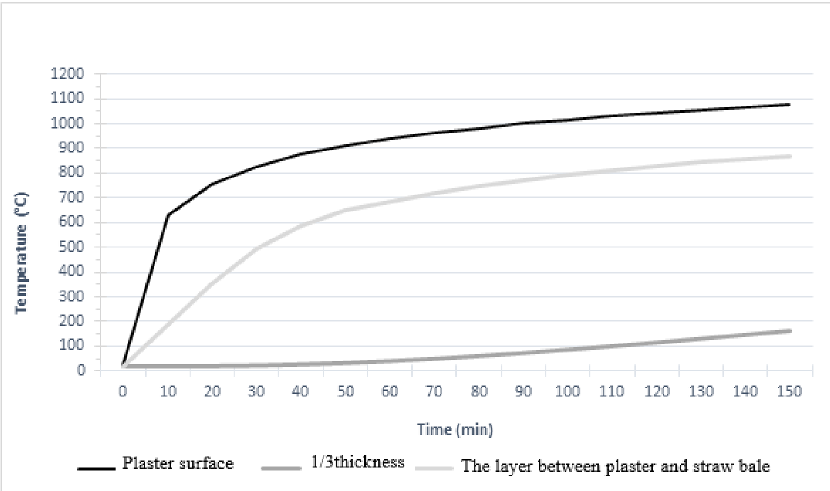

Fig. 9 Temperature measured in individual layers of the wall.

On the unheated side of the sample, the temperatures were much lower than the temperatures measured in one-third of the thickness from the clay plaster. This means that the examined sample would maintain thermal insulation criterion I during the entire duration of the model fire (the average temperature on the unexposed side of the structure must not increase by more than 140 °C according to STN EN 13 501-2:2023).

We assume that the integrity of sample E on the exposed side was violated because, at the 20th minute, the ignition temperature of the straw in the layer between the clay plaster and the straw bale was exceeded (the measured temperature was 350.33°C).

Based on the obtained results, it can be assumed that during the entire duration of the test, the load-bearing and stability criterion R will also be preserved. Therefore, the structure under investigation could be classified as 15 REI/D2 or 120 (150) by STN EN 13 501-2:2023 REI/D3.

The comparison of the temperatures during the test in the authorized PAVUS test room and the output from the simulations is shown in Fig. 10. The temperature curves are compared in the part behind the internal clay plaster, and the temperature rises steadily. The graph in Fig. 10 shows that there is only a negligible difference between the values from PAVUS and the simulation results, and the measured and predicted values largely overlap. Comparing the simulation results and the results from PAVUS suggests that the model is validated and usable for further simulations.

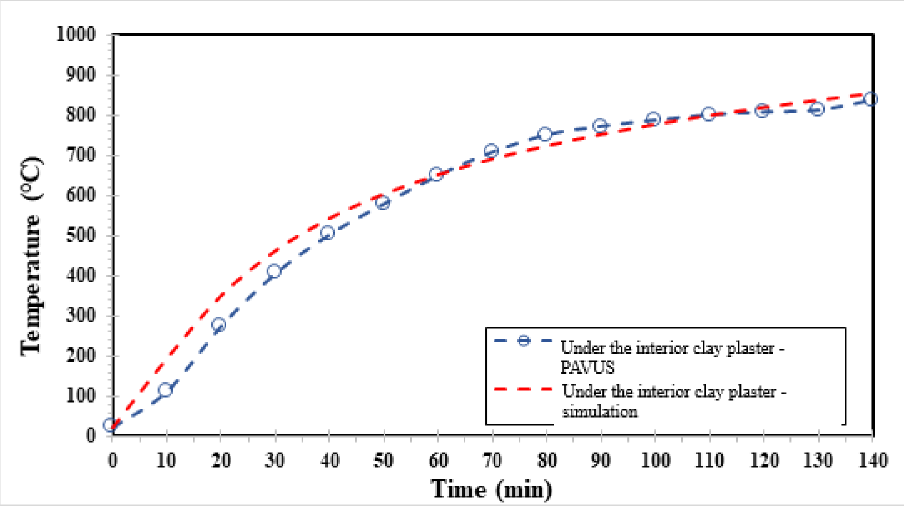

Fig. 10 Comparison of temperatures in validation.

Marković and Milić (2018) describe the results of the experiment by Grelat (2004), which was carried out in France and achieved remarkable results. The experiment was carried out on a wooden structure filled with straw bales with dimensions of 1.85 x 1.9 x 0.4 m. The authors (Marković and Milić, 2018) described the above experiment as follows:

The surface of the wall exposed to the fire load is plastered in two layers with lime plaster 2 cm thick over the plaster strip, while the other side is plastered with the addition of chopped hemp as a binder in the lime plaster. The thickness of the straw bale layer in the wall was 36 cm. The model is equipped with thermometers that measure the temperature in the wall and are placed on the surface of the exposed wall and inside the construction. The wall was subjected to a fire load for 85 minutes with a temperature of 800 °C on the fire-loaded side. Temperatures measured inside the structure (in the straw layer) did not exceed 200 °C. The construction did not collapse during the test, and its load-bearing capacity was not impaired (Marković and Milić, 2018).

CONCLUSION

A simulation of fire load on a structure made of straw bales was performed. The temperature was set according to a standard temperature curve. The simulation result met expectations as the straw wall resisted the fire for more than 120 (150) minutes. On the unexposed side of the sample, the temperature increased only slightly during this time, and there was no integrity violation. By adhering to the mentioned fire resistance criteria, it can be assumed that the load-bearing and stability criteria of the structure will also be adhered to. According to STN EN 13 501-2:2023, the investigated structure can be classified as 15 REI/D2 or 120 (150) REI/D3. Based on the comparison of the simulation results and the results from the authorized PAVUS testing laboratory, the model can be considered valid and usable for further simulations.

At the same time, the results of the simulation revealed that the plaster covered the structure from the exposed side for approximately 20 minutes and created an insulating barrier against the heat source and oxygen access to the straw. Then, the plaster starts to crack. After the integrity is broken, straw bales behave like solid wood, meaning the outer surface burns and creates char, protecting the other fibers below the surface from the flames. Such behavior is evidenced by the temperatures measured during the simulation in 1/3 of the thickness of the straw bale from the clay plaster.

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